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Building a sustainable future:

A COMPARATIVE LIFE CYCLE ASSESSMENT OF A CROSS-LAMINATED TIMBER AND A LIGHTWEIGHT STEEL FRAME BUILDING

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Master thesis report

Title

Building a sustainable future: a comparative life cycle assessment of a cross-laminated timber and a lightweight steel frame building.

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Front page image

Interpretation of a "*futuristic city with wooden and steel houses in a forest with solar panels and windmills*" created by DALL-E 2, AI software created by OpenAI.

Preface

The master thesis in front of you started with the desire to better understand the impact of building with timber and adding to the body of knowledge on this subject. This desire was met by a question Nico van Hoogdalem had on the sustainability potential of reusable steel in comparison with timber. Together with Mingming Hu, Bernhard Steubing, and Mike Slootweg, this question developed into the following report between the months of February and November of 2022.

This report could not have been completed without the friendly and insightful criticism by my primary supervisor, Mingming Hu. Especially her talent for cutting through my, at times too convoluted, ideas to distill the main point has been greatly appreciated. The help of Bernhard Steubing has also been invaluable to me, through his insight on timber buildings and the LCA method. I appreciated our conversations on different methods for including carbon storage and end-of-life benefits, often with the outcome being: “either method is valid, as long as you specify how and why you chose it’.

I would also like to thank Mike Slootweg, first for bringing me into contact with Nico van Hoogdalem and helping me start my thesis, but mainly for helping get through the moments I got stuck in my research. His advice to simply switch to a different task if I got stuck on one turned out to be very helpful. Furthermore, I am grateful for Marc van der Meide, who helped me understand the software used, Activity Browser, far better.

Next, I would of course express my appreciation for Nico van Hoogdalem, who inspired the topic of my thesis, to compare the sustainability of building with steel or timber for the Dutch housing crisis, and for his knowledge of and connections in the Dutch construction industry. Through his network I got into contact with Urban Climate Architects who provided the data on the timber building case study, and Re-Buildit who provided the data for the steel frame variant. The collaboration of these companies has allowed my thesis to be grounded in real data, for which I am very grateful.

Finally, I am grateful for all the support I have received from my personal network, through friends, family, and my girlfriend, who all were available when needed to listen to my struggles with the topic and the process and helped me get through the difficult moments. I would especially like to express my gratitude to the immeasurable patience and care of my girlfriend Sharon, without whom the following report would not have been of the same quality.

Summary

The Netherlands has faced rapidly increasing housing prices over the previous years. As a counter measure, the government is aiming to increase the construction of new houses from around 70 thousand annually to 100 thousand annually, to achieve 900 thousand new houses by 2030. At the same time the world is facing a climate crisis and the Netherlands has pledged to decrease its emissions by at least 50% in 2030 in respect to 1990. The country must therefore reduce the impact of new built houses to be able to build more while reducing the total emissions.

Currently most houses are built with reinforced concrete which is generally not seen as a sustainable construction method due to the carbon emissions related to cement production. Building houses with cross-laminated timber panels or lightweight steel frames are proposed alternatives with a lower expected carbon footprint. This study was set up to perform a life cycle assessment of a steel and a timber building to compare their impact and find out under which circumstances building with steel or timber is a more sustainable option. A case study was found of a timber building and a hypothetical alternative was designed with steel frames which were both studied under three scenarios. The scenarios represent the choices that could be made regarding material production and waste treatment, ordered from worst-case, to expected, to best-case scenario.

When including the climate impact of construction, the treatment of waste, end-of-life benefits and carbon storage, the timber building performed better than the steel building in every scenario regarding global warming. However, waste treatment, end-of-life benefits and carbon storage are all dependent on future processes and emissions happening after 2030. When only the construction is included, the steel building outperformed the timber variant in the expected and best-case scenario. For this reason, building more houses with lightweight steelframes produced with at least 50% recycled steel would be the most beneficial for the Netherlands to reach its 2030 climate goals. When taking a longer timespan into consideration, timber buildings are the preferred choice due to the carbon storage effect, as long as the forests are replanted sustainably.

Either alternative was found to be a better alternative than the current houses built with reinforced concrete. If all houses built before 2030 were made with the alternative production methods this could save at least 20 Megaton of CO_2 emissions. Because the alternatives researched made efficient use of materials, no significant issues were found for the demand of wood or steel in the Netherlands. In fact, steel demand is likely to decrease due to the reduced need for reinforcement steel. Further improvement on both alternatives is possible by increasing the potential lifespan of the buildings and reducing the emissions related to energy use in the production of materials.

The outcomes of this study may influence decision making depending on the weight the Dutch government gives to its climate goals of 2030 versus its total impact on climate change. Constructing steelframe houses may reduce construction emissions by 4% compared to timber by 2030 but would result in 64% more emission in 2100 due to the missed-out carbon storage. In general, the construction industry can improve a lot by increased use of low-carbon alternatives such as lightweight recycled steel and biobased materials.

Table of Contents

Glossary of Terms and Abbreviations

Abbreviation	Definition
AB	Activity Browser
ALO	Agricultural land occupation
CC	Climate change
CLT	Cross-laminated timber
CO_2	Carbon dioxide
EOL	End-of-life
FU	Functional unit
GHG	Greenhouse gas
GW	Global warming
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LSF	Lightweight steel frame
MD	Metal depletion
PV	Photovoltaic
RC	Reinforced concrete

List of Tables

List of figures

1. Introduction

1.1. Background

Housing in the Netherlands is rapidly becoming more expensive. Selling prices in 2021 are over 50% higher than in 2015 (CBS, 2022a). This has created pressure on the Dutch government to intervene. Part of the proposed solution to this issue is the construction of new houses. On "Prinsjesdag" 2021 the government presented their plans to invest 1 billion euro to build 900,000 new houses by 2030 (Rijksoverheid, 2021). With a current production of 70 thousand houses a year, this will require a significant increase in materials and labour.

Parallel to the Dutch housing crisis runs the global climate crisis. To keep global warming below 2 degrees as per the Paris Agreement, the EU agreed on a reduction of carbon emissions by 55% in 2030, compared to 1990 (BBC, 2021). In 2010, around 15% of all greenhouse gas emissions originated from the burning of natural gas to heat buildings, and 5% from the construction of new buildings (Bijleveld et al., 2014). This demonstrates that to meet the target, new houses should be built with less emissions during both the production and use phase. According to Bijleveld et al. the largest share of the construction industry's emissions stem from material use, responsible for 70%. Reducing these emissions while increasing the number of houses built will be challenging and requires a well-informed strategy. Currently these building materials mostly consist of concrete by weight. For housing construction, this is over 75% of the mass (Arnoldussen et al., 2020). The production of concrete releases a significant amount of greenhouse gases. This means finding alternatives with a smaller impact could be an effective way to bring down the emissions share of the construction industry.

This report proposes to investigate the environmental impacts of two alternatives to concrete. The first alternative is the use of construction with cross-laminated timber (CLT), which has been receiving more attention over the previous years. Amsterdam has the ambition to have 20% of new construction made of timber from 2025 onwards (Metropoolregio Amsterdam, 2020). Timber is considered a more environmentally friendly alternative to concrete as wood is renewable, stores carbon, is lighter and requires less energy to process (Peñaloza, Erlandsson, & Falk, 2016).

A different approach to more sustainable construction is using lightweight steel frames (LSF), which allow houses to be built quickly and disassembled easily. These frames could then be reused in new construction or recycled into new frames. Re-Buildit Group is a company producing such frames and will support this research with data on their production processes. As a large part of the impact of steel comes from the energy intensive production process, reuse of the material significantly decreases its impact. On top of this, Re-Buildit is constructing a steel frame factory that can run on electricity from solar panels which could further reduce associated emissions.

Timber's reuse and recycling options are more limited, and an increased demand in timber from the construction industry may cause other issues besides global warming, such as biodiversity and forest area loss. Therefore, assessing these alternatives over their combined impact on climate change and material demand while accounting for carbon storage and reuse is required to make a full comparison. This paper carries out a life cycle assessment (LCA) to include all these considerations and provide a comparison of steel and timber construction in the Netherlands.

1.2. Knowledge gap

Due to the concerns on climate change and the impact of the building industry expressed in the introduction a lot of research has been done into this topic. Much of the papers study the impact of the energy use of buildings and how to reduce this, as it accounts for 17.8% of global emissions (Ritchie, 2020). However, the emissions due to material productions is increasingly being considered in studies, as they will grow more important to the construction sector when energy related emissions decrease. Currently, most houses around the world are constructed with concrete and steel, for which the production contributes at least 10% of global emissions (United Nations Environment Programme, 2021). Research has been done to find out what alternative strategies would bring the largest reduction in emissions. One study from 2021 found that for Western Europe the most effective options would be to make design more lightweight, use more biomass, recycle more materials and reduce floorspace (Zhong et al., 2021). These are also the strategies that the proposed alternatives try to implement. A steelframe house uses a lighter structure with less steel and concrete than a conventional reinforced concrete (RC) house. If the frames are easily demountable, this can also increase recyclability. Wooden buildings built with cross-laminated timber (CLT) on the other hand apply more biobased materials instead of regular materials to bring down emissions.

To compare specific buildings or building materials life cycle assessments are commonly performed to allow comparison of two alternatives on a variety of impacts and trace these impacts to different points in their lifecycle. A Norwegian study compared a steel and concrete building with a CLT building of the same type, and found that the timber variant caused 25% less greenhouse gas (GHG) emissions in the production stage and 13% less in all stages (Eliassen, Faanes, & Bohne, 2019). However, the study only included material production, transport, and energy use. Another paper that compares conventional building materials with timber did include waste treatment and the end-of-life (EOL) stage and found that a CLT building produces 50% less GHG emissions than a reinforced concrete (RC) building during material production and construction. However, emissions were larger during the operational stage and EOL. Overall, the timber building still produced 30 to 34% less GHG emissions over its lifetime. Different wood construction products have also been tested against each other in a study of CLT and glued-laminated timber which found CLT to have a 40% smaller impact (Balasbaneh & Sher, 2021). Neither of these studies implemented the carbon storage effect of wood. A review paper of LCA studies of CLT versus RC houses concluded that the CLT version performed better in every study, but that the methods varied a lot between different studies (Cadorel & Crawford, 2019). The effect of carbon storage was either excluded, considered as neutral, or as a percentage sequestration.

Some research has been done into steelframe houses, but far less than into CLT and biobased building methods. A Brazilian study compared a conventional brick house with a light steel frame (LSF) house and found that the LSF house contributed 16% less to global warming in the construction phase (Caldas et al., 2017). However, because the designs had different insulation values the brick house eventually performed better in the use phase. The study did not include potential uses for the material after EOL. A study on structural steel and timber did include various types of steel and timber waste treatment, as well as methods of accounting for biogenic carbon (Morris, Allen, & Hawkins, 2021). In their results, high recycled content steel could closely match the impact of timber if it was incinerated at EOL. This study only compared the materials as a structural element, not in application in a house. A study that did compare an LSF house with a timber frame house concluded that the timber building emitted 2.2% less emissions but did not include recycling or carbon storage effects (Coelho et al., 2014). Finally, a Portuguese study compared a prefabricated LSF and wood frame house with two types of conventional RC houses. The study did include recycling, but not carbon storage, and found that the prefabricated houses have a smaller impact than the conventional ones, with the wood frame house being the smallest contributor to global warming (Tavares et al., 2021).

Overall, it appears that CLT has been studied in LCAs more frequently than LSF houses, but with widely varying choices regarding the inclusion of recycling or reuse, and carbon storage. The studies that involved LSF did not include potentially higher recycled content, and the study into steel that did include this didn't study it in the context of a house. Therefore, there is still a gap regarding the sustainability of LSF houses if the used steel has a high recycled content and is potentially reused at EOL. At the same time, this should be compared with a CLT house that is also recycled or reused and includes a form of carbon storage. By including different scenarios for these options mentioned above, a more complete indication can be given as to what the extent of influence is of these different choices.

1.3. Research question

To contribute to the discussion of what type of housing would be more sustainable for the Netherlands to adopt, and to add to the knowledge gap described above, the study aims to answer the following research question:

Under which circumstances is timber or steel frame construction the more environmentally sound option for houses built in the Netherlands before 2030?

The following sub-questions correspond to this main question:

- How do the two alternatives compare regarding global warming impact?
- What is the influence of different production and end-of-life choices?
- Which processes or materials contribute most to the global warming impact?
- How significant is the carbon storage effect of timber?
- How could either alternative contribute to the 55% emission reduction plans for 2030?
- How large is the influence of either choice on steel or timber demand in the Netherlands?

1.4. Organisation of the report

Chapter 2 will explain what methods will be taken to answer the research questions stated above. First it will go into why LCA is the chosen method, then discuss LCA procedures such as goal and scope definition and inventory analysis. Next, Chapter 3 will show the results including impact assessment on global warming, land use and metal depletion, followed by extrapolating these results to the national level. This section will discuss the impact of either building method on the national climate plans and material demands for timber and steel. Finally, chapter 3 will give a sensitivity analysis on the impact of lifespan and substitution choices. These results will be discussed in Chapter 4, giving an interpretation of what they mean, the implications for the Dutch construction industry and limitations of the chosen methods. Finally, the report will conclude the findings of the research and give recommendations regarding sustainability choices and future research.

2. Methodology

Because the main research question asks what the environmental impact of building with timber or steel is, a life cycle assessment (LCA) is deemed the most suitable method to answer this. By carrying out an LCA the total impact over the lifetime of a building on a selected number of impact categories can be found, and these results can also be split up to see the contribution of different material, processes, and lifecycle stages. Furthermore, an LCA is a good method to compare alternative solutions with the same function and allows for the use of scenarios to test the effect of different circumstances or choices. Details on the LCA method used will be given in section 2.1. Next, the goal & scope will be discussed in section 2.2.

This study uses the LCA methodology applied to a single case study of a timber building and a hypothetical alternative of the same building made with steel frames. The choice for the case study is based on the research question and expected demographic trends. The process of finding a case study and information on the selected case are discussed in section 2.3. Next, this case study is turned into a simplified system for which data is collected. This is discussed in the Inventory Analysis in section 2.4. Finally, section 2.5 explains how the results from the LCA are used to estimate the impact of either building method at the national level.

2.1. LCA method

The study will apply a life cycle assessment as prescribed by ISO 14044 and the LCA Handbook (Guinee, 2002). The four stages of an LCA are shown in Figure 1. First, the goal and scope of the study must be defined, in paragraph 2.2. Next the inventory analysis is set up, which discusses the boundaries, flowcharts, and data collection in paragraph 2.4. Based on the inventory and associated emissions, the impacts can be assessed. This report uses the ReCiPe impact category family, as this is developed in the Netherlands and commonly used there (Huijbregts et al., 2016). The included impact categories are climate change, agricultural land occupation, and metal depletion. Climate change can be considered the most important one as this relates to the overarching global crisis. Agricultural land occupation is included to measure the effect of wood demand, as this indicator relates to land use for forestry too. Metal depletion is included as the steel building is expected to have a much larger impact on this and to measure the effect of recycling and reuse of steel. These impact categories and their units are shown in Table 1.

Table 1: Impact categories included and their indicators and units.

Impact category	Indicator	Unit
Climate change	GWP100	kg CO_2-eq
Agricultural land occupation	ALOP	m^2-year
Metal depletion	MDP	kg Fe-eq

A simplified LCA will suffice for the goals of this study, mainly focusing on material impacts and transport. The software used for the organisation and calculations is Activity Browser (Steubing, de Koning, Haas, & Mutel, 2020). The database used is the ecoinvent cut-off database version 3.8.

To determine how large the impact of the various construction materials is a contribution analysis is carried out after the impact assessment. This is only done for the climate change impact, as this is considered the most important category. The contribution of all materials is found by inspecting the Sankey diagrams of both alternatives.

A sensitivity analysis is carried out to see how sensitive the results are to changes in certain assumptions or choices. This will be performed on the lifetime of the buildings, the choices for substitution materials, and the electricity input for the main structural materials. These analyses are carried out by redoing the calculations with different choices and comparing the percentage change.

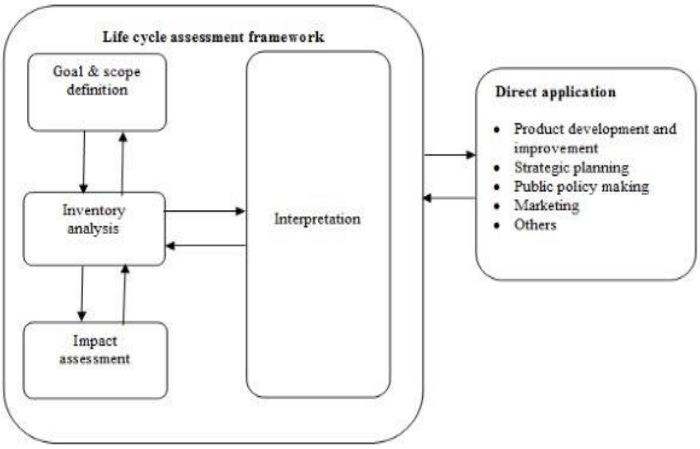

Figure 1: LCA framework as set by ISO 14040

2.2. Goal & scope definition

2.2.1. Goal

The main aim in performing this LCA is to evaluate and compare the sustainability of using steel or timber as structural material for housing. The LCA is used to quantify their environmental impact, which is meant as possible insight for both policy makers and construction companies to allow for more sustainable decision making. For example, the results can be used for making plans to build with either building method. Another application could be to improve on the most carbon intensive parts of the investigated methods. Furthermore, the results can be used to make better scenarios for the climate impact of the Dutch construction industry in the coming decade. Because the input data for the LSF building is based on planned production processes from Re-Buildit, the outcomes should not be used for marketing until these processes have been verified.

The research is conducted by a student as master thesis for the program Industrial Ecology from Leiden University and the TU Delft. The main research question on whether steelframe houses might provide a more sustainable alternative than timber houses was inspired by iCircl, with whom the researcher has collaborated closely with. The researcher has also collaborated with Urban Climate Architects who provided data on the timber case study, and Re-Buildit who provided data on the hypothetical steelframe alternative. The researcher is not financially tied to or has an interest in these companies. The study is supervised by two researchers from Leiden University and a PhD candidate, as well as the director of iCircl.

2.2.2. Scope

The LCA is carried out to identify the impact on climate change of construction processes in the Netherlands until 2030, which means the temporal, geographical and technical scope must fit this goal. For this reason, the study uses the most recent data available in ecoinvent, from the Netherlands or as close as possible, and with modern and realistic processes. The following paragraphs discuss each of these in more detail. Other lifecycle aspects that might be relevant to the building might be the costs and social impacts, but these are not included in this study.

Geographical

As the study is set in the Netherland the aim is for all processes included to be as close to this as possible. Transport distances are based on the closest suppliers to the building site, except when a specific manufacturer is used in the case studies. During data collection ecoinvent processes for the Netherlands were preferred, followed by European Economic Region processes and then Global processes.

Temporal

The study will focus on new constructions to be built before 2030, as this is the timeframe set by the Dutch government to reduce emissions by 49% (Rijksoverheid, 2019) and to build 900 thousand new houses (Rijksoverheid, 2022b). The impact is considered over a longer timeframe to account for reuse, recycling, and carbon storage in the timber. As the functional unit for this study includes years of living space, the lifespan of the building is an important factor in the results. Typically, buildings are designed for a lifespan of at least 50 years and many LCA studies follow this principle (Cadorel & Crawford, 2019). However, while certain elements may have to be replaced after 50 years, the structural elements are generally still sound. For this reason, this study sets the timeframe for the lifespan of the building at 75 years. The possible influence of different lifespans is investigated in the Sensitivity Analysis.

Construction stages

The different stages involved in the lifetime of a building have been standardized by Euronorm EN 15804 into four main stages: the product stage, construction process stage, use stage and end-of-life stage. Besides these, a category is included for benefits obtained from materials leaving the system boundary, for example through recycling. These are subdivided into smaller substages. The diagram of this model is shown in Figure 2. This study only focuses on the product stage including transport to the construction site (A1-A4), the end-of-life stage but without demolition (C2-C4) and includes benefits beyond the system boundary (D). This same approach was used by Passarelli (2018) and Morris, Allen & Hawkins (2021). Installation and demolition processes (A5 & C1) are left out as these are expected to be similar due to the use of prefabricated elements. The exclusion of the use stage (B1-B7) is partly justified by making sure both alternatives have a similar insulation value so operational energy, the main driver of use phase emissions, is assumed equal. Maintenance is also expected to be minimal to the structural materials over the building's lifetime. For ease of communication from now on the stages A1-A4 are also referred to as the Construction stage, stages C2-C4 as Waste Treatment, and stage D as EOL Benefits.

Technological

For both buildings, the structural elements will be included in the study, as well as the insulation material and foundation. Other elements, such as the façade or interior, are considered independent from the choice of construction material and therefore excluded. For the steel frame building, the technology as proposed by Re-Buildit will be considered, which is discussed further in the inventory analysis. For timber frames, the analysed material are CLT-panels, as these are currently the most used elements for timber constructions.

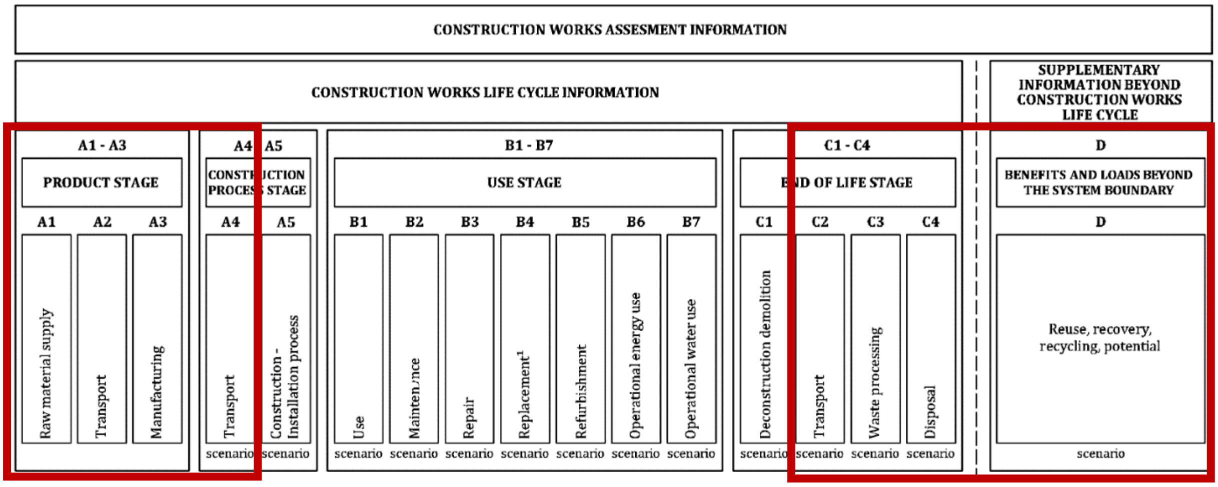

Figure 2: Construction stages differentiated by EN 15804, included stages in red boxes

2.2.3. Functional unit

The main function of the building is to provide living space, which is commonly expressed in square meters floor area. To account for the lifespan of the building the temporal dimension is included in years. Furthermore, the quality and comfort of the living space is taken into account by including the level of insulation, measured by the R-value. This results in the following **functional unit**: *Providing 1 m^2 of living space for 1 year with an R-value of >5*, shortened to **FU** from here on out. An overview is given in Table 2.

Table 2: Function, functional unit, alternatives, and reference flows used in this study

Function	Providing insulated living space
Functional Unit **(FU)**	Providing **1** m^2 of living space for **1** year with an R-value of **>5**
Alternatives	Timber structure Steel structure
Reference flows	Providing 1 m^2 of living space for 1 year with an R-value of >5 with a timber structure Providing 1 m^2 of living space for 1 year with an R-value of >5 with a steel structure

2.2.4. Scenarios

Three scenarios have been created to answer the question of under which circumstances steel or timber is a more sustainable option for the construction of houses. These scenarios are meant to show the impact of different choices that can be made for construction material and its treatment at the end-of-life. The subjects of these choices are the composition of the structural steel and what happens to the retrieved steel at end-of-life, the rotation period of the trees used for the CLT, and the treatment of CLT after use. The scenarios are labelled *Worst-case*, *Expected*, and *Best-case*. The Expected scenario is considered the most likely, as it fits best with Re-Buildit's production plans for steel and the average rotation period for spruce CLT. The EOL treatment of both materials is based on the expectation that current practices will improve. The other scenarios serve as boundaries, with *Worst-case* representing the least sustainable choices based on current practices. The *Best-case* scenario includes the choices that are considered the best realistically possible. An explanation of each scenario and a justification for the choices is given below. Finally, a summary of the scenarios and their differences is shown in Table 3.

Worst-case

In the worst-case scenario, all structural steel used is virgin, meaning that this is the first application of the iron after mining and processing. When the building is demolished, all of the steel can be recovered, but there are no programs in place to easily allow its reuse. Therefore, most of the steel is recycled for new purposes. Although no exact number for the current recycling rate of structural steel can be given, estimates have been made for 90% recycling and 10% reuse (Gorgolewski, Straka, Edmonds, & Sergio, 2006) and 93% recycling and 7% reuse (Sansom & Avery, 2014). For this study, 90% recycling and 10% reuse is assumed. The chosen timber will likely come from Europe, where spruce trees typically have a rotation period between 80 and 100 years. The length of this rotation period influences the size of the effect of carbon storage, with longer rotation periods diminishing this effect. This will be further explained in section 0. In the worst-case, the spruce has a rotation period of 100 years. After its use, no effort is put into finding a new application for the wood, and thus all of it will be incinerated with energy recovery in the form of heat and power.

Expected

In this scenario considerable effort is put into increasing the sustainability of our society, resulting in better sourced materials and more circular options at end-of-life. The steel input is assumed to be 50% virgin, and 50% recycled steel. After its use, a large part of the steel can be reused directly as steel frames. For this reason, 50% is assumed to be recycled, and 50% is reused as steel frames. The timber in this scenario is assumed to be sourced from spruce trees with an average rotation period of 90 years. After deconstruction new applications for the CLT have been found, although at a lower grade of quality then the initial wood. Here, the retrieved timber is for 85% recycled by shredding the wood and turning it into particleboard. The remaining 15% has no new purpose and is incinerated with energy recovery.

Best-case

In the best-case scenario sustainability is one of the key choices in designing new buildings, and platforms have been set up to allow the reuse of building materials. The steel frames used are produced from fully recycled steel. At its end-of-life 90% of this steel is reused, while 10% is deemed unfit for reuse and is therefore recycled. The timber is sourced from spruce trees with a rotation period of 80 years. In this case the CLT panels are properly protected during their lifetime and are easily demountable. Therefore, a large part of the panels can be reused in another building after deconstruction. In a study analysing a carefully planned design for reusing CLT panels, a reuse rate of 70% was found (Passarelli, 2018), which is the assumed number for reuse here. The remaining material is recycled by shredding for turning it into particleboard.

Table 3: Scenarios for steel composition and EOL treatment

Scenario	Steel input	Steel EOL	Tree rotation period	Timber EOL
Worst-case	100% primary	90% recycled 10% reused	100 years	100% incinerated
Expected	50% primary 50% secondary	50% recycled 50% reused	90 years	85% recycled 15% incinerated
Best-case	100% secondary	90% reused 10% recycled	80 years	70% reused 30% recycled

2.3. Case study selection

As mentioned at the beginning of chapter 2, this study uses a case study as subject of the life cycle assessment. The case study was intended to be a reasonable representative of sustainably built living space. The following section will explain how the case was chosen, by first going into the current state of the Dutch housing stock, then into expectations of future developments. Finally, the chosen case study will be introduced. Section 2.4 will further explain how the selected case was transformed into the LCA model.

According to the Central Bureau for Statistics (CBS) the Netherlands typically builds around 70 thousand new houses each year, although this reduced to below 50 thousand after 2011's economic crisis (CBS, 2022b). In 2021 almost 69 thousand new dwellings were constructed according to CBS, most of which were dwellings were realised in Zuid-Holland, followed by Noord-Holland and Noord-Brabant. The most used housing type with 40% of new constructions was apartments (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2021). The average floor space per dwelling is 120 square meters (CBS, 2022c).

Because the scope of this study is housing in the Netherlands until 2030, future development must be considered too. Although there is already a housing shortage this is expected to grow further in the coming years. This is due to a population growth from 17.5 million people in 2021 to 18.3 million in 2030, and a household growth from 8.1 million in 2021 to 8.7 million in 2030 (Rijksoverheid, 2022a). Most of these are single-person household and this group will also grow the fastest (CBS, 2021). According to CBS, these consist mainly of elderly people and young adults. To accommodate this growth the government is planning on increasing the annual construction of houses to 100,000 (Rijksoverheid, 2022b). This will require a faster development process which includes regulation protocols but also construction methods such as the use of prefabricated elements.

Although not all different housing types can be captured in a single case study, due to the developments discussed above an argument can be made for studying an apartment building made with prefab elements. This type of building will fit the increased number of single-person households, is the preferred housing type for elderly (Akkermans, Kloosterman, & Reep, 2020) and can be built quickly. Through iCircl's network a case was found that matches most of these criteria called De Grote Kreek designed by Urban Climate Architects for the Dutch Salvation Army as a place to provide shelter and care to the homeless in Rotterdam. It consists of three building layers and a total floor space of 2400 square meters, of which 2175 square meters of living space. The building holds 50 care units and a communal room. Designed with high standards of sustainability, the entire structure is made of cross-laminated timber walls and floors on a concrete foundation. The current use is meant for at least 10 years, after which it may be converted to apartments. For this reason, the building is constructed at the same level of quality with regards to noise and temperature insulation as required for housing regulation. An illustration of the building can be seen in Figure 3. The building is under construction at the time of writing this report.

Figure 3: Rendered image showing the design of De Grote Kreek. Retrieved from https://www.ucarchitects.com/projects2/grotekreek/# on 8-11-2022.

2.4. Inventory analysis

2.4.1. System boundaries

This study aims to compare the life cycle impacts of load-bearing timber and steel used for housing construction. Because their application is different, and different amounts are required to construct a similar building, these materials are considered at building level. For this reason, all structural, load-bearing elements are included, which means the foundation piles, ground floor, walls, and upper floors. As the functional unit includes the insulation value, the amount of insulation is also accounted for. Other building elements, such as top floors and wall sidings are included if there is a functional difference between the two main materials. For this reason, the screed floors in the timber building are included because the steelframe floors include such a layer. In contrast, windows, doors, and the façade are excluded as these are independent from the structural material. A simple diagram of the building and main sub-structures can be found in Figure 4. Small building materials such as connection pieces and screws are excluded too due to lack of data. Their contribution to the whole of emissions is generally small so this is considered acceptable.

For the main structural materials, steel and timber, this study follows a cradle-to-cradle approach. The impacts from resource extraction, production and transport are all included up to the point that the material is available for another function. The other materials, such as concrete or insulation, are followed cradle-to-grave, with the final process being waste treatment by either incineration or landfill. Waste transport and disposal is included for all materials. As stated, the benefits and loads beyond the system boundary are only included for the main construction materials under investigation, timber, and steel.

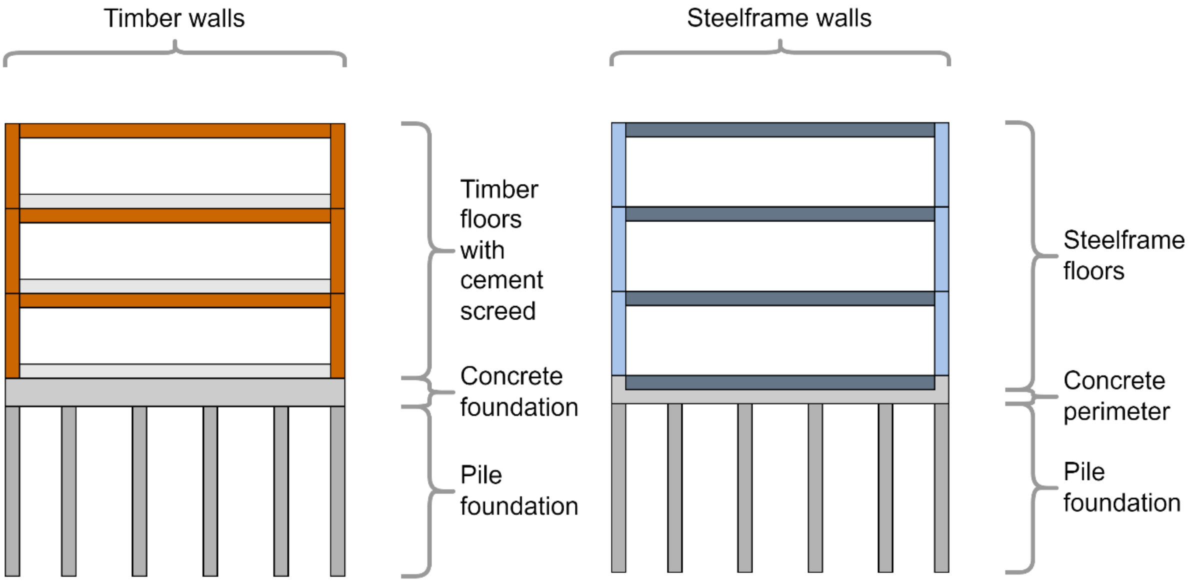

Figure 4: Diagram of structural elements included in LCA with timber on the left and steel on the right.

2.4.2. Flowcharts

This section will present flowcharts of the life cycle of each variant including the relevant processes and boundaries. At the top of each diagram the stages are shown as named by EN 15804: product stage, construction *process stage*, *use stage*, *end-of-life stage*, and *benefits and loads beyond system boundary*. Because not all substages are included in the scope of this study, below the stage the numbers of the included substages are given. For the product stage all substages are included. In the construction and process stage only transport of the materials to the building site is included. For the use stage none are considered. However, because the function of the building is occupation, this is still considered part of the use stage, although no additional materials or processes are added. At end-of-life only demolition is excluded. Waste treatment is shown as a singular background process, but in fact includes the standard treatment processes as given in ecoinvent for all waste materials except CLT and steel profiles. As the treatment of these two materials depends on the scenario, more details can be found in section 2.4.3 on data collection. Benefits beyond the system boundary are included too, and similar to waste treatment the specifics depend on the scenario. Details on this can be read in section 2.4.4 on substitution.

The processes or materials included are shown in boxes with a grey background if they come from an ecoinvent process, or white if created for this study. Transport is not shown in these flowcharts. Waste flows are shown by dashed lines, and multifunctional processes, which for example produce two goods or turn a waste into a good are marked by the letter M. Both alternatives contain a multifunctional process when waste CLT or steel frames are recycled or reused. The flowchart of the timber variant is shown in Figure 6 and of the steel variant in Figure 7. The steel variant includes two foreground processes as input to the construction stage, called steelframe concrete floor and steelframe wall. These processes are specific to Re-Buildit's production method of their prefabricated steelframes and left out of the main flowchart to preserve its clarity. The processes and materials that go into these products are shown in Figure 5. The details and amounts of each material and how they were gathered are discussed in the next section on data collection.

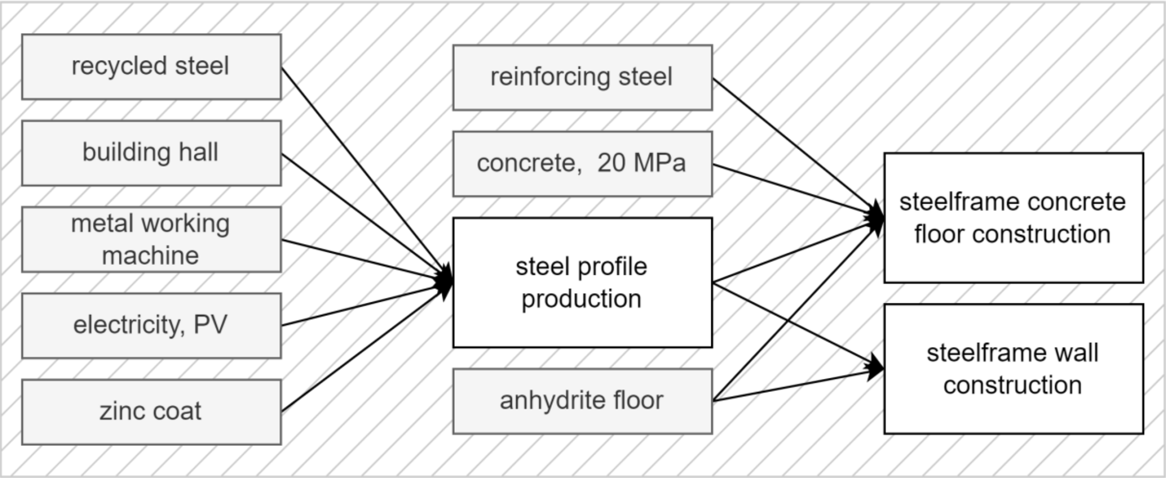

Figure 5: Flowchart showing the materials required to produce steel profiles and frames.

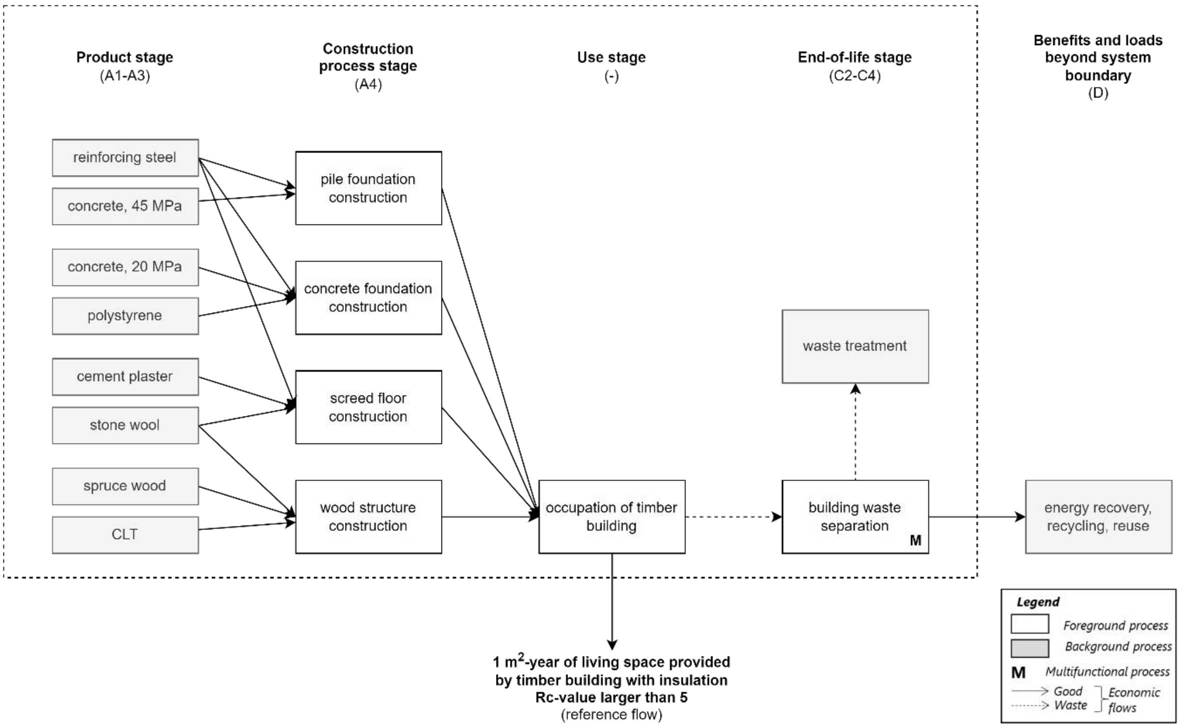

Figure 6: Flowchart showing processes and materials of the timber variant

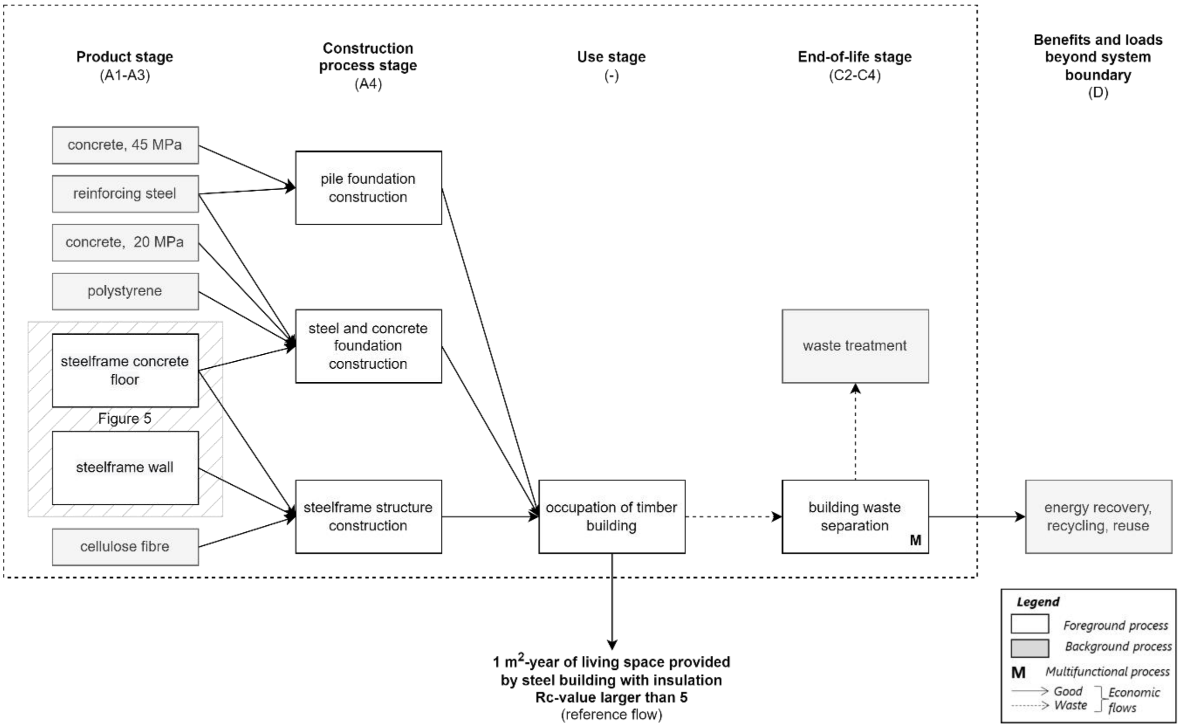

Figure 7: Flowchart showing processes and materials of the steel variant.

2.4.3. Data collection

As mentioned in the introduction, this paper uses a case study of a modern CLT building to provide accurate amounts of the building materials required. This case study is also used as basis for the steel variant. The amounts for the alternative design are calculated by using the square meters of walls and floors and translating these to the amounts of materials required to produce a similar building with a steelframe structure. The paragraphs below will first explain the case study and variant further, and then clarify how these were converted to material amounts. For each material a matching ecoinvent material or process was found. In the cases where no corresponding data was available in ecoinvent, a proxy was used, and these will be labelled as such.

Case study Grote Kreek

De Grote Kreek is a modern timber building designed by Urban Climate Architects for the Dutch Salvation Army as a homeless shelter in Rotterdam. The building is currently under construction in November 2022. The structure is designed to be entirely made from CLT panels as walls, floors, and the roof. It consists of three building layers and a total floor space of 2400 square meters, of which 2175 square meters of living space. A diagram of the CLT structure is visible in Figure 8 showing the walls and floors, as well as a photograph of the building being constructed. The architecture firm has provided technical drawings, as well as quotations for the building materials, which were used as input data for the material amounts and transport distances when a supplier was given. The building uses 2460 m^2 of CLT for the floors of the 1st and 2nd storey and the roof. All inside and outside walls together make up 2705 m^2. The ground floor is a concrete slab instead of CLT. On each floor a layer of stone wool insulation and screed is poured to create a soldi and flush surface and provide noise and temperature insulation.

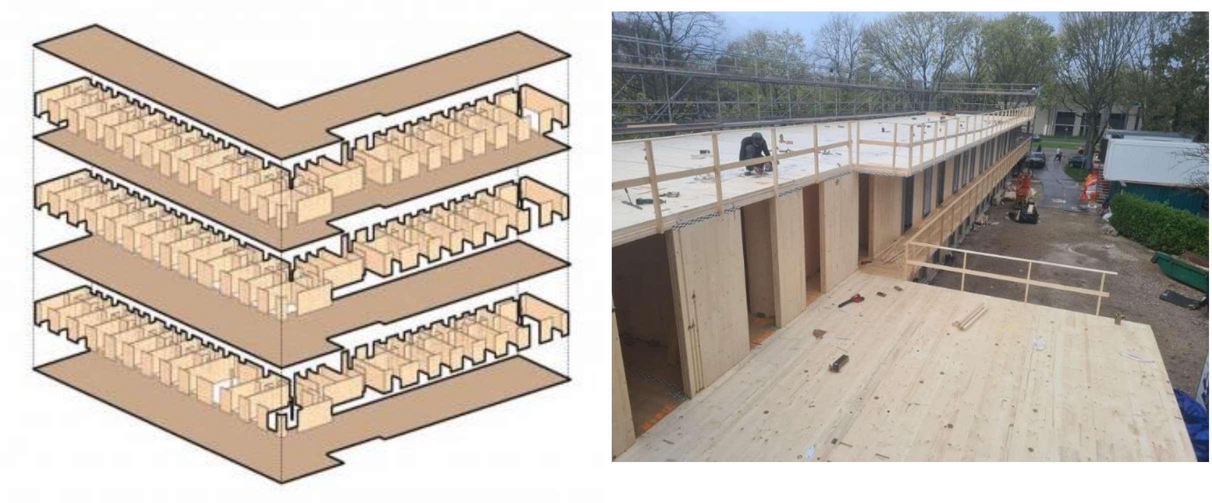

Figure 8: Left: Diagram of Grote Kreek structure showing CLT walls and floors. Right: Photo of the building under construction. Retrieved from https://www.ucarchitects.com/projects2/grotekreek/# on 8-11-2022.

Re-Buildit steelframe variant

As alternative to the timber building, the same building structure could be created with steel frames. Currently, Re-Buildit has designed two types of elements, which are steelframe floors and steelframe walls. The steelframe floors consist of C-shaped steel profiles, a reinforced concrete bottom layer and an anhydrite top layer, visible in Figure 9. The steelframe walls are also made by connecting C-shaped steel profiles, with anhydrite plates on both sides and in case of an outer wall filled with cellulose insulation. A diagram can be seen in Figure 10. Re-Buildit has shared two product information sheets which specify the design of these elements and materials used. Further details on the production process were received from company employees.

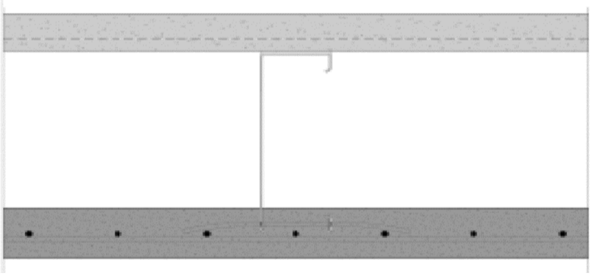

Figure 9: Diagram of steelframe floor element, consisting of a reinforced concrete bottom layer and an anhydrite top layer connected by steel C-profiles.

Building materials

As stated, the amounts of building materials required for the timber building were mainly collected from technical drawings and quotations, with some gaps filled by correspondence with the architect. For the pile foundation with concrete slab and perimeter detailed technical drawings were provided which were used to determine the total amounts of concrete, reinforcement steel and polystyrene insulation. The main CLT structure was determined from a quote which stated the total square meters of walls and floors, as well as the thickness of every timber element. This allowed for the calculation of the required cubic meters of CLT. Insulation was calculated by measuring the total area of outside walls and multiplying by a thickness of 160 mm, as this is the insulation thickness shown in the drawings. The amount of cement and steel needed for the screed floors with reinforcement that cover the concrete ground floor and CLT storeys were also determined from the drawings.

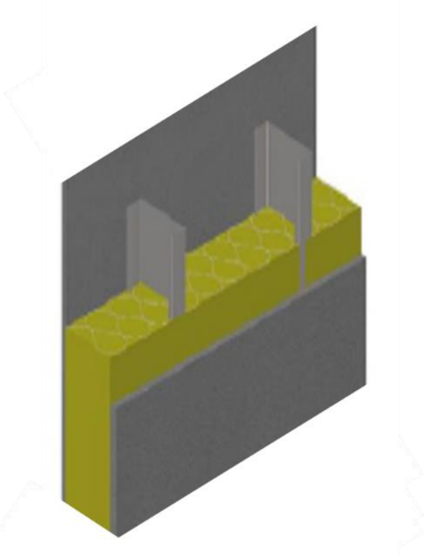

Figure 10: Diagram of steelframe wall element consisting of anhydrite plates connected by steel C-profiles with cellulose insulation.

For the steel variant, the same building structure was assessed, but with steel frames as opposed to cross-laminated timber. The foundation piles, concrete perimeter and polystyrene were assumed to be the same, although instead of a concrete slab at the ground floor a steelframe floor was assumed. According to Re-Buildit, their floors use 14 kg of steel per square meter, have a concrete layer at the bottom of 7 centimetres thick and an anhydrite top layer of 4 cm. Reinforcement was assumed to be 8 mm thick with a core-to-core distance of 100 mm. As stated, these floorplates are used for ground floor as well as the storeys and roof. The walls made by Re-Buildit consist of 5 kg of steel per square meter, and 3 cm of anhydrite plates at both sides. The outer walls are filled with 15 cm of cellulose insulation. These amounts were multiplied by the 2460 m^2 of floors and 2705 m^2 of walls to gain the total material requirements for the steel variant. Some materials had to be converted from volume to mass, for which a density had to be found. These could be determined either by ecoinvent documentation, manufacturers websites or other online sources. All these calculations and sources, as well as unit processes can be found in Appendix 'Unit Process Data'. The total amount for each material used is given in

Table 4.

Steel profile production

Both the steelframe walls and floors use steel profiles, which are made by cold rolling sheet steel rolls into C-shaped sections. Because the exact processes and energy requirements for creating individual walls or floors could not be determined, these are calculated for the entire factory and connected to the steel profiles. This ensures the impact of creating the walls and floors is also included. The factory has a floorspace of 18000 m^2 and a total machine weight of 56000 kg. The roof is covered with 3600 solar panels that should produce enough electricity to run the factory. The assumption was made that these are 3 kWp panels producing on average 285 kWh per year. The factory has a planned production capacity of up to 6.5 million square meter wall, and thus could process 32.5 million kg of steel a year. However, it starts out at 10% of that capacity. For this reason, an average production is assumed of 3.25 million square meter per year, for an assumed lifetime of 50 years.

The steel sheets used for the profiles are planned to be bought from a Swedish factory in Luleå which is set to produce and recycle steel with sustainably produced hydrogen. Because this is not yet available in ecoinvent, conventional low-alloy steel is used. For virgin steel the hot-rolled low-alloyed steel in ecoinvent was used, and for recycled steel the electrically produced version was used, as this approach was also used by Zhong et al (2021). Besides hydrogen as energy source for the steel production, Re-Buildit plans to use hydrogen-based trucks for transport. Similarly, this was not yet available in ecoinvent so conventional trucks were used for transport. For all trucks, the sustainability class EURO5 was assumed.

Waste treatment

For waste treatment the standard processes available in ecoinvent were used for all materials except the steel profiles and CLT. These were chosen as market processes to include transport of the waste. The steel frames are however taken back to the factory in Overijssel to be taken apart for reuse. From there also market processes were used to include transport of separated materials. For anhydrite and cellulose no ecoinvent processes could be found so proxies were used. For anhydrite gypsum treatment was used as proxy, which is landfilled. For cellulose paperboard was found as proxy which is incinerated. The waste treatment of each material is also shown in

Table 4.

Some materials in ecoinvent are split over different treatment methods, which is shown by the “&”-sign. The treatment of CLT and steel profiles depends on the scenario, which is showed by the “/”-sign. The next section will go into the way waste treatment and substitution is handled for these last two materials.

Table 4: Material quantities for both alternative building designs and waste treatment.

Materials	Timber building	Steel building	Unit	Waste treatment
Minerals				
Concrete, 45 MPa	83.2	83.2	m^3	Landfill & recycling
Concrete 20 MPa	176.2	252.4	m^3	Landfill & recycling
Cement screed	293.7		ton	Landfill
Anhydrite		312.8	ton	Landfill (gypsum as proxy)
Stone wool	38.0		ton	Landfill
Metals				
Reinforcing steel	26.8	37.2	ton	Landfill & recycling
Steel profile		58.1	ton	Recycling / reuse
Biobased				
CLT	690.7		m^3	Energy recovery / recycling / reuse
Spruce	0.3	0.3	ton	Incineration
Cellulose		13.0	ton	Incineration (paperboard as proxy)
Plastics				
Polystyrene	6.2	6.2	ton	Incineration

2.4.4. Substitution

Life cycle assessments attempt to follow the supply chain of a product from extraction of raw materials to treatment of waste so all emissions coupled to the product can be accounted for. However, dilemmas arise when processes have multiple uses, for example if a process creates two useful products. In such cases, called multifunctional processes, a choice must be made in how to split the emissions over both uses. In this study, multifunctionality arises at the handling of the building waste, as denoted by the letter “M” in the flowcharts on page 20. Here, most building materials are assumed to be sent to regular waste treatment, but the structural timber and steel frames are expected to still be useful after application in the building, either through energy recovery, recycling, or reuse.

One way to deal with this is substitution, which assumes the secondary products after the building's lifespan displace the production of new primary production. Therefore, the environmental burden of producing new energy or materials is subtracted. This method was chosen as it works well with the used model and software, and used in literature on the same topic (Jayalath et al., 2020; Morris et al., 2021). The substituted environmental burden is reported as End-of-Life benefits, shown in the D module of Figure 2. The following paragraphs will explain how the substitution choices were made and why. A summary of this information is also shown in Table 5.

Energy recovery

Incineration of wood products can produce heat and electricity. It is assumed that this additional heat and power reduces demand from the standard heat and power production. The amount of heat and electricity produced is based on the ecoinvent 3.8 process *heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014*. In this process, 1 MJ equivalent of wood chips is incinerated to produce 0.45 MJ of heat and 0.15 MJ of electricity, so with a total efficiency of 60%. In standard units, this corresponds to 0.0529 kg of wood chips incinerated producing 0.45 MJ of heat and 0.0417 kWh of electricity. These values were multiplied by the amounts of waste timber that were incinerated in a specific scenario. The substituted heat and electricity displace energy production 75 years after the construction of the building, so there is no accurate way to predict the energy production process that is substituted. If society manages to become fully carbon neutral after 2050, then there might not be any emissions substituted when incinerating wood. On the other hand, incineration mainly happens in the worst-case scenario. For this reason, the most sustainable processes for heat and electricity generation in ecoinvent were used which were respectively the combustion of biogas to produce heat and electricity production by wind turbines.

Recycling

CLT can be recycled into particleboard, for which it is first shredded and then glued together. In the recycling scenarios this shredding process is included as waste treatment. Then, and the same weight is substituted by primary wood chips from logging and sawing, which are used in the production of particleboard. Steel can be fully recycled by melting down the steel scraps. In the ecoinvent steel making process, iron scrap is used as input for the steel making process. Therefore, if steel beams from a steelframe house are taken back in they are separated by Re-Buildit and can substitute iron scrap to produce new steel.

Reuse

In the reuse scenarios, the material is assumed to be of good enough quality to be applied in the same way as the original. Therefore, the same ecoinvent flow is used as substitution. As steel is treated with zinc to protect it from rusting, the assumption was made here that it would get a new zinc coating to protect it during a full new building lifespan. The CLT is assumed to have been treated well during its lifetime allowing a new application, although the manufacturer states its lifetime at 100 years so after use in the building for 75 only 25 years would be left. Conversely, properly treated mass timber has existed for centuries in historical buildings so that is the premise for the best-case scenario.

Table 5: Waste treatment and substitution materials to end-of-life timber and steel.

Waste material	EOL Scenario	Treatment	Substitution material
CLT	Energy recovery	Incineration	Heat from biogas Electricity from wind
	Recycling	Shredding	Wood chips
	Reuse	None	CLT
Steel profile	Recycling	None	Iron scrap
	Reuse	Zinc coating	Steel profile

2.4.5. Biogenic carbon storage

Timber and other products made from biomass mainly consist of carbohydrates, which are created during photosynthesis from carbon dioxide and water. This means that during the lifetime of a tree it reduces the total amount of carbon dioxide in the atmosphere and sequesters it in its wood. Biomass products such as timber are therefore seen as a form of carbon storage during the use of the product. When the carbon is released through decomposition or incineration this is often considered carbon neutral as this is not adding carbon dioxide to the global carbon cycle like burning fossil fuels is. However, the effect on global warming from the use of biomass depends on the moment the carbon is released and whether the trees grow back (Cherubini et al., 2011). An example from the same paper is shown below in Figure 11. The line shows carbon stock in standing biomass, which is harvested and released at point (a). At point (b), the biomass starts growing back and reaches its previous balance again at point (c). The time that's required for the biomass to fully recover is called the *rotation period* of a specific plant. During the rotation period the total carbon dioxide in the atmosphere is higher which contributes to global warming and thus is not carbon neutral. On the other hand, if the carbon in the harvested biomass is released after the passing of the rotation period the atmospheric carbon dioxide is decreased for a while leading to a net negative effect on global warming. For these reasons the actual effect on climate change by the use of biomass is dependent on the amount of

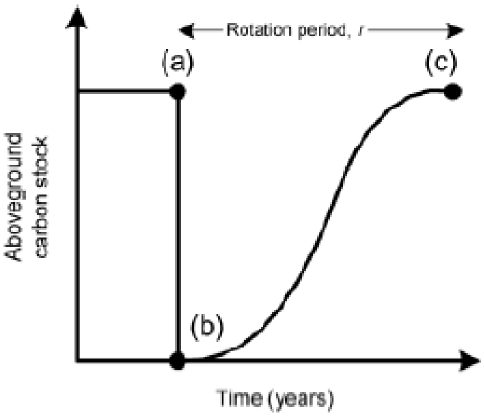

Figure 11: Graph showing carbon storage in biomass and its recovery after harvest (Cherubini et al., 2011, p. 416).

carbon stored, the rotation period of the plant that is used and the amount of time between the start of regrowth and the release back into the atmosphere.

The amount of carbon stored in the biomass or CLT in this case cannot be determined completely accurately but can be estimated based on averages of the type of wood used. The architect of the wooden building for example estimates the total amount for their building at 570 tons of carbon dioxide, although this includes the wooden facades (Stedebouw & Architectuur, 2022). The Austrian company that produced the CLT that is used in De Grote Kreek, KLH, has made their own online tool to calculate the carbon storage in a specific volume of their CLT. Using this tool, a storage of 548.6 tons of carbon dioxide was calculated. The calculation sheet can be found in 'Appendix C: KLH biocarbon calculation'. The third option is through the inventory analysis, in which biogenic carbon is included under the name "carbon dioxide, non-fossil, resource correction". The total amount is -534 tons which is negative because in ecoinvent it is coupled to the use of CLT and considered an uptake. This final amount, a carbon dioxide storage of 534 tons is used in the following calculations.

The other two factors of influence, rotation period and storage period can be used together to calculate a factor value that can be multiplied with the stored carbon to calculate the effect on global warming. Guest, Cherubini & Strømman wrote a paper in which they calculated those factors for a range of combinations of rotation period between 1 and 100 years and storage period between 0 and 100 years (2013, p. 26). They collected these values in a table which is used in this study. For the storage period 80 years is used, as the building lifetime is assumed at 75 years which is rounded up because the table only includes whole decades. The rotation period is dependent on the source of the wood. According to the ecoinvent documentation files of the wood used for CLT, the rotation period for spruce can be 80 years when grown in Sweden or 100 years when grown in Germany. Because a longer rotation period results in a smaller decrease in global warming potential this is used for the worst-case scenario, and the shorter rotation period in the best-case scenario. The average of both is used in the expected scenario. All values are collected in Table 6 below.

Table 6: Biogenic carbon storage effect on global warming calculated for three different scenarios.

	Worst-case	Expected	Best-case
Carbon storage [tons]	534	534	534
Storage period [years]	80	80	80
Rotation period [years]	100	90	80
GWP_{bio} factor value	-0.27	-0.33	-0.38
GWP100 [tons CO_2-eq]	-144.18	-176.22	-202.92
GWP100 per FU [kg CO_2-eq/m^2-yr]	-0.88	-1.08	-1.24

2.5. Comparison at the national level

Although the results of the LCA, after following the steps described in the sections above, provide an answer on whether the impact of the steel or timber building is larger, the question of which method is most sustainable for the Netherlands is not fully answered by this. Therefore, after section 3.1 with the results of the Impact assessment, section 3.2 uses these results and the inventory analysis to calculate the average impact and material requirements per house built and put it into the context of the Netherlands. This is done for the impact on climate change and timber and steel demand if all houses were to be built with either construction method. First, the results per functional unit are multiplied by the expected lifespan of 75 years and average area of Dutch houses to get the impact per house. Next, this is multiplied by 100 thousand houses to have a result per year, or 900 thousand to see the total impact before 2030.

For the climate change category, the impact is compared to the average impact of new built houses in the Netherlands, most of which are constructed with reinforced concrete. Furthermore, the total impact of all houses built before 2030 is put into perspective by comparing it to the national carbon budget to keep global warming below 1.5 °C. For timber and steel demands, the material use found in the Inventory Analysis is compared to the annual production and consumption of either material to put it into context of current material flows in and out of the Netherlands.

3. Results

3.1. Impact assessment

3.1.1. Global warming

In light of the increasing challenges that global warming brings to society, the impact of the building construction on climate change can be considered the most important. To assess this, the impact category GWP100, global warming potential over 100 years as determined by the IPCC, was calculated for the three scenarios as described in Section 2.2.4. These have been split into the categories *Construction (A1-A4)*, *Waste treatment (C2-C4)*, *EOL benefits (D)*, and *Carbon storage*, which can be seen in Figure 12. Note that only the construction segments have a solid fill to indicate this data is factual. The other segments are counterfactual due to their dependence on future processes, which is represented by the pattern fill. A diamond is included to show the sum of these four categories, named *Total*.

As the share of recycled steel in the steel profiles increases from 0% in the worst-case scenario to 100% in the best-case scenario, the impact on climate change from the construction decreases. In the worst-case scenario the steel variant has a larger impact than the timber variant for the construction stage, but smaller in the expected and best-case scenario. In all scenarios, waste treatment for the steel variant has a larger impact than for timber. The timber alternative has its biggest impact in waste treatment in the worst-case scenario. This is associated with the incineration of timber for energy recovery. At end-of-life, timber receives the largest benefits in the best-case scenario, in which most CLT is reused, followed by the worst-case scenario in which it is incinerated. Incineration appearing more beneficial than recycling may be unexpected, but recycled wood could potentially still

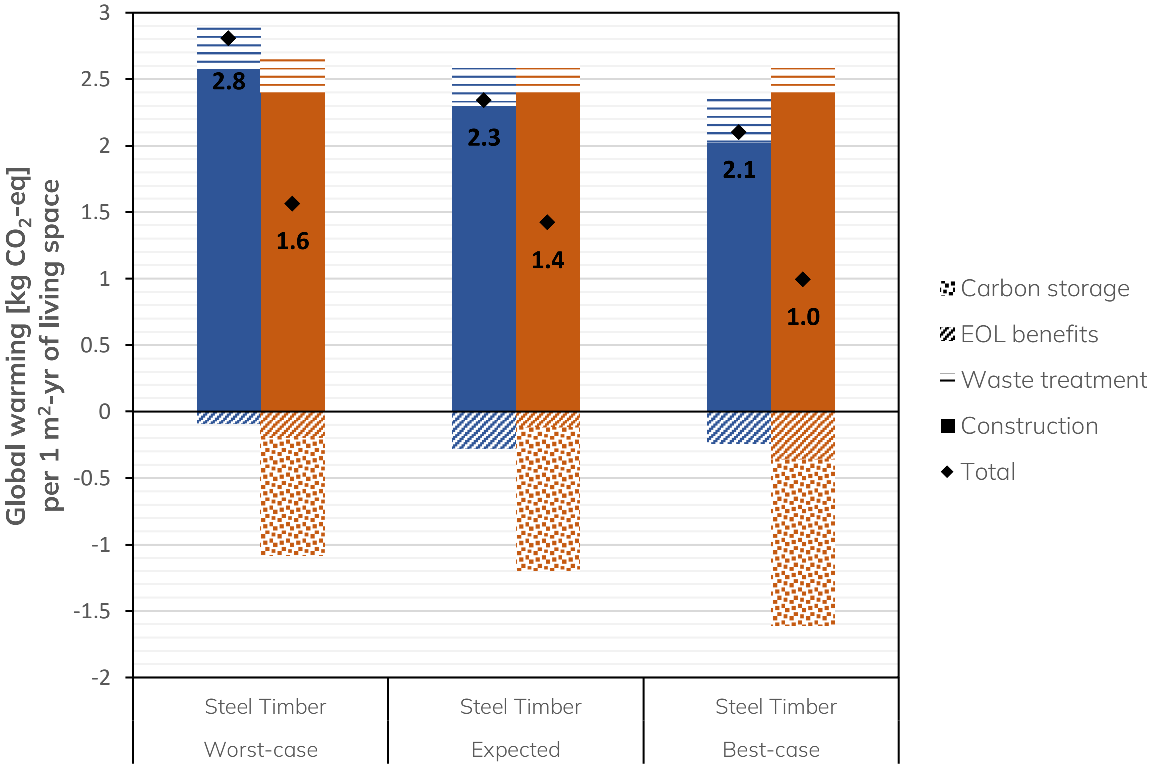

Figure 12: GWP100 assessment of both variants under three scenarios. Four stages named Construction, Waste treatment, EOL benefits, and Carbon storage are shown by the filled and patterned bars. The sum of these, called Total, is shown as a diamond.

be burned after recycling, as well as after reuse. The steel building has the largest EOL benefits in the expected scenario, although more steel is reused in the best-case scenario. However, the steel profiles in the best-case scenario have a smaller impact which means substitution benefits of these are smaller too. The total impact is still most favourable in the best-case scenario.

Contribution of construction elements to global warming

The contribution to global warming of the different construction materials was determined by analysing the Sankey Diagrams created by the program. All Sankey diagrams can be found in Appendix D. The results for these materials are shown in Figure 13. The results for the timber variant are shown in a single bar representing all scenarios in this figure as the impact of the construction stage does not change. For all alternatives and scenarios, the main contributor is also the material being investigated. The effect of using recycled steel is clearly visible as the contribution of steel decreases from 44% in worst-case to 29% in the best-case scenario. Coincidentally, the impact of the steelframes in the best-case scenario is 0.584 kg CO_2-eq per FU while for timber this is 0.588.

Transport of the main material is also a significant contributor, especially for the timber variant where it is responsible for more than a third of the emissions of the material itself. Both buildings use mostly the same foundation, with the same piles and concrete perimeter with polystyrene insulation. However, the steel variant uses reinforced concrete in its steelframe floors which explains the larger contribution.

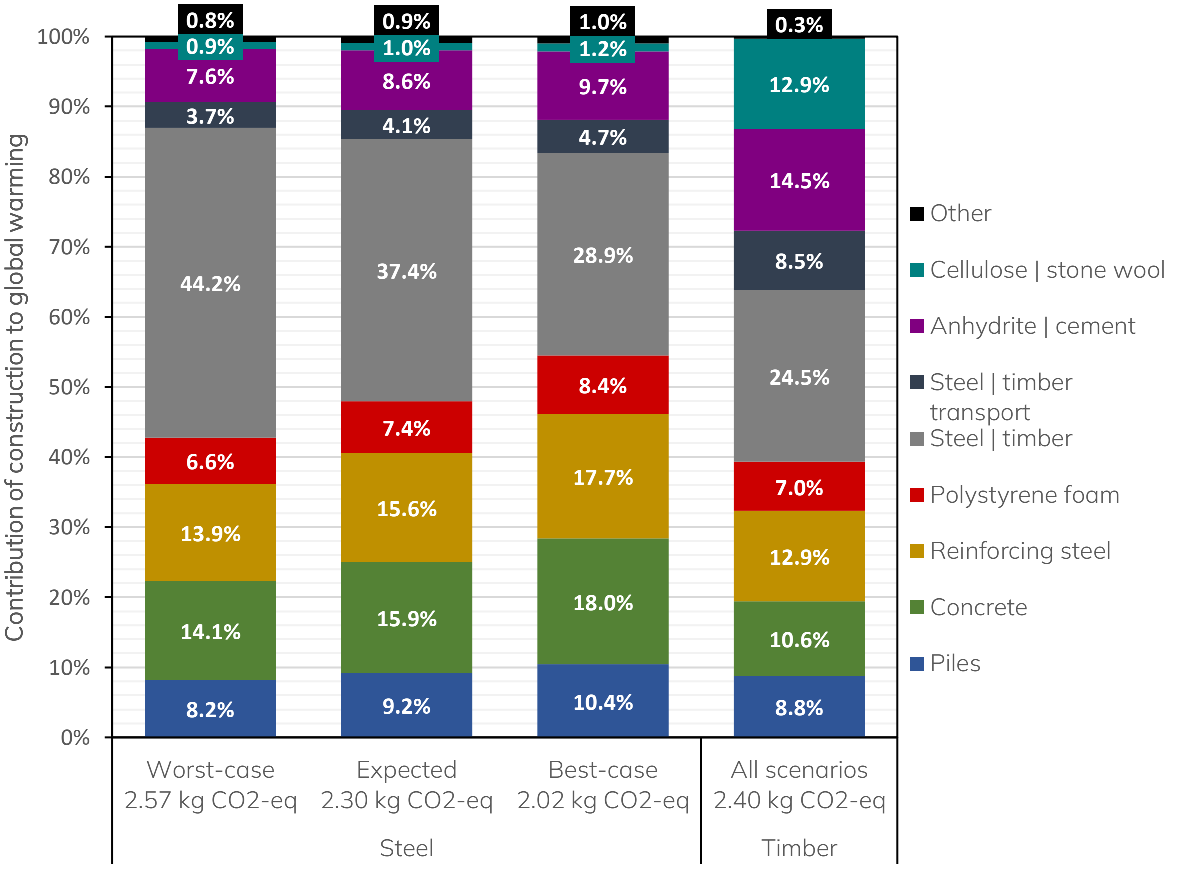

Figure 13: Contribution to global warming of main construction materials for each variant and scenario. Climate change impact is shown below each scenario. When the alternatives use a different material for the same application this is shown by a vertical line.

A main difference between the alternatives is the use of cellulose insulation in the steel version and stone wool in the timber version. The stone wool is responsible for 12.9% of the total global warming impact of the structure, whilst the impact of the cellulose is small enough to fall in the category *other*. Another main difference is the use of anhydrite for the walls and floors in the steel variant and the use of cement screed floors in the timber variant.

Contribution of waste treatment to global warming

Besides the impact of construction, the impact of waste treatment was analysed as well to identify hotspots. A chart showing the percentage contributions of the treatment of the main materials is displayed in Figure 14 on the following page. In this diagram three bars are again shown for the timber variant as the treatment of the CLT panels is dependent on the scenarios. In all scenarios and alternatives, the incineration of polystyrene is clearly a significant contributor to the global warming impact. It is only the second largest contributor in the expected and best-case scenario for steel, where the treatment for reuse has a bigger impact. Polystyrene is a fossil material that is incinerated at end-of-life which contributes to global warming. Transport adds to the impact of the steel variant as the steelframe walls and floors are assumed to be taken back to the factory where they are taken apart. The steel frames that are reused are coated with a new layer of zinc to protect them from rusting for another full lifecycle. However, this clearly has a large impact on global warming relative to the treatment of the other waste materials, although offset by its reuse potential.

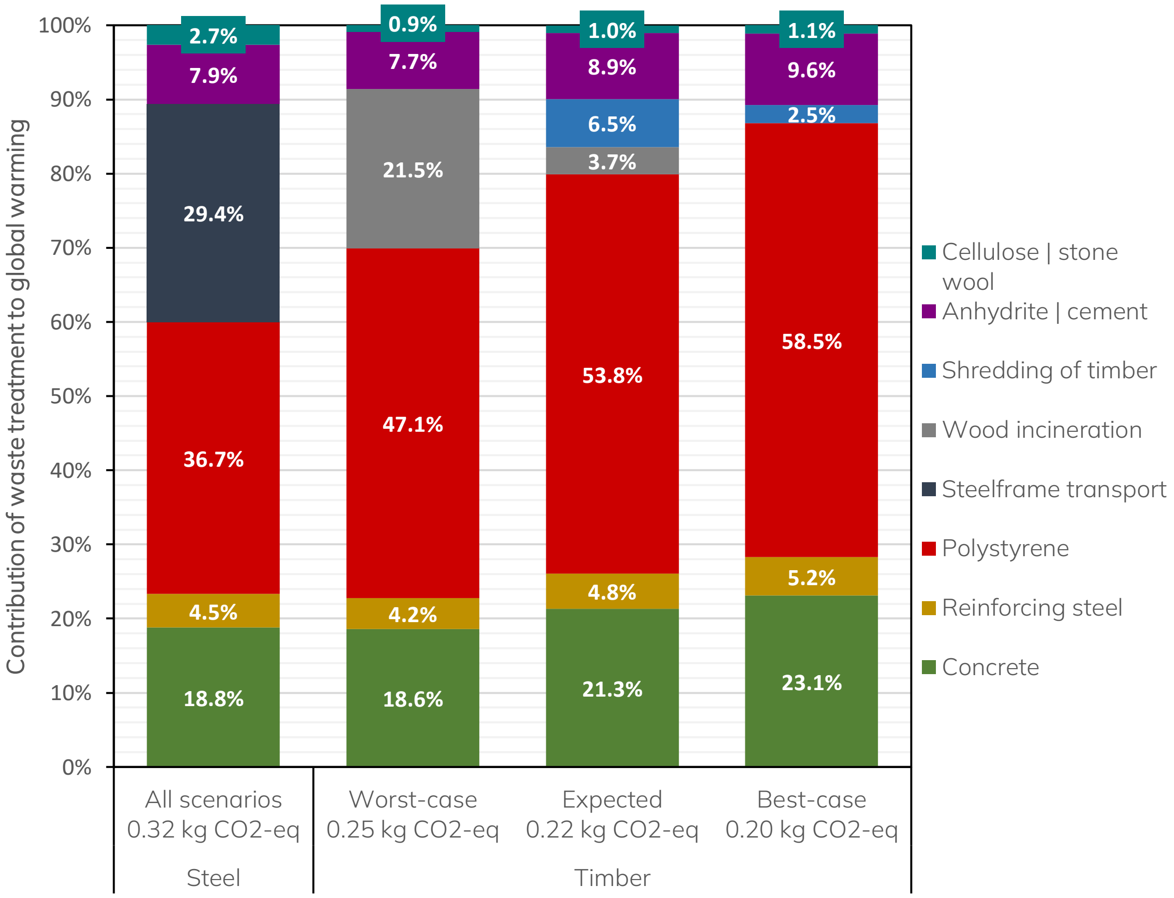

Figure 14: Contribution to global warming due to waste treatment of materials for each variant and scenario. Climate change impact is shown below each scenario. Different materials with the same application are separated by the vertical line.

The incineration of timber releases the stored carbon in the wood resulting in enhanced global warming, although this too is offset by carbon storage over the lifetime of the building and energy recovery. Another contributor to the timber variant is the shredding of CLT which is necessary for recycling.

3.1.2. Land use

As timber is a biological resource, it requires an amount of land area for a certain amount of time to grow. In the ReCiPe impact category, this is expressed as agricultural land occupation, with the unit square meter-year. The results for this impact category in the construction phase of the expected scenario are shown in Table 7. The results for the other phases and scenarios show minor differences, except for the EOL benefits of timber in the best-case scenarios, due to the substitution of CLT. Showing the construction phase therefore gives the clearest indication of the amount of forest land needed to produce the necessary timber. As expected, the timber variant has a larger impact on ALO than steel, with a factor of 106.66 between them.

Table 7: Results for agricultural land occupation and required forest area for the construction stage

Impact category	Steel construction	Timber construction	Unit	Factor
Agricultural land occupation per FU	0.11	11.95	m^2-year	107

3.1.3. Metal depletion

Metals are a finite resource on earth, and so the use of these can lead to depletion of ore deposits. The impact of this is expressed as *metal depletion* or *mineral resource depletion,* with the unit Fe-equivalents. As the main load-bearing material in the steel variant is a metal, the expectation is that this will have more impact on metal depletion than timber. This expectation was confirmed for all three scenarios, as can be seen in Figure 15. The impact of the steel variant on metal depletion decreases from worst to best scenario, as the recycled content of the construction steel increases. The more steel is reused at EOL, the further the metal depletion is reduced. The timber variant shows no change over the scenarios, so a single bar is shown. The main cause of impact in the timber building is the reinforcing steel, which does not change composition over the scenarios.

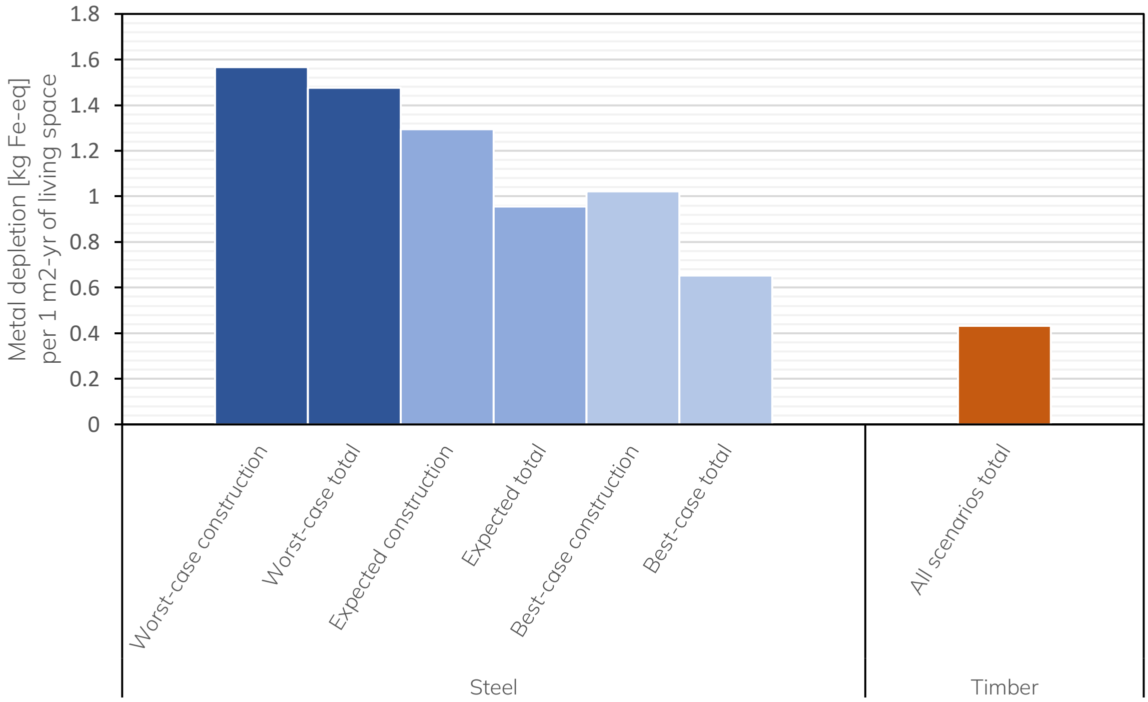

Figure 15: Metal depletion of both alternative buildings. For the steel variant, the results are shown for the construction stage in each scenario, and the total which also includes waste treatment and EOL benefits. The results for the timber building do not change over the scenarios or stages.

3.2. Impact at the national level

This section of the report is meant to give an indication of the impact if all the new required houses would be built with either construction method, to relate the impact per functional unit to the research question of which method is most sustainable for the Netherlands. The same order is followed as section 3.1, first discussing global warming, then the impact of wood use and then metal.

3.2.1. Climate change

To determine the impact of either alternative on the total yearly global warming due to the construction of houses in the Netherlands the results from section 3.1.1 can be used. Because the numbers in Figure 12 are given per functional unit, so per square meter-year, they must be converted first to calculate the impact per house. To do this the results can be multiplied by 75 years for the expected lifespan of the building and by 120 m^2 which is currently the average dwelling size in the Netherlands (CBS, 2022c). Only the emissions from the construction stage are relevant before 2030, as the others happen after the building's lifespan which is around 2100. This study only includes the building structure of a house, which is also the main contributor to a building's climate impact. According to the Dutch Green Building Council the structure of a new built house typically accounts for 61% percent of its total impact, which is visible in Figure 16 (DGBC, 2021). By dividing the total impact for a house by 0.61 the total expected impact of the complete house can be estimated.

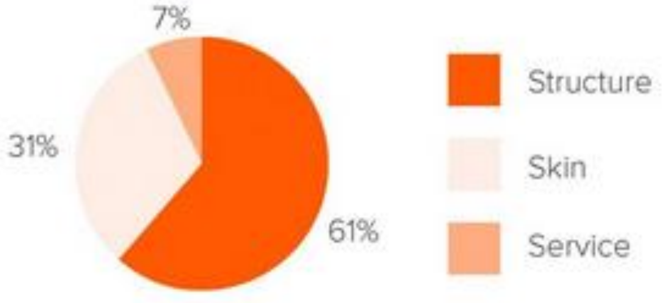

Figure 16: Diagram showing the impact of building materials split over structure, which includes foundation and building shell, the skin which includes finishings and the façade, and service which includes installations. Based on Arnoldussen et al. (2020, p. 49), retrieved from https://dgbc.foleon.com/building-life/dgbc-roadmap-whole-life-carbon/leidende-principe

Next, this result is multiplied by 100,000 to get a yearly emissions estimate, and 900,000 to get a total emission estimate before 2030. All these results are shown in Table 8. Looking at the expected annual emissions for 100,000 houses, the largest impact is 3,800 kiloton CO_2-eq if all houses are built with steel in the worst-case scenario, and the smallest 2,984 kiloton in the best-case scenario. If all buildings are constructed in timber the annual emissions would be 3,543 kiloton CO2-eq.

Table 8: Impact on global warming for houses made with either variant in three scenarios.

	RC		Steel		Timber	
	-	Worst	Expected	Best	All	Unit
Impact per house	59.32	38.00	33.92	29.84	35.43	ton CO2-eq
Per 100,000 houses	5.93	3.80	3.39	2.98	3.54	Mton CO2-eq
Per 900,000 houses	53.39	34.20	30.53	26.86	31.88	Mton CO2-eq

An extensive report on material flows and impacts in of the Dutch construction sector found that materials used for the construction of houses in 2014 were responsible for a total emission of 2,966 kiloton CO_2-eq (Arnoldussen et al., 2020) which was 1.88% of that year's emissions in the Netherlands (Le Quéré et al., 2015). However, in 2014 only 50,000 houses were built, the smallest amount of the past decade (CBS, 2022b). Constructing the 100,000 houses with 2014s conventional production methods would therefore lead to 5,932 kilotons of emissions. Contrary to the results from section 3.1.1 the emissions calculated by Arnoldussen et al. do not include transport so the total may be higher than this reported number. Still, all steelframe and timber options would produce 50% to 64% fewer carbon emissions than the 2014 building method if the same number of houses was built, as visible in Figure 17.

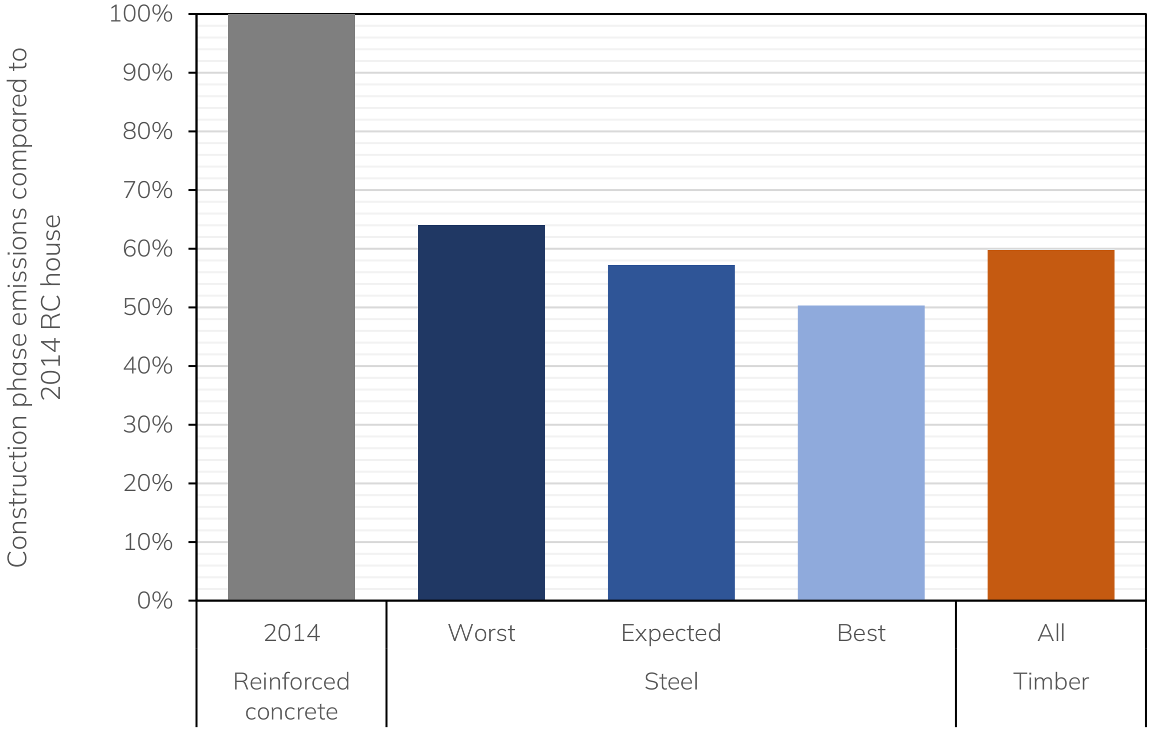

Figure 17: Emissions of investigated building methods compared to average emissions for 2014 houses.

Emissions as share of the national carbon budget

Another way to look at climate impact is the concept of a carbon budget. An IPCC working group estimated that for a 67% chance to stay below 1.5 °C the world could emit around 400 Gt of carbon dioxide after 2020 (IPCC, 2021). If this number is divided by the total world population and multiplied by the Dutch population, a carbon budget for the Netherlands could be set at 860,000 kilotons. This is a total amount of carbon that the Netherlands could emit, so to calculate the share of this taken up by construction of houses all stages must be included. For this reason, the numbers from the Total category of section 3.1.1 are multiplied by 75 years lifespan and 900,000 houses of 120 square meters. Dividing these results with the 860,000 kilotons given above results in the percentages shown in Table 9. This cannot be directly compared to the impact of the conventional RC house described in the previous section because that impact was only for materials and excludes waste treatment and EOL benefits. However, to give an indication, the material impact of 900,000 RC houses was shown to be 53.39 Mton in Table 8, which is 6.2% of the carbon budget.

Table 9: Share of the Dutch carbon budget of 900,000 houses built with LSF or CLT

	Steel			Timber		
	Worst	Expected	Best	Worst	Expected	Best
Percentage of carbon budget	2.6%	2.2%	2.0%	1.5%	1.3%	0.9%

3.2.2. Wood demand

One of the sub-questions asks what the impact of either construction method would have on current material flows in the Dutch economy. This is first calculated for the timber building. The structure requires 690.7 m^3 of CLT according to the building material quotations. This is used to create a floorspace of 2175 m^2. The average dwelling in the Netherlands currently has a size of 120 m^2 (CBS, 2022c) so this is used to calculate the required timber for a typical house. Next, the government has pledged to aim to yearly construct 100,000 new houses which results in 3.8 million m^3 of timber required yearly to build these houses. These numbers are also collected in Table 10.

Table 10: Amount of timber required for case study, average dwelling, and yearly construction.

Required timber	Amount	Unit
Grote Kreek (2175 m^2)	690.7	m^3
Average dwelling (120 m^2)	38.1	m^3
100,000 average dwellings	3,810,759	m^3

The next question is how much timber is available. The Austrian manufacturer of the CLT used by the Grote Kreek, KLH, uses spruce wood although other coniferous types of wood can be used as well. When all harvest of coniferous wood in the Netherlands is combined, a yearly production of 0.7 million m^3 is found (AVIH, n.d.). The requirement is thus more than five times the current harvest of suitable wood in the Netherlands. However, when looking at Europe as a whole the yearly harvest of coniferous roundwood is 259 million m^3 (Eurostat, 2021), which means a small harvest increase would suffice for the increased demand. The scale of these numbers is made visible in Figure 18.

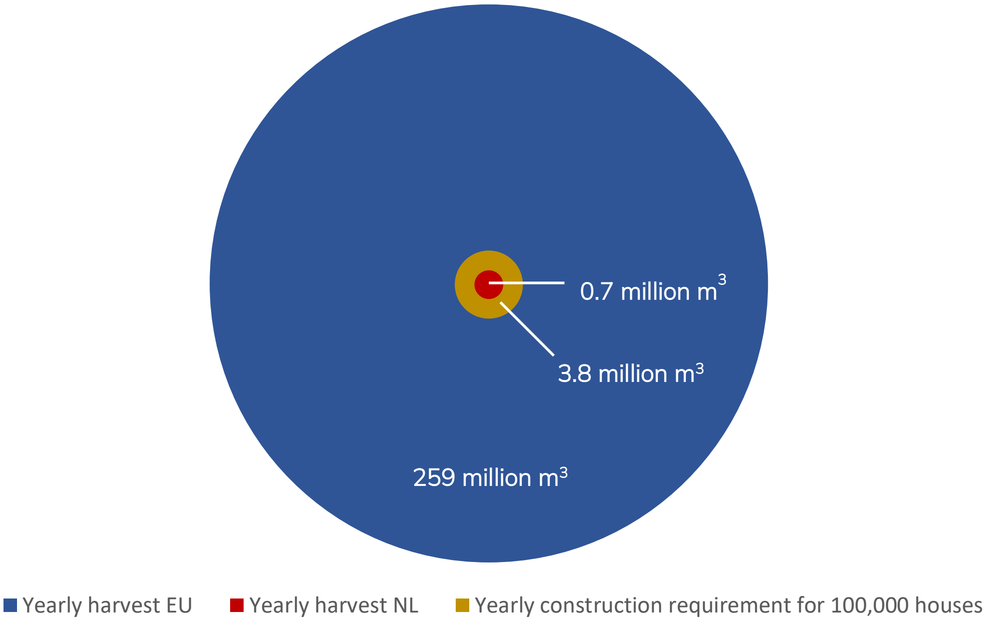

Figure 18: Coniferous roundwood harvested and required, expressed by the size of each circle

3.2.3. Steel demand

Just like the question what the impact of building houses with timber has on wood demand in the Netherlands, the same counts for the steel variant and steel demand. This calculation is also performed on the timber building because of the reinforcing steel used. In 2014 steel and iron made up 4% of the total materials used for the construction of new houses (Arnoldussen et al., 2020). This corresponds to 364,800 tons for the 50,000 houses built that year so building 100,000 would require 729,600 tons if using the same method. Most of this steel is used in the reinforcement of concrete. The timber building requires 26.8 tons of reinforcement steel for the 2175 m^2 of floorspace or 1.48 ton per 120 m^2 house. The steel building uses 37.15 tons of reinforcing steel and 58.12 tons for the steel frames. The total 95.27 ton for the building translates to 5.26 tons of steel per house and 526,000 tons for the desired annual production. The timber alternative would thus need only 20% of the amount of steel of convention construction methods and the steel version 72%.

Table 11: Steel requirements for the average reinforced concrete house of 2014 and the steelframe and timber alternative.

Required steel	RC house (2014)	Steel building	Timber building	**Unit**
Grote Kreek (2175 m^2)	-	95.27	26.84	ton
Average dwelling (120 m^2)	7.30	5.26	1.48	ton
100,000 average dwellings	729,600	526,000	148,000	ton

Next, these numbers are compared to the current steel demand in the Netherlands. In 2021 a total of 6.6 million tons were produced while 4.6 million tons were used by the Dutch economy, meaning it is a net exporter (World steel association, 2022). Building houses in either reinforced concrete, steel, or timber would respectively require 16%, 11% and 3%, shown in Figure 19. For this reason, changing the building method to either alternative would more likely decrease the steel demand of the Netherland. The fact that the steel alternative requires less steel than the reinforced concrete houses from 2014 might be related in part due to the steelframes not requiring any reinforcement in the walls. All numbers are collected in Table 11.

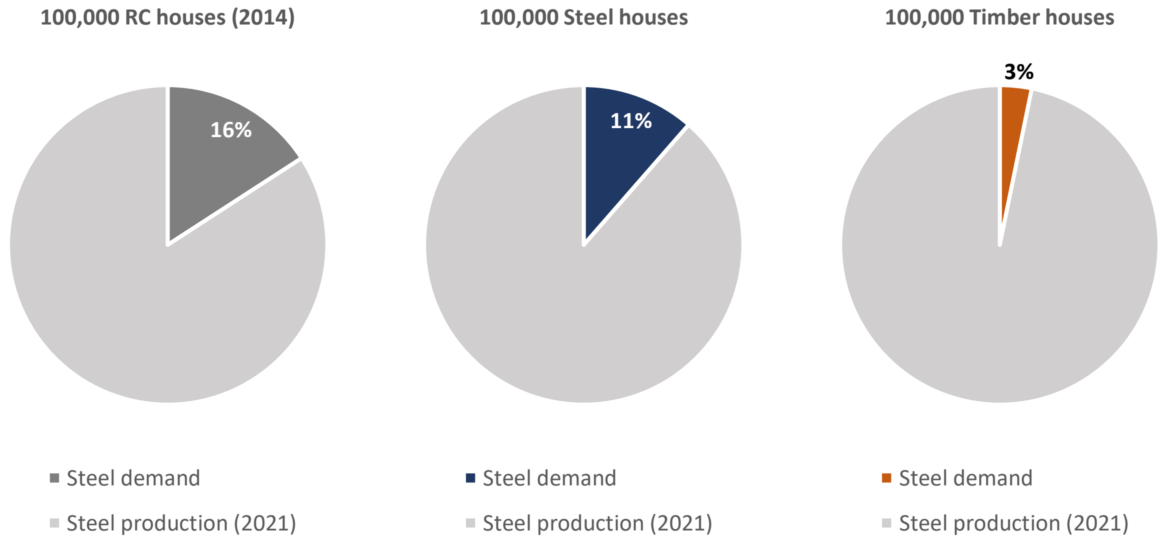

Figure 19: Steel demand to produce 100,000 RC, steel, or timber houses as share of the 2021 total steel production in the Netherlands.

3.3. Sensitivity analysis

3.3.1. Lifespan

Certain choices that were made during the research affected the outcome significantly. This section will demonstrate the effect if different choices or assumptions had been made. The first and most influential one is the lifespan of the building. As the functional unit is square meter per year, the expected lifespan directly affects the outcome. This means that if the expected lifespan is doubled, the outcome is halved. This relation between the two can be expressed as a change in lifespan of factor X resulting in a change of outcome of 1/X. A graph displaying this effect can be seen in Figure 20. At 50-years lifespan, the yearly impact of building use is 150% of the yearly impact when the building is in use for 75 years.

Another aspect that is influenced by the lifespan of the building is the effect of carbon storage. While timber is used in the building and new trees grow, the total amount of carbon dioxide in the atmosphere is decreased, as explained in section 2.4.5. This effect is dependent on the rotation period of the used tree type and the storage period, in this case the building lifespan. The results for a rotation period of 80 and 100 years are shown in Figure 20. Clearly, the longer the storage period, the larger the carbon storage effect. Most notably here is the fact that for a rotation period of 100 years and a lifespan below 53 years the carbon storage effect becomes negative, which means the use of timber under these conditions increases global warming instead of reduces. The combination of both effects results in a decreasing impact on global warming with an increased building lifespan, especially for timber which also benefits from increased carbon storage effect over longer lifespans.

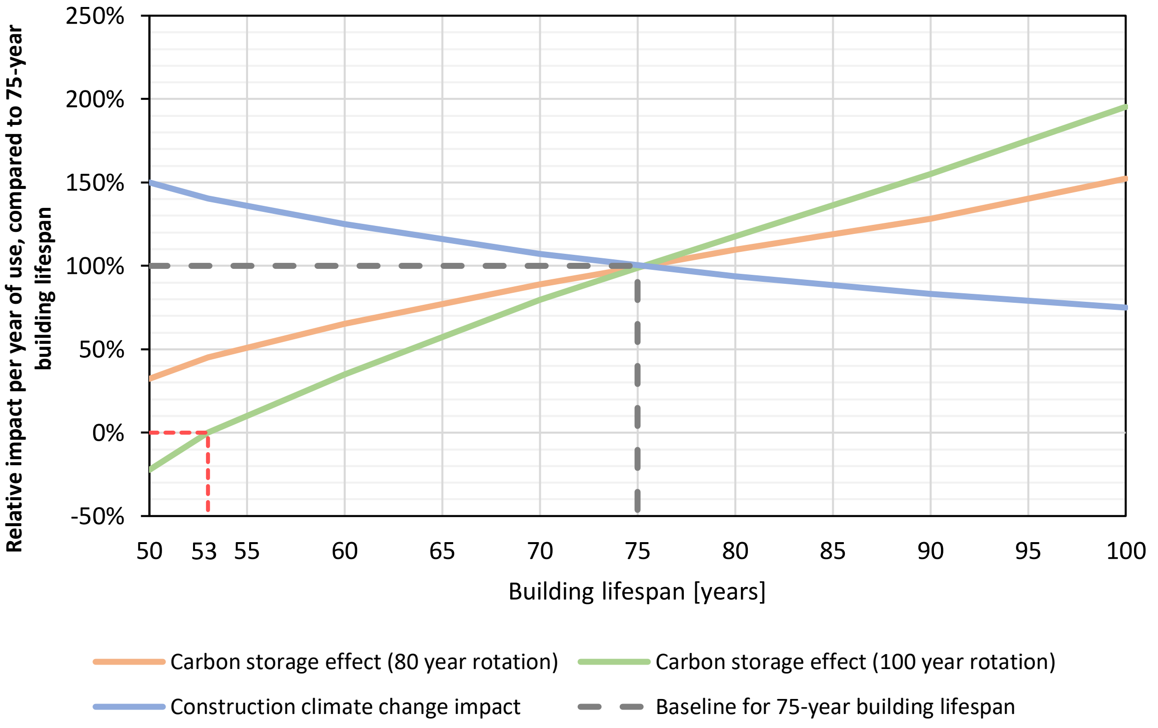

Figure 20: Relative impact per year of use for carbon storage and construction for building lifespans between 50 and 100 years. The dashed grey line shows the 100% baseline at 75 years. The red dashed line shows that the carbon storage effect becomes negative with a building lifespan below 53 years and a rotation period of 100 years.

3.3.2. Substitution materials for recycling

The choice for which material is substituted in the recycling scenarios is less straightforward than for incineration or reuse. The reason for this is the fact that recycling changes the properties of the material so a different material is substituted than the waste itself. Cross-laminated timber can for example be recycled into particleboard, which can then be used for flooring or wall cladding (Azambuja et al., 2018). The main resource for primary particleboard is wood chips which are a side product of wood sawing, for example to create CLT. To account for the recycling of CLT into particleboard with substitution the choice had to be made whether to choose particleboard directly or wood chips for the substitution impact. The difference in impact between these two materials is more than a factor of 10 as can be seen in Table 12. The change on the total impact in the EOL benefits stage is also shown in the table, with a slightly smaller factor of change as part of the benefits come from the incineration in the *expected* scenario. When this is taken together with all other stages and carbon storage in the *expected* scenario the total impact for the timber building would be reduced by 64%. Because the impact per cubic meter of particleboard is larger even than the CLT the choice was made to include wood chips as substitution for the recycled CLT.

A similar story can be told for the recycling of steel. To produce primary steel, mainly pig iron is used with some iron scrap. Again, the question is asked whether the recycled steel replaces mainly pig iron or other steel scrap. The factor of change however is even larger between these two materials than between particleboard and wood chips, in this case pig iron has an impact more than 60 times that of iron scrap. Again, this difference and the impact on the *expected* scenario on the EOL benefits stage and total impact is given in Table 12. In this situation the final reduction is 12%, because half of the EOL steel is reused instead of recycled.

This large difference between the two materials can in part be explained by the fact that the cut-off version of the ecoinvent database was used, but this will be discussed further in section 4.3 *Limitations*.

Table 12: Impact of substitution options in the 'expected' scenario and factor of change.

	Wood chips	Particleboard	Unit	Factor of change
Impact substituted material	-0.09	-0.99	kg CO_2-eq / FU	11.52
Total EOL benefits	-0.12	-1.02	kg CO_2-eq / FU	8.79
Impact of all stages	1.42	0.52	kg CO_2-eq / FU	0.36
	Iron scrap	**Pig iron**	**Unit**	**Factor of change**
Impact substituted material	-0.004	-0.282	kg CO_2-eq / FU	64.42
Total EOL benefits	-0.435	-0.712	kg CO_2-eq / FU	1.64
Impact of all stages	2.345	2.068	kg CO_2-eq / FU	0.88

3.3.3. Electricity input for CLT and LSF production

A main driver of emissions coupled to materials is the production of energy required to make them. Because countries are still working on reducing the carbon impact of their energy systems, the emissions related to the materials used are also expected to come down. This section aims to explore the potential impact of such changes to the production of CLT and LSF. Re-Buildit is planning to build a factory for steel frames running on solar energy, so first the impact of their choice will be compared to the same factory without solar panels. Then, the effect of using solar energy in the production of the steel itself and of the CLT panels is calculated and compared to the results in section 3.1.1.

The production of 1 kg of profiled steel in Re-Buildit's factory releases 3.19 kg CO_2-eq into the atmosphere. If their electricity supply were replaced by the Dutch grid electricity mix this would be 3.22 kg CO_2-eq, an increase of about 1%. This small difference is explained when inspecting the Sankey diagram of the steel profile production, most emissions are due to the production of the steel itself and the zinc used for coating the steel. So, although the use of solar panels by the factory does give a benefit, larger benefits can be gained by improving the production process of the steel and zinc. In the best-case scenario, all input steel is produced with an electric convertor. By replacing the electricity input of this process with solar electricity an indication of these potential benefits can be found. For this electrically produced steel, electricity is responsible for 47.7% of its emissions. The impact of steel produced with photovoltaic (PV) electricity is 30.1% lower than the impact of steel produced with grid electricity. Using this to make steel profiles results in a 10% smaller impact per kilogram of steel profile.

The same calculation can be done for the CLT, for which electricity is used to cut and shape the panels. In the ecoinvent process electricity accounts for 25.6% of the global warming impact of CLT. Replacing this with photovoltaic electricity results in a 19.6% smaller impact. The relative change between production of steel profiles and CLT with grid or photovoltaic electricity is shown in Figure 22. Note that the emissions per kg of steel profile is at least five times higher than for a kg of CLT. However, the steel building uses in total 58.1 tons of steel profiles, while the timber building uses 331.5 tons of CLT. These amounts are responsible for 95.3 and 96.1 kg CO_2-eq respectively, so the impact of only the structural materials is very close together, and the steel building benefits from the efficient use of the profiles. Switching the production of these materials to PV electricity reduces the total impact further, the relative effect of this is shown in Figure 21.

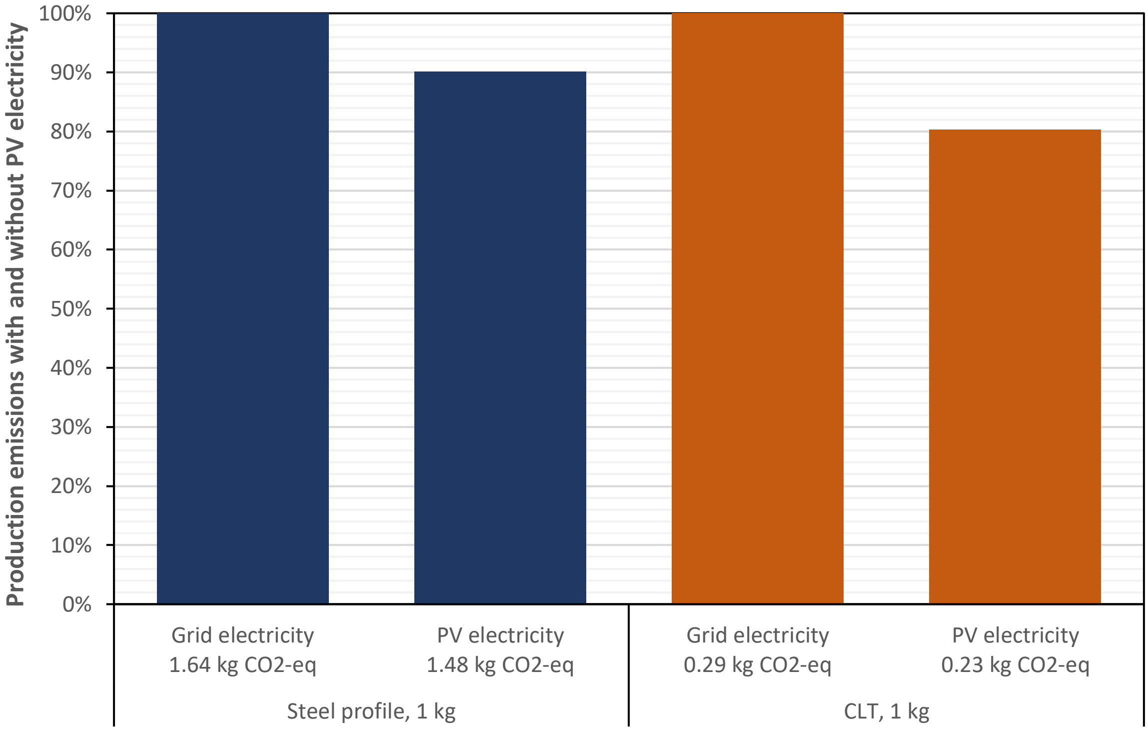

Figure 22: Emissions for 1 kg of steel profile or CLT with PV electricity relative to production with grid electricity. The absolute emissions per kg are stated below each bar.

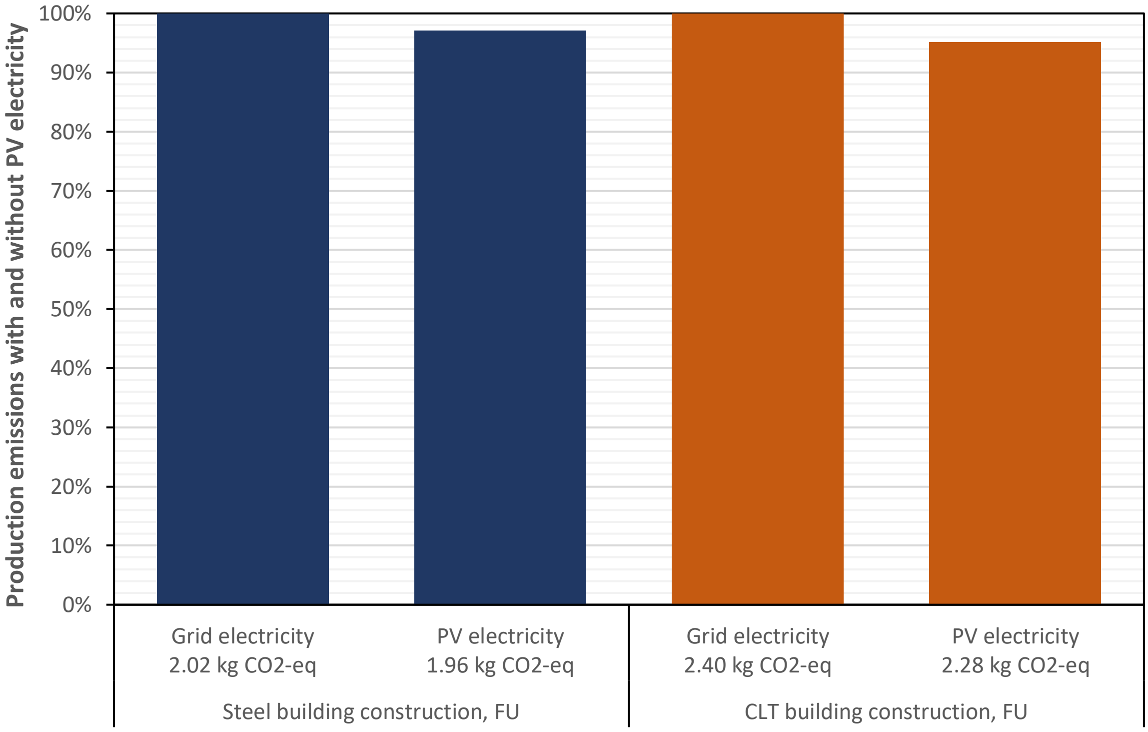

Figure 21: Emissions for the construction stage of the steel or timber building in the best-case scenario with the main material produced with PV electricity, relative to production with grid electricity. The absolute emissions per functional unit are stated below each bar.

4. Discussion

4.1. Interpretation

Looking at the main results on global warming in Figure 12 the timber variant clearly has a smaller total impact in all three scenarios. A surface level analysis would thus conclude that the timber is a more environmentally sound option under all circumstance as answer to the research question. However, more valuable information can be gained from a more in-depth review of the results. The total impact includes waste treatment and EOL benefits, which are both reliant on potential future emissions. These are modelled with current processes and environmental flows but are set to happen after deconstruction of the houses in 75 years. If society achieves its goal of becoming carbon neutral from 2050 onwards, these might reduce to zero. As the steel alternative has a smaller footprint for construction in both the expected and best-case scenario it might even be the more beneficial option for the 2030 emission reduction targets. This may be a surprising result as timber in general has a smaller footprint than steel. However, inspection of the contribution analysis in 3.1.1 and sensitivity analysis in section 3.3.3 helps explaining this outcome. The timber indeed has a smaller footprint per kilogram as seen in the sensitivity analysis, but six times the amount by weight is required. This results in the total emission of both materials being very close in the best-case scenario, with the LSF structure corresponding to 0.584 kg CO_2-eq per FU while for CLT this is 0.588. The remaining difference between the two structures is due to the supporting materials of the timber building, mainly cement and stone wool contributing more. Still, the timber building eventually results in a smaller impact due to the carbon storage effect taking place during the use of the building, provided the trees are replanted and the forests sustainably managed.

The contribution analysis of the construction phase shows that timber and steel are the largest contributors to their respective alternative which justifies the larger focus these materials get. Further improvement on the emission intensity of these materials will also have the most beneficial results on the total building's impact. Furthermore, both materials in these case studies are transported large distances – the CLT comes from Austria and the steel rolls from Sweden – and this is clearly visible in their contributions. Re-Buildit is planning to transport these on hydrogen powered trucks which would benefit the timber variant as well. This was however not modelled as this technology is not yet available in the databases. The contribution analysis shows that transport is responsible for 4% of the construction stage emissions for steel and 8% for timber, so while improvement is worthwhile it is not necessarily of high importance, though more so for timber than steel.

The applied conventional supporting building materials – reinforced concrete and cement, and polystyrene and stone wool insulation – are responsible for most of the remaining construction emissions. Low-carbon alternatives could allow reduction in the total emissions. For example, the steel variant uses anhydrite instead of cast plaster and cellulose insulation in place of stone wool which show far smaller footprints. These same conventional materials also make up most of the waste treatment emissions with polystyrene performing exceptionally poorly. This is a fossil-fuel based material and is incinerated at EOL releasing these carbons. A better alternative or reuse would provide large benefits. However, polystyrene is currently treated with a toxic flame retardant making it unsuitable for recycling (EPS Nederland, n.d.).

Contrary to expectations the total impact of waste treatment for the steel version increases from worst-case to best-case. This is mainly explained by the increased shares of reuse. The steel profiles were assumed to require a new coat of zinc to protect them against rusting for another lifetime. Adding this zinc layer is highly-carbon intensive and this is visible in the results. Under proper inspection of returned steel frames, a smaller amount might suffice to reduce the impact. The steel alternative also has transport as large contributor to the waste treatment emissions as the steelframe walls and floor are transported whole back to their factory before disassembly. Disassembly at the construction site would reduce this, but care must be taken this does not decrease the quality of the materials suitable for reuse.

The material demands for both main materials are not likely to become an issue when viewed in the European context as described in section 3.2. Although the Netherlands will not be able to provide the required materials on its own, it currently already imports most materials and building houses in timber or steel will increase these imports with a relatively small amount.

Finally, the lifespan of the buildings is very influential, as an increase of its use time would reduce the need for building new houses. This is something that should be considered when developing new houses. The effect is even stronger for buildings made with timber due to the carbon storage effect. Measures that might increase the lifetime of a building are the handling of the materials, ease of servicing, and possibly modularity of the design. Future demographic developments cannot be predicted accurately so a building that can easily be changed to potentially changed requirement stands a larger chance of having an increased lifetime. Both case studies took this into account by building with panels or frames that could be demounted and replaced if needed. Unfortunately, this benefit is difficult to include in an LCA, but this will be discussed further in section 4.3 on Limitations.

4.2. Implications

The results largely confirm the position of parties viewing timber as the most sustainable construction material for houses. This is mostly thanks to the carbon storage effect related to biobased materials which greatly reduces the final climate impact when used over a long enough time. Unfortunately, this effect is currently not included in the sustainability performance calculation of buildings which is mandatory for permits (Keijzer, Klerks, Leeuwen, Nijman, & Fraanje, 2021). This study might aid organisations pushing to change these regulations to include carbon storage and thus strengthen the case for biobased construction materials.

However, at the same time the results demonstrate the improvement potential of building with steel, especially as recycled steel is used and produced with sustainable energy sources. In fact, it could release a smaller amount of carbon dioxide in the construction stage which would help in reaching the 2030 climate goals. Furthermore, the reuse potential of steel is likely higher than of CLT which makes it more suitable for the planned fully circular economy in 2050.

Either way, both alternatives provide a large benefit over conventional construction methods using reinforced concrete (see section 3.2.1.). As such, it is important that construction companies keep enhancing the production methods of houses with low-carbon materials and build more sustainable supply chains. To achieve this, it might be necessary for the government to set guidelines and regulations, like Amsterdam aiming for 20% of houses made with wood, as well as adjusting calculation methods to help innovative companies demonstrate the full benefits of their designs.

Finally, this study might be able to start more discussion between the choice of reducing carbon emissions at this moment as quickly as possible or make the most sustainable long-term choice. Building in ways that have the least current impact on the climate helps with reaching sustainability goals and makes keeping in line with the Paris agreement easier. At the same time, short-term decision making can be seen as part of the cause for the climate crisis, and so building in ways that have the lowest final impact on the climate or are most suited for circularity may be preferable.

4.3. Limitations

There are several factors that limit the generalizability of this study. The main factor is the use of a single case study for each variant. This study design gives an indication of the differences between both alternatives, but the industry applies a large variety of different housing types, building methods and designs. The case studies also use different supporting materials for floors and insulation, which might be transferable to the alternative material to a certain extent. For this reason, the results on the global warming impact should only be discussed together with the contribution analysis as this gives a better indication of the burden attributed to each material.

Furthermore, the steel case study is based on plans of Re-Buildit which are state-of-the-art, but not yet brought into practice. As such, a complete and accurate study on the impact of their building methods should be made further along the development of their company.

Another point that must be stressed is the uncertainty of future processes for recycling and reuse, and the lifespan of the used materials. Cross-laminated timber has only been in use since the 90s, so their lifespan in practice still remains to be seen, although mass timber has been made to last for centuries with proper maintenance in historical buildings. The treatment of waste and potential for reuse or recycling are similarly uncertain, as the organisation of the economy in 75 years is unpredictable. For this reason, less weight should be given to these aspects relative to the impact of the construction stage.

There are also some imperfections in the applied LCA method. The ecoinvent database used was the cut-off version, but EOL benefits were included by substitution. The consequential database is more applicable for substitution. However, using the consequential database gave unrealistic results in the construction and waste treatment stages, which were deemed more important. In general, the reliability of substitution as a way of dealing with the multifunctionality of recycling or reuse can be challenged. The results are highly dependent on the chosen material for substitution, and the reduced demand of primary materials is also dependent on future processes. Finally, there are some limitations due to the completeness of the research. For example, the impact of the CLT panels does not change in the construction phase over the three scenarios, although for this material too improvements might be made by using more sustainable energy sources in the production. Furthermore, the cost of materials and building methods is left out, while this is normally a major factor in decision making for companies and governments.

5. Conclusion and recommendations

By performing a life cycle assessment on a timber building and a steelframe alternative this research aimed to discover under which circumstance these would be more sustainable to build in the Netherlands in the coming decade. If all lifecycle stages of these buildings are combined, it becomes clear that timber houses are the most beneficial in all scenarios. This is in a large part influenced by the carbon storage effect of using timber in buildings over a long enough timeframe. When only the emissions that are caused before 2030 are included, the steel building might be a better option as long as the recycled content of the input steel is at least 50%. In all circumstances though both alternatives contribute far less to the climate crisis than conventional reinforced concrete houses. However, both also still need improvements before 2030 if the goal of 55% reduction in carbon emissions compared to 1990 is to be reached. This might already be achieved by the general downwards trends in emissions coupled to energy use, however.

The chosen materials do not seem to lead to significant issues in material supply or demand. The steelframe house uses less steel than a conventional house so steel demand is projected to decrease. If all houses would be constructed with CLT the demand for timber would go up and the Netherlands is not able to provide enough wood by itself. However, countries like Sweden and Germany have large volumes of growing forests and a small increase in harvest rates would provide enough additional timber for the Netherlands. In either case, measures to increase the reuse potential provide large benefits on both resource depletion and climate impact. Designing buildings to be easily taken apart helps in making reuse more feasible. However, the benefits of such designs are difficult to capture in an LCA. The same thing goes for extending the lifespan of a building, which could for example be helped by designing it to be modular so it can be changed to future desires. This is something that could be studied next, first on how to include such design choices in LCA and next to discover how big the benefits could be.

Other aspects that would be a logical next step to research are the differences in life cycle costing, as ultimately financial interests weigh heavily in decision making. Also, the potential construction speed would be interesting to find out if the Netherlands is to increase its yearly number of new houses built from 70 thousand to 100 thousand. Finally, to get a truly holistic view of the matter the social aspects should be included better, regarding comfort for example.

Last, this study clearly shows the benefits of switching to innovative alternatives instead of keeping with the conventional building methods. Light steel frames and cross-laminated timber perform better than reinforced concrete, but also anhydrite has a smaller impact than gypsum and the same counts for cellulose when compared to stone wool.

With this thesis demonstrating that using low-carbon and biobased materials, designing buildings for a long lifespan, and designing for reuse provide measurable benefits to the current way of building, it is time for the Dutch government and construction industry to implement these principles and truly start building a sustainable future.

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Appendices

Appendix A: Excel file ‘Unit Process Data’

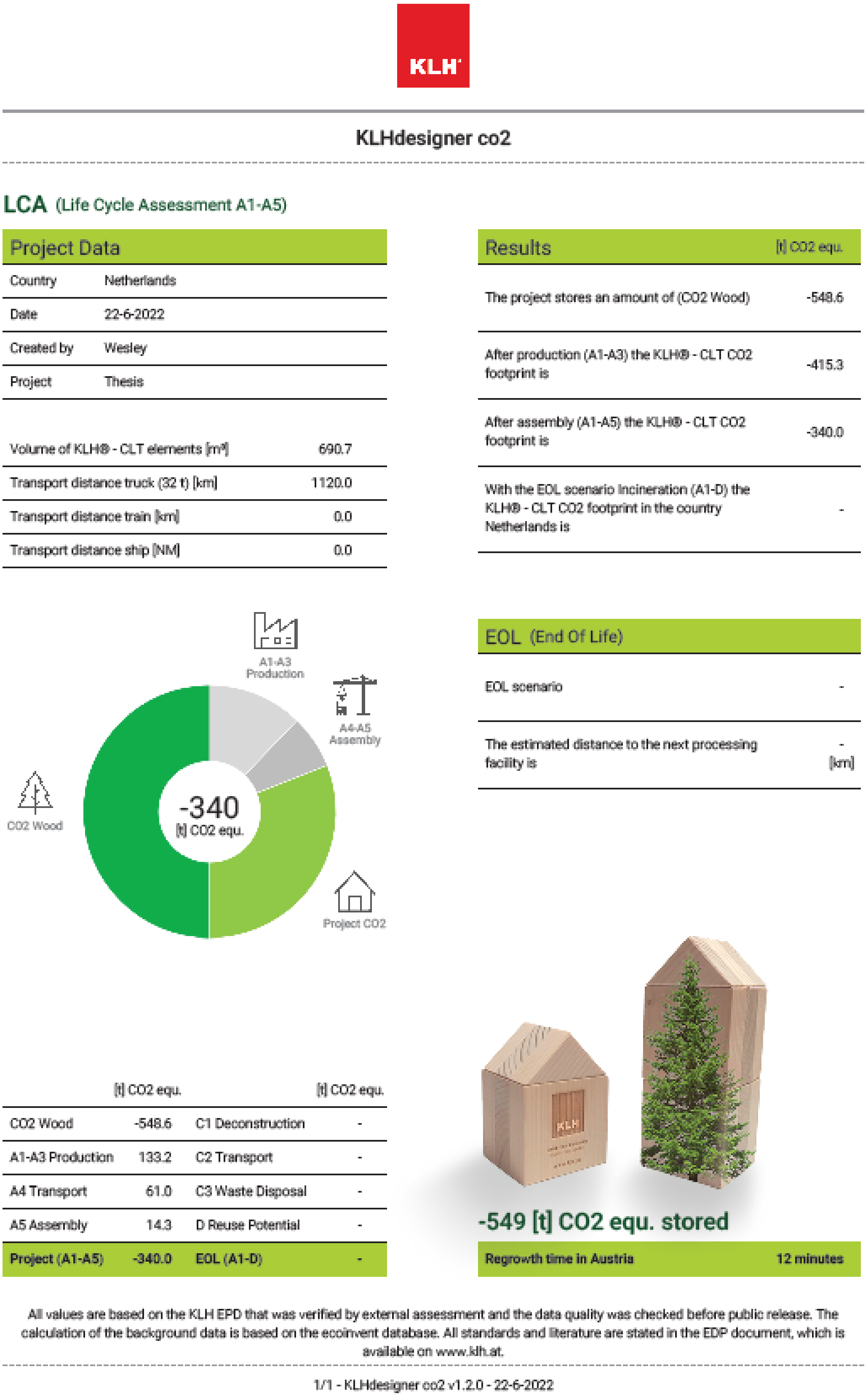
Includes Unit Processes for Timber and Steel variant, and calculations sheets. The first two sheets contain an overview of all unit processes entered into Activity Browser. The sheet ‘Piles’ includes the calculation for the pile foundation, which is valid for both alternatives. The next sheets, colored brown at the bottom, contain the calculations for each respective unit process for the timber building. The grey coloured sheets contain the calculations for each respective unit process for the steel building.

Appendix B: Excel file ‘Results’

This is a file that contains the preliminary results of the impact assessment carried out with Activity Browser. Sheets A, C and D contain respectively the results for stages A1-A4, C2-C4, and D. The ‘Total’ sheet is a combination of these, and the next sheets show the data split over the impact categories and graphs of this data.

Appendix C: KLH biocarbon calculation

Retrieved from https://www.klhdesigner.at/co2/



KLHdesigner co2

LCA (Life Cycle Assessment A1-A5)

Project Data	
Country	Netherlands
Date	22-6-2022
Created by	Wesley
Project	Thesis

Volume of KLH® - CLT elements [m³]	690.7
Transport distance truck (32 t) [km]	1120.0
Transport distance train [km]	0.0
Transport distance ship [NM]	0.0

Results	[t] CO2 equ.
The project stores an amount of (CO2 Wood)	-548.6
After production (A1-A3) the KLH® - CLT CO2 footprint is	-415.3
After assembly (A1-A5) the KLH® - CLT CO2 footprint is	-340.0
With the EOL scenario Incineration (A1-D) the KLH® - CLT CO2 footprint in the country Netherlands is	-

EOL (End Of Life)	
EOL scenario	-
The estimated distance to the next processing facility is	- [km]

	[t] CO2 equ.		[t] CO2 equ.
CO2 Wood	-548.6	C1 Deconstruction	-
A1-A3 Production	133.2	C2 Transport	-
A4 Transport	61.0	C3 Waste Disposal	-
A5 Assembly	14.3	D Reuse Potential	-
Project (A1-A5)	**-340.0**	**EOL (A1-D)**	**-**

-549 [t] CO2 equ. stored

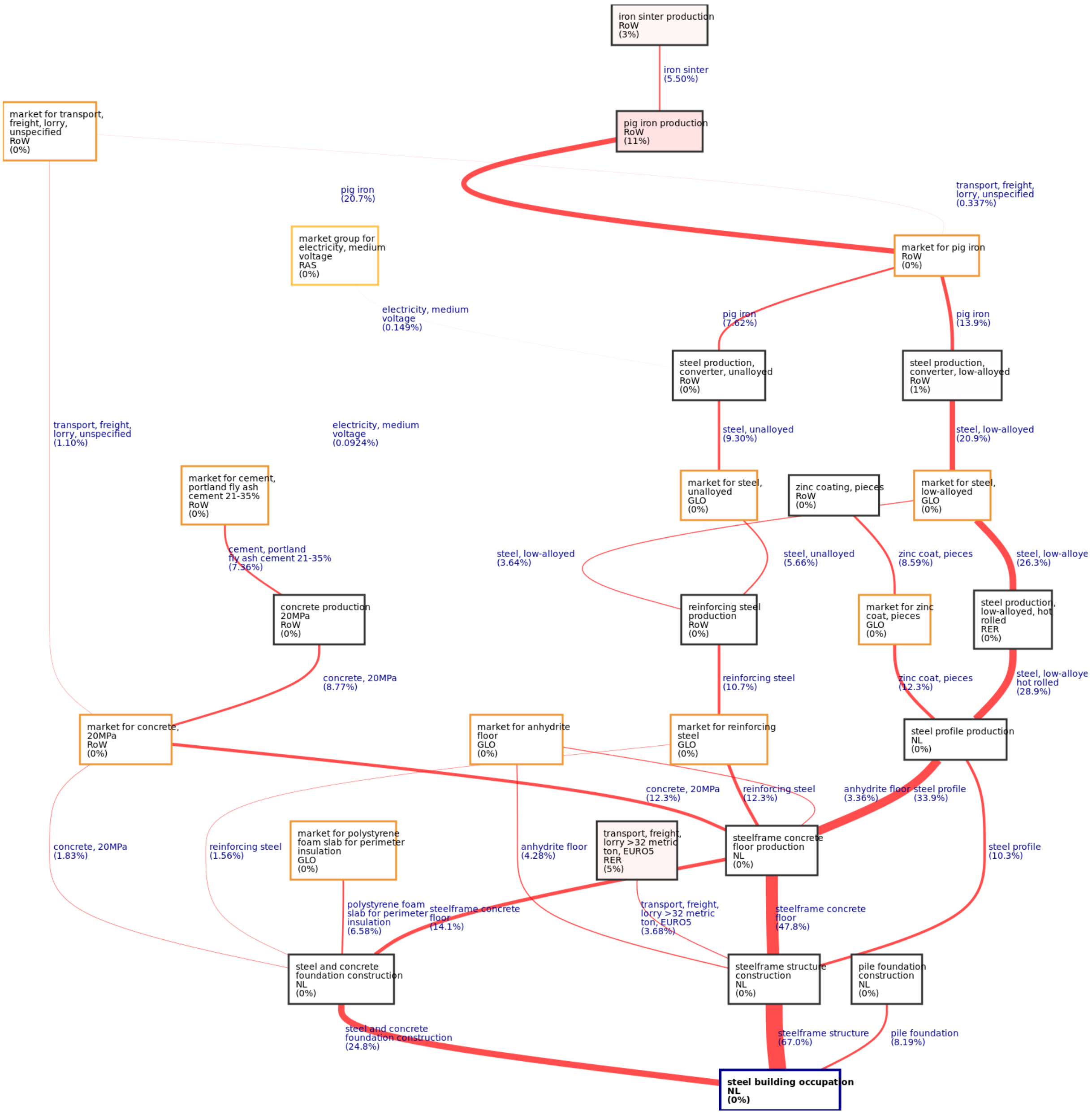
Regrowth time in Austria	**12 minutes**

All values are based on the KLH EPD that was verified by external assessment and the data quality was checked before public release. The calculation of the background data is based on the ecoinvent database. All standards and literature are stated in the EDP document, which is available on www.klh.at.

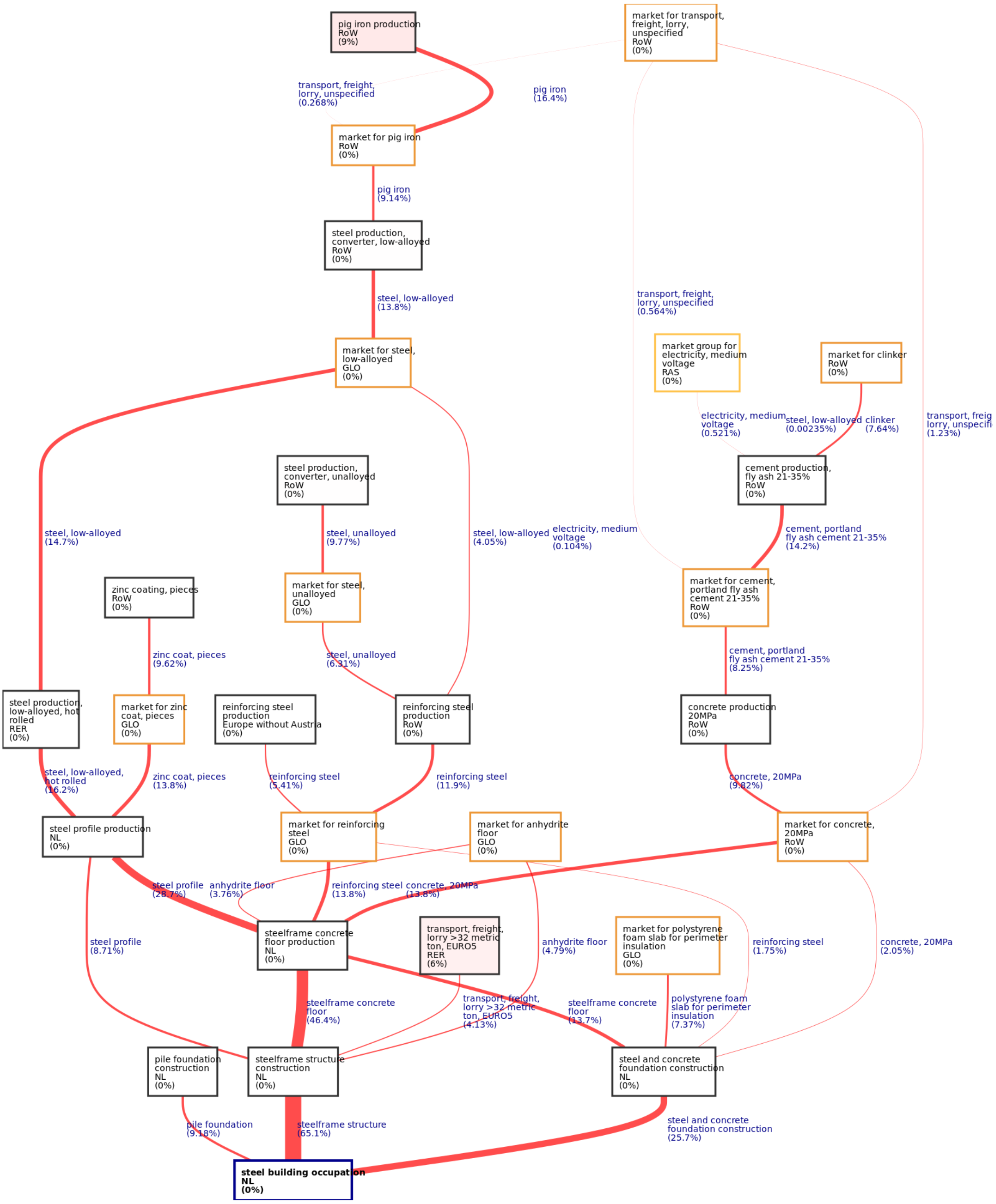
1/1 - KLHdesigner co2 v1.2.0 - 22-6-2022

Appendix D: Sankey diagrams

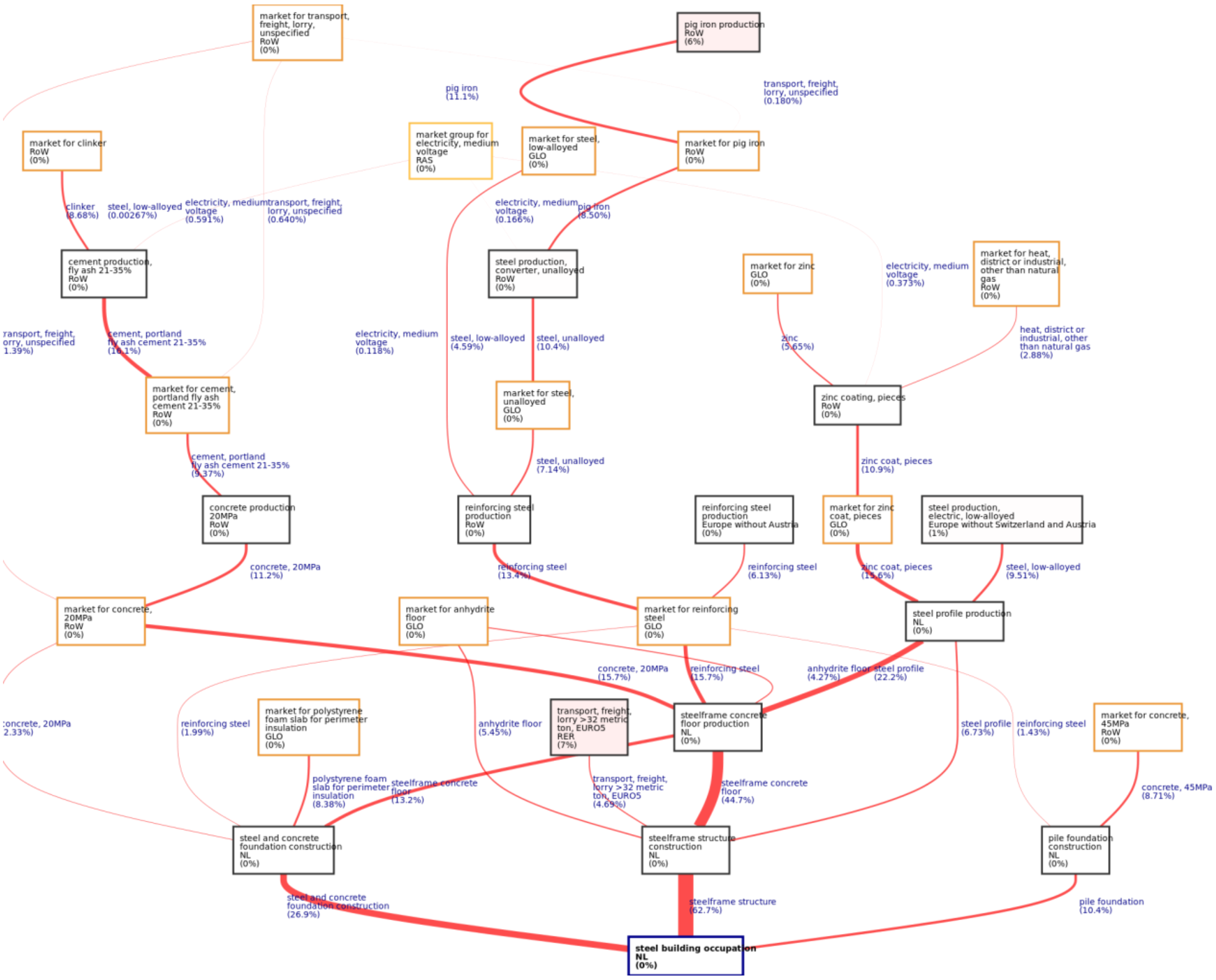
Appendix D1: Worst-case steel construction



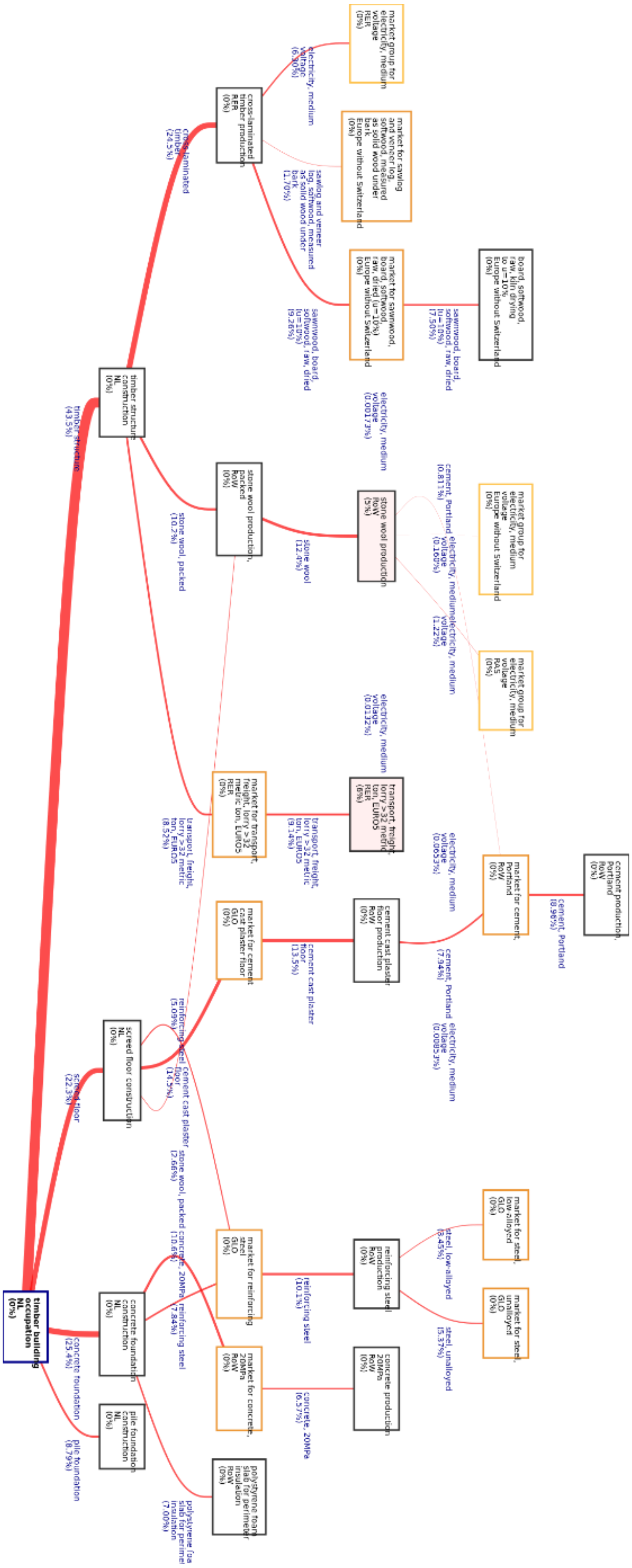
Appendix D2: Expected steel construction



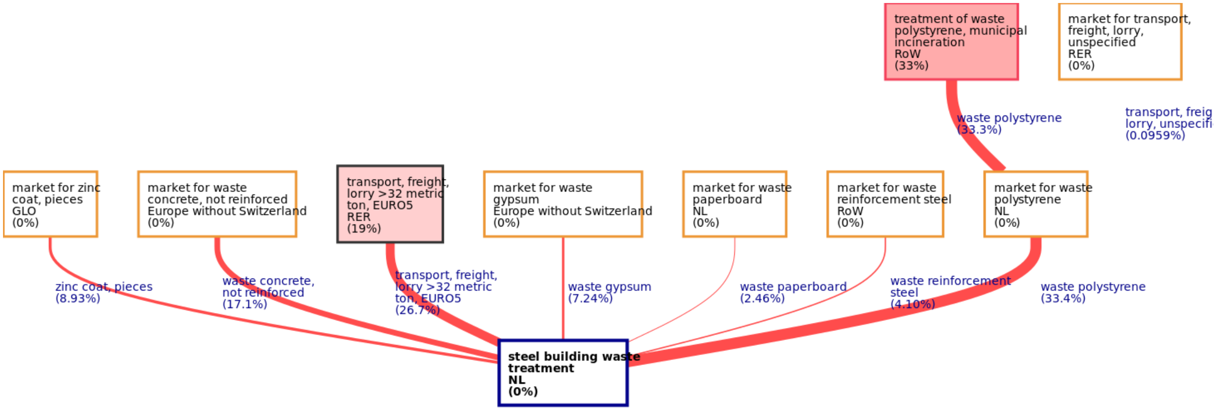
Appendix D3: Best-case steel construction



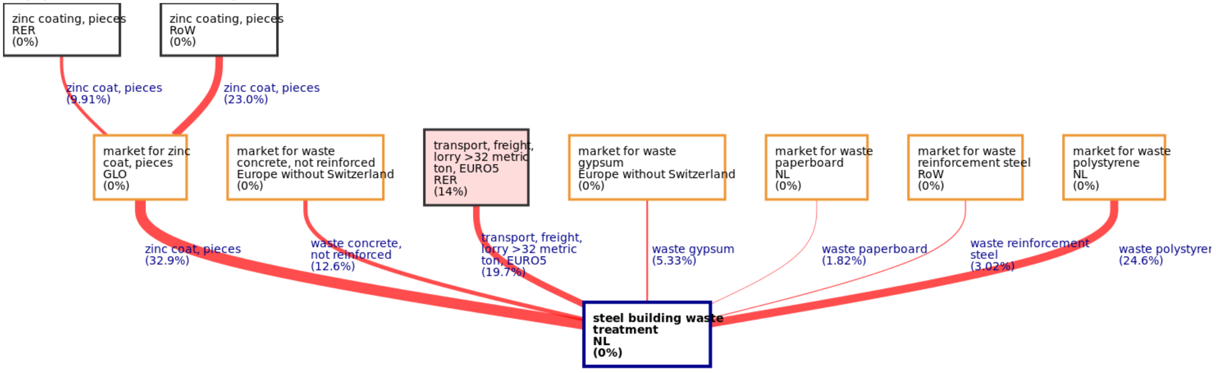
Appendix D4: All timber construction



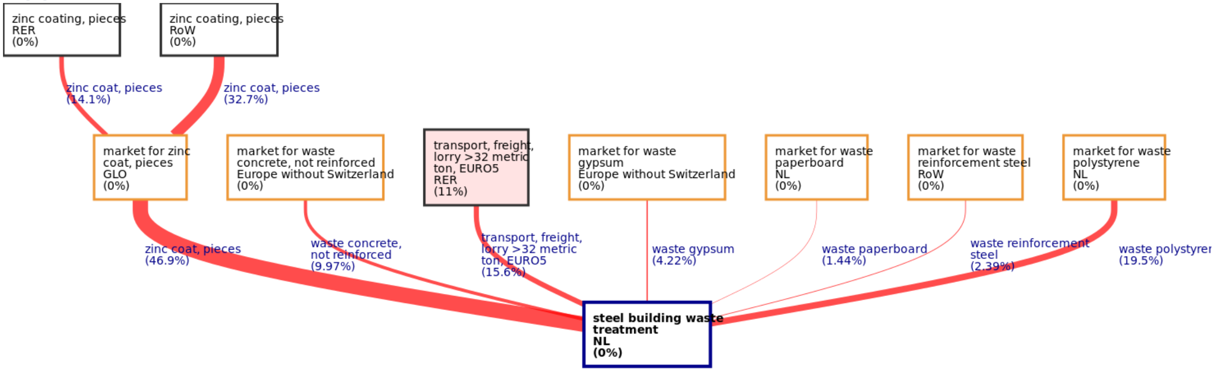
Appendix D5: Worst-case steel waste treatment



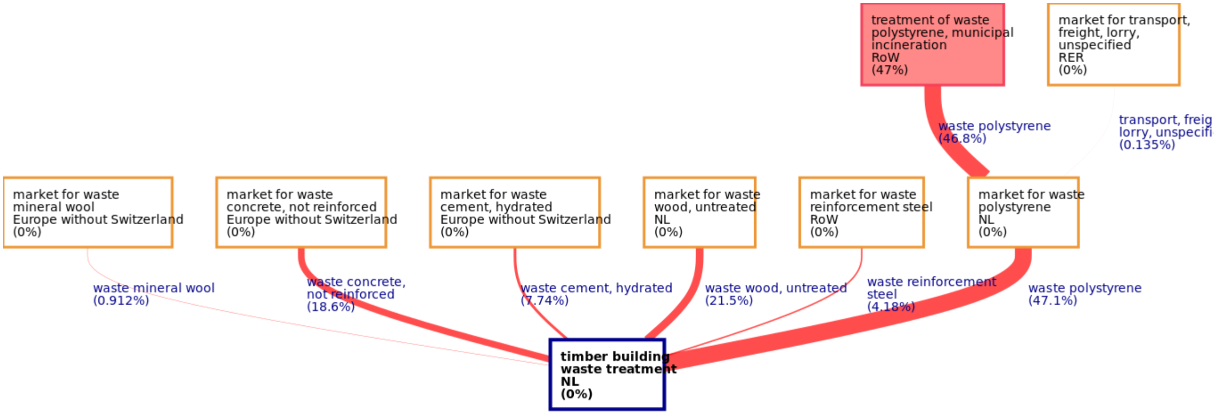
Appendix D6: Expected steel waste treatment



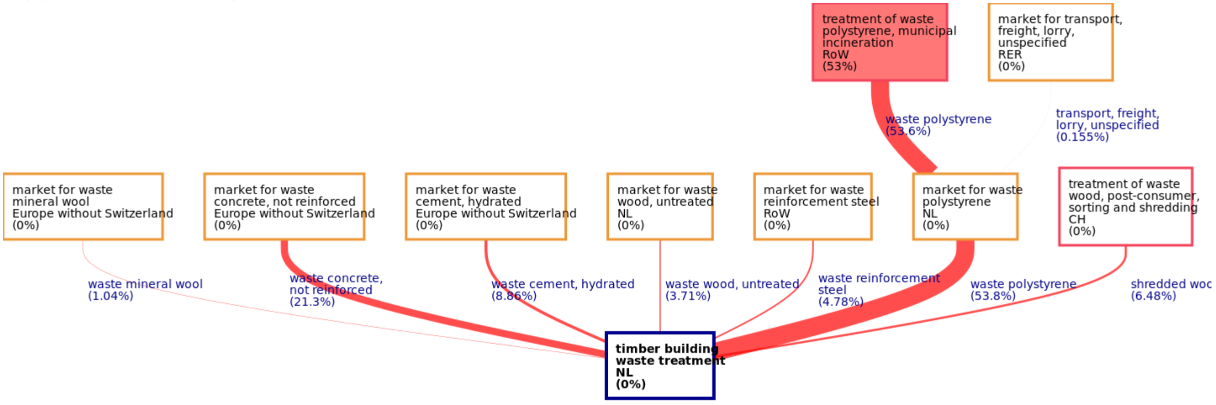
Appendix D7: Best-case steel waste treatment



Appendix D8: Worst-case timber waste treatment



Appendix D9: Expected timber waste treatment



Appendix D10: Best-case timber waste treatment