Sustainable timber structures

Quantitative research evaluating the potential effects of carbon sequestration and cascading strategies in the Netherlands based on a comparison of the Dutch and European life cycle assessment methodologies

W. W. van Wijnen

TUDelft

ARCADIS

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Quantitative research evaluating the potential effects of carbon sequestration and cascading strategies in the Netherlands based on a comparison of the Dutch and European life cycle assessment methodologies

By

Willem Wouter van Wijnen

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> “*Part of building for a sustainable future is about totally rethinking so many of the systems that we work in, not just changing the building material.*”
>
> Andrew Waugh
> Architect and timber specialist

Preface

This thesis is the final deliverable of my graduation project to obtain a master's degree in Building Engineering - Structural Design at the Delft University of Technology.

After previously having worked on a sustainability topic for my bachelor's thesis with pleasure, it was again with great joy to expand my knowledge of life cycle assessments and sustainability concepts in the construction sector such as circularity and cascading strategies. In this research, the topic of sustainability is combined with timber structures. Since the industrial revolution, timber was regarded, by most, as an ancient way of building. Recently, this changed due to the increased awareness for sustainability by the construction sector in combination with the sustainable characteristics of timber. Nature inclusive construction can help for a better environment, as shown in this and other research. Being privileged to live next to a forest, it was a great way to ponder my thoughts and challenges about this thesis in an environment so closely related to my topic. That said, sustainable forestry is crucial in the strategy of nature inclusive building. Otherwise, it will result in counterproductive environmental effects.

I did this research at the structural design and engineering department of Arcadis, a design and consultancy firm. Arcadis has the vision of "improving the quality of life", which was a great match with the topic of this thesis. The freedom given to define the topic was a nice challenge, primarily to define the scope and limitations to obtain meaningful results. Working at the office was pleasant, even though shorter as planned due to the Covid-19 pandemic.

My sincere gratitude goes to all members of my graduation committee for their guidance, constructive feedback and discussion we had. Specifically, Roel Schipper for chairing the committee; Henk Jonkers for providing the license to retrieve environmental data; Geert Ravenshorst for inviting me to the Houtdag (national timber day), which was a great inspiration at the start of my thesis; and Pieter Timmerman, my supervisor from Arcadis, for providing the case study.

I would also like to thank Sander Pasterkamp from the TU Delft for answering my questions about elongation of the reference service life of buildings, Tom de Boer from the Nationale Milieudatabase for answering my questions about the assumptions in the end of life modelling of timber, and Nout Barentsen for his great visualisation of my idea for the cover.

Finally, I would like to thank my family and friends for their support.

Wouter van Wijnen
Oostvoorne, October 2020

Summary

To meet the climate goals set by the government, the building sector needs to reduce its contribution to the environmental burden on society. However, the current situation in the Netherlands presents a major challenge to build more to reduce the housing shortage, while at the same time reducing its environmental footprint. Therefore, alternative solutions to the status quo should be considered, which can reduce the environmental impact of buildings.

The goal of this thesis is to determine the environmental impact of various multi-storey timber residential buildings and to make a comparison with the status quo: a concrete building. Hence, the formulation of the main research question: Which timber typologies have the lowest environmental impact for multi-storey buildings in the Netherlands at 30, 50 and 70 meters high and how does this compare to a concrete alternative?

To answer the main research question, the following methodology is used:

1. Reference projects are studied to determine the trends in the timber construction sector. Based on these results, the main timber typologies and available design choices are mapped. As well as the (engineered) timber products available on the market.
2. The sustainability of timber structures is assessed by performing a literature study on three different scales: the macro-, meso- and micro-scale. The macro-scale represents the global forestry level in which the carbon cycle, carbon sequestration (i.e. capture and storage) and forest certification are discussed; the meso-scale represents the building level in which the durability and cascading strategies (i.e. strategies to elongate the lifespan) are discussed; the micro-scale represent the environmental impact of the material itself.
3. The environmental impact is quantified using the fast-track life cycle assessment (LCA) methodology. Two data sources are evaluated by performing a data analysis. The first being the ‘Nationale Milieu Database’ (NMD) which is prescribed by the Dutch ‘Milieuprestatie Gebouw’ (MPG), the second being Environmental Product Declarations (EPDs) according to the European EN 15804 standard. Furthermore, the differences between the Dutch and European methods are discussed and evaluated.
4. For the main timber typologies, identified by the reference project study in the range as set by the main research question, a variant study is set-up using a parametric environment. The variant study analyses the environmental impact of main load bearing structures, the relative

contribution of structural components and the effect of cascading strategies (i.e. elongation of buildings lifespan, equalising the functional and technical lifespan).

5. The research is concluded by a case study in which the environmental impact of a timber alternative is compared with an equivalent concrete benchmark. Based on these results the global warming reduction potential of timber structures is determined.

The infographic in Figure S.1 shows how the individual parts of the research are related to each other; a simplified representation of LCA; and the main differences between the Dutch and European LCA methodologies.

The Dutch MPG is based on the European standard EN 15804 with several changes, as indicated in the infographic. The main difference is that the Dutch methodology prescribes four additional environmental impact categories: human toxicity potential, freshwater aquatic eco-toxicity potential, marine aquatic eco-toxicity potential, and terrestrial eco-toxicity potential. Each impact category quantifies an environmental burden. Thus, the MPG is more elaborate than the European standard, which prescribes a minimum of seven specific impact categories. This difference causes problems for engineered timber products specifically since the Netherlands has a limited forestry industry. These products are therefore primarily imported from abroad. Foreign manufacturers quantify the environmental impact according to the European standard and cannot be directly implemented in the NMD without an additional LCA study since four impact categories are missing. This limits the availability of reliable and up to date timber data sources in the Netherlands.

A limitation of the MPG methodology is the ‘black box’ approach to quantify the environmental burden. By specifying input (material types and quantities), the output (shadow price) is obtained without questioning the underlying data source (NMD database). The NMD does not make the Dutch EPDs, which are the origin of the database, publicly available. Some Dutch manufacturers publish the EPDs which are included in the NMD. However, this is most often not the case. In contrast with the NMD as a data source, the EPDs are more transparent, which allows for studying and verifying the underlying assumptions for life cycle scenarios made by the LCA practitioner. In the data analysis, the difference between the two methodologies is assessed, even though the cause of differences cannot be determined due to the non-transparency of the NMD.

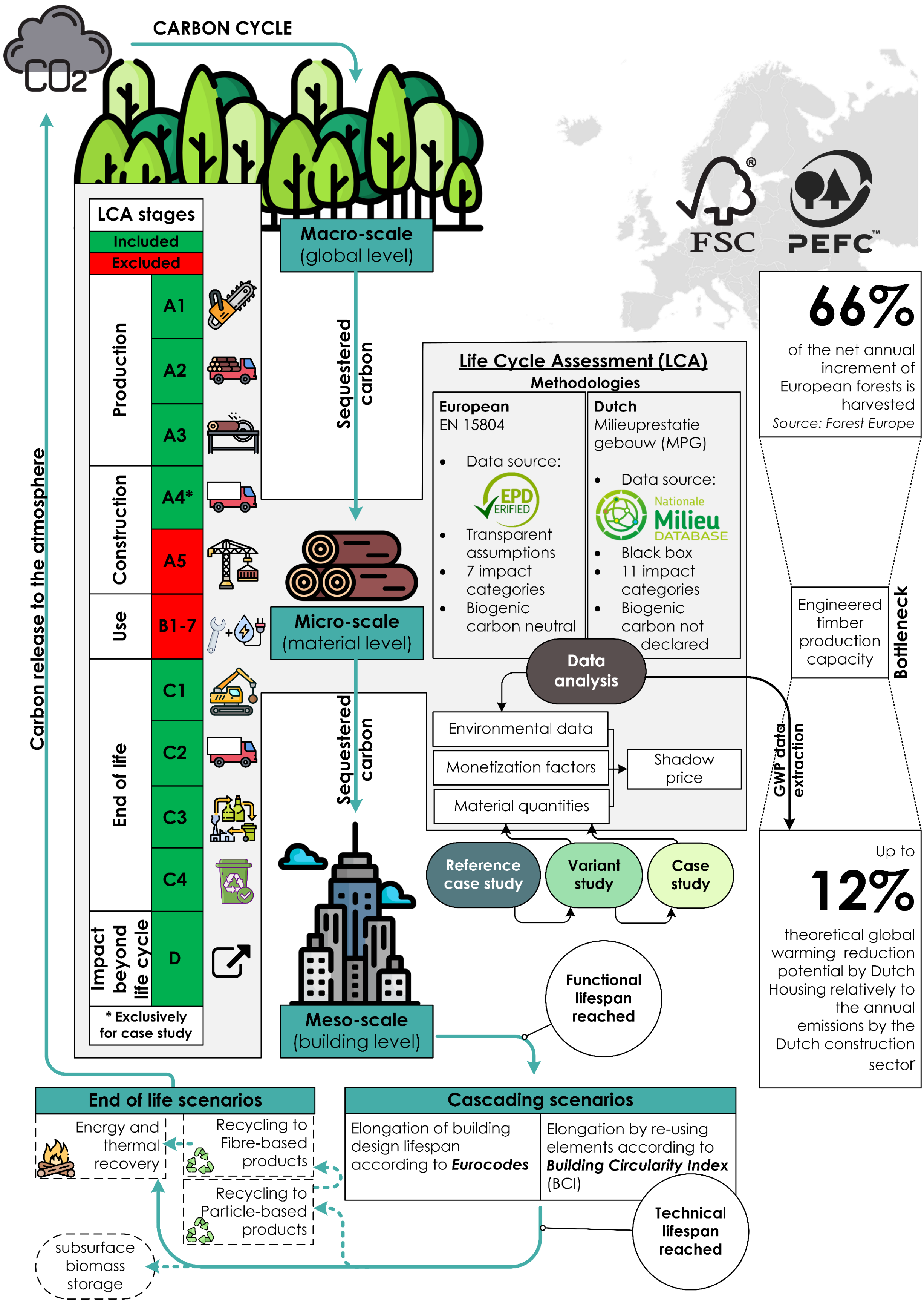

Figure S.1: Infographic of thesis

The data analysis is performed based on 19 third party verified EPDs and NMD data for sustainably certified timber. To compare the two data sources, the same monetization factors are used to derive the shadow price. From the data analysis, it was found that the selection of timber environmental data sources is highly sensitive. Choosing the European EPDs leads to a 55% shadow price reduction compared to the NMD for glued laminated timber (based on the seven impact categories which are declared for both sources). According to the NMD, the shadow price is increased by 62% when including the additional four impact categories. However, by evaluating a European EPD for a wall assembly an estimation of the human toxicity potential is possible. Similar to the other impact categories, the obtained value is significantly lower compared to the NMD data, indicating the same data sensitivity as found in the minimum seven impact categories. Therefore, a thorough review is required when selecting data sources to identify their underlying assumptions, validity, and comparability. For the case study, it was found that by changing the data source to the Dutch NMD, the timber alternative would perform worse for the environmental impact than the concrete benchmark.

In the studied EPDs inconsistencies were found in the modelling of the re-use and recycling scenarios. By incorrectly modelling the biogenic carbon content beyond the life cycle, an overestimation of the benefits occurs in some EPDs. Additionally, the way the MPG and EPDs treat the energy and thermal recovery scenario is different. The studied EPDs assume substitution of natural gas for thermal recovery and the current electricity mixture for energy recovery. This mixture currently consists of predominantly fossil fuels. In some cases, this assumption can lead to a negative shadow price for timber due to the large substitution effect of fossil fuels. However, the energy mixture will change to a more sustainable scenario by the time the timber reaches its end of life scenario. Therefore, the MPG methodology prescribes rules for material equivalency in LCA stage D (i.e. biomass will replace biomass, not fossil fuels). For comparability, the interpretation of end of life scenarios is manually corrected for the following sections of this thesis (variant and case study). Eliminating inconsistencies in re-use and recycling scenarios and the delay effect of the energy mixture.

The beneficial effect of carbon sequestration, which effectively lowers the carbon dioxide (CO_2) concentration (temporarily) in the atmosphere, is not incorporated in the LCA methodology. Quantification of biogenic carbon content is excluded in the MPG methodology, whereas it is included in European EPDs. Both methodologies yield the same results due to the static reference timeframe of LCA, resulting in a net-zero biogenic carbon balance in EPDs since the stored carbon in timber is assumed to be released at the end of life stage regardless of scenario.

Material passports could be used to monitor the increase in carbon sequestration in the timber buildings and structures of the industry as a whole. Using this approach, the benefits can be attributed to timber buildings until the market converges to the point where timber buildings are replaced by timber buildings and no additional benefits of carbon sequestration occur besides the net annual increase of the housing stock.

From the case study, it followed that the environmental impact of multi-storey residential buildings is lower than a concrete equivalent. For this specific case study comparison, it was found to be a 17% difference in shadow price between the two. The choice for either a post and beam or mass timber typology does not lead to significant differences for the default 50-year design lifespan. The choice for a certain type of floor system has the largest impact on the total environmental burden of the structure. By analysing two cascading scenarios, being a flexible floorplan scenario and re-use scenario, the first was found to have the largest reduction potential (63% versus 40%) based on the same elongation of lifespan. Overall, it can be concluded that a difference can be made to the environmental impact of the build environment by cascading scenario, regardless of the choice of construction material. In case of timber structures, additional benefits occur due to the lower relative environmental impact and the carbon sequestration.

The annual global warming reduction potential, by increasing the market share of timber in the housing sector, was estimated to be a maximum (based on 100% market share) of 12% of the national annual global warming potential by the construction sector and production of construction materials. This is valid until market saturation occurs, after which the potential is reduced to 6%. By using cascading strategies, the time before reduction can be elongated. Further reduction can be achieved by application of timber in offices, public and industrial buildings. However, it was found that the production capacity of engineered timber proved to be currently insufficient to reach the market potential. This will result in upscaling challenges for the engineered timber manufacturers when the demand will increase.

Conclusively, it can be said that the Dutch MPG methodology is a good extension of the European EN 15804, including a wider range of environmental impact categories. Also, the monetization to shadow prices gives a good basis for comparison. Ideally, the shadow price, representing the burden to society as a whole, should be charged (polluter pays principle). This will lead to more and effectively lowering of the environmental impact and innovation of the construction sector compared to a set MPG requirement. However, this requires more up-to-date and transparent data in the NMD.

Contents

Glossary

ADP	Abiotic depletion potential
AP	Acidification potential
BCI	Building circularity index
BIM	Building information modelling
CBS	Centraal bureau voor statistiek
CCS	Carbon capture and storage
CE	Circular economy
CLT	Cross laminated timber
CML	Centrum voor milieuwetenschappen Leiden
CNC	Computer numerical control
DLCA	Dynamic life cycle assessment
EP	Eutrophication potential
EPD	Environmental product declaration
ETS	European Emission Trading System
FAETP	Freshwater aquatic eco-toxicity potential
FSC	Forest stewardship council
GFA	Gross floor area
Glulam (GLT)	Glued laminated timber
GWP	Global warming potential
HTP	Human toxicity potential
HVAC	Heating ventilation and air conditioning
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LVL	Laminated veneer lumber
MAETP	Marine aquatic eco-toxicity potential
MND	Module not declared
MPG	Milieuprestatie gebouw
MT	Mass timber
NIBE	Nederlands instituut voor bouwbiologie en ecologie
NLT	Nail laminated timber
NMD	National milieu database
ODP	Ozone depletion potential
P&B	Post and beam
PEFC	Programme for Endorsement of Forest Certification
POCP	Photochemical ozone creation potential
RSL	Reference service life
SBK	Stichting bouwkwaliteit
TETP	Terrestrial eco-toxicity potential

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Introduction

This chapter introduces the thesis by describing the background and relevance of the topic in Section 1.1. Then, the research definition is presented in Section 1.2 based on the identified knowledge gaps. Lastly, the outline is given in Section 1.3.

1.1 Background and relevance

Developing more housing while having lower emissions. Currently, this is a major challenge for the built environment in the Netherlands. To meet the climate goals as agreed upon with the United Nations, the Dutch government reached a climate agreement in which is stated that carbon dioxide (CO_2) emissions should be reduced to 49% in 2030 and 95% in 2050 [1]. The most used structural materials for buildings, concrete and steel, have a significant contribution of 15% to global human-induced CO_2 emissions [2]. Therefore, alternative solutions should be considered to construct more sustainable structures. Recently, this is also recognised by the Dutch parliament. On the 29th of October 2019, two motions were accepted. They state that it should be investigated how timber construction can be implemented to a greater extent and how much it will contribute to decreasing the environmental impact of the construction sector [3, 4].

In comparison to steel and concrete, timber has many advantages, as shown in Figure 1.1:

- The material is renewable and can be classified as a circular building material when certified wood from sustainably managed forests is used.
- Timber stores CO_2 and is, therefore, a natural and cheaper alternative to carbon capture and storage (CCS) facilities.
- Less energy is required to extract the material and manufacture the products than concrete and steel, resulting in lower embodied energy.
- Timber can easily be recycled to other products or used as biomass.
- Timber can be manufactured in any desired shape by computer numerical control (CNC) milling and can easily be adapted after completion of construction, thus a highly adaptable material.
- Timber has a lower density than concrete and steel resulting in lighter structures.

- Fast construction is possible since the material is lightweight, is prefabricated offsite and has low tolerances.
- Users living in timber buildings experience better health and wellbeing [5].

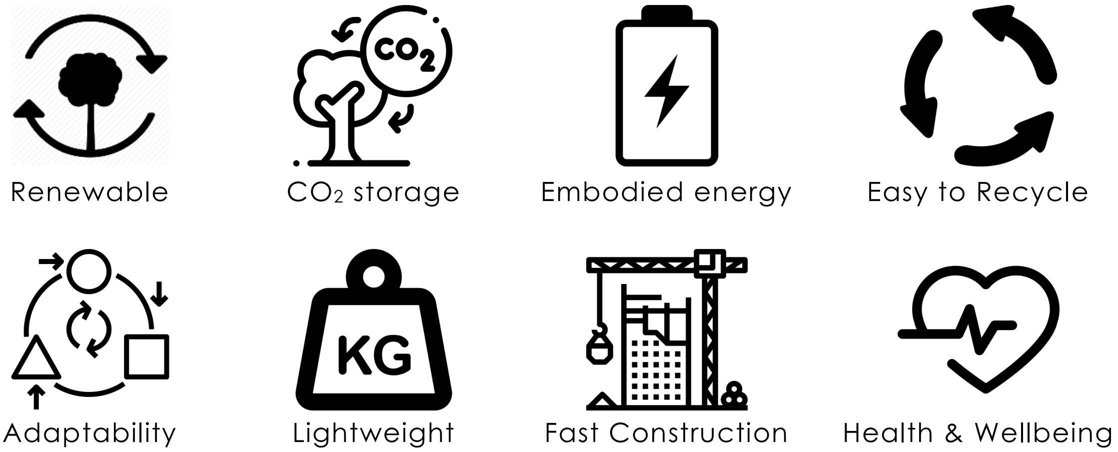
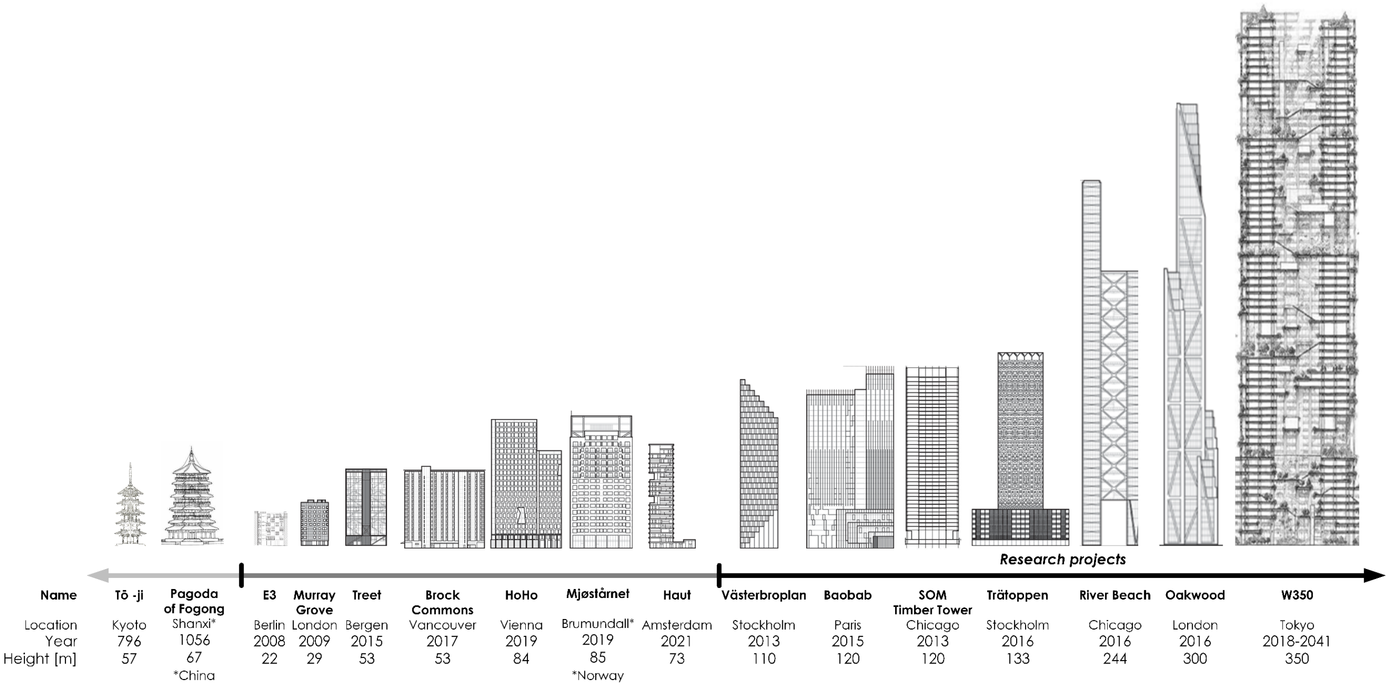


Figure 1.1: Advantages of timber structures

Timber is one of the oldest construction materials used by humanity. Though, not often applied for buildings in modern construction after the discovery of metals and concrete during the industrial revolution. Older examples of tall timber structures exist, such as the Sakyamuni Pagoda of Fogong Temple in China. The temple was constructed in 1056 and has a height of 67 meters [6]. After the Great Fire of London in 1666, many building codes specified that timber construction should be limited to 6 stories or lower [7]. Recently, a revival of multistorey timber construction occurred after lifting these regulations. Various projects have been completed, and studies are ongoing to analyse the potential to go even taller [8-12].

Figure 1.2 shows the evolution of timber and hybrid timber buildings over time. Currently, the tallest timber building in the world is 85 meters (Mjøstårnet). The tallest timber building in the Netherlands will be 73 meters and completed in 2021 (Haut). These examples indicate that timber buildings are still in the lower spectrum of high-rise structures.



Name	Tō -ji	Pagoda of Fogong	E3	Murray Grove	Treet	Brock Commons	HoHo	Mjøstårnet	Haut	Västerbroplan	Baobab	SOM Timber Tower	Trätoppen	River Beach	Oakwood	W350
Location	Kyoto	Shanxi*	Berlin	London	Bergen	Vancouver	Vienna	Brumundall*	Amsterdam	Stockholm	Paris	Chicago	Stockholm	Chicago	London	Tokyo
Year	796	1056	2008	2009	2015	2017	2019	2019	2021	2013	2015	2013	2016	2016	2016	2018-2041
Height [m]	57	67	22	29	53	53	84	85	73	110	120	120	133	244	300	350

*China

*Norway

Figure 1.2: Evolution of (hybrid) timber buildings

Building images in this figure retrieved from skyscrapercenter.com

The two ancient buildings, shown in Figure 1.2, are examples of fully timber buildings and still stand today. Indicating the durability of timber as long as appropriately maintained. Modern buildings where the main load-bearing structure is constructed entirely from timber exists, such as Murray Grove in London. Though this building has a limited height of 29 meters. Examples of greater height, shown in Figure 1.2, all use a hybrid system involving steel or concrete. The main reason is to resist lateral loading [13], while also mitigating other problems such as low sound insulation and vibrations due to timber's low mass.

For the timber typology, it is unknown what the environmental impact will be for different configurations of the stability and floor systems [14]. Parts of a building will contribute more than others, such as the foundation, floors and core. Also, geometrical variation can influence the total impact on the environment. A denser column grid leads to shorter spans and a reduction of the structural height of a floor system. A parametric study is beneficial to analyse many configurations in an early design phase. Though no parametric shadow price calculator is developed yet [14].

The topic of this thesis followed from the fact that knowledge gaps are present for the environmental impact of timber and hybrid timber buildings.

1.2 Research definition

1.2.1. Objectives

The objective of this study is to make a global analysis of various timber main load-bearing structures and assess them on their environmental impact. Through these analyses, the typologies which can be applied best regarding their environmental impact will be determined. This knowledge will help to evaluate in the preliminary design phase which of these systems have the lowest environmental impact for standard buildings at different heights. Additionally, the effect of cascading strategies on the environmental impact is analysed and a comparison with a traditional multi-storey concrete structure is made to show the potential of timber structures.

1.2.2. Research questions

Main question

Which timber typologies have the lowest environmental impact for multi-storey buildings in the Netherlands at 30, 50 and 70 meters high and how does this compare to a concrete alternative?

Sub-questions

1. What are the most common timber and hybrid timber stability and floor systems in practice?
2. What is the environmental impact of the materials used in these systems?
3. How much can cascading strategies reduce the environmental impact based on the functional and technical lifespan of timber?
4. What is the individual environmental contribution of the different structural components in timber buildings?
5. What is the global warming reduction potential of timber alternatives compared to a concrete equivalent?

1.2.3. Methodology and scope

The study is based on timber data from Environmental Product Declarations (EPDs). The main advantage of this data source is that underlying assumptions can be studied, which is not possible via the Nationale Milieu Database (NMD). Performing Life Cycle Assessments (LCA) of single materials will be excluded from the scope of this research, since a fast track LCA approach is used.

The level of detail will be limited to the preliminary design phase for the structural designs. The focus of the research is the environmental impact of timber buildings, not the ultimate limits of timber systems which require a more detailed structural study. Also, building physics will be excluded from the scope. As stated in the main research question, the analysed height will be at 30, 50 and 70 meters. This range is based on reference projects as shown in Figure 1.2 and a feasibility study previously performed at Arcadis [15]. For the structural variants, a single square floorplan will be used with a residential function. The parametric modelling will be done in the Dynamo environment in combination with RFEM structural software, which is the default inhouse parametric workflow at Arcadis.

The comparison with traditional multi-storey apartment buildings will be made through a case study. For the case study the project ‘Bay House’ in Rotterdam is chosen. This structure is currently being developed by Arcadis using a concrete design, which is the most common structural material for apartment buildings in the Netherlands. Steel apartment buildings are therefore excluded from the scope. A ‘Fast Track’ LCA of this concrete structure will be performed as a benchmark for the timber alternative. The results from the variant study will be used to identify the best environmental timber alternative at the height of the case study.

1.3 Outline

The flowchart in Figure 1.3 shows the thesis outline. In phase I, a literature study and data analysis are performed and will focus on answering the first two thesis sub-questions. Firstly, identifying the most common timber and hybrid timber stability and floor systems in practice by studying literature from reference cases. Secondly, identifying the framework to assess the environmental impact of structures. Followed by answering the second thesis sub-question based on this framework and the identified materials as used in the timber typologies from chapter 2.

Subsequently, a variant study is performed in phase II. Chapter 4 presents the modelling process of the parametric variant study, including the used assumptions for the structural model and the parametric design space. For these structural variants, the environmental impact is determined in chapter 5, answering thesis sub-questions 3 and 4.

Lastly, in phase III, a comparison between timber structures and a concrete case study is made as well as an estimation of the global warming reduction potential by timber structures. This answers the final sub-question and together with results from previous chapters leads to answering the main thesis question.

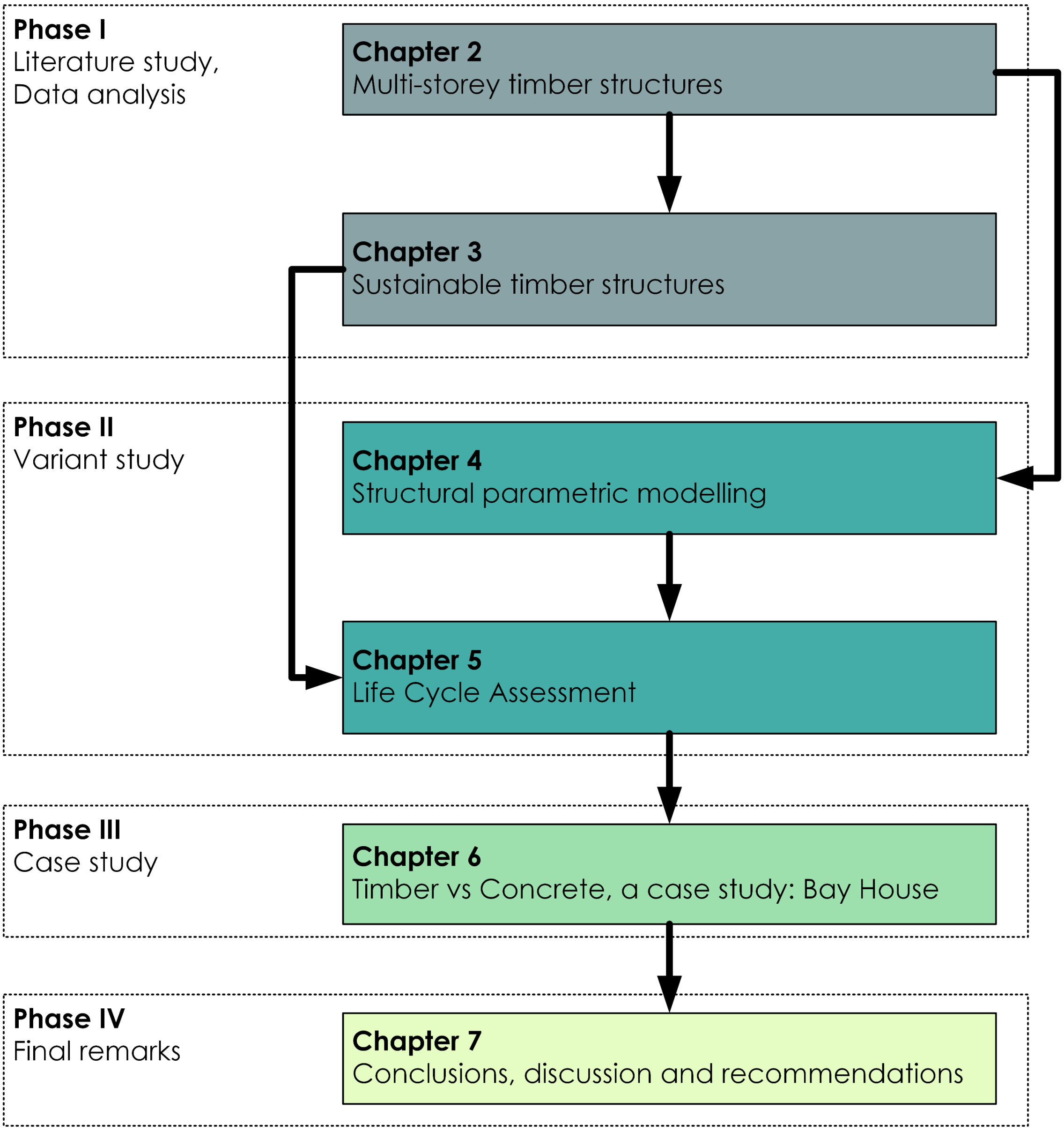


Figure 1.3: Thesis outline

2

Multi-storey timber structures

In this chapter, a classification of timber building typologies is established based on various reference projects. This includes main typologies, stability systems, floor systems, connection types and fire safety strategies. First, twelve reference projects are introduced in section 2.1. Based on these projects, their characteristics are inventoried in section 2.2. The chapter concludes with a description of the timber engineered products commonly used in the analysed reference projects.

2.1 Reference projects

This section presents twelve reference cases to study the most common timber and hybrid timber buildings from practice. A selection was made based on new developments and significance in multi-storey timber construction, see Figure 2.1 for the selected projects.

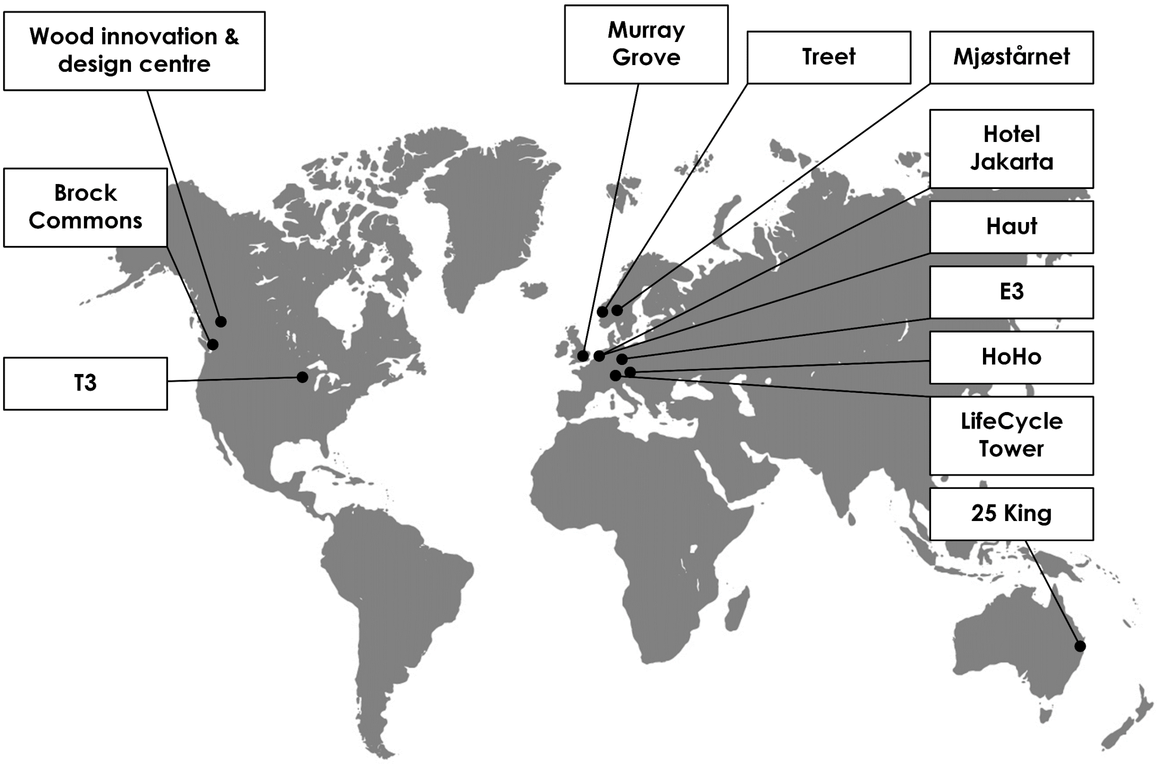


Figure 2.1: Overview of reference projects

2.1.1. E3

Location	Berlin, Germany
Project status	Completed
Year	2008
Height	23 m, 7 storeys
Building function	Residential
Material type	Hybrid Timber, Concrete & Steel
Superstructure construction time	7 weeks (7 days per storey)
Costs	€1,628,000.- (€1,715.- per m^2)
Architect	Kaden Klingbeil Architekten
Structural engineer	Bois Consult Natterer BCN Julius Natterer, Tobias Linse
Timber manufacturer	N/A

The E3 building in Berlin was the first timber building in Europe of seven storeys. Changes were made to the German regulations which allowed for timber buildings up to five storeys instead of the original three storeys. By studies, the structural and fire safety was proven, which allowed the project to pioneer above the limit of five storeys. The interior walls are non-load-bearing, resulting in a flexible floorplan layout only limited by two concrete HVAC shafts, see Figure 2.2.

Stability system

The load-bearing CLT façade provides the stability of the structure. An exterior free-standing concrete core is present but was exclusively required for fire safety measures.

Floor system

A hybrid floor system was used of CLT slabs in combination with a concrete top layer. The ground floor was constructed entirely from concrete.

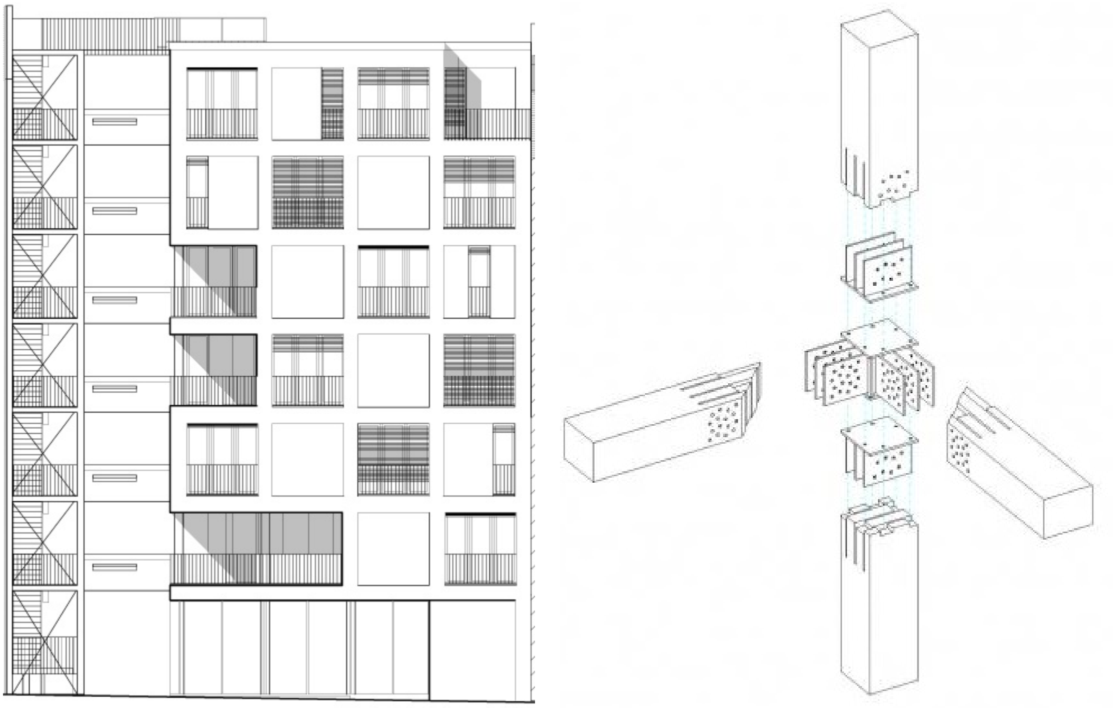
Detailing

A custom steel joint was designed to connect the glulam post and beam system. Figure 2.2B shows the detail which is composed of steel connector plates and bolts.

Fire safety strategy

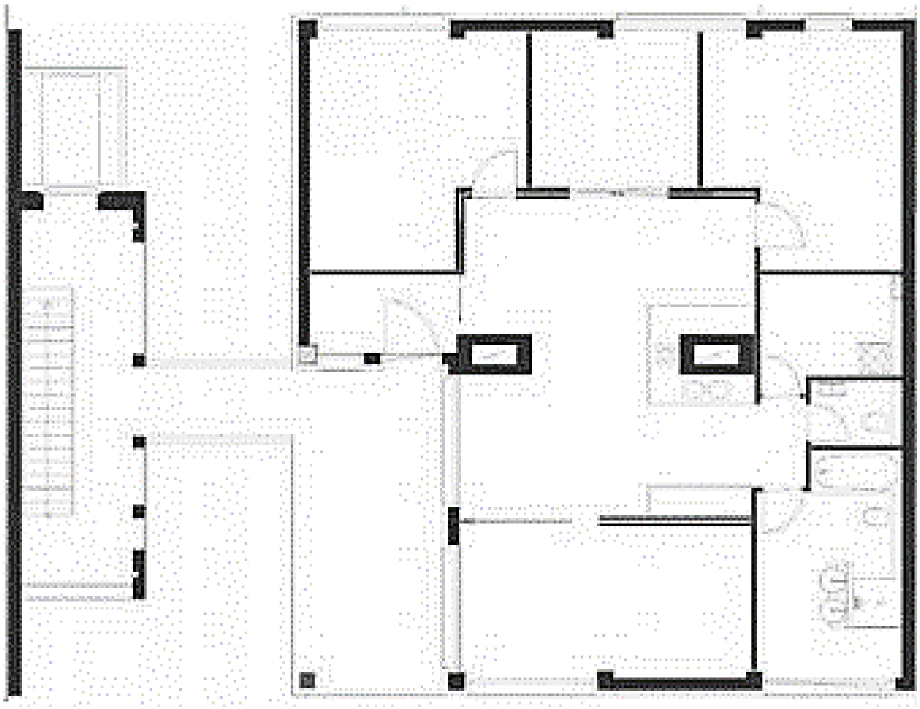
Next to the separate concrete core for evacuation, the building itself uses a passive fire safety strategy consisting of encapsulation of the walls with gypsum panels. The ceiling, which is the bottom of the CLT slab, is exposed and treated with a fire-retardant coating.

All factual information in this reference case is based on [16, 17]



(A) Load bearing facade and exterior core

(B) Connection detail



(C) Floorplan

Figure 2.2: E3 Berlin [16]

2.1.2. T3

Location	Minneapolis, United States
Year	2016
Project status	Completed
Height	26 m, 7 storeys
Building function	Office
Material type	Hybrid timber & concrete
Superstructure construction time	9.5 weeks (9 days per storey)
Costs	N/A
Architect	Michael Green Architecture, DLR Group
Structural Engineer	Magnusson Klemencic Associates
Timber manufacturer	StructureCraft

In the United States, the T3 building was the first modern timber structure to be completed. At the time, it utilised the maximum height as specified in Minnesota regulations for timber buildings. See Figure 2.3 for an impression of the structure.

Stability system

T3 was designed as a Glulam post and beam type structure, similar to the E3 building in Berlin. Though, the structural stability is provided by a more conventional concrete core.

Floor system

Prefabricated Nail-laminated timber (NLT) slabs were used for the flooring. This system is structurally efficient for one-way spans since all wood fibres run in a single direction. This system is more common in the United States and Canada than in Europe, where mostly CLT and LVL is used. The ground level was constructed entirely from concrete.

Detailing

Steel connector plates were used to connect the post and beam system. The columns are continuously connected and notched at the locations of the connection with the beams.

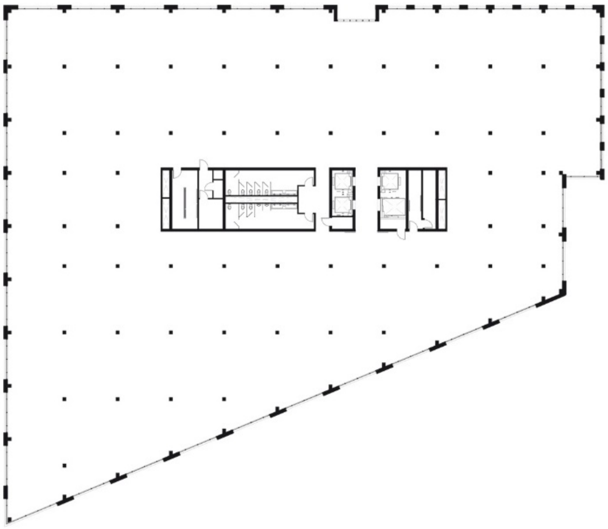
Fire safety strategy

The building relies on an active fire safety strategy using a sprinkler system.
All timber ceilings, beams and columns are exposed without additional fire-retardant coating.

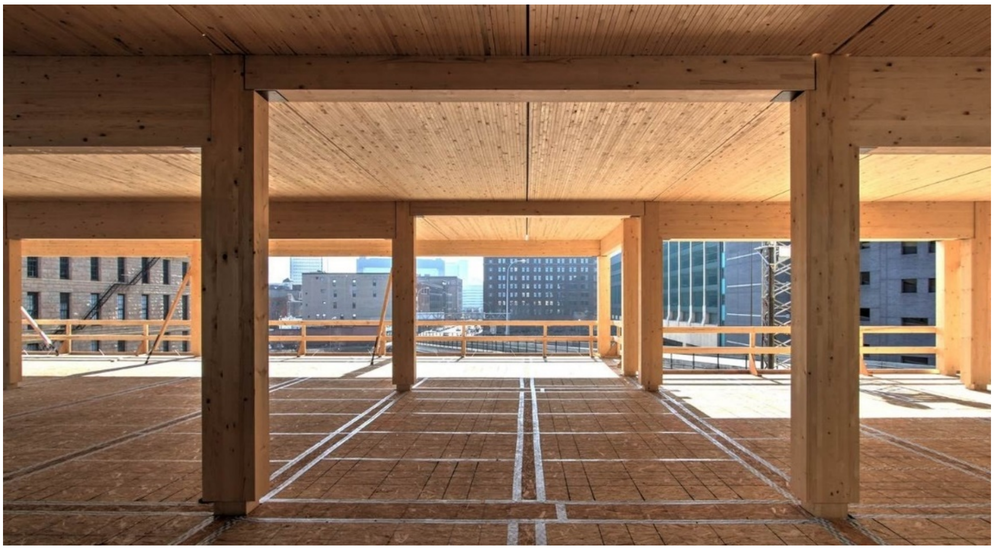
All factual information in this reference case is based on [18-21]

(A) Impression [20]

(B) Structural model [20]



(C) Floorplan [21]



(D) Detail of notched column and beam connection [20]

Figure 2.3: T3 Minneapolis

2.1.3. LifeCycle Tower One

Location	Dornbirn, Austria
Year	2012
Project status	Completed
Height	27m, 8 storeys
Building function	Office
Material type	Hybrid Timber & Concrete
Superstructure construction time	8 days (1 day per storey)
Costs	N/A
Architect	Hermann Kaufmann Architekten
Structural Engineer	Merz Kley Partners
Timber manufacturer	Wiehag

The LifeCycle Tower (LCT One) was the prototype of a newly developed hybrid timber system for residential and office buildings. See Figure 2.4 for the impression of the building.

Stability system

The developed modules were designed as a hinged Glulam post and beam system, in which the Glulam beams are integrated with the floor slab. A concrete core provides stability.

Floor system

A hybrid timber-concrete slab was developed using a ribbed design. The Glulam ribs support the concrete top layer. Concrete edge beams are used to transfer the loads from the slabs to the columns, see Figure 2.4C. Standardised floor modules are prefabricated off-site, resulting in a construction time of one day per storey.

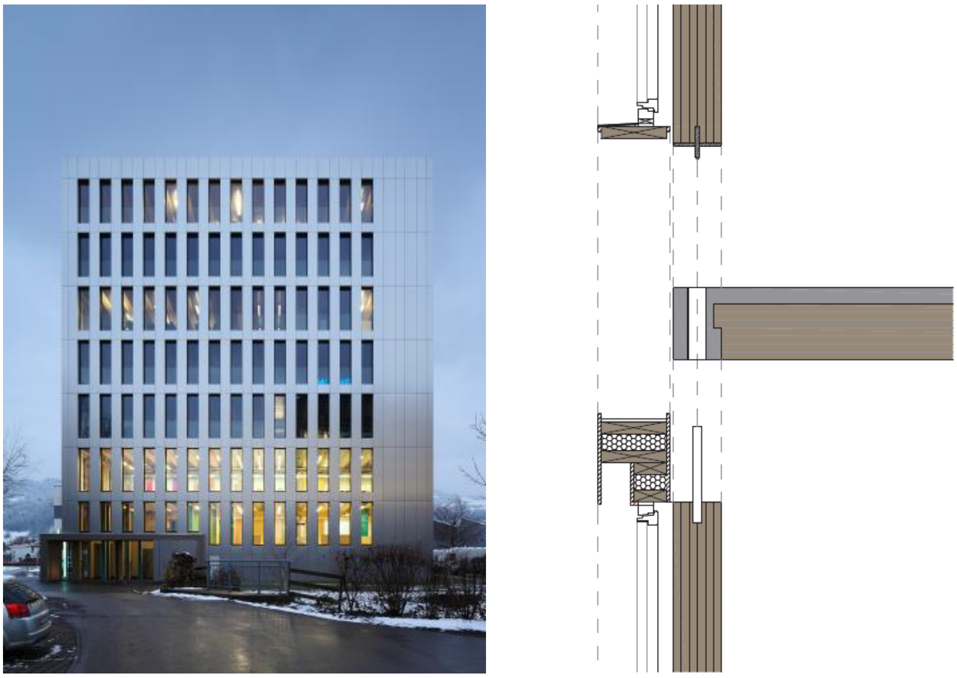
Detailing

The floor to column connection is designed using steel connector plates to the timber and grouting to the concrete edge slabs, see Figure 2.4B. This approach reduces the ability to re-use elements in other structures. Calculations showed the system to be feasible up to 30 storeys.

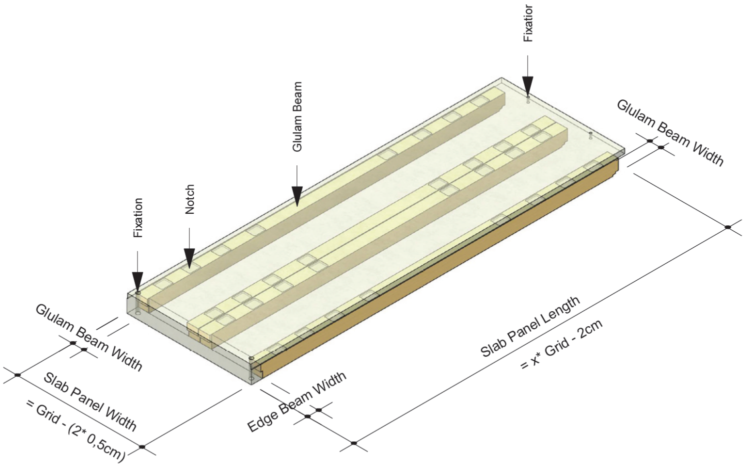
Fire safety strategy

Initially designed including sprinklers, tests proved them to be redundant. The hybrid system itself has sufficient fire performance, leaving the timber beams and columns exposed.

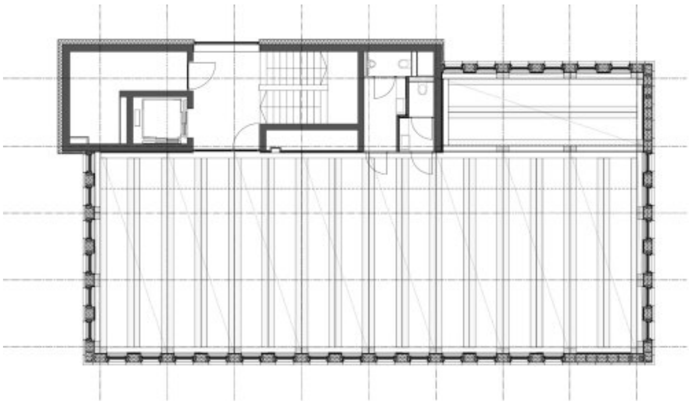
All factual information in this reference case is based on [22-25]



(A) Impression [22] (B) Connection detail [23]



(C) Floor system [23]



(D) Floorplan [25]

Figure 2.4: LifeCycle Tower One

2.1.4. Stadthaus, Murray Grove

Location	London, United Kingdom
Year	2009
Project status	Completed
Height	29 m, 9 storeys
Building function	Residential
Material type	Fully timber
Superstructure construction time	9 weeks (7 days per storey)
Costs[1]	€4,323,200.- (€1,496.- per m^2)
Architect	Waugh Thistleton Architects
Structural Engineer	Techniker, Jenkins & Potter
Timber manufacturer	KLH Massivholz

[1] Converted from GBP to EUR based on 2009 average exchange rate

Murray Grove was the first fully timber structure in the world and at the time of its completion the tallest timber residential building in the world. This project was the start of many more CLT structures in the United Kingdom. See Figure 2.5 for the impression of the building.

Stability system

The structure was designed as mass timber structure and has, therefore, CLT shear walls providing stability and uses CLT for the core of the building. The shear walls are also incorporated as load-bearing façade. The walls are 128 mm thick.

Floor system

Two-way spanning CLT slabs are used for the floor system, with a thickness of 146 mm.

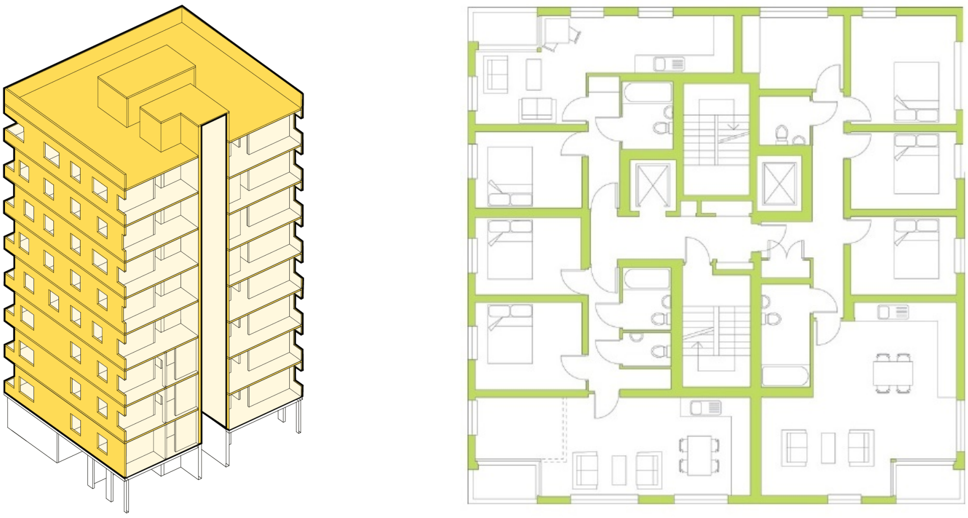
Detailing

The CLT elements, both walls and floors, are connected using steel ties, angel brackets, and mechanical fixings as shown in Figure 2.5C. It was calculated that a maximum of 15 storeys is feasible using this construction technique. By using interleaved connections between the walls and floors, the structural capacity could be increased eight times.

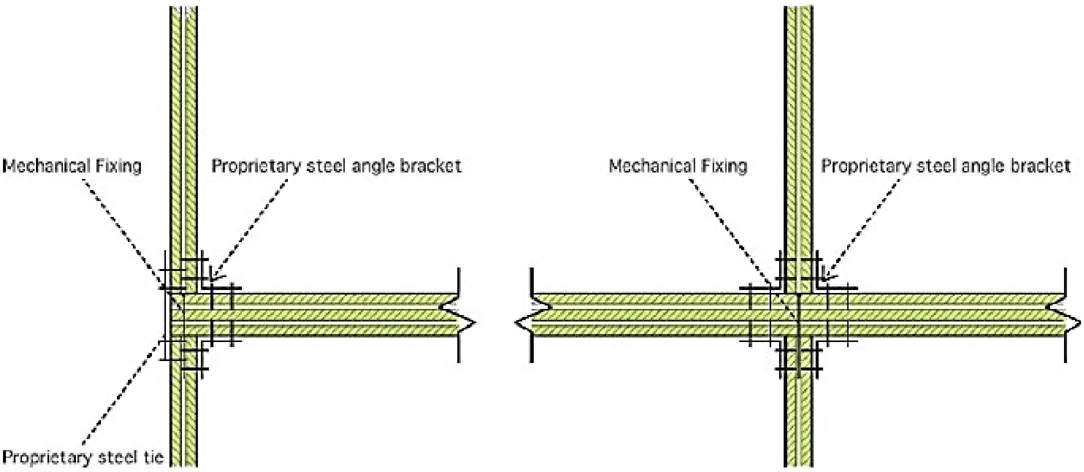
Fire safety strategy

The timber structure is completely encapsulated by gypsum panels effectively increasing the fire resistance by 30 minutes compared to the alternative with exposed timber.

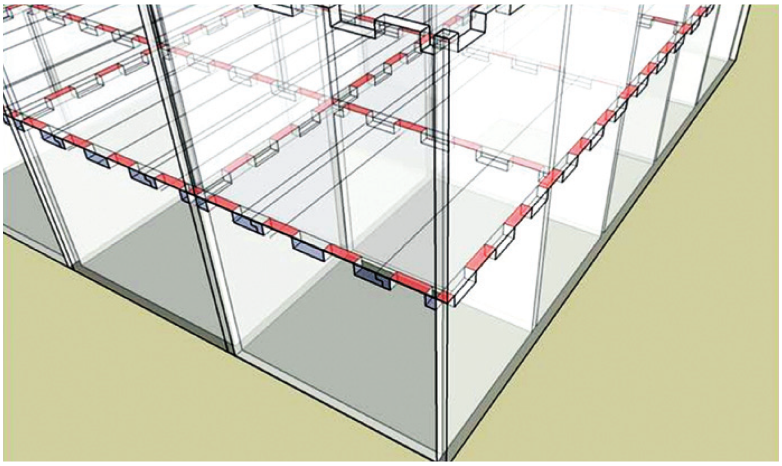
All factual information in this reference case is based on [5, 26, 27]



(A) Section [5] (B) Floorplan [27]



(C) Connection detail [27]



(D) Interleaved wall and floor [26]

Figure 2.5: Murray Grove

2.1.5. Wood innovation and design centre

Location	Prince George, Canada
Year	2014
Project status	Completed
Height	29.5 m, 6 storeys
Building function	School
Material type	Fully Timber
Superstructure construction time	N/A
Costs[1]	€17,000,000.- (€3,525.- per m^2)
Architect	Michael Green Architecture
Structural Engineer	Equilibrium Consulting
Timber manufacturer	Structurelam

[1] Converted from CAD to EUR based on 2014 average exchange rate

The Wood innovation and design centre was constructed for the University of Northern British Columbia. The project was the first to introduce CLT in Canada. It features a mezzanine level to include a lecture hall, requiring larger spans than in the previous reference projects. See Figure 2.6 for the impression of the building.

Stability system

The building was designed as a Glulam post and beam type structure in which the lateral stability is provided by a timber core using CLT elements.

Floor system

The CLT floor elements are staggered, creating cavities below the ceiling and in the floor for HVAC systems as shown in Figure 2.6B.

Detailing

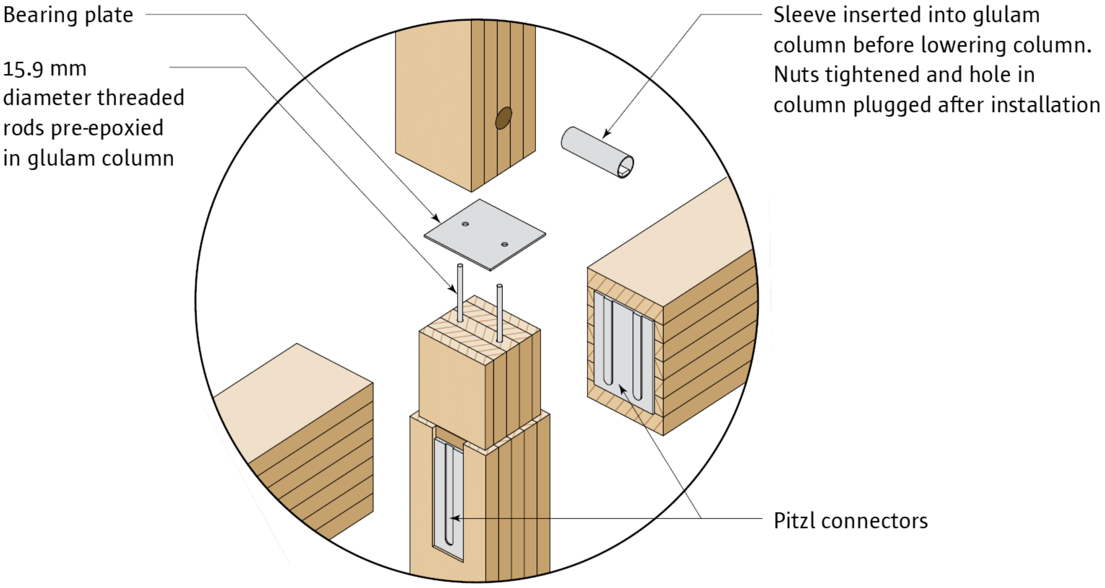
The column to beam connection uses Pitzl connectors, see Figure 2.6C. This allows the columns to be continuously connected. The CLT core elements are anchored to a concrete base layer using anchors and shear brackets.

Fire safety strategy

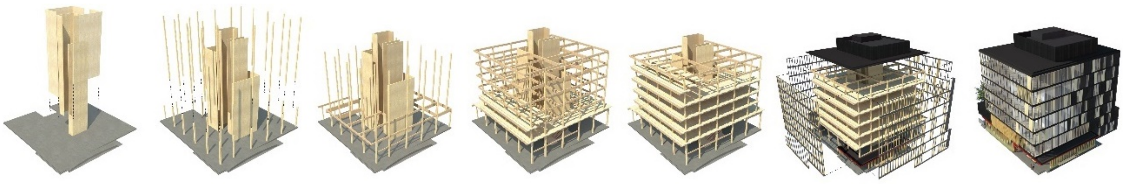
The timber load bearing structure is fully exposed and is designed using the reduced cross section method. Additional measures have been taken for the CLT core and stairwells. An intumescent fire-retardant coating is used to prevent fire spread and the joints were tested for their effectiveness to create a smoke barrier. A sprinkler system is integrated in the staggered floor elements.

All factual information in this reference case is based on [25, 28, 29]

(A) Impression [28] (B) Staggered CLT floor [28]



(C) Connection detail [28]



(D) Construction sequence [25]

Figure 2.6: Wood innovation and design centre

2.1.6. Hotel Jakarta

Location	Amsterdam, the Netherlands
Year	2018
Project status	Completed
Height	30 m, 12 storeys
Building function	Hotel
Material type	Hybrid Timber
Superstructure construction time	N/A
Costs	€30,000,000.- (€1,820.- per m^2)
Architect	SeARCH architecture and urban planning
Structural Engineer	Pieters Bouwtechniek
Timber manufacturer	Derix

Hotel Jakarta is a hybrid timber concrete structure in which the hotel rooms are prefabricated modules. The modules include all HVAC installations and bathrooms pre-installed. It is the highest timber modular building in the Netherlands. See Figure 2.7 for the impression of the building.

Stability system

The first two floors consist of a concrete table structure using a concrete portal frame. This creates a rigid base for the prefabricated modules. Concrete cores provide stability for the upper floors together with the stability of the stacked prefabricated modules.

Floor system

Both the table structure and prefabricated modules use concrete floors.

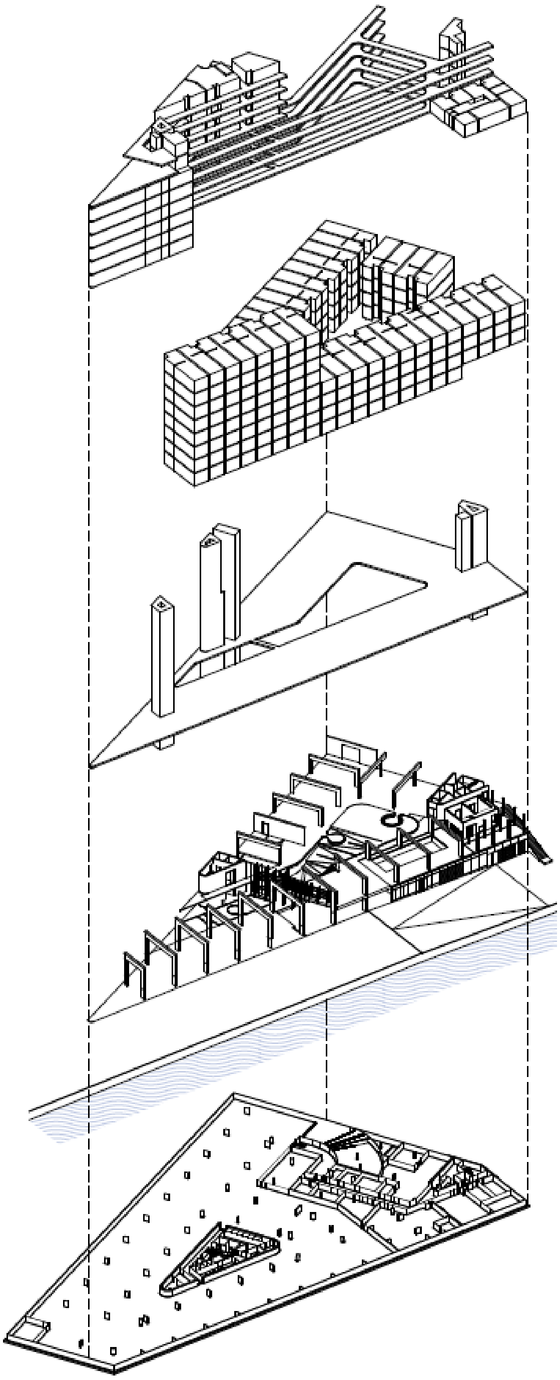
Detailing

The CLT walls of the prefabricated modules are connected to the concrete floors with embedded steel anchors. The connectors are glued in the CLT walls, as shown in Figure 2.7C.

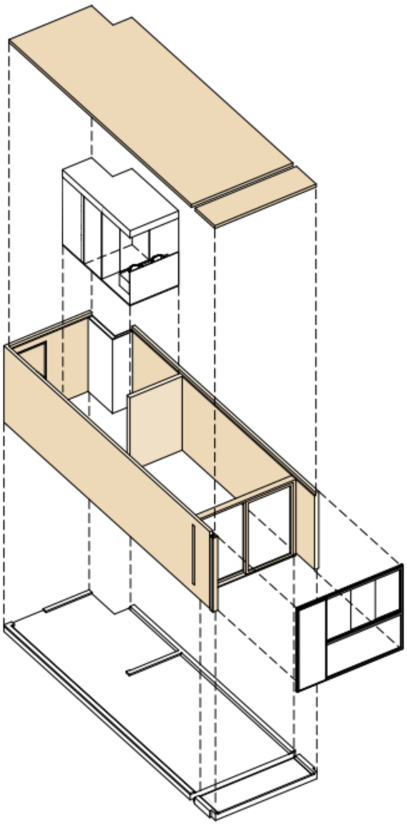
Fire safety strategy

The CLT walls and timber columns and beams are exposed. A sprinkler system is used as an active fire safety strategy. Tests were performed to determine the charring properties during a fire.

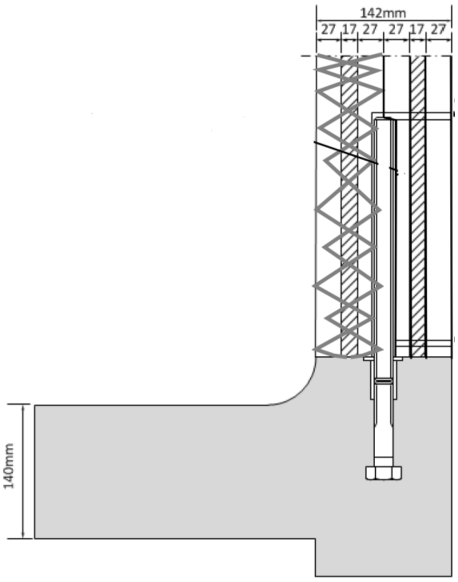
All factual information in this reference case is based on [30-32]



(A) Exploded view of load bearing structure [31]



(B) Prefabricated module [31]



(C) Connection detail [30]

Figure 2.7: Hotel Jakarta

2.1.7. 25 King

Location	Brisbane, Australia
Year	2018
Project status	Completed
Height	47 m, 10 storeys
Building function	Office
Material type	Fully Timber
Superstructure construction time	N/A
Costs[1]	82,000,000.- (€4,300.- per m^2)
Architect	Bates Smart
Structural Engineer	Aurecon
Timber manufacturer	Wiehag, Stora Enso

[1] Converted from AUD to EUR based on 2014 average exchange rate

25 King is the tallest timber building in Australia. Since it is located in a declared termite area, the ground floor is constructed from concrete. This creates a physical barrier for termites. It was estimated that it takes around eight hours to regrow the used timber from the Austrian forest. See Figure 2.8 for the impression of the building.

Stability system

The building was designed as a Glulam post and beam type structure. Stability is provided by a CLT core and additional timber bracing in the façade.

Floor system

CLT slabs are used for the floor system.

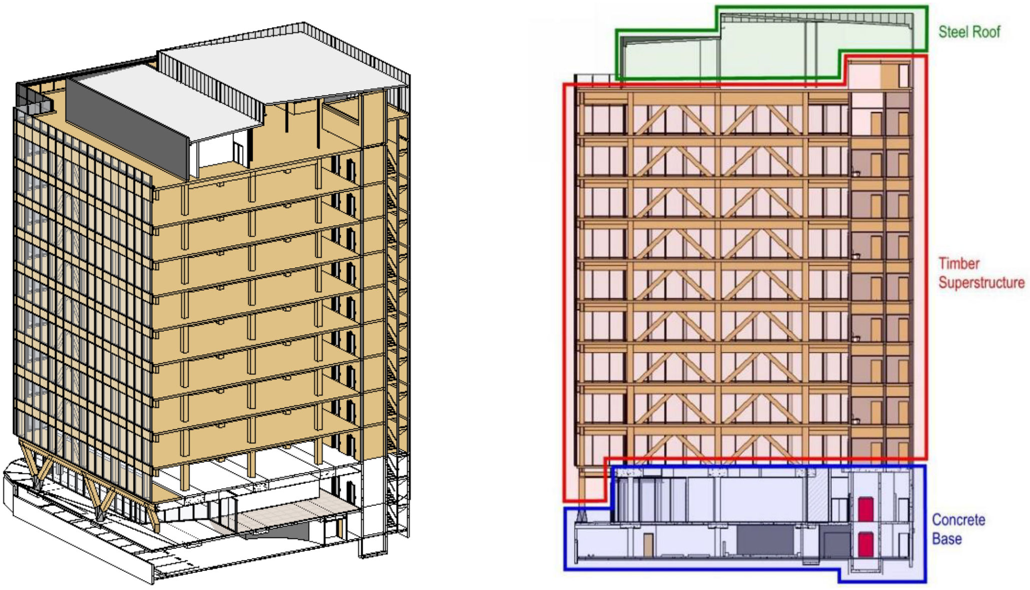
Detailing

Similar to the Wood innovation and design centre, Pitzl connectors are used to create the column to beam connection (Figure 2.8C), resulting in continuously connected columns. The bracings use steel connectors embedded in the timber, see Figure 2.8D.

Fire safety strategy

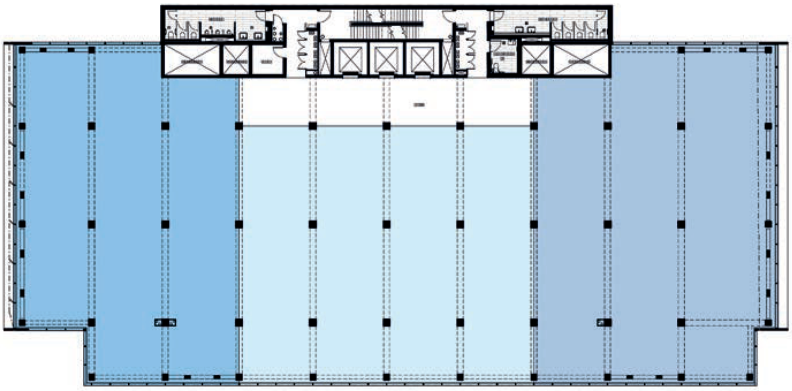
The load-bearing structure is fully exposed, excluding the top of the floor which is covered by a concrete finishing layer. Therefore, a sprinkler system is chosen as active fire protection. Additionally, the structural elements have been designed to withstand a fire of two hours.

All factual information in this reference case is based on [33, 34]



(A) Section [33]　(B) Bracing [33]

(C) Connection detail (bracing) [33]　(D) Connection detail (beam) [33]



(E) Floorplan [34]

Figure 2.8: 25 King

2.1.8. Treet

Location	Bergen, Norway
Year	2015
Project status	Completed
Height	49 m, 14 storeys
Building function	Residential
Material type	Hybrid Timber & Concrete
Superstructure construction time	N/A
Costs	N/A
Architect	Artec
Structural Engineer	Sweco
Timber manufacturer	Moelven, Kodumaja

Treet was the tallest timber structure in the world at the time of completion. It uses an unconventional, table-like, structure. Every five floors a concrete deck is present, transferring all loads from the above five floors to the diagrid. On top of the concrete decks, five layers of prefabricated timber modules are stacked. See Figure 2.9 for the construction sequence of the building.

Stability system

Although the structure has a CLT shaft for elevators and stairs, it is not structurally connected to the main load-bearing structure. Therefore, it does not contribute to the stability of the building. The stability is exclusively provided by the Glulam diagrid. The concrete decks improve the dynamic behaviour of the building.

Floor system

CLT floors are integrated within the prefabricated timber modules.

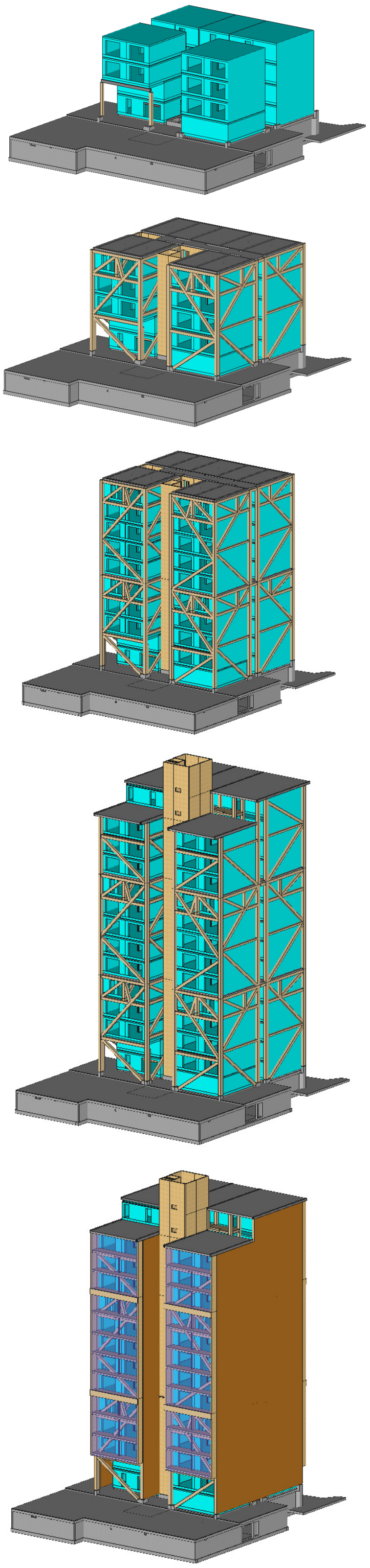
Detailing

The Glulam diagrid uses slotted-in steel plates with dowels and is connected to the concrete using steel anchors.

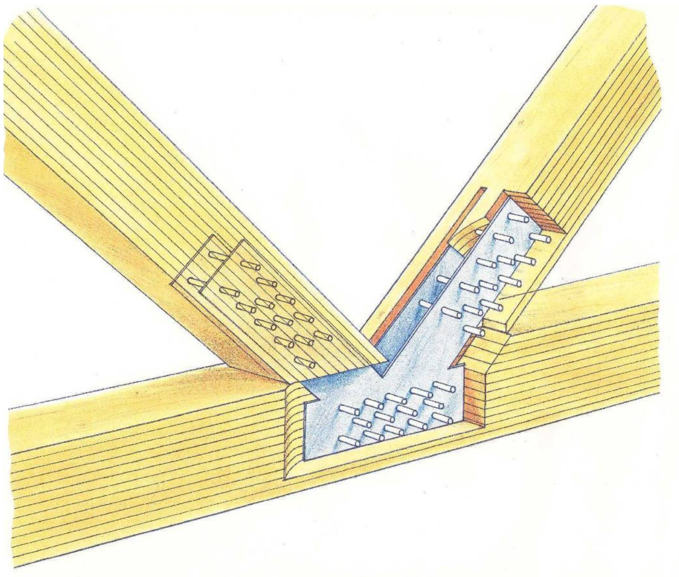
Fire safety strategy

The structure is designed for 90-minute fire resistance. Since the stabilizing elements are exposed, their steel connector plates are located in the residual cross-section and have intumescent fire seals. Furthermore, a sprinkler system is installed and escape routes have a fire-retardant coating.

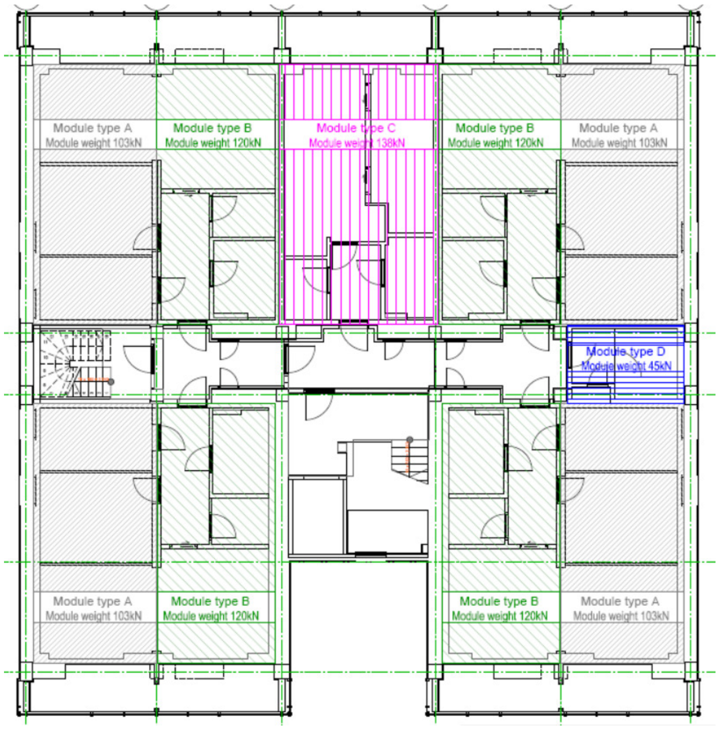
All factual information in this reference case is based on [25, 35]



(A) Construction sequencing



(C) Slotted in steel plates



(B) Floorplan

Figure 2.9: Treet [35]

2.1.9. Brock Commons

Location	Vancouver, Canada
Year	2017
Project status	Completed
Height	53 m, 18 storeys
Building function	Residential
Material type	Hybrid Timber, Concrete & Steel
Superstructure construction time	N/A
Costs[1]	€36,450,000.- (€2,430.- per m^2)
Architect	Hermann Kaufmann Architekten, Acton Ostry Architects
Structural Engineer	Fast + Epp
Timber manufacturer	Structurlam

[1] Converted from USD to EUR based on 2017 average exchange rate

The student building Brock Commons was the tallest timber structure in the world at the time of completion, surpassing Treet. All required penetrations in structural elements were included in the prefabrication process, reducing construction time on-site. See Figure 2.10 for the impression of the building.

Stability system

Two concrete cores provide the stability of the building.

Floor system

The structure was designed as a post and beam type structure. However, the two-way spanning CLT floor slabs act as a beam, reducing the total floor to floor height.

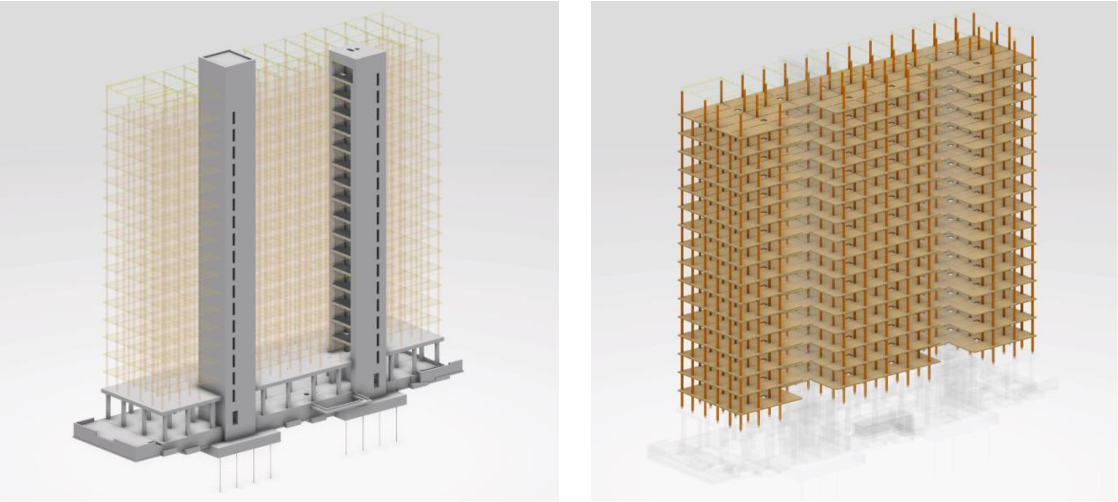
Detailing

A steel connector was designed to connect the Glulam columns and CLT floor slabs. The connector is split into two parts and installed at each column end during prefabrication of the columns off-site (Figure 2.10C). This allows for easy access to install the CLT slabs and fast connection between columns. The floor slabs were connected to the concrete core using steel angle plates (Figure 2.10D).

Fire safety strategy

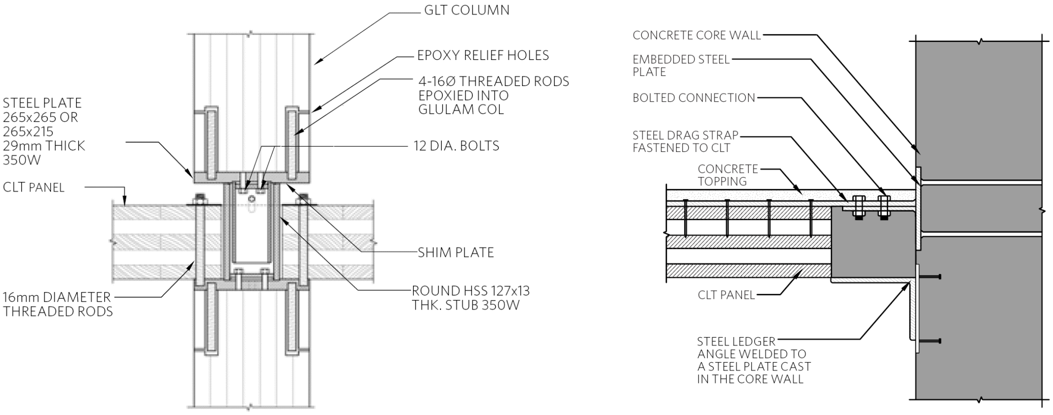
Both passive and active fire safety measures are present in the building. The structure is fully encapsulated with gypsum panels and a sprinkler system is present throughout the building, including the apartments.

All factual information in this reference case is based on [36, 37]



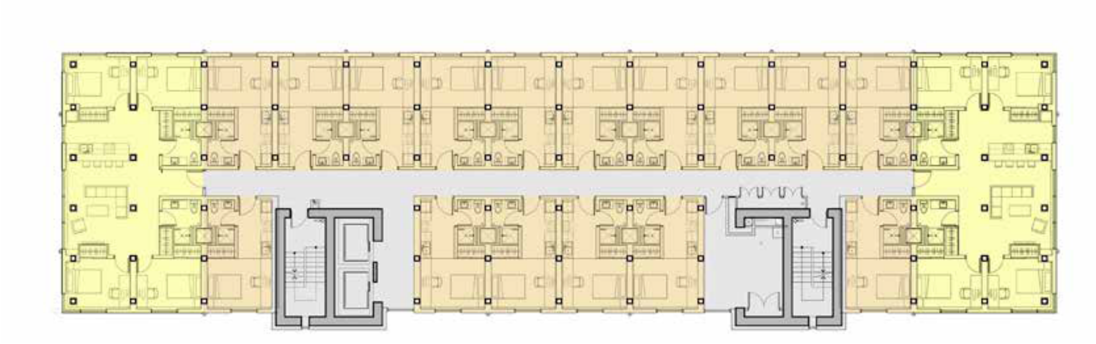
(A) Concrete cores [36]

(B) Timber structure [36]



(C) Column-Floor connection [37]

(D) Floor-Core connection [37]



(E) Floorplan [37]

Figure 2.10: Brock Commons

2.1.10. Haut

Location	Amsterdam, the Netherlands
Year	2020
Project status	Under construction
Height	73 m, 21 storeys
Building function	Residential
Material type	Hybrid Timber, Concrete & Steel
Superstructure construction time	-
Costs	N/A
Architect	Team V Architectuur
Structural Engineer	Arup
Timber manufacturer	N/A

Haut is the first timber tower to be completed in the Netherlands of considerable height. See Figure 2.11 for the impression of the building.

Stability system

The timber part of the building is designed as the mass timber typology, using CLT shear walls for stability with a maximum thickness of 300 mm. Additionally, a concrete core is used to meet the requirements for stability.

Floor system

CLT slabs are used for the floor system. In the cantilevering part of the structure, the floor is supported by additional steel beams.

Detailing

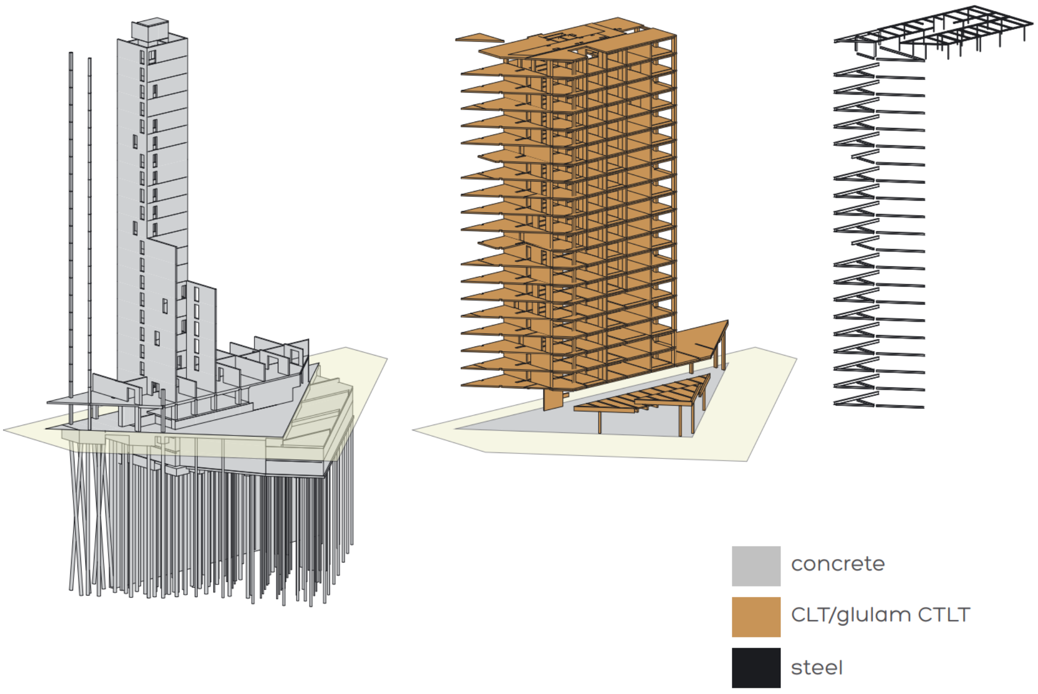
The timber shear walls are connected by steel strips to avoid decoupling at higher wind loads. CLT slabs are connected to the shear walls using angle strips.

Fire safety strategy

The timber CLT ceilings are exposed, while on top of the timber slabs a cement layer is applied. Encapsulation was chosen for the CLT walls. An active fire safety strategy with sprinklers is used in the complete building.

All factual information in this reference case is based on [38, 39]

(A) Impression [39]　　(B) Floorplan [39]



(C) Division in structural material

Figure 2.11: Haut [38]

HoHo

Location	Vienna, Austria
Year	2018
Project status	Completed
Height	84 m, 24 storeys
Building function	Mixed
Material type	Hybrid Timber & Concrete
Superstructure construction time	N/A
Costs	€65,000,000.- (€2,600.- per m^2)
Architect	RLP Rüdiger Lainer + Partner
Structural Engineer	Woschitz Group
Timber manufacturer	N/A

The mixed-use Hoho building is a combination of timber and concrete structure. See Figure 2.12 for the impression of the building.

Stability system

CLT façade elements were used in combination with a concrete core to provide stability to the building.

Floor system

A hybrid floor system was used of CLT slabs with a concrete top layer. These floors were prefabricated off-site. Loads are transferred to a prefabricated concrete edge beam. Which transfers the loads further through the Glulam columns, see Figure 2.12C&D.

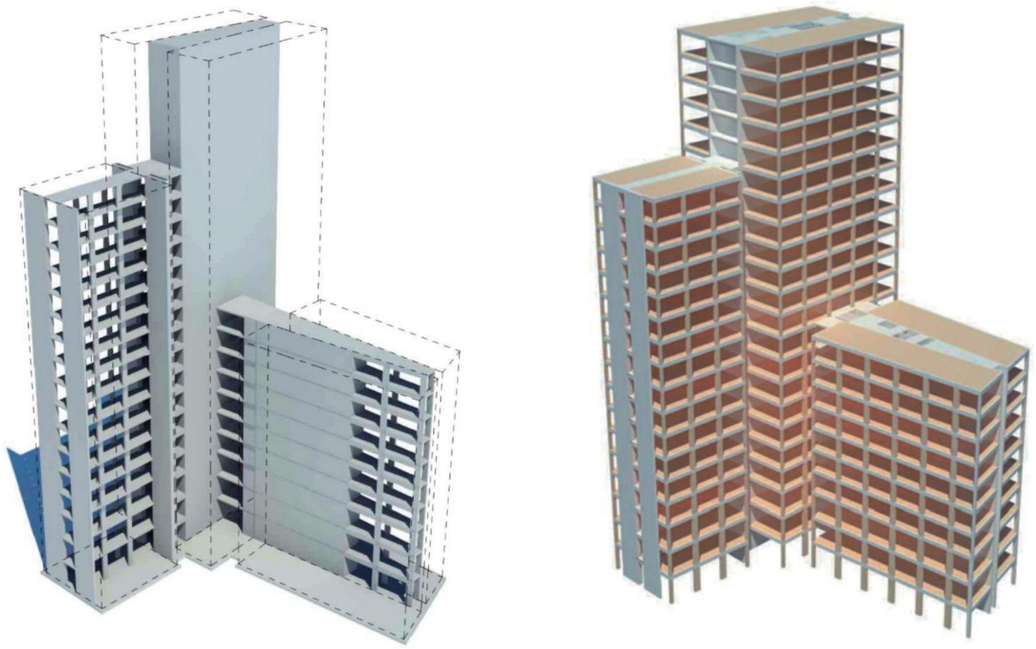
Detailing

Both the timber columns and hybrid floor slab were connected to the concrete edge beam using grouting and reinforcement steel. This reduces the possibility to demount the structure and re-use elements.

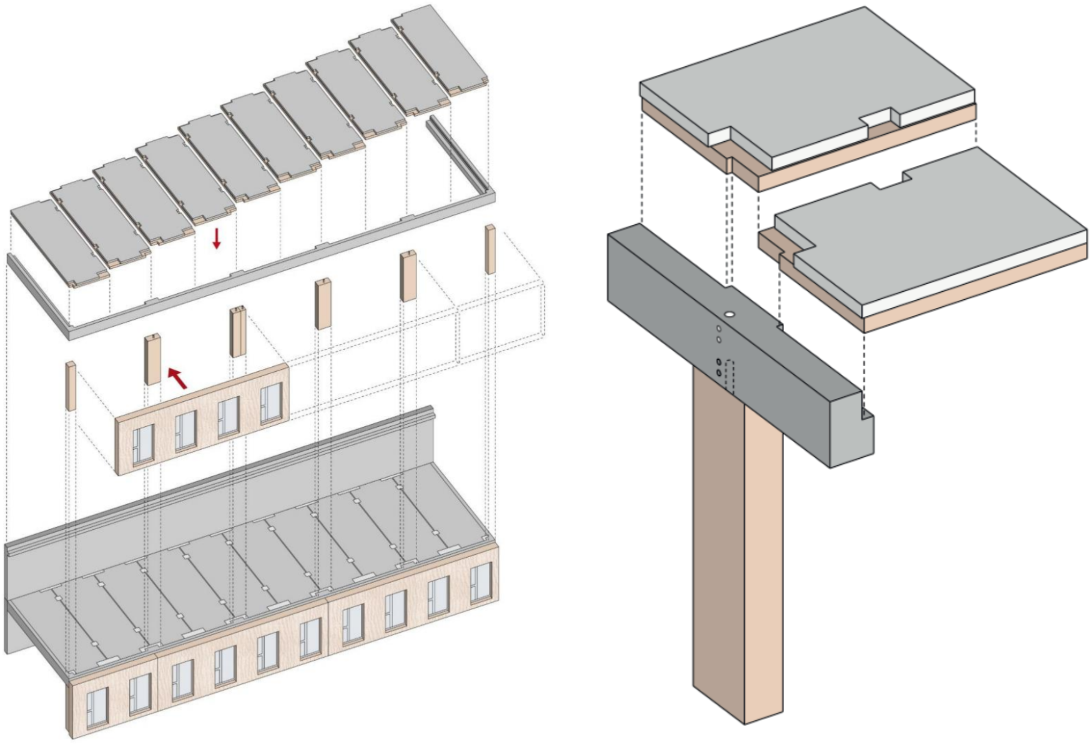
Fire Safety Strategy

A similar fire safety strategy is used as in the Haut Amsterdam project. CLT walls, columns and ceilings are exposed. Again, a sprinkler system is used to suppress a potential fire.

All factual information in this reference case is based on [40, 41]



(A) Concrete core (B) Timber structure



(C) Storey assembly (D) Connection to edge beam

Figure 2.12: HoHo [41]

2.1.12. Mjøstårnet

Location	Brumunddal, Norway
Year	2019
Project status	Completed
Height	85 m, 18 storeys
Building function	Mixed
Material type	Hybrid Timber & Concrete
Superstructure construction time	1 year
Costs	N/A
Architect	Voll Arkitekter
Structural Engineer	Sweco
Timber manufacturer	Moelven, MetsäWood

Currently, Mjøstårnet is the tallest timber building in the world. This was realised by increasing the angle of the roof structure and therefore surpassing the HoHo building in Vienna. See Figure 2.13 for an impression of the building.

Stability system

CLT wall elements are used for the stair and elevator shafts. However, these walls do not contribute to the stability of the building. Glulam diagonals are the only stabilizing elements present. To improve the dynamic behaviour, the top six floors are made of concrete.

Floor system

The timber floors are made of an assembly of Glulam ribs and an LVL deck. The floor system is supported by additional Glulam beams.

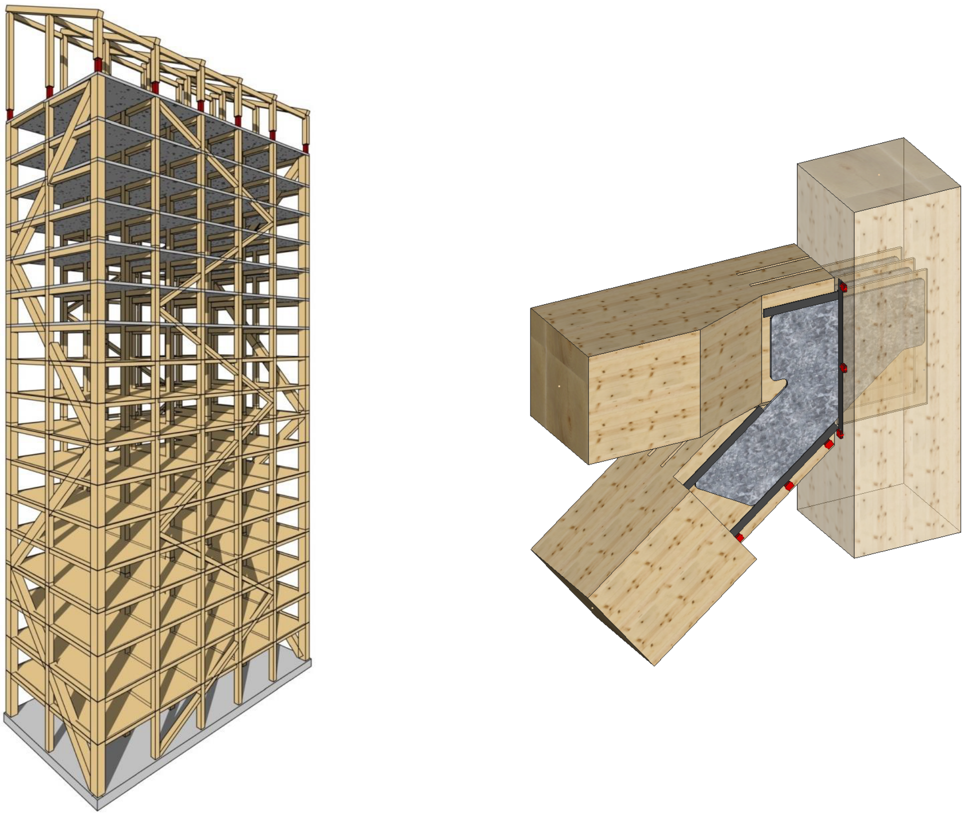
Detailing

Slotted-in steel plates and dowels are used to connect the timber elements.

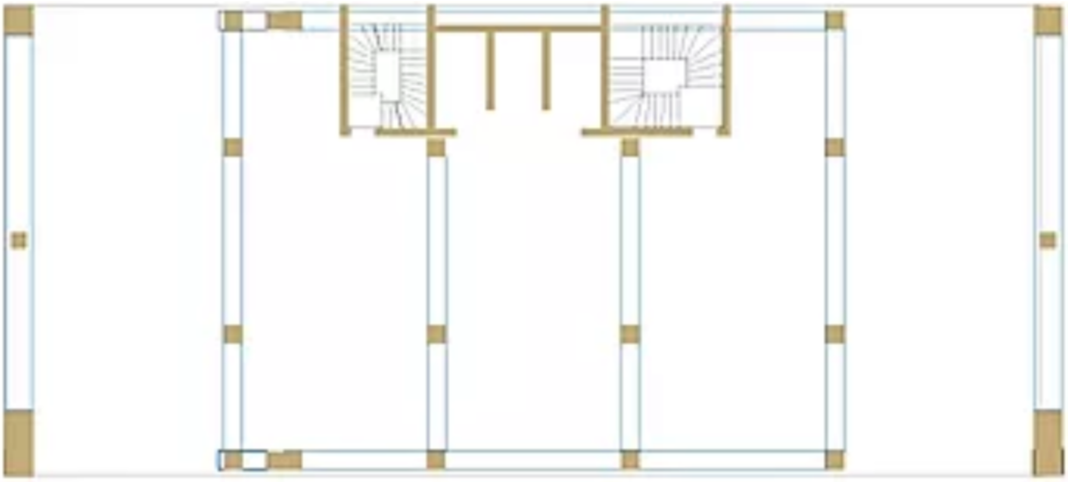
Fire Safety Strategy

The structure is designed with a 120-minute fire resistance requirement for the main load-bearing elements. Secondary elements (floors) are designed for 90-minute fire resistance. The floor slab is encapsulated, and the exposed Glulam columns and diagonals are designed using the reduced cross-section method. All visible wood is treated with fire retardant coating and walls along the escape route are encapsulated with gypsum panels. The embedded steel connections have intumescent seals. The exposed columns were tested in a furnace and proved to be self-extinguishable. Additionally, the building has a sprinkler system.

All factual information in this reference case is based on [42]



(A) Structural model (B) Connection with diagonals



(C) Floorplan

Figure 2.13: Mjøstårnet [42]

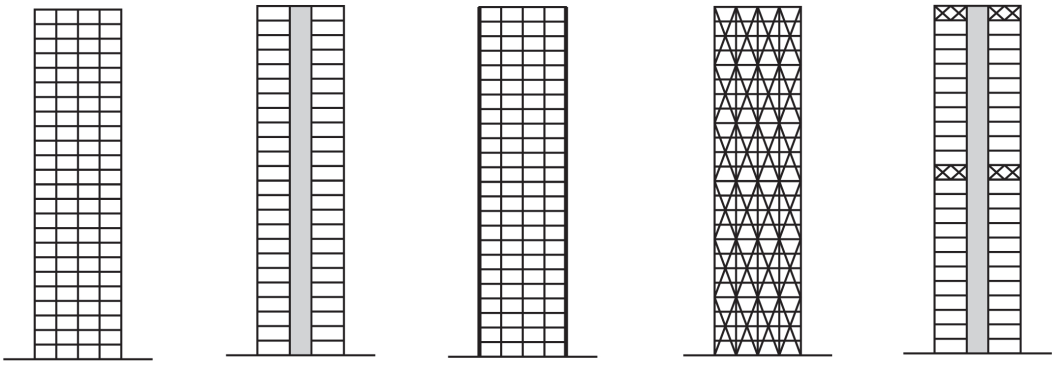
2.2 Structural typologies

Two basic typologies can be identified from the reference cases: the post and beam typology and the mass timber typology. Various stability and floor systems are used, see Table 2.1 for the complete overview and characteristics of the reference projects.

The post and beam typology has as basis a frame structure. Though, it is only used for stability in combination with a load-bearing façade in the lowest reference case: E3, Berlin. All other projects do not use the frame for stability due to the relatively low moment capacity of connections in timber structures. Additional stability systems which are used in the post and beam typology are the centralized core, either made of timber or concrete; a load-bearing façade made from CLT elements; or using timber diagonals in the form of bracings or a diagrid (See Figure 2.14). Due to the lightweight nature of timber, a concrete mass can be applied to improve the dynamic behaviour of tall timber towers.

The mass timber typology has as basis CLT shear walls providing stability. Optional additional systems are a centralized core, made of timber or concrete; or using CLT elements as load-bearing façade, creating a tube stability system.

None of the reference cases and other timber projects worldwide use the outrigger system, which is usually applied in the taller spectrum of buildings beyond the height of the tallest timber tower: Mjøstårnet. An academic study by van de Kuilen et al. shows the principle in combination with timber structures [43]. In the study, an outrigger is proposed using tensile steel bars, integrated within mass timber CLT elements. The outrigger system is also feasible in combination with the post and beam typology as presented by Boellaard in a study for the Eindhoven University of Technology [44].



(A) Frame (B) Core (C) Load bearing façade (D) Diagrid (E) Outrigger

Figure 2.14: Stability systems [15]

Table 2.1: Overview reference projects

		Project											
		E3	T3	Lifecycle tower	Murray Grove	Wood innovation centre	Hotel Jakarta	25 King	Treet	Brock Commons	Haut	HoHo	Mjøstårnet
Function	**Residential**	X			X				X	X	X	Mixed	X
	Office		X	X				X					
	Public					X	X						
Typology	**Post & beam**	X	X	X		X	X	X	X	X		X	X
	Mass timber				X		X				X	X	
Stability	**Frame**	X											
	Timber shear walls				X		X				X		
	Timber core				X	X		X					
	Concrete core		X	X			X			X	X	X	
	Load bearing Façade	X			X							X	
	Outrigger												
	Diagrid/ Bracing							X	X				X
	Concrete mass								X				X
Floor	**CLT**				X	X		X	X	X	X		
	LVL												X
	NLT		X										
	Hybrid timber-concrete	X		X			X					X	
Fire safety	**Exposed timber**	X	X	X		X	X	X	X		X	X	X
	Encapsulated timber	X			X				X	X	X		X
	Sprinkler system		X			X	X	X	X	X	X	X	X

The most common floor system in timber structures is the CLT slab. Optionally, it can be used to span in two directions, as has been done in the Brock Commons project. Another common floor system is the LVL rib panel, though only present in one of the reference cases. Nail laminated timber is used in a single reference project, T3 in Minneapolis, and is specifically used in the North American market. Hybrid timber-concrete floor systems are available, though limit the re-use of elements due to the grout connections between timber and concrete.

For fire safety, two main strategies can be identified: exposed timber and encapsulated timber. The aesthetics of exposed timber is in most cases preferred by architects and has proven to be beneficial for health and wellbeing of inhabitants of timber buildings [5]. To achieve a sufficient fire resistance of the structure, the reduced cross-section method is used to determine the required element sizes during a fire. This method relies on the charring of timber, creating an undamaged layer behind the charring layer. Charring of timber is predictable and described by the charring rate expressed in millimetres per minute. The residual cross-section must be able to carry the load during the full duration of the fire resistance criteria of the building. This results in more substantial dimensions for the elements compared to the encapsulated approach. To improve the fire resistance and reduce the fire spread, either an intumescent or fire-retardant coating can be applied. Intumescent coatings protect the timber by swelling when exposed to heat, resulting in a protective insulating layer. Fire retardant coatings limit the fire spread by releasing a dampening gas when exposed to heat.

The encapsulated approach covers all timber elements with gypsum panels to insulate the timber structural elements. These boards postpone the charring of the structural elements by evaporating the water content from the gypsum.

Additionally, a sprinkler system can be installed to suppress or extinguish a fire. This system is applied in nine of the twelve reference projects in combination with the exposed or encapsulated timber strategy.

2.3 Challenges for timber structures

The main challenges for fully tall timber buildings can be deduced from the reasons in the reference cases to use a hybrid timber-concrete system instead.

Structurally, the mass and stiffness are relatively low. Leading to challenges regarding the stability, dynamic behaviour and could lead to tension in the foundation. Furthermore, the low mass impacts the building physics of the structure regarding the vibration and acoustical requirements.

Since wood is a combustible material, a critical attitude towards the fire safety of timber buildings is present in the building industries. Recent testing of laminated timber products shows self-extinguishment under certain conditions. Nevertheless, compartmentalization and evacuation routes still form challenges in permitting and approval of fully timber buildings, requiring extra physical testing. Therefore, designers often choose a concrete core to speed up the process.

Additionally, the logistics of the building site are challenging. Monitoring and regulating of the moisture in the timber products are critical for the durability of the structure. Therefore, the exposure to the elements at the construction site should be limited. Though, this issue is present for both timber and hybrid timber structures.

Hybrid timber buildings introduce their own challenges primarily formed by the complexity of different expansion and contraction properties of timber and concrete or steel.

2.4 Engineered timber

Wood is an inhomogeneous and orthotropic material, resulting in a large variance in material properties. Engineered timber resulted from a need for timber products with larger dimensions and more uniform material properties by removing the natural defects in sawn timber. See Appendix A for the material properties of sawn and engineered timber strength classes.

Compared to steel and concrete, timber is not as strong but it has a high weight to strength and weight to stiffness ratio as shown in Figure 2.15. This can result in lightweight structures even though it requires relatively large element sizes due to the low strength to volume ratio.

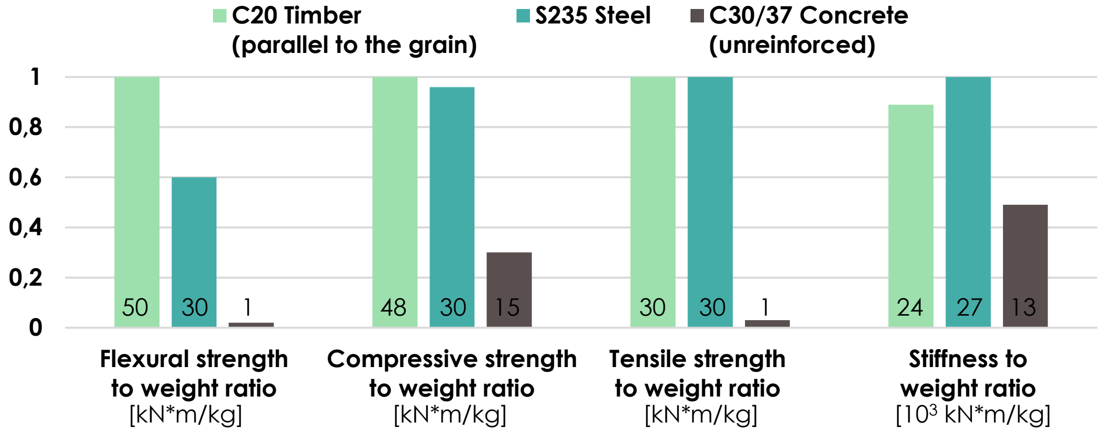


Figure 2.15: Comparison of material properties timber, steel and concrete

2.4.1. Glued laminated timber

Glued laminated timber, also known as Glulam or GLT, was introduced on the market in 1906 in Germany [25]. The product consists of lamellas orientated in a single direction, which are connected by adhesives and finger joints, as shown in Figure 2.16. Glulam is typically made from coniferous wood species. Spruce trees are the most commonly used species, although Pine, Fir, Douglas Fir and Larch based Glulam is also produced [45].

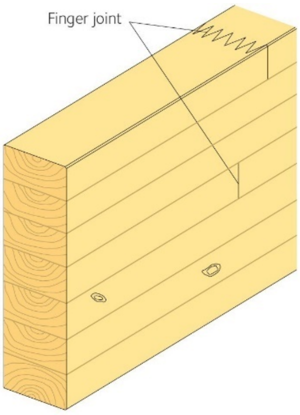


Figure 2.16: Glulam [46]

Glulam elements can be manufactured both for straight and curved structural elements. They are mainly used for beams, columns and arches. Though glulam panels spanning a single direction are also available. Separate strength classes are developed for glued laminated timber ranging from GL20 to GL36. These classes have a suffix depending on the strength classes of the individual lamellas, where GLXXh has a homogeneous composition and GLXXc has a combined composition in which the middle lamellas have a lower strength grade (see Appendix A.2). Recent studies show that higher strength grades can be achieved up to GL55 [47]. However, these products are not readily available on the market.

2.4.2. Laminated veneer lumber

At the end of the 20th century, a variant of plywood named laminated veneer lumber (abbreviated to LVL) was developed in the United States. Contrary to plywood, LVL has veneers orientated in a single direction. The structural elements are formed by applying adhesives under high temperature and pressure [48]. European produced LVL is typically made from Spruce or Pine [49].

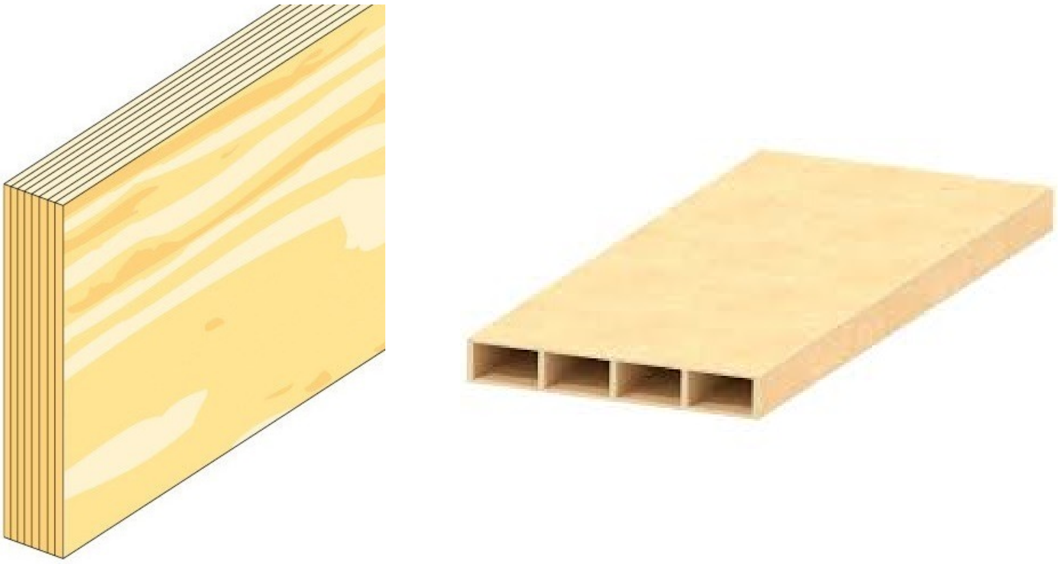


Figure 2.17: LVL [46]

LVL is used as beams, columns, wall panels and hollow box floor system (Figure 2.17). Strength classes range from LVL22 to LVL80 and are subdivided into two classes: LVLXXp and LVLXXc, where suffix p has exclusively parallel veneers and suffix c can have up to 20% of crossband veneers oriented perpendicular to the main direction. The material properties of all LVL strength classes are included in Appendix A.3.

2.4.3. Cross laminated timber

The latest development in engineered timber products has a similar production process as Glulam only differentiating it by alternating the orientation of the lamellas. Hence the name cross laminated timber, also known as CLT or X-lam. See Figure 2.18 for the build-up of the product. CLT was developed during the 1990s in Austria. Similar to Glulam, Spruce is the predominant species used for CLT production with Pine, Fir, Douglas Fir and Larch used as alternatives [5].

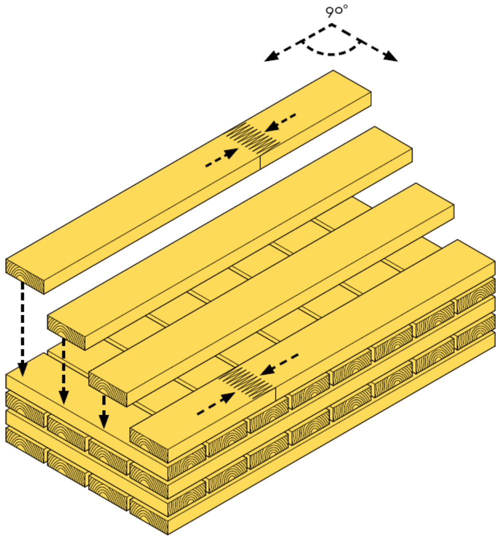


Figure 2.18: CLT [5]

CLT is used for wall and floor elements since they have good bending and shear mechanical properties due to the crossed orientation of the lamellas. No separate strength classes are yet available for CLT. The material characteristics are therefore derived from the sawn timber strength classes of the individual lamellas and specified by the manufacturers. Typically, C24 grade is used throughout the complete panel. Optionally, a non-uniform build-up can be chosen, using lower strength grades for the inner lamellas. In this configuration, the outer layers use C30 grade lamellas, while the inner layers use C14 to C18 [50]. Appendix A.4 presents the material characteristics of a C24 CLT panel.

3

Sustainable timber structures

In this chapter, the definitions of sustainability and circularity are discussed in the first two sections. Followed by the description of the life cycle assessment framework and criteria for the Dutch environmental performance criterion (MPG) in section 3.3. The sustainability of timber structures on macro, meso and micro scale (Figure 3.1) are discussed in respectively sections 3.4, 3.5, and 3.6. The macro-scale deals with sustainability considerations on the global forestry level; the meso-scale with lifespan and cascading strategies on building level; and the micro-scale with the environmental impact of the material itself. This chapter is concluded by a critical in section 3.7.

(A) Macro-scale
Global level

(B) Meso-scale
Building level

(C) Micro-scale
Material level

Figure 3.1: Timber multi-scale research approach

3.1 Sustainability defined

In 1987, the World Commission on Environment and Development, also known as the Brundtland Commission, was tasked by the United Nations to formulate a long-term strategy regarding sustainability. In their report, ‘Our Common Future’, the commission defined sustainable development as follows:

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” [51, p. 2.IV]

The commission considers four ‘needs’ which indicate the level of prosperity: availability of finite resources; clean environment by minimising harmful emissions; social fairness and economic growth [52]. In 1994, John Elkington categorised sustainability in three main fields: ‘People, Planet and Profit’. These categories can be related to the ‘needs’ as defined by the Brundtland Commission. Availability of finite resources and a clean environment can be related to Planet. Social fairness is related to People. Profit can be related to all four ‘needs’ since external environmental and social costs can be quantified, which represent the total burden to society [52]. These external costs should be included in the price of the product. Though this is often not the case.

The definitions by Brundtland Commission and John Elkington are still commonly used to this day. Peters and Wiltjer translate these definitions to the following aspects applicable for structural engineers:

"Increase service life of buildings; limit material use; use sustainable materials; consider the environmental impact of construction and transport; and design the structure for circular use in the future." [53, p. 43]

These aspects can be related to Planet and Profit. The category of People, defined as social fairness, is not directly influenced by engineers. Aspects related to social fairness are typically represented in other stages of the building sector. Manufacturers, together with governing organisations, determine the working conditions and fairness for employees and communities where the building materials originate from. The choice for a product of a particular manufacturer is in most cases made by contractors. Another aspect to social fairness of the built environment is the choice to build in a specific location, which is decided by the spatial planning departments of the government. Other aspects related to Planet and Profit are also influenced by other parties, such as the choice of finishing materials in the building and design of the building physics and installations of the building. Therefore, sustainable building design is an integral cooperative effort of architects, engineers, contractors, manufacturers, and governing bodies.

3.2 Circularity defined

During the last century, raw material extraction has increased 20 times (Figure 3.2). Due to the increasing world population and developing regions, the need for resources will increase further resulting in depletion and higher emissions. These developments conflict with the previously cited definition for sustainability. Next to the environmental consequences, scarcity of materials will have a negative impact on the economic position of the Netherlands since 68% of raw materials is imported [54].

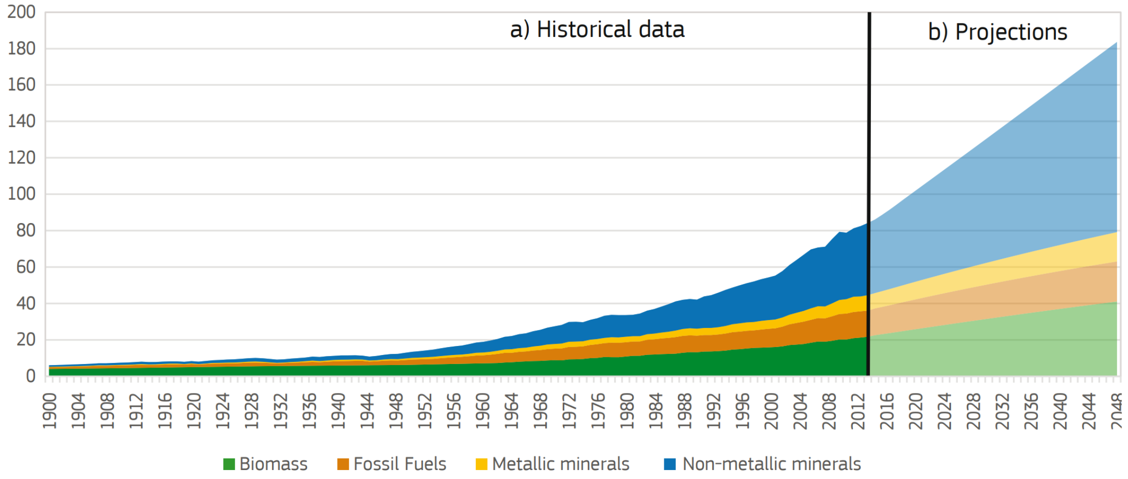


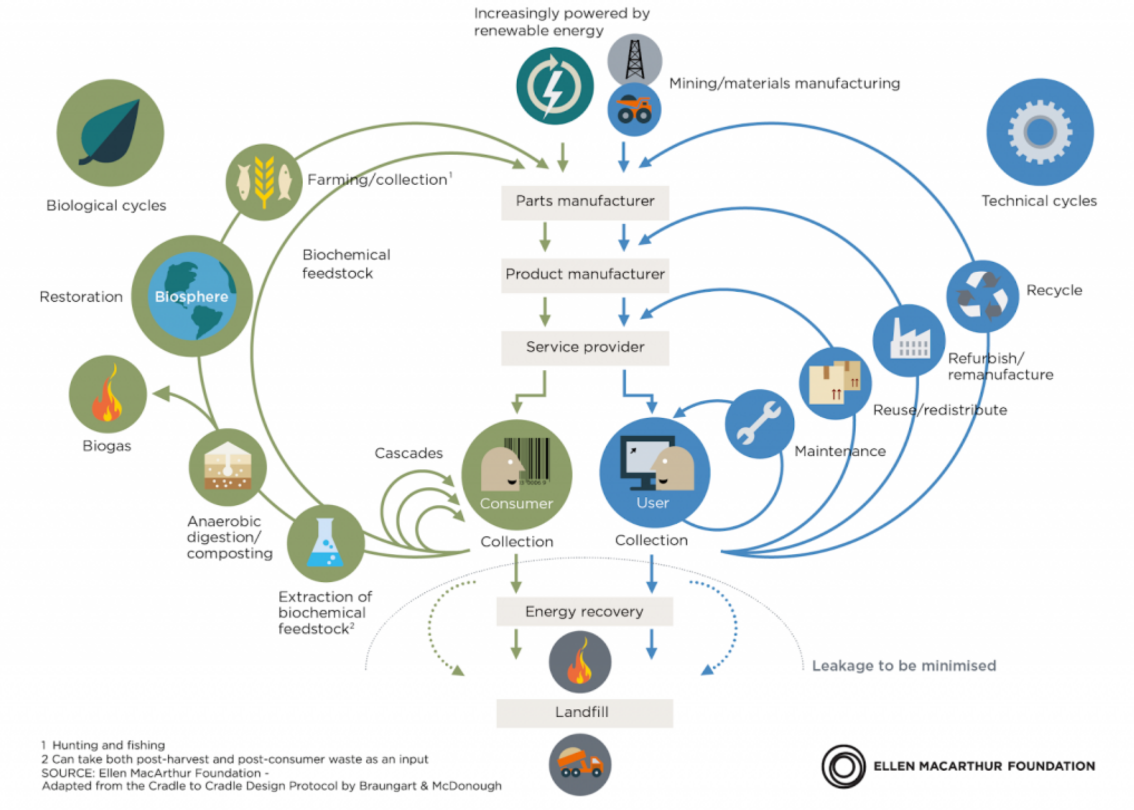
Figure 3.2: Global material extraction in billion tonnes [55]

To counter these negative developments, the Dutch government set a target to transfer from a linear to a circular economy (CE) by the latest of 2050 [54]. CE is interpreted in many ways. Therefore, Kircherr et al. analysed 114 different definitions to the following general definition:

"CE is an economic system that replaces the 'end-of-life' concept with reducing, alternatively re-using, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level, meso level and macro level, with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers." [56, p. 229]

The Ellen MacArthur foundation differentiates two types of circularity cycles: biological cycles and technical cycles. The characteristics of these cycles are shown in Figure 3.3. Forests, wood, and timber products are part of the biological cycle which is naturally regenerating. Cascading is the principal of using wood as biobased products for as long as possible, before using it as biomass. This is an essential factor to allow the biosphere to replenish.

Technical cycles use finite resources as raw material. It is therefore vital to keep these materials in the 'loop' to avoid exhaustion of the supply. Steel and concrete are part of this cycle and should be maintained, re-used, refurbished or recycled, minimizing the amount used for recovery and landfilling.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
SOURCE: Ellen MacArthur Foundation -
Adapted from the Cradle to Cradle Design Protocol by Braungart & McDonough

Figure 3.3: Circular economy [57]

The construction sector in the Netherlands contributes to approximately 50% to the national resource use. Currently, more than 95% of the waste produced in the sector is recycled, though not remaining the same quality (downcycling) [54]. Besides the reduction of waste, reducing material use, re-use and transformation of existing buildings and re-use of building elements, the biobased economy is part of the strategy of the government to reach the target of a circular economy in 2050.

Various initiatives provide tools to stimulate circularity in the construction sector via ‘material passports’ and marketplaces. Madaster is an example of material passport platform. It registers the quantity and quality of used materials and links it to building information models (BIM). Various marketplaces for structural materials are available in the Netherlands, such as the Circular Building Platform by BAM or Insert by BOOT. Currently, Platform CB’23 (an initiative by Rijkswaterstaat, Rijksvastgoedbedrijf, de Bouwcampus and NEN) develops a uniform framework for material passports allowing for exchange between different platforms.

3.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method to quantify the environmental impact of products or services. The method can be used to identify the largest contribution to the environmental impact to optimize the product or service. Alternatively, a comparison of the environmental impacts of variants of the product or service can be made.

3.3.1. Methodology

The principles and framework of the general LCA methodology are described in the ISO 14040 standard. The LCA framework consists of four phases, as indicated in Figure 3.4. The first phase defines the goal and scope of the LCA; in the second phase, called Life Cycle Inventory (LCI), the data for input and output resources of the system is collected; the third phase, called Life Cycle Impact Assessment (LCIA), translate the data from the LCI to environmental impact categories; the fourth and final step is the interpretation of the data in which the findings of the assessment are reviewed and presented [58]. In the Netherlands, the obtained data for the environmental impact categories are converted by the weighting of the categories to a single ‘shadow price’ indicator for easier interpretation [59].

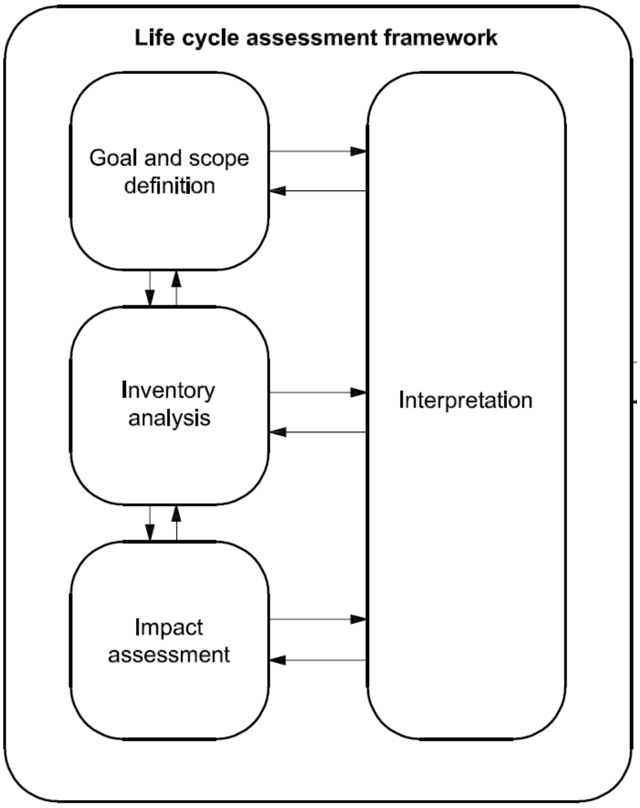


Figure 3.4: Life Cycle Assessment framework according to ISO 14040 [58]

The total life cycle of a building can be divided into five stages: the production stage, construction stage, use stage, end of life stage and the effects beyond the building life cycle by re-use, recycling, or recovery. These stages have various sub-stages, as depicted in Figure 3.5. The minimum of life cycle stages which should be declared according to the EN 15804 standard for construction products are the product stages A1-A3, this is known as cradle to gate assessment. A cradle to grave assessment includes all stages from the production stage to end of life stage (A-B-C). When all stages are included (A-B-C-D) it is a cradle to cradle assessment in which remaining resources at the end of life stage form the input for another lifecycle [60].

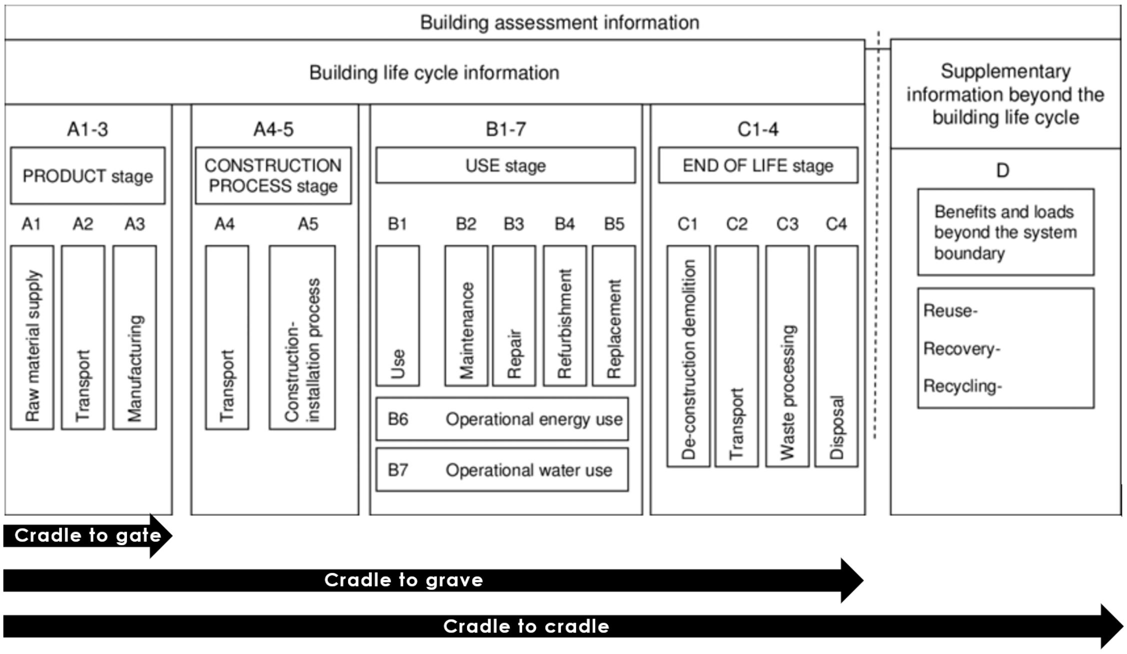


Figure 3.5: Life Cycle stages [Adapted from 61]

The approach as described in ISO 14040 is an elaborate process of several months performed by specialists. This approach is known as the classical LCA in which the environmental impact of a single product is determined [62]. The results of classical LCA are documented in Environmental Product Declarations (EPD) and stored in databases such as the Dutch Nationale Milieu Database (NMD) or the international Ecoinvent database.

Buildings consist of a diversity of building materials and products. Therefore, another approach is available called the ‘Fast Track’ LCA [62]. This type of LCA uses the results from classical LCA’s as input to compare design alternatives or to provide required documentation for building permits. Various tools are available to make ‘Fast Track’ LCA calculations such as, ‘GPR gebouw’, ‘DGBC materialentool’ and ‘MRPI Free Tool’ [59]. The ‘Fast Track’ LCA is a fast approach to quantify the environmental impact of a building, though the validity and comparability of the results depend on the chosen data sources.

To make sure that results of an LCA are comparable, a functional unit is defined in the goal and scope. It states the functionality of the assessed system in the study and the unit in which it is expressed [62].

Next to the environmental impact categories, an LCA includes indicators describing resource use. This includes parameters for re-use, recycling and energy recovery, which are declared in module D. Other parameters for the use of secondary materials and energy, originating from previous life cycles, are used in all life cycle modules. These parameters give fundamental insight into the circularity of a product. Though, the use of module D is controversial amongst LCA experts, since it is a pre-allocation of an uncertain future scenario based on the assumptions of the LCA performer [63].

Quantifying the environmental impact of circular products can be modelled in two ways. First, the reference service life can be extended, representing the entire service life of the number of (re)use cycles. The effects of the re-use cycles, both positive and negative environmental contributions, are modelled in the use stage (module B). The second option is to perform a multi life cycle assessment (mLCA). In this method, each cycle is modelled as separate LCA and are aggregated to obtain the results of the circular product. Challenges in this method arise for the allocation and use of module D [64].

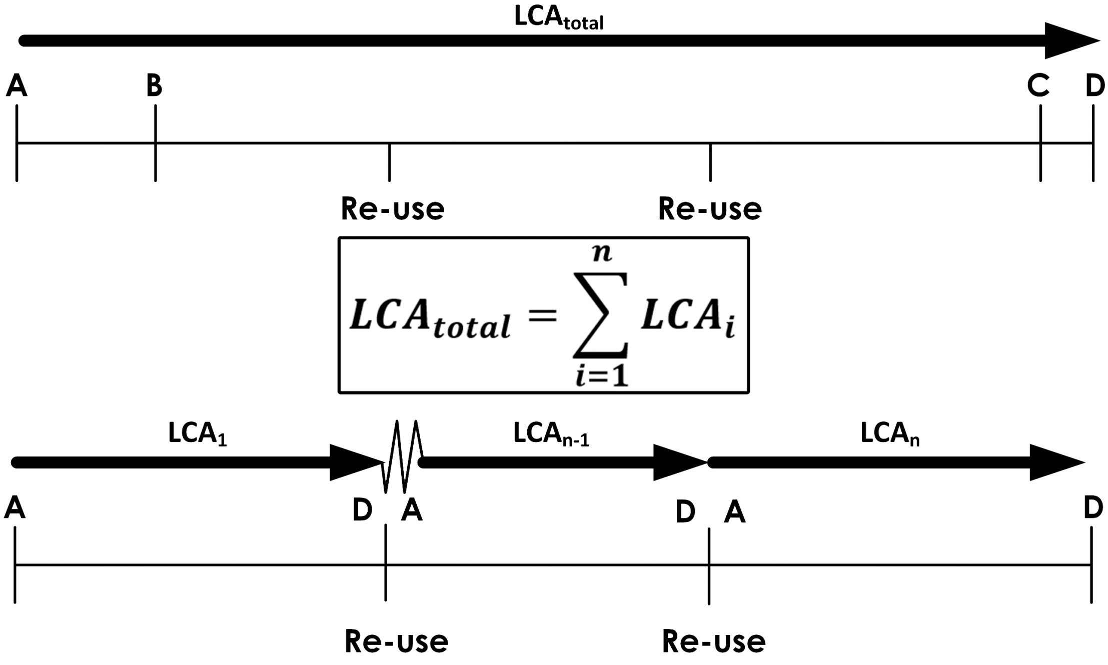


Figure 3.6: Circularity in LCA [Adapted from 64]

3.3.2. Environmental impact categories

As stated in section 3.3.1, the collected data from the LCI is assigned to environmental impact categories during the LCIA. Various LCIA methods are available, containing different impact categories. In the Netherlands, the CML-2 baseline method is mostly used [63]. This method was developed by the Institute of Environmental Sciences (CML) at Leiden University in 2001.

Other methods used in the Netherlands are TWIN2011 by the Dutch Institute for Building Biology and Ecology (NIBE) and RECIPE by a cooperation of the RIVM, CML, Radboud University Nijmegen and Pré Consultants [65, 66]. These methods contain more environmental impact categories than CML-2 baseline and have different normalisation and weighting of the data [67]. Therefore, LCA results based on these methods are not comparable with the CML-2 method.

CML-2 baseline contains a total of eleven environmental impact categories, which are the most used in LCA. A short description is given based on publications by Jonkers and GreenDelta [52, 67]:

GWP	**Global warming potential** GWP quantifies the effects of anthropogenic (human-induced) greenhouse gases. This includes carbon dioxide (CO_2), methane (CH_4), Chlorofluorocarbons (CFCs), Ozone (O_3) and Nitrous oxide (N_2O). These greenhouse gases are converted to the reference unit: kg CO_2 equivalent. The effect of global warming results in the disturbance of climatic phenomena and temperature change, resulting in decrease of biodiversity.
ODP	**Ozone depletion potential** Contrary to the negative effect of ozone as greenhouse gas in the lower atmosphere, it prevents harmful ultraviolet radiation entering earth in the higher atmosphere. Halogenated gases cause damage to the ozone layer, resulting in negative effects for human health and ecosystem qualities. The combined effect of all contributing gases is converted to the reference unit, which is kg CFC-11 equivalent.
AP	**Acidification potential** Emitted acidic compounds react in the atmosphere with water, creating the phenomenon of acid rain. This effect damages ecosystems, decrease biodiversity and has a corrosive effect on structures. Examples of compounds causing acid deposition in the atmosphere

	are sulphur oxides (SOx) and nitrogen oxides (NOx). The reference unit is kg SO_2 equivalent.
EP	**Eutrophication potential** Eutrophication is the process of disproportional organic growth by increased available nutrients in an ecosystem. This leads to oxygen depletion in water bodies, resulting in loss of biodiversity. Nitrogen (N) and phosphorous (P) compounds induce eutrophication and its effect is expressed in kg PO_4^{3-} equivalent.
POCP	**Photochemical ozone creation potential** Next to the contribution of ozone in the lower atmosphere to global warming (see GWP), it is toxic for humans and nature at high concentrations. Combustion of fossil fuels emit carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NOx) and volatile organic compounds (VOCs). These elements react by photochemical oxidation to form ozone. This type of air pollution is known as smog. The reference unit is kg ethylene (C_2H_4) equivalent.
ADP	**Abiotic depletion potential** This environmental impact category is split into two subcategories: ADP-E and ADP-F, the first is the ADP for non-fossil resources the latter for fossil resources. These categories are measures for the scarcity of abiotic (non-living) finite resources, such as minerals, metals and fossil fuels. ADP-E has a reference unit of kg antimony (Sb) equivalent; ADP-F has either the same reference unit as ADP-E or MJ net calorific value. This can be converted by the following factor: 4.81E-4 kg antimony per MJ [68].
HTP	**Human toxicity potential** HTP measures the toxic substances affecting human health. Both the toxicity and the dose of harmful compounds determine the relative contribution to the impact category. The reference unit is kg 1,4 dichlorobenzene (DB) equivalent.
FAETP	**Freshwater aquatic eco-toxicity potential** This environmental impact category quantifies toxic substances, affecting organisms living in freshwater aquatic ecosystems. Examples of affecting components for this impact category are wastewater, mining of heavy metals and fossil fuel extraction. The reference unit is kg 1,4 dichlorobenzene (DB) equivalent.

MAETP **Marine aquatic eco-toxicity potential**

This environmental impact category is similar to FAETP, quantifying toxic substances. MAETP is aimed at organisms living in marine aquatic ecosystems. For example, Persistent organic pollutants (POPs) are toxic components found in the sea. They are resistant to deterioration, resulting in accumulation in the food chain. Most POPs are the result of industrial by-products. The reference unit is kg 1,4 dichlorobenzene (DB) equivalent.

TETP **Terrestrial eco-toxicity potential**

This environmental impact category is similar to FAETP and MAETP, quantifying toxic substances. TETP is aimed at organisms living on land. Agricultural pesticides are examples of harmful substances at higher concentrations. Accumulation in the food chain occurs, causing similar problems than POPs for marine ecosystems. The reference unit is kg 1,4 dichlorobenzene (DB) equivalent.

For the previously described environmental impact categories, TNO and CE Delft developed weighting factors to monetarize the environmental impact, the so-called shadow price. These prices represent the prevention costs, which must be made to reach the environmental goals set by the government [68].

Table 3.1: Shadow prices for CML-2 baseline method [68]

		Environmental impact category	Reference unit	Shadow price [€/kg equivalent]	Source
EPD	NMD	GWP	kg CO_2 eq.	€ 0.05	CE
		ODP	kg CFC-11 eq.	€ 30.00	CE
		AP	kg SO_2 eq.	€ 4.00	CE
		EP	kg PO_4^{3-} eq.	€ 9.00	CE
		POCP	kg C_2H_4 eq.	€ 2.00	CE
		ADP-E	kg Sb eq.	€ 0.16	TNO
		ADP-F	kg Sb eq.	€ 0.16	TNO
		HTP	kg 1,4 Db eq.	€ 0.09	TNO
		FAETP	kg 1,4 Db eq.	€ 0.03	TNO
		MAETP	kg 1,4 Db eq.	€ 0.0001	TNO
		TETP	kg 1,4 Db eq.	€ 0.06	TNO

3.3.3. Environmental product declarations

LCA results are documented in Environmental product declarations (EPDs) by programme operator agencies, such as the Dutch MRPI. These declarations ensure independently verified environmental impact data conform to ISO 14025 and EN 15804. EPDs are publicly available via programme operators or manufacturers of the declared product.

The benefit of EPDs compared to data from databases, such as the NMD, is that all underlying assumptions and background information are documented and can be verified. EN 15804 specifies the minimum seven environmental impact categories which should be included in an EPD. This is less extensive than the eleven categories used in the NMD, see Table 3.1. Both the NMD and EPDs include the global warming potential impact category, though the Dutch framework (see section 3.3.4) makes an exception for biogenic carbon allowing it to be excluded [68]. Even though this yields the same results over the total life cycle since all stored biogenic carbon will be released at the end of life stage, it results in differences when only the cradle to gate stages are studied.

3.3.4. Dutch Legislation for the building sector

Stichting Bouwkwaliteit (SBK) developed the environmental performance criterion 'Milieuprestatie Gebouw' (MPG). This method is based on the standards EN 15804 for environmental product declarations and EN 15978 for the sustainability of buildings and uses the NMD as data source [68]. Thus, using the CML-2 environmental indicators and accompanying shadow prices, see section 3.3.2.

Since 2018, the Building Decree 2012 (*Bouwbesluit 2012*) specifies a requirement for the MPG which is a requisite to obtain a building permit in the Netherlands. This is required for all newly constructed residential buildings of any size and offices larger than 100 m^2. The MPG can be calculated according to Equation (1) and is expressed in shadow price per square meter gross floor area (GFA) per year [€ / m^2 GFA / year].

$$MPG = \frac{NMD\ data\ * Material\ quantity\ * Environmental\ costs}{Lifespan * Gross\ floor\ area} \qquad (1)$$

Currently, the MPG requirement is set at a maximum value of 1.0, which is achieved for all buildings without additional efforts to lower the sustainable impact of the building. This requirement will be increased to reach the sustainability goals set by the government, promoting circular construction further [69, 70], see Table 3.2. An MPG calculation takes all applied materials in a building into account up to the turnover to the owner. This includes the foundation, columns, beams, floors (including floor finishing), walls (load-bearing and non-load bearing), roofs, façades and installations. The operational energy use of the building is included in a separate environmental performance criterion: 'Bijna energieneutral gebouwen' (Beng).

Table 3.2: MPG requirement

Year	MPG requirement [€/m² GFA/year]
2018	1.0
2021	0.8
2030	0.5

3.4 Timber as renewable resource, the macro-scale

The macro-scale deals with sustainability considerations on the global forestry level, see Figure 3.1 for the other analysed scales.

3.4.1. The carbon cycle

Carbon is an essential element for all organisms. On earth, this element is stored and exchanged between the geosphere, hydrosphere, biosphere and atmosphere [71], see Figure 3.7. This process is known as the carbon cycle and contains greenhouse gases when released to the atmosphere.

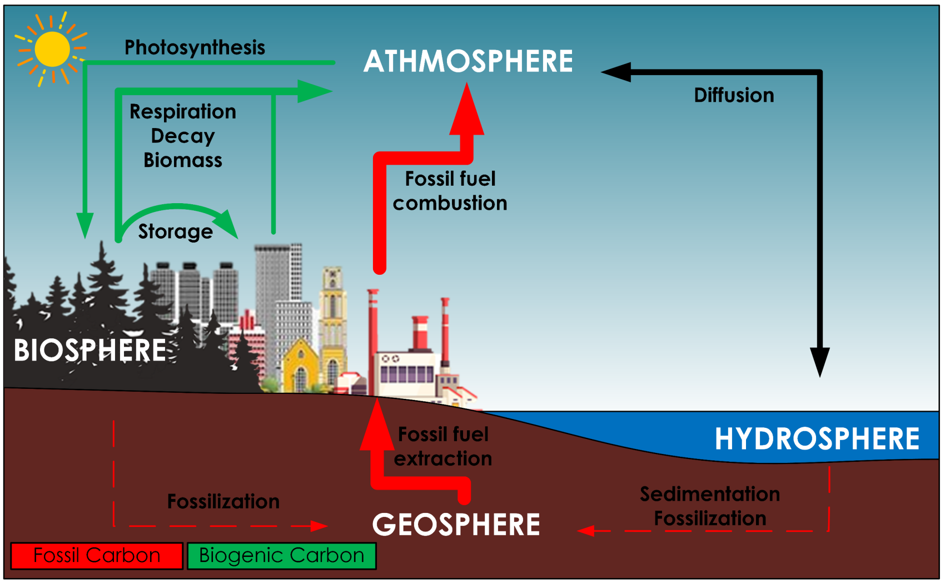


Figure 3.7: Carbon cycle

Two types of carbon can be identified in the cycle: fossil and biogenic carbon. The former is originated from decomposed material in the geosphere, the latter from biomass in the biosphere [72]. A clear distinction can be made between fossil and biogenic carbon based on the duration they are stored. Formation of fossil carbon takes millions of years opposed to 1 – 10000 years for biogenic carbon [73]. Therefore, fossil-based resources are classified as non-renewable, whereas biogenic based resources are classified as renewable. In recent years, combustion of fossil fuels increased the concentration of greenhouse gases in the atmosphere on top of the natural flux within the system [71]. These additional anthropogenic emissions will be part of the biogenic carbon cycle for the foreseeable future.

Forests are a natural carbon storage within the much shorter biogenic carbon cycle. Trees absorb CO_2 through photosynthesis forming oxygen in the process, see Equation (2). Small fractions of CO_2 release during the lifespan of trees through respiration. The CO_2 will re-enter the atmosphere at the end of life gradually through natural deterioration or directly when burned [74], see Equation (3). When opted for burning wood at the end of life stage, it is a sustainable alternative for fossil fuel-based energy production, since no additional fossil carbon is released from the geosphere.

$$6\ CO_2 + 6\ H_2O + \text{Solar Energy} \xrightarrow{\text{Photosynthesis}} C_6H_{12}O_6 + 6\ O_2 \qquad (2)$$

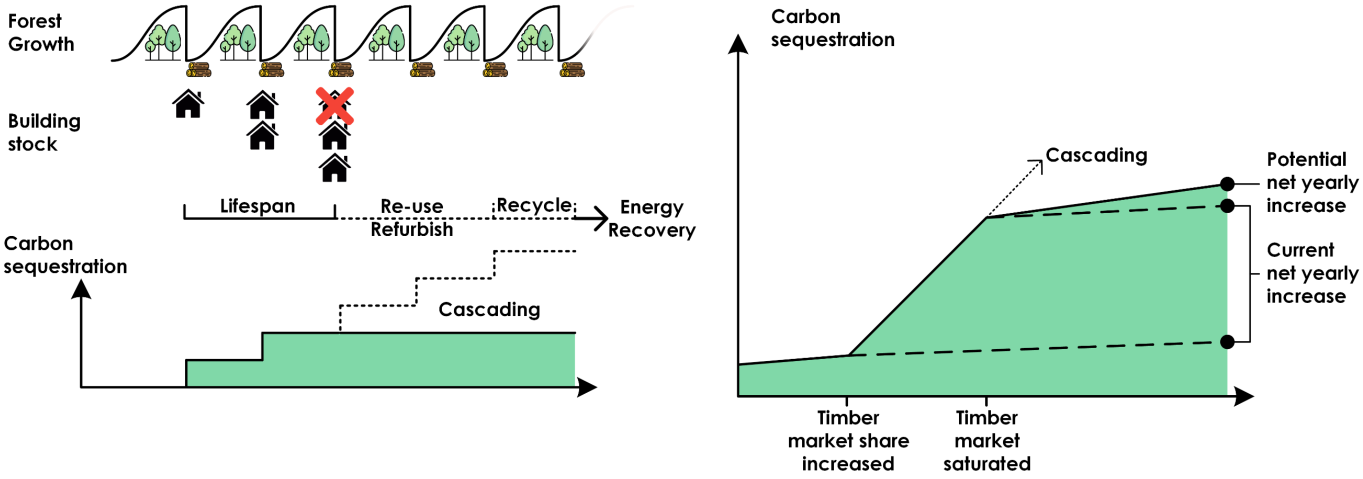
$$C_6H_{12}O_6 + 6\ O_2 \xrightarrow{\substack{\text{Respiration}\\ \text{Decomposition}\\ \text{Burning}}} 6\ CO_2 + 6\ H_2O + \text{Heat} \qquad (3)$$

3.4.2. Carbon sequestration

Carbons sequestration is the process of capture and storage of CO_2 in natural or artificial carbon sinks, effectively lowering the concentration CO_2 in the atmosphere. This part of the carbon cycle has a positive contribution to global warming and should not be mistaken with the term embodied carbon. Embodied carbon is the total carbon footprint throughout the supply chain of a product or service, representing the emitted greenhouse gases [75].

Forests, and therefore wood and wood-based products, are an example of natural carbon sequestration. The main advantage over artificial carbon sequestration (e.g. CO_2 storage in the seabed of the North Sea) is the additional benefit of carbon storage, on top of the primary function of the product. Thus, natural carbon sequestration is always the more efficient option compared to the artificial alternative, which solely serves the function of carbon capture and storage. Additionally, the process of artificial carbon storage is in an early development stage and in most cases an energy-intensive process with potential risks of CO_2 leakage [76]. Considering that these types of projects are used for polluting power plants, it will lower the efficiency of these plants, only shifting the problem since the need for more power increases. In case of storage below seabed, the risk of leakage in the ocean is present with acidification as a result [76].

Besides the sequestered carbon in forests, the building sector can increase the total capacity of carbon storage when constructing timber structures, see Figure 3.8. A requisite for the increase in sequestered carbon is the use of timber from sustainable forestry. Global increase of carbon storages is exclusively realised by additional timber structures above the already existing ones [62]. Hence, the large potential by increasing the timber market share since steel and concrete dominate the building sector. The carbon sequestration strategy in timber buildings is a short-term solution, converging to the point where timber buildings are replaced by timber buildings, resulting in no additional carbon sequestration besides the fraction of timber buildings in the yearly net increase of housing stock.



(A) Meso-scale (B) Macro-scale

Figure 3.8: Carbon sequestration

The amount of sequestered carbon can be calculated by the formula from EN 16449 based on the biogenic carbon content [77], see Equation (4):

$$P_{CO_2} = \frac{44}{12} * cf * \frac{\rho_\omega * V_\omega}{1 + \frac{\omega}{100}} \tag{4}$$

In which:

$P_{CO_2} = \ stored\ CO_2\ [kg]$
$cf = carbon\ fraction\ of\ oven\ dry\ wood\ mass\ (defaul = 0.5)$
$\omega = moisture\ content\ (default = 12\ \%)$
$\rho_\omega = wood\ density\ at\ moisture\ content\ \omega\ [kg/m^3]$
$V_\omega = wood\ volume\ at\ moisture\ content\ \omega\ [m^3]$

Based on this relationship, the stored CO_2 in timber products is approximately one metric ton per cubic meter, depending on the density of the wood species.

As explained in section 3.3.3, the biogenic carbon flow is declared in the production stage and at the end of life stage of an LCA, resulting in a net-zero biogenic carbon balance. The beneficial effect of lowering the CO_2 concentration in the atmosphere by carbon sequestration during the life cycle of the product is therefore not incorporated in LCA [62], since classical LCA only deals with input and output material flows and their emissions during the reference period of the LCA. On global or national level, a Dynamic Life Cycle Assessment (DLCA) method is available which can account for the change of the total sequestered carbon over time [78, 79]. DLCA is applicable for forests and the complete timber production industry, i.e. the macro-scale. On the individual building level, DLCA is not used since it has a static reference timeframe which does not capture the effects on the macro-scale.

3.4.3. Forest growth cycles and certification

Forest growth, together with the tree harvesting rate, dictates the sustainability of forestry. Contrary to individual trees, the growth rate of natural forests declines while the forest ages [74, 80, 81]. Eventually, a forest reaches an equilibrium state in which the total biomass stays constant, as shown in Figure 3.9. The carbon sequestration rate of forests is proportional to the growth rate [74], leading to a saturation stage where no additional carbon sequestration occurs. Therefore, forest preservation is less efficient to act as carbon sink than managed forests used for production of durable timber. This strategy is sustainable when the carbon in the timber products is stored for at least the same time it takes to sequester the same amount of carbon in the forests.

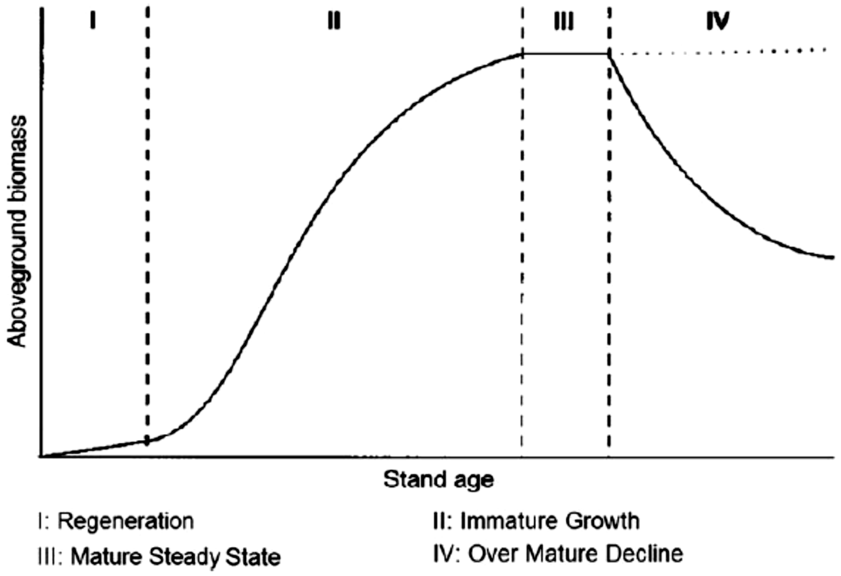


Figure 3.9: Forest growth cycle [81]

Certified wood from forest certification programs ensures that it originated from sustainably managed forests. The two largest organisation who certify sustainable forestry are the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). These organisations guarantee that the harvesting rate of forests does not exceed levels which can be sustained permanently [82]. Besides the preservation of forest resources, other goals are the maintenance or improvement of the ecosystem and socioeconomics of the sector. Approximately 130 million hectares out of the total 230 million hectares European forest area (excluding Russia, Greece and Iceland) is certified by either FSC or PEFC [83]. This results in a total of 55% coverage in Europe. See Figure 3.10 and Figure 3.11 for the distribution per country of respectively FSC and PEFC certified forests.

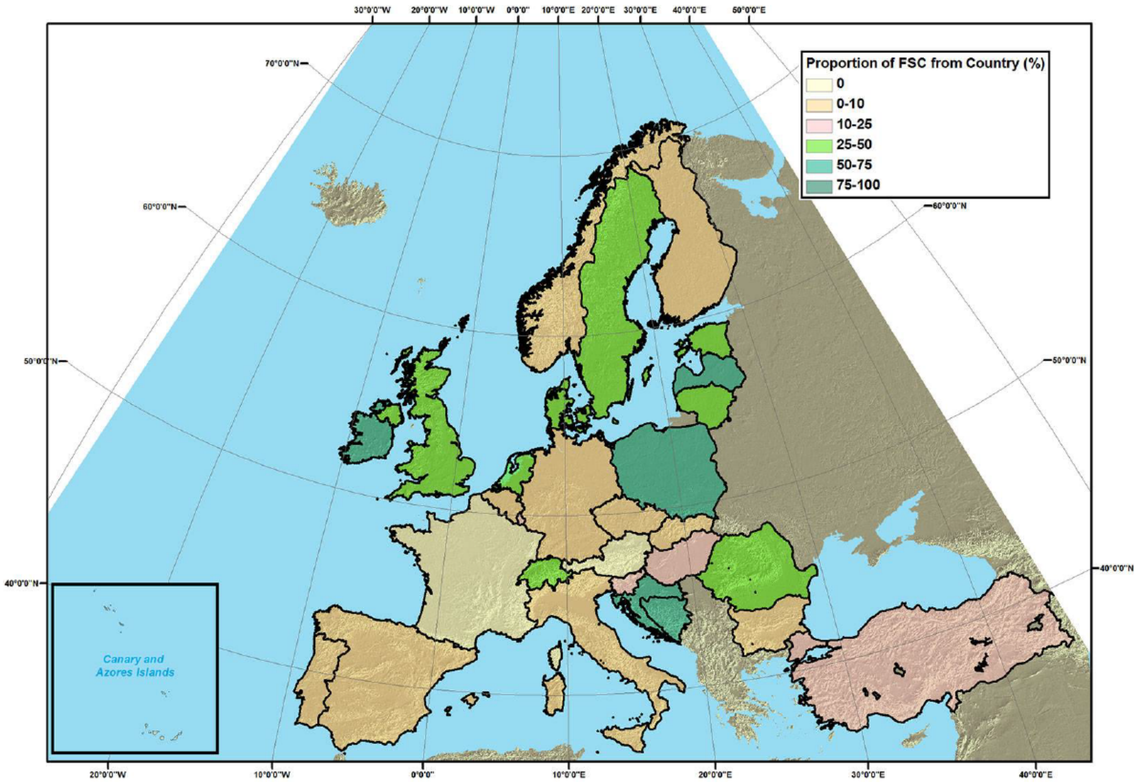


Figure 3.10: FSC certified forests in Europe as of 2018 [83]

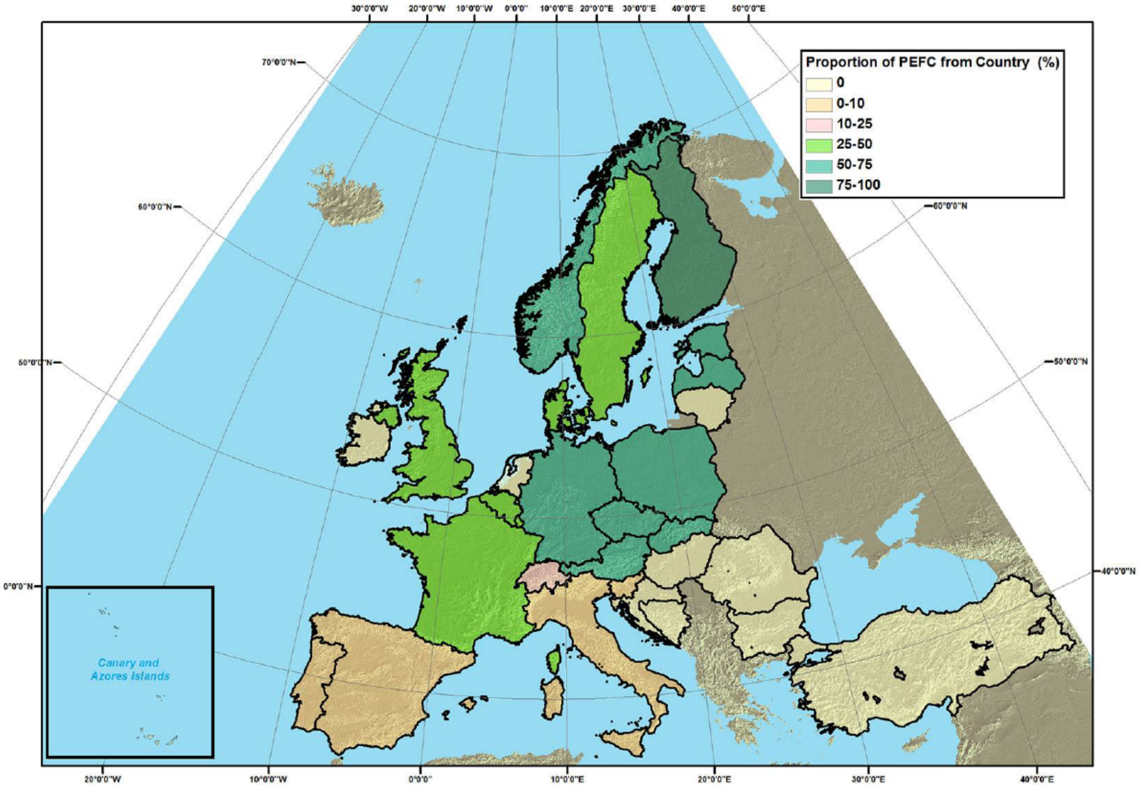
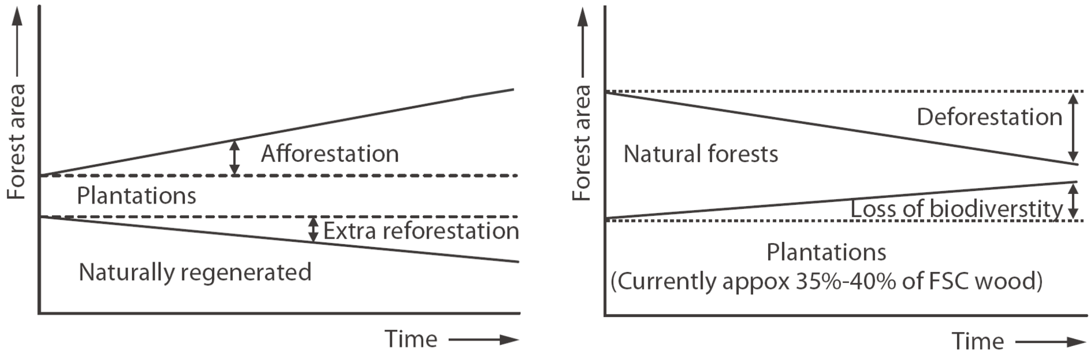


Figure 3.11: PEFC certified forests in Europe as of 2018 [83]

Because of the certification of sustainable forestry, the net annual increment of European forests equals 840 million cubic meters, of which 66% is harvested [84]. This leads to afforestation in Europe since not all forest available for wood supply is utilized; a similar relationship is valid for North American forests. Therefore, a distinction is needed between the use of softwood in timber products and the use of tropical hardwood, resulting in deforestation due to a higher demand than the available sustainable supply, as shown in Figure 3.12.



(A) European and North American softwood

(B) Tropical hardwood

Figure 3.12: Forest demand affecting the total forest area [78]

3.5 Timber as sustainable structure, the meso-scale

The meso-scale deals with lifespan and cascading strategies on building level, see Figure 3.1 for the other analysed scales.

3.5.1. Lifespan of buildings

The lifespan, commonly referred to as reference service life (RSL), of a building is part of the life cycle assessment, as elaborated in section 3.3.4. The complexity of RSL is its interpretation based on different perspectives. Technical, functional, and economical lifespan are the most important perspectives to quantify the RSL [85]:

- **Technical lifespan**
  The technical lifespan of a building is defined as the period the building can physically fulfil the required structural performance. This depends on the technical lifespan of the assembly of all individual structural elements.
- **Functional lifespan**
  The functional lifespan is defined as the period the building fulfils the user's requirement. Over time, the way buildings are used change. For example, adjustments in the floorplan layout due to changing demands; or changes in building physics requirements of façades.
- **Economical lifespan**
  The economical lifespan is defined as the period that exploitation costs (e.g. costs for maintenance, repair, and HVAC utilisation) of the building is lower or equal to the revenue. After this period, the exploitation of the building is no longer profitable. The economical lifespan strongly depends on the tendency of the market.

Another complexity of RSL is that buildings consist of many different elements, each with different ranges of lifespan. This is described by Brand's shearing layer theory, shown in Figure 3.13. The theory states that there is no such thing as a building, but several layers of longevity of built components [86]. For the structure shearing layer, the Dutch national annex of EN 1990 specifies a minimum RSL of 50 years for residential buildings and offices.

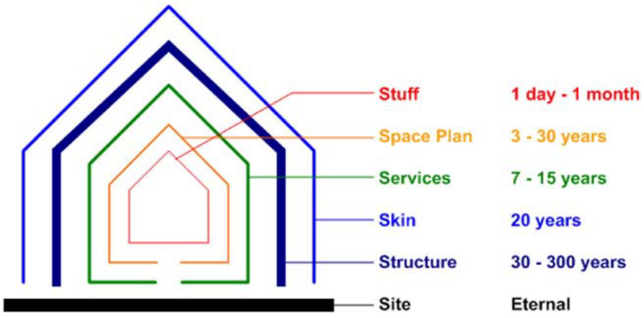


Figure 3.13: Brand's theory of shearing layers [87]

The motive for demolishing buildings is for only 5% caused by reaching the technical lifespan, i.e. having structural defects [88]. The remainder of the motive of demolition is primarily related to the functional lifespan, resulting in waste production of materials which could still be of use in another functional context.

A study by Vonck showed three strategies and corresponding design perspectives to equalize the technical and functional lifespan of buildings, as depicted in Figure 3.14. Strategy A is applicable for buildings with a single function throughout its lifespan (e.g. churches and monuments); strategy B uses a flexible design to accommodate different functions throughout the building's lifespan; strategy C optimizes the lifespan on component level, i.e. using a demountable design and re-using the components [88]. For residential buildings strategies B and C are feasible. The choice for timber typology, as discussed in section 2.2, results in further limitations for the optimization strategies. Both strategies B and C can be applied to the post and beam typology due to its open floorplan. For the mass timber typology, only the latter strategy is feasible since the fixed load-bearing walls cannot be adapted to accommodate a different layout or function.

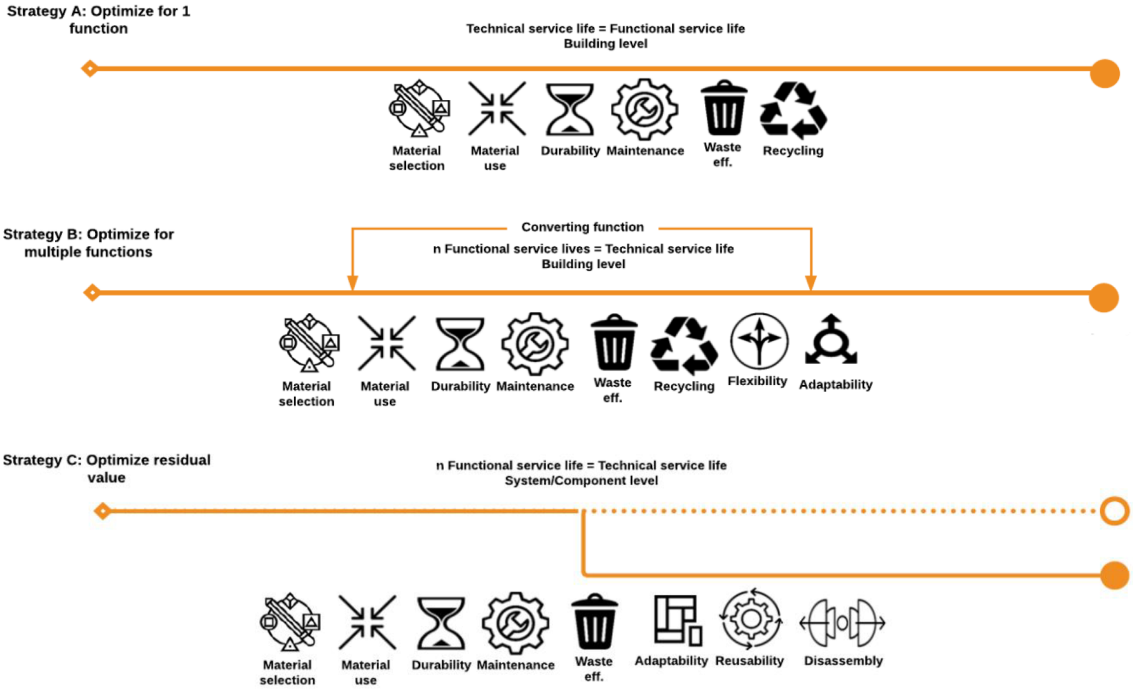
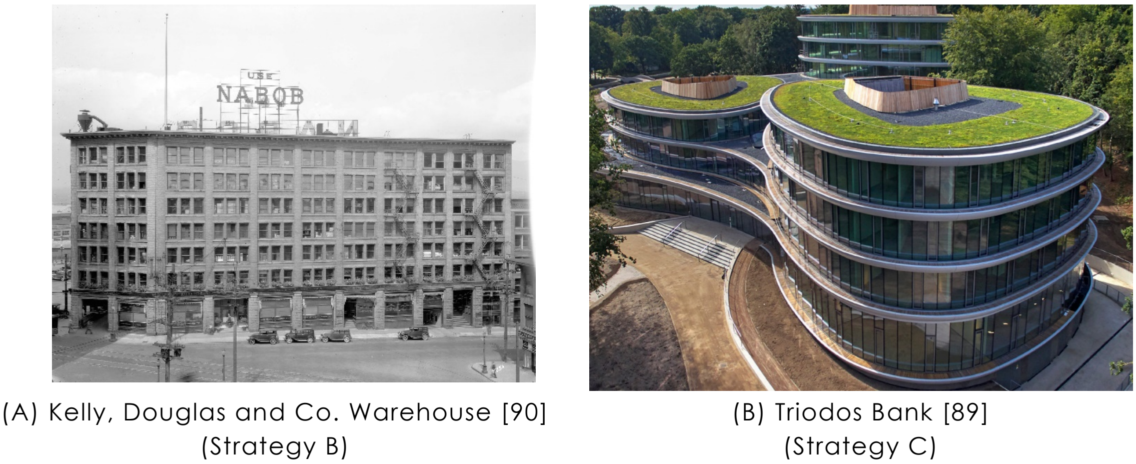


Figure 3.14: Strategies and design perspectives to optimize a building's lifespan [88]

Examples of timber buildings using either strategy B or strategy C are presented in Figure 3.15. The Kelly, Douglas and Co. Warehouse in Vancouver, Canada, was constructed in 1905. The structure uses the timber post and beam typology and a masonry façade. Initially, it was used as a warehouse but converted in 1988 to a mixed-use office, retail, and restaurant function (strategy B). The construction of the Triodos Bank in Driebergen-Rijsenburg, the Netherlands, was finished in 2019. It is a fully demountable timber structure which can either be remounted at a different location or re-used as individual structural elements (strategy C) [89].



(A) Kelly, Douglas and Co. Warehouse [90]
(Strategy B)

(B) Triodos Bank [89]
(Strategy C)

Figure 3.15: Project examples of lifespan optimization strategies

3.5.2. Timber durability

The technical durability of timber structures can be categorized into two categories: the biological durability and durability due to mechanical properties and time-dependent behaviour.

Biological durability

The biological, or natural, durability of wood depends on the species and their resistance to degradation mechanisms (e.g. resistance to micro-organisms, insects, moisture, radiation, and chemicals). See Table 3.3 for the durability classes (based on resistance to micro-organisms) of the most used species in timber building products.

Table 3.3: Biological durability classes (NEN-EN 350) [91]
1 = most durable, 5 = least durable

Species	Class
Spruce	4
Pine	3-4
Larch	3-4
Fir	4
Douglas Fir	3

Use classes, as prescribed in EN 335 and EN 460, are used to determine if the biological durability is sufficient for the intended application of the timber product. The timber products used in buildings belong to use class 1, for indoor dry applications. Table 3.4 specifies that any wood species is accepted for this use class, effectively resulting in an infinite biological durability.

Table 3.4: Required biological durability per use class (NEN-EN 335 & 460) [92, 93]

O = biological durability sufficient
(O) = biological durability normally sufficient, for certain uses treatment may be advisable
(X) = Preservative treatment normally advisable, for certain uses biological durability sufficient.
X = Preservative treatment is necessary

Use class		Biological durability class				
		1	2	3	4	5
1	Indoor, dry	O	O	O	O	O
2	Indoor, risk of wetting	O	O	O	(O)	(O)
3	Outdoor, above ground	O	O	(O)	(O) – (X)	(O) – (X)
4	Outdoor, ground contact	O	(O)	(X)	X	X
5	Outdoor, saltwater contact	O	(X)	(X)	X	X

Mechanical properties and time-dependent behaviour

In the case of indoor dry applications of timber without the risk of biological degradation, the technical durability is affected by overloading the structure and load duration. Resulting in breakage of bonds on a molecular level [94]. The load duration effects on the strength parameters of timber are experimentally derived. Figure 3.16 presents the regression equation of Madison, which is used to determine the modification factors (k_{mod}) for the load duration classes in the Eurocode [95]. The ultimate load resistance decreases for longer load durations and cumulative loads to an asymptote, see Figure 3.16.

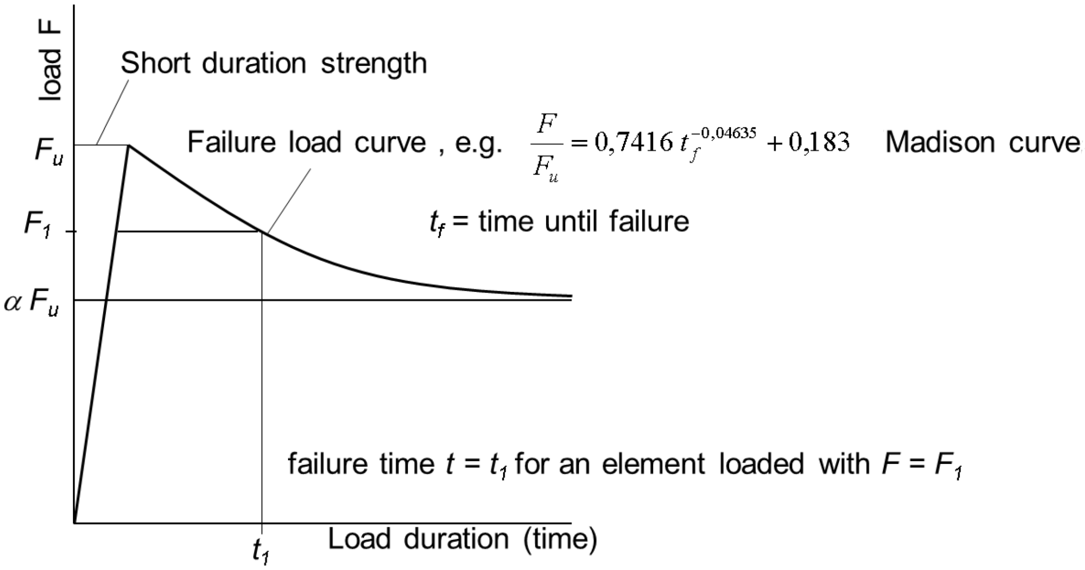


Figure 3.16: Strength parameters and time-dependent behaviour (Madison curve) [95]

3.5.3. Cascading scenarios and effects on the structural design

The cascading scenarios which are feasible for timber buildings are discussed in section 3.5.1, see strategies B and C in Figure 3.14. From now on, these strategies will be referred to as the flexible scenario (strategy B) and the demountable scenario (strategy C). The considered scenarios in this study are presented in Figure 3.17, including their effects on the MPG environmental performance criterion and structural design.

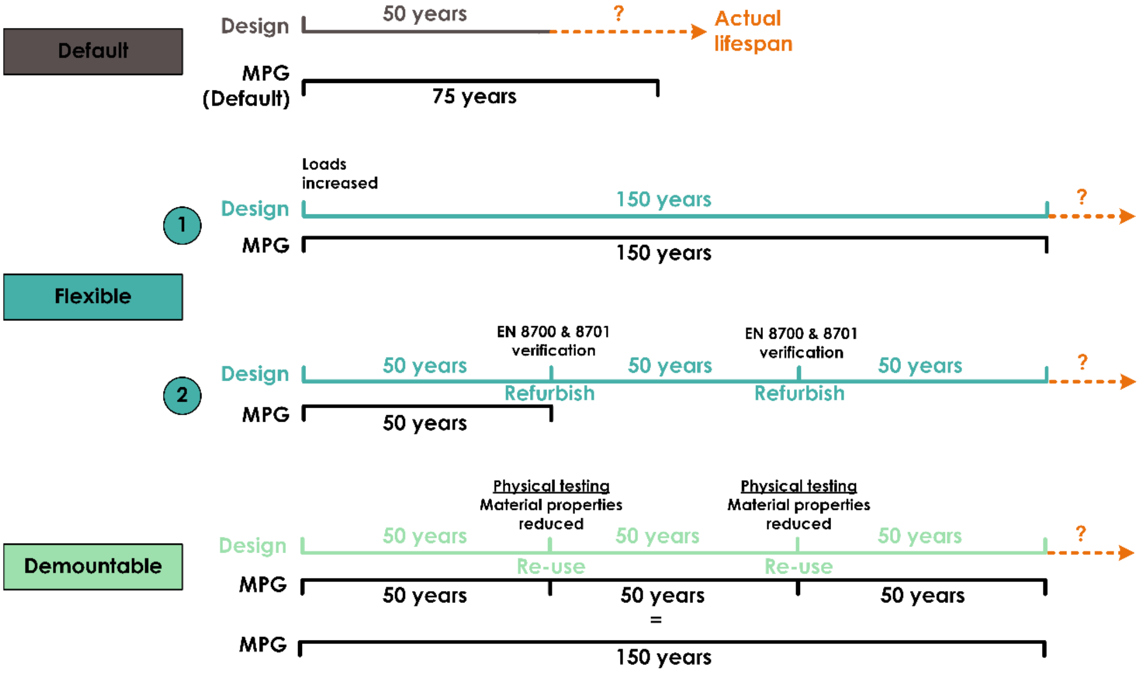


Figure 3.17: Cascading scenarios, design & MPG lifespans

Default scenario

The default scenario follows the current practice in which buildings are designed for the minimum 50 years. After the intended 50 years, the building may still be in use. However, additional benefits of the environmental impact due to the longer lifespan are not quantified. The regulation for specific building lifespan which should be used for MPG calculations specifies a default lifespan for residential buildings of 75 years based on life expectancy studies for buildings [96], see Figure 3.17.

Flexible scenario

A building with a flexible floorplan layout and function can elongate the lifespan of the building. The default lifespan for residential buildings of 75 years can be doubled to a maximum of 150 years for the flexible scenario according to the specific building lifespan regulations [96].

Two options are available for this scenario. The first being to design the structure for 150 years in advance. This is accounted for in the structural design by increasing the variable loads, since the chance that the maximum load occurs during the lifespan increases.

Alternatively, the structure can be designed for the minimum 50 years and reassessed when renovation and transformation take place to accommodate a different function. This does not guarantee that the structure has sufficient residual capacity and complies with the governing codes of that time. Verification of the residual capacity is performed according to EN 8700 and 8701 for a minimum extension of 15 years. These codes specify that the same level of safety should be achieved as newly build structures for both the physically altered elements and the preserved elements. Though it is possible to use lowered partial safety factors (about 10% lower) in case of a valid motive that reaching the equivalent level of safety of a new buildings result in disproportional costs [97].

For renovated or transformed buildings, the environmental performance criterion MPG is not specified according to the Building Decree 2012 and are thus not quantified. Therefore, the first option for the flexible scenario is chosen for the variant study in which the benefits for environmental impact is quantified, see Figure 3.14.

Demountable scenario

The individual elements can be re-used in case the structure is detailed with demountable connections. It is vital to know the residual material properties of the re-used elements to verify the required level of safety.

Multiple studies report the reduction of material properties and specify visual grading rules for reclaimed timber elements [98-101]. These values are derived by physical testing of the reclaimed specimens. The studies consistently recommend the following practice:

- The modulus of elasticity can be assumed to be the same as the virgin material.
- If the load history is known, the reduction of the strength properties is estimated to be between 20% and 55% compared to the virgin material depending on the accumulated load history, bolt holes and defects.
- If the load history is unknown, a conservative value of 55% strength reduction compared to the virgin material should be chosen for the reduction of strength properties.
- The modification factor for load duration (k_{mod}) is increased for the second use phase to 1.0 for instantaneous and short-term loads, 0.98 for medium-

term loads, and 0.90 for long-term and permanent loads. This is related to the fact that the largest strength reduction takes place in the initial 50 years of use, see Figure 3.18.

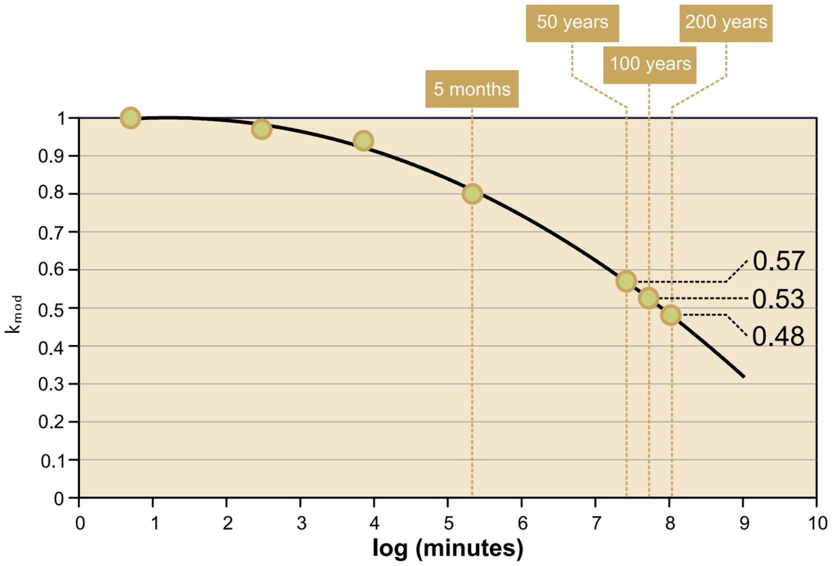


Figure 3.18: Timber strength loss over time [100]

The previous described method estimates the residual material properties by reducing the time dependent strength properties followed by an increase of the k_{mod} values to account for the slowing reduction effect. Accuracy of this approach is highly dependent on the assumed load history, which can explain the very conservative assumption of 55% reduction. In practice, the actual material properties can be determined for reclaimed timber by physical testing. Currently this is the usual method to determine residual material properties based on consultation of professionals, involved in projects utilizing reclaimed elements.

For the variants in the next chapters of this study, an alternative approach is chosen based on the theoretical re-use potential (see Section 4.4.3), since the load history is unknown and properties cannot be tested for the hypothetical variants. This avoids conservative results which do not represent the current practice.

3.6 Timber as sustainable construction material, the micro-scale

The micro-scale deals with the environmental impact of the material itself, see Figure 3.1 for the other analysed scales. The study is based on 19 environmental product declarations for sustainably certified timber (see Appendix B.1 for the full list). The environmental indicators are derived using the CML-2 LCIA method. All used data is third party verified and in compliance with the governing standards ISO 14025 and EN 15804. Additionally, the results are compared with data from the NMD and other construction materials.

3.6.1. Manufacturing (LCA stages A1-A3)

The manufacturing of timber products consists of the natural tree growth, tree harvesting, transport to the factory and the industrial processing to the final product. This process is depicted in Figure 3.19.

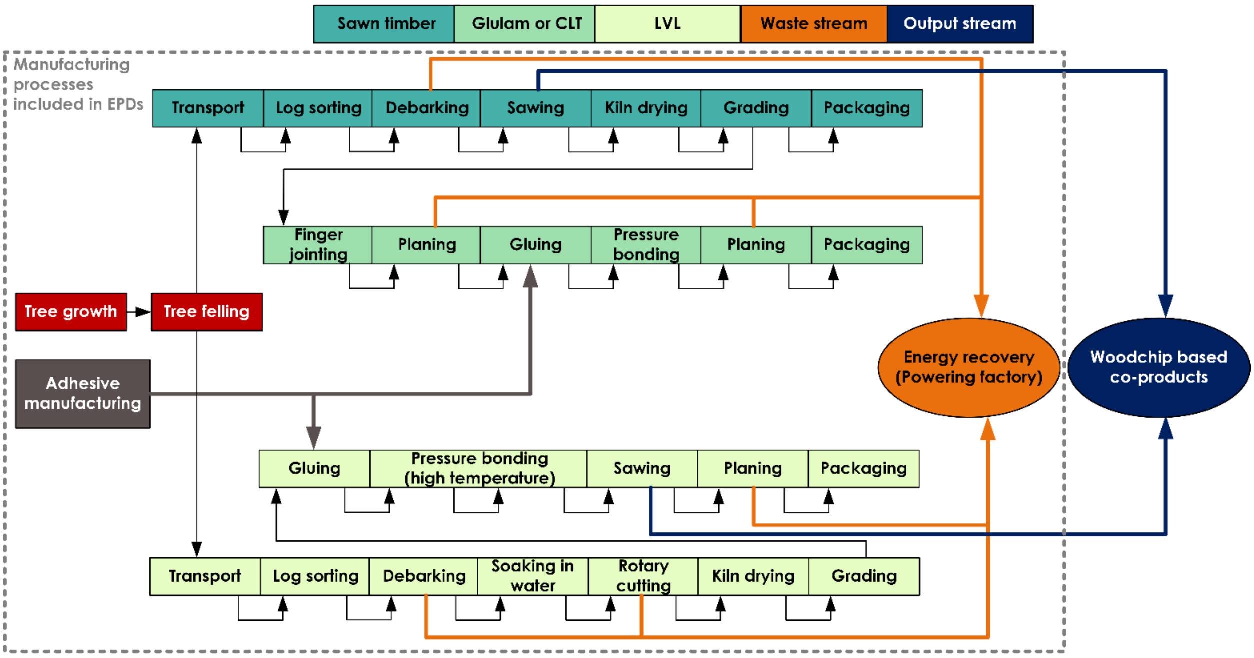


Figure 3.19: Manufacturing process of sawn timber, Glulam, CLT and LVL

Both the production of Glulam and CLT is an extension to the process of sawn timber. Additional environmental burden occurs due to the manufacturing of adhesives and energy use in the bonding process. The main differences between sawn timber and LVL is the way the logs are processed. After the debarking, the logs for timber planks are sawn while logs for LVL are peeled by rotary cutting. The bonding process of LVL occurs at high temperature, which is not required for Glulam and CLT.

During the production process of timber, several wood waste streams reduce the forest product conversion efficiency. On average, 50% of the original volume of roundwood ends up in sawn timber and 60% in LVL [102]. The remaining percentage consists of the bark, offcuts and sawdust. The bark and sawdust are used as biomass to (partially) power and heat the factory; the offcuts are processed to woodchips and used in the production stream of other wood-based products [5].

Table 3.5 shows the contribution of the manufacturing process (cradle to gate) to the environmental impact categories, including average data and its variation. All data is converted to represent the environmental impact of one kilogram of material, eliminating density variation in the declared EPDs.

Table 3.5: Environmental impact data analysis for timber EPDs(stages A1-A3)
MND = Module not declared

		Data per 1 kg material								
		$\text{GWP}_{\text{fossil}}$	GWP_{bio}	$\text{GWP}_{\text{total}}$	ODP	AP	EP	POCP	ADP-E	ADP-F
		kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.	kg CFC-11 eq.	kg SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	kg Sb eq.
Sawn Timber	**Stora Enso**	7.17E-02	-1.59E+00	-1.52E+00	1.36E-08	5.09E-04	2.43E-04	2.24E-05	6.48E-08	5.23E-04
	Swedish Wood	3.03E-01	-1.57E+00	-1.27E+00	**MND**	4.59E-04	1.10E-04	3.96E-05	2.55E-07	4.77E-04
	Wood for Good	2.23E-01	-1.71E+00	-1.49E+00	5.26E-12	1.34E-03	2.63E-04	9.46E-05	1.07E-08	1.43E-03
	Mean	1.99E-01	-1.62E+00	-1.42E+00	6.79E-09	7.71E-04	2.06E-04	5.22E-05	1.10E-07	8.09E-04
	Max / Min Factor	4.2	1.1	1.2	2578	2.9	2.4	4.2	23.8	3.0
Glulam	**Binderholz**	2.31E-01	-1.62E+00	-1.39E+00	**Outlier**	8.80E-04	2.05E-04	9.74E-05	7.75E-08	1.43E-03
	Moelven	1.44E-01	-1.67E+00	-1.53E+00	2.30E-09	8.84E-04	2.02E-04	9.77E-05	7.67E-08	9.70E-04
	Martinsons	9.07E-02	-1.67E+00	-1.58E+00	8.60E-09	6.74E-04	1.67E-04	1.07E-04	8.14E-08	6.30E-04
	Rubner	**MND**	**MND**	-1.39E+00	5.52E-08	1.81E-03	3.66E-04	2.22E-04	2.18E-07	1.39E-03
	Schilliger	**MND**	**MND**	-1.46E+00	1.25E-08	9.38E-04	2.13E-04	2.93E-04	5.24E-08	1.26E-03
	Studiengemeinschaft	3.29E-01	-1.61E+00	-1.28E+00	1.85E-09	1.49E-03	3.52E-04	2.58E-04	1.50E-06	2.04E-03
	Mean	1.99E-01	-1.64E+00	-1.44E+00	1.61E-08	1.11E-03	2.51E-04	1.79E-04	3.34E-07	1.29E-03
	Max / Min Factor	3.6	1.04	1.2	30	1.7	1.7	3.0	28.7	1.6
LVL	**Stora Enso**	3.41E-01	-1.58E+00	-1.24E+00	7.08E-08	1.99E-03	6.88E-04	2.04E-04	1.70E-06	3.29E-03
	Steico	6.36E-01	-1.60E+00	-9.66E-01	8.00E-11	2.63E-03	3.57E-04	3.05E-04	8.72E-08	4.10E-03
	Metsä Wood	2.74E-01	-1.65E+00	-1.38E+00	4.06E-11	2.28E-03	4.63E-04	1.94E-04	1.68E-06	2.64E-03
	Mean	4.17E-01	-1.61E+00	-1.19E+00	2.36E-08	2.30E-03	5.03E-04	2.34E-04	1.16E-06	3.35E-03
	Max / Min Factor	2.3	1.04	1.4	1743	1.3	1.9	1.6	19.5	1.6
CLT	**Binderholz**	2.23E-01	-1.62E+00	-1.40E+00	7.76E-10	8.83E-04	2.00E-04	1.43E-04	2.24E-07	1.48E-03
	Egoin	**MND**	**MND**	-1.31E+00	4.69E-08	1.92E-03	4.36E-04	2.76E-04	9.26E-07	2.20E-03
	KLH	3.94E-01	-1.65E+00	-1.25E+00	4.02E-08	2.04E-03	6.88E-04	3.13E-04	1.29E-06	2.50E-03
	Martinsons	1.06E-01	-1.67E+00	-1.56E+00	1.05E-08	6.74E-04	1.42E-04	8.14E-05	1.79E-07	7.98E-04
	Studiengemeinschaft	3.70E-01	-1.71E+00	-1.26E+00	1.56E-09	1.17E-03	2.64E-04	2.08E-04	1.36E-06	1.97E-03
	Rubner	**MND**	**MND**	-1.44E+00	6.90E-08	1.49E-03	2.91E-04	2.07E-04	1.79E-07	1.40E-03
	Stora Enso	1.28E-01	-1.56E+00	-1.43E+00	1.73E-08	5.11E-04	7.38E-04	**Outlier**	7.87E-08	9.81E-04
	Mean	2.44E-01	-1.64E+00	-1.38E+00	2.66E-08	1.24E-03	3.94E-04	2.05E-04	6.05E-07	1.62E-03
	Max / Min Factor	3.5	1.1	1.3	89	4.0	5.2	3.8	17.3	3.1

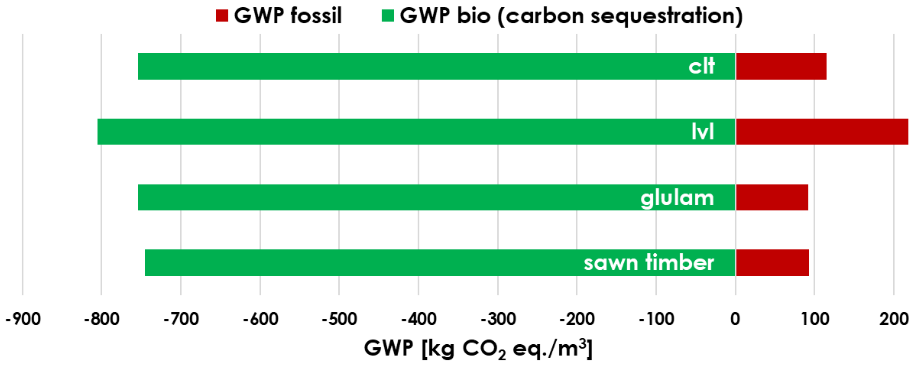


Figure 3.20: Division of total global warming potential in the manufacturing stage

To assess the contribution to global warming potential (GWP), a distinction between the fossil GWP and biogenic GWP is required, see Figure 3.20 for the division of the GWP. Biogenic GWP represents the sequestered carbon in the product. Variation of this impact category is minimal since it is directly related to the amount of material, which can be calculated according to Equation (4). Biogenic waste streams used as biomass are included in the assessments. This results in approximately 14-21% of the sequestered carbon to be directly emitted. Waste streams used in other production processes (co-products) are allocated to their respective life cycle as primary material.

Fossil GWP data shows a larger variation related to regional and production differences. Regional differences arise in the distance between forest and factory. Efficiency of the production process, waste management and division between renewable and fossil energy used in the factory also result in variation in fossil GWP. The largest contributions to fossil GWP are, in decreasing order, the use of fossil fuels during tree felling, production of adhesives, transport to the factory and used energy.

The ozone depletion potential (ODP) is caused by the emission of gases depleting the stratospheric ozone layer. Largest contributors are the production of fossil fuels used during tree felling and production of adhesives. Therefore, sawn timber has a lower ODP compared to Glulam, CLT and LVL since no adhesives are used. This environmental impact category has a large variance as shown in Table 3.5.

Main drivers of the acidification potential (AP), eutrophication potential (EP) and Photochemical ozone creation potential (POCP) are caused by the combustion of fossil fuels during tree felling and biomass combustion for the heat generation of the drying process. Formaldehyde based adhesives contain volatile organic compounds contributing to the POCP. However, these are present in such low concentrations that results for the POCP show marginal increase compared to alternatives using formaldehyde-free adhesives.

Abiotic depletion potential for non-fossil resources (ADP-E) is dominated by the use of wood as raw material and energy generation utilizing biomass. Table 3.5 shows a relatively large variance for this impact category, related to the contribution of biomass to the total amount used energy which is factory dependent. Abiotic depletion potential for fossil resources (ADP-F) consists of the use of fossil fuels during tree felling and transport; fossil energy use in the factories; and the manufacturing of adhesives.

Generally, glued timber products have a higher environmental impact due to the manufacturing of adhesives and additional production steps. LVL has the overall highest impact per kilogram material due to the energy intensive bonding process.

Table 3.6 shows the embodied energy based on the EPD data analysis. A distinction is made for energy use and energy stored in the raw material. Renewable energy stored in raw materials is relatively constant for all types of timber products, this is expected since the stored energy is directly proportional to the material quantity. The average use of renewable energy is 1.2 to 2.5 times higher than fossil energy. Glulam, CLT and LVL also have a small storage in raw materials of non-renewable energy due to the use of adhesives.

Table 3.6: Embodied Energy data analysis for timber EPDs(stages A1-A3)
MND = Module not declared

		Data per 1 kg material					
		Renewable primary energy			**Non-renewable primary energy**		
		Energy	**Raw material**	**Total**	**Energy**	**Raw material**	**Total**
		MJ	**MJ**	**MJ**	**MJ**	**MJ**	**MJ**
Sawn Timber	**Stora Enso**	3.43E+00	1.65E+01	2.00E+01	1.10E+00	0.00E+00	1.10E+00
	Swedish Wood	6.97E+00	1.48E+01	2.18E+01	1.64E+00	0.00E+00	1.64E+00
	Wood for Good	4.74E+00	1.76E+01	2.24E+01	3.28E+00	0.00E+00	3.28E+00
	Mean	5.05E+00	1.63E+01	2.14E+01	2.01E+00	0.00E+00	2.01E+00
	Max / Min Factor	2.03	1.19	1.12	2.97	-	2.97
Glulam	**Binderholz**	5.37E+00	1.71E+01	2.25E+01	3.21E+00	2.18E-01	3.43E+00
	Moelven	7.63E+00	1.71E+01	2.48E+01	3.43E+00	3.84E-01	3.81E+00
	Martinsons	3.66E+00	1.72E+01	2.08E+01	1.14E+00	2.30E-01	1.37E+00
	Rubner	7.87E+00	1.65E+01	2.44E+01	2.95E+00	2.80E-01	3.23E+00
	Schilliger	3.90E+00	1.70E+01	2.10E+01	4.19E+00	4.38E-01	4.63E+00
	Studiengemeinschaft	5.72E+00	1.70E+01	2.27E+01	4.62E+00	2.66E-01	4.89E+00
	Mean	5.69E+00	1.70E+01	2.27E+01	3.26E+00	3.03E-01	3.56E+00
	Max / Min Factor	2.15	1.04	1.19	4.07	1.90	3.58
LVL	**Stora Enso**	6.07E+00	1.80E+01	2.41E+01	6.32E+00	4.25E+00	1.06E+01
	Steico	1.06E+01	1.71E+01	2.77E+01	8.24E+00	6.21E-01	8.86E+00
	Metsä Wood	1.30E+01	1.71E+01	3.01E+01	4.12E+00	2.36E+00	6.48E+00
	Mean	9.89E+00	1.74E+01	2.73E+01	6.23E+00	2.41E+00	8.64E+00
	Max / Min Factor	2.14	1.05	1.25	2.00	6.85-	1.63
CLT	**Binderholz**	6.13E+00	1.70E+01	2.31E+01	3.30E+00	2.27E-01	3.52E+00
	Egoin	**Outlier**	1.73E+01	6.81E+01	6.22E+00	1.68E-01	6.39E+00
	KLH	2.20E+00	1.71E+01	1.93E+01	5.41E+00	3.41E-01	5.75E+00
	Martinsons	3.70E+00	1.72E+01	2.09E+01	1.18E+00	2.70E-01	1.45E+00
	Studiengemeinschaft	3.78E+00	1.69E+01	2.06E+01	4.59E+00	2.63E-01	4.85E+00
	Rubner	6.03E+00	1.65E+01	2.25E+01	2.95E+00	1.88E-01	3.14E+00
	Stora Enso	3.47E+00	1.59E+01	1.94E+01	1.33E+00	7.19E-01	2.05E+00
	Mean	4.22E+00	1.67E+01	2.10E+01	3.57E+00	3.11E-01	3.88E+00
	Max / Min Factor	2.78	1.08	1.20	5.25	4.28	4.40

3.6.2. Construction process and use stage (stages A4-B7)

Stage A4, indicating the transport to the construction site is project-specific and therefore in most EPDs excluded, others specify an assumed distance. See Appendix B.2 for all assumed distances. Furthermore, the construction installation process (stage A5) is in all EPDs excluded since this is project-specific, though several EPDs declare the module for the waste stream of the packaging material.

The use stage has no environmental burden. No replacement or maintenance is expected during a building's life cycle, and the products itself has no operational energy use. Generally, the use stages are not declared in the studied EPDs since there is no environmental impact related to the stages B1 to B7.

3.6.3. End of life scenarios (LCA stages C1-C4 + D)

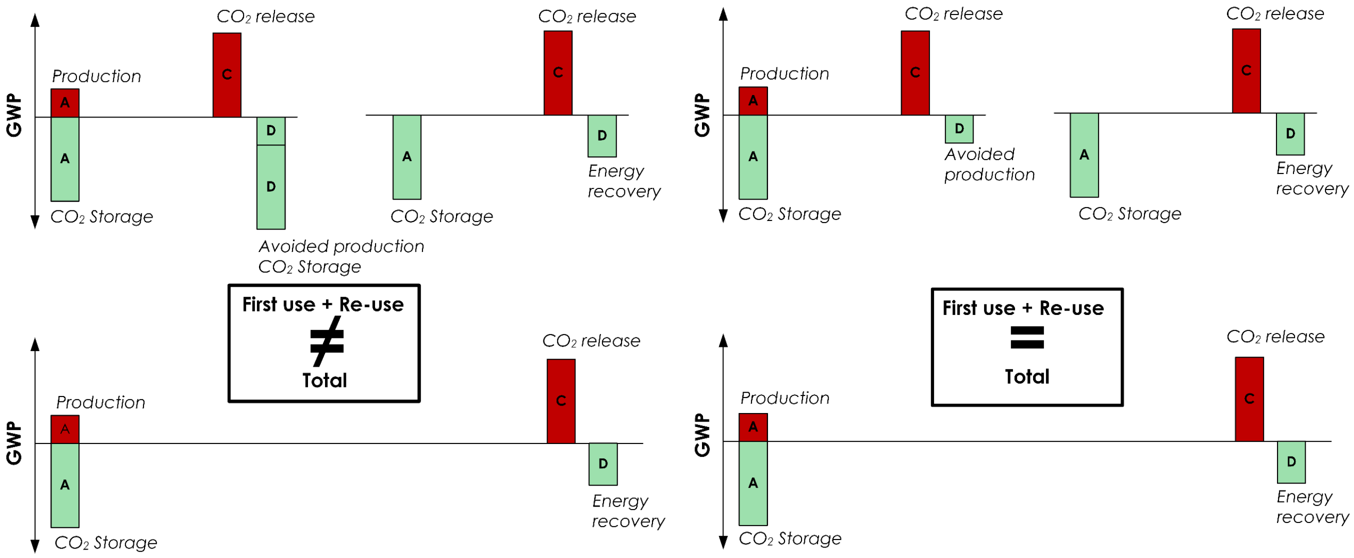
Four types of end of life scenarios are quantified across the studied EPDs: Re-use, Recycling, Energy & Thermal recovery, and landfilling. In Appendix B.2 the declared end of life scenarios are specified per EPD. In case multiple EPDs have the same end of life scenario, the average environmental impact has been determined, see Table 3.8 for the results.

Regardless of the end of life scenario, the biogenic carbon content is assumed to be emitted in LCA stage C according to the EN 15804 framework [60]. The environmental impact of the transport in the end of life stage (C2) is regional specific. Therefore, the results are harmonized to represent the Dutch distances according to the Dutch Institute for Building Biology and Ecology (NIBE). The distance for a re-use scenario is not specified and is therefore assumed to be the same as recycling, see Table 3.7.

Table 3.7: NIBE end of life transport distances

Scenario	Distance [km]
Re-use	50
Recycle	50
Energy/Thermal recovery	150
Landfill	100

Interpretation of the re-use and recycling scenarios show inconsistencies regarding the biogenic carbon content in stage D, which comprises the benefits and burdens beyond the boundary of the LCA. As shown in Figure 3.21, the re-use and recycling potential is in most EPDs incorrectly modelled (excluding EPDs by EPD International AB), assuming all biogenic carbon remains stored in the timber (benefit). However, excluding the fact that it will re-enter the atmosphere at the end of the re-used or recycled life cycle (burden). This will result in allocation problems and double counting of the benefits since re-used material enters the second life cycle burden-free but counts the stored carbon. Incorrectly modelled end of life scenarios are adjusted, as shown in Table 3.8.



(A) Incorrectly modelled (B) Correctly modelled

Figure 3.21: Inconsistencies in modelling of re-use and recycling end of life scenarios

EPDs specifying a scenario for energy recovery, assume substitution of natural gas for thermal energy production and the current electricity mixture for electricity production. This mixture consists predominantly of fossil fuels, see Figure 3.22. By the time that timber products reach the end of life scenario, the electricity mixture should be transformed to reach the environmental goals by the government. Replacing fossil fuels by renewable energy sources. Therefore, the Dutch MPG methodology prescribes rules for material equivalency in LCA stage D [68]. Meaning that biomass will replace biomass, not fossil fuels. Taking this into account, the energy and thermal recovery scenarios have been adjusted to comply with the Dutch methodology. The calculation is based on the lower heating value of wood and the net efficiency of Dutch incineration plants (18% electricity 31% thermal recovery) [68]. This lowers the benefits of recovery compared to fossil fuel replacement by approximately 70% for the shadow price, see Table 3.8 for the data and Appendix B.4 for the derivation.

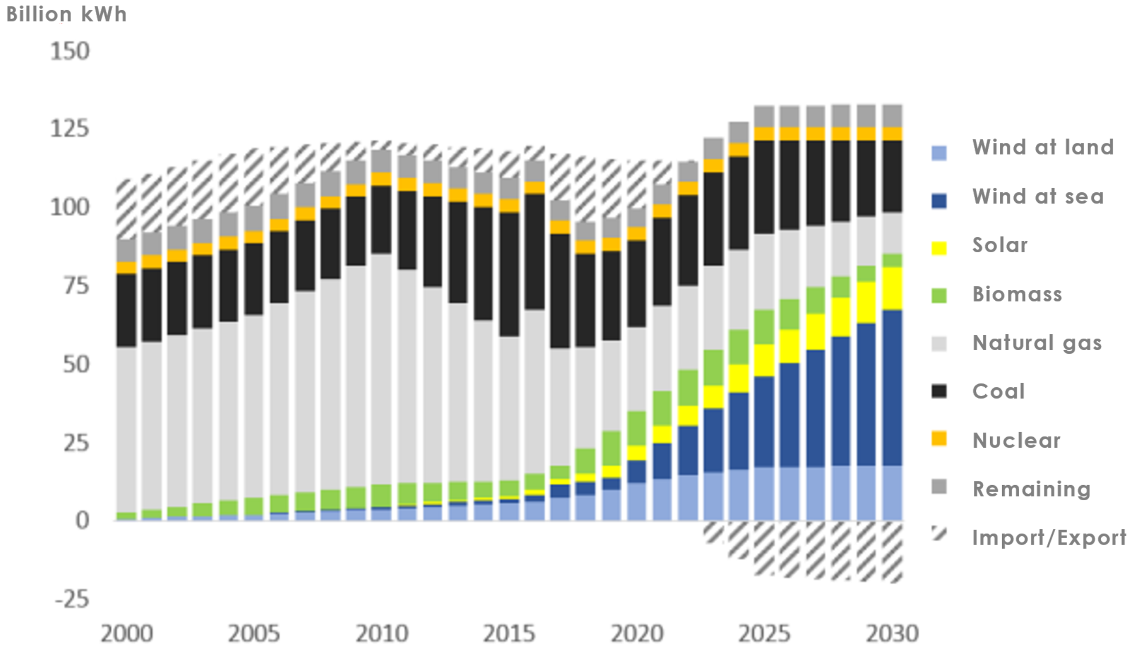


Figure 3.22: Electricity mixture of the Netherlands according to the National Energy Examination (NEV-2017) [Adapted from 103]

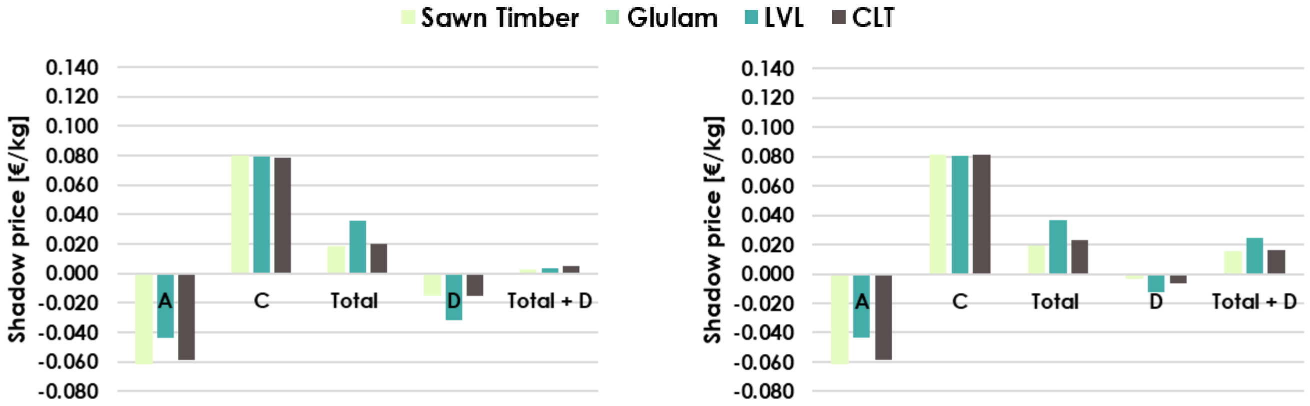
Two EPDs specify a landfilling scenario, each modelling the benefits and burdens in LCA stage D differently. Either a conservative approach is chosen in which no benefits are allocated; or taking into account the methane uptake from landfilling, replacing natural gas.

Table 3.8: Environmental impact data analysis for timber EPDs(stages C1-C4 + D)
D* = adjusted stage D

			Data per 1 kg material						
			GWP	**ODP**	**AP**	**EP**	**POCP**	**ADP-E**	**ADP-F**
			kg CO₂ eq.	**kg CFC-11 eq.**	**kg SO₂ eq.**	**kg PO₄ eq.**	**kg C₂H₄ eq.**	**kg Sb eq.**	**kg Sb eq.**
Sawn Timber	**Re-use**	**C**	1.60E+00	1.38E-09	2.87E-05	1.78E-05	4.29E-07	7.43E-10	8.64E-05
		D	-1.66E+00	-2.57E-04	-4.87E-04	-2.26E-04	-2.24E-05	-4.74E-04	-4.38E-04
		D*	**-7.17E-02**	-2.57E-04	-4.87E-04	-2.26E-04	-2.24E-05	-4.74E-04	-4.38E-04
	Recycle	**C**	1.61E+00	2.21E-09	9.58E-05	3.90E-05	1.14E-06	1.22E-08	1.39E-04
		D	-1.62E+00	-1.01E-08	-1.25E-04	-1.77E-04	-9.17E-06	-1.41E-09	-1.62E-04
		D*	**-3.85E-02**	-1.01E-08	-1.25E-04	-1.77E-04	-9.17E-06	-1.41E-09	-1.62E-04
	Recover	**C**	1.62E+00	2.21E-09	1.26E-04	4.70E-05	1.29E-06	1.22E-08	2.06E-04
		D	-9.00E-01	-1.32E-07	1.18E-03	7.00E-04	8.54E-05	8.09E-08	-7.80E-03
		D*	**-4.34E-02**	**-1.41E-08**	**-1.15E-03**	**-3.74E-04**	**-1.79E-04**	**-9.33E-08**	**-2.36E-04**
	Landfill	**C**	1.65E+00	5.04E-09	2.60E-04	2.39E-03	8.62E-06	3.14E-08	3.27E-04
		D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Glulam	**Recover**	**C**	1.65E+00	3.36E-10	7.40E-05	1.54E-05	8.05E-06	3.31E-09	1.11E-04
		D	-6.53E-01	-2.36E-08	-2.78E-04	-5.52E-05	5.78E-07	-1.98E-07	-5.06E-03
		D*	**-4.34E-02**	**-1.41E-08**	**-1.15E-03**	**-3.74E-04**	**-1.79E-04**	**-9.33E-08**	**-2.36E-04**
LVL	**Re-use**	**C**	1.58E+00	1.05E-09	2.17E-05	4.40E-06	8.96E-07	8.94E-09	4.12E-05
		D	-3.37E-01	-6.96E-08	-1.96E-03	-6.84E-04	-2.04E-04	-1.69E-06	-3.24E-03
	Recycle	**C**	1.59E+00	3.20E-09	1.37E-04	2.54E-05	3.27E-06	1.30E-08	1.24E-04
		D	-1.22E-01	-1.49E-08	-7.90E-04	-2.96E-04	-1.06E-04	-5.55E-07	-9.71E-04
	Recover	**C**	1.79E+00	5.96E-09	2.48E-04	1.14E-04	4.78E-06	5.88E-08	2.79E-04
		D	-8.22E-01	-6.23E-08	-5.96E-04	-2.73E-05	-6.11E-05	-1.69E-07	-6.68E-03
		D*	**-4.34E-02**	**-1.41E-08**	**-1.15E-03**	**-3.74E-04**	**-1.79E-04**	**-9.33E-08**	**-2.36E-04**
	Landfill	**C**	2.03E+00	6.66E-09	2.45E-04	2.77E-03	1.07E-04	3.34E-08	2.65E-04
		D	-3.47E-02	-4.35E-09	-2.53E-05	-4.37E-06	-1.98E-06	-1.84E-09	-2.69E-04
CLT	**Re-use**	**C**	1.56E+00	1.35E-09	2.88E-05	1.76E-05	4.24E-07	7.27E-10	8.62E-05
		D	-1.68E+00	-1.60E-08	-4.83E-04	-7.21E-04	-1.41E-05	-7.81E-08	-8.95E-04
		D*	**-1.28E-01**	-1.60E-08	-4.83E-04	-7.21E-04	-1.41E-05	-7.81E-08	-8.95E-04
	Recycle	**C**	1.62E+00	2.83E-09	1.04E-04	3.26E-05	2.27E-06	2.16E-08	1.58E-04
		D	-8.45E-01	-1.08E-08	-4.18E-04	-1.77E-04	-3.88E-05	-1.48E-07	-4.62E-04
		D*	**-6.77E-02**	-1.08E-08	-4.18E-04	-1.77E-04	-3.88E-05	-1.48E-07	-4.62E-04
	Recover	**C**	1.64E+00	2.86E-09	1.66E-04	1.01E-04	1.33E-05	3.16E-08	1.92E-04
		D	-7.85E-01	-4.15E-08	-4.13E-05	1.22E-05	-8.70E-07	-2.22E-07	-5.50E-03
		D*	**-4.34E-02**	**-1.41E-08**	**-1.15E-03**	**-3.74E-04**	**-1.79E-04**	**-9.33E-08**	**-2.36E-04**

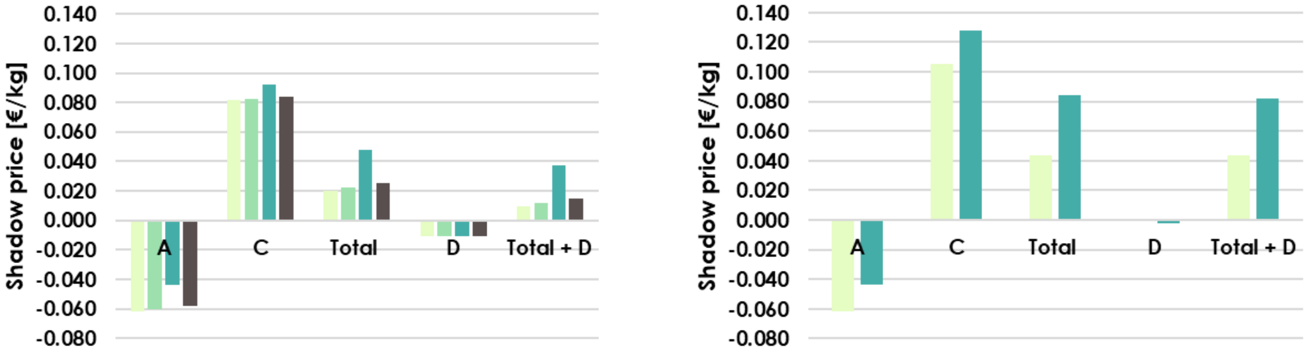
3.6.4. Overview of aggregated data

The total environmental impact of timber products is determined by summing the individual LCA stages, see Figure 3.23 for the results. Sawn timber has the lowest overall environmental impact due to the lack of adhesives in the product and a smaller burden of the production process. Glulam and CLT have the same order of magnitude per kilogram material since the production process is similar. LVL has the highest environmental impact as a result of the more energy-intensive manufacturing process compared to Glulam and CLT. Overall, the environmental impact of timber products deviates due to different production processes. The carbon storage in LCA stage A and emission in stage C is constant per kilogram material for the compared timber products.



(A) Re-use

(B) Recycle

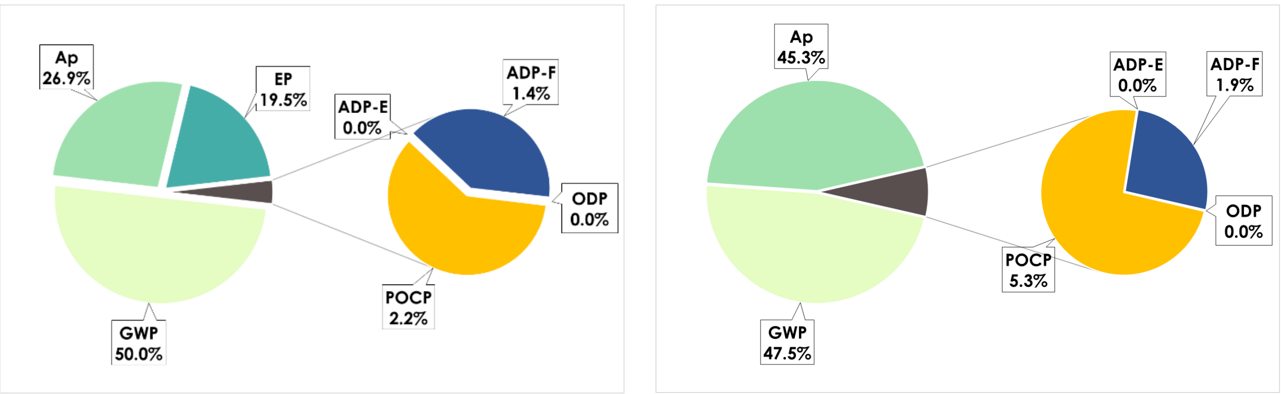


(C) Energy/Thermal recovery

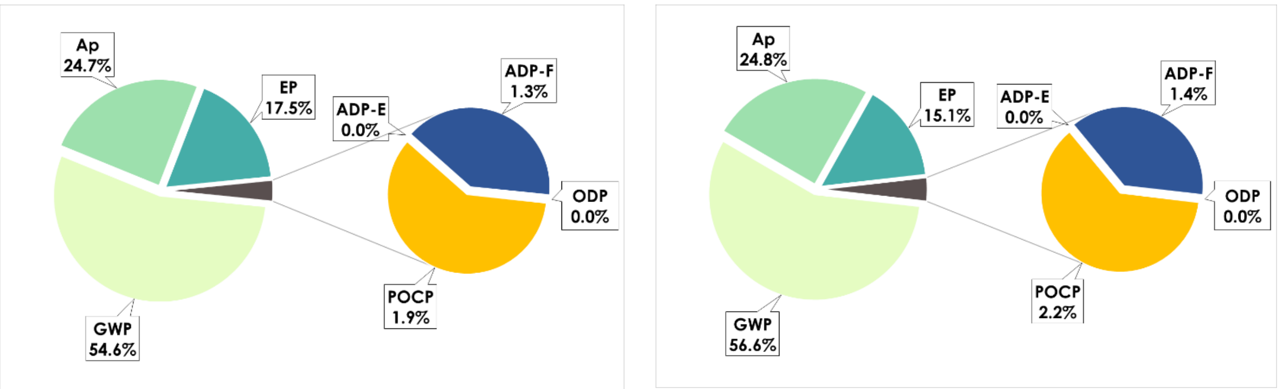
(D) Landfilling

Figure 3.23: Aggregated data of timber EPDs

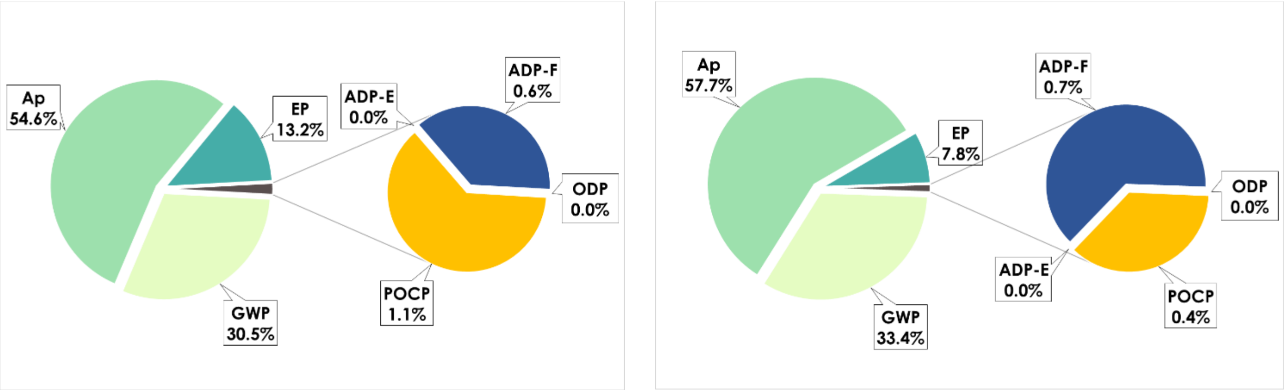
The largest contributors to the shadow price are the global warming potential, acidification potential and eutrophication potential regardless of the end of life scenario, see Figure 3.24.



(A) Total (Re-use) (B) Total + D (Re-use)



(A) Total (Recycling) (B) Total + D (Recycling)



(A) Total (Recovery) (B) Total + D (Recovery)

Figure 3.24: Contribution of environmental impact categories for CLT

3.6.5. Comparison of EPDs and NMD

The results from the EPD data analysis differ significantly with the available data in the NMD. The NMD only specifies data for sawn timber and Glulam. CLT panels are derived from the Glulam data and LVL is absent from the database. Figure 3.25 shows the differences in the environmental impact categories (excluding LCA stage D) for Glulam. A 55% reduction of the shadow price is obtained for the EPD data compared to the NMD, based on the seven impact categories which are quantified for both the EPDs and the NMD.

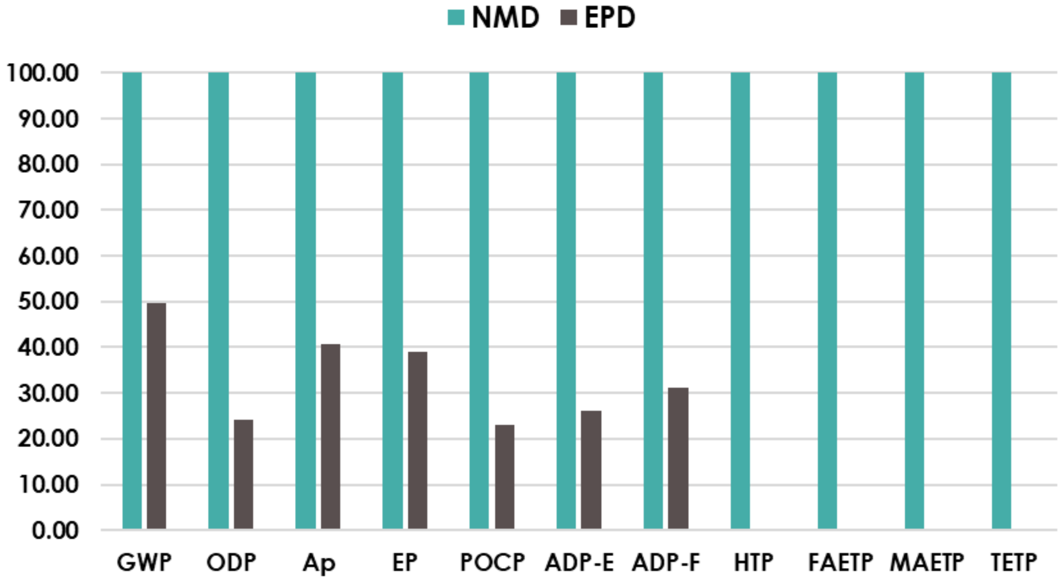


Figure 3.25: Relative fraction of environmental impact categories to the shadow price NMD versus EPD

An important difference is that the NMD provides data for the human toxicity potential (HTP) and the three ecotoxicity potentials (see also section 3.3.3). By evaluating these impact categories based on the NMD data, the shadow price is increased by 62% (53% by HTP, 9% by the total of ecotoxicity potentials). None of the timber EPDs specify data for these additional impact categories and are therefore not directly verifiable. By evaluating an EPD for a wall assembly, which partly uses Spruce sawn timber, an estimation of the human toxicity potential is possible by extracting the specific data related to the timber parts. This results in an HTP which is 81% lower compared to the NMD data. Thus, using the NMD data for these four impact categories is a conservative approach. See Appendix B.6 for the HTP verification.

3.6.6. Comparison of timber, steel and concrete

A comparison of timber with steel and concrete is made in Figure 3.26. These results include the seven environmental impact categories, which are consistently declared for both European EPDs and the NMD (see section 3.3.3).

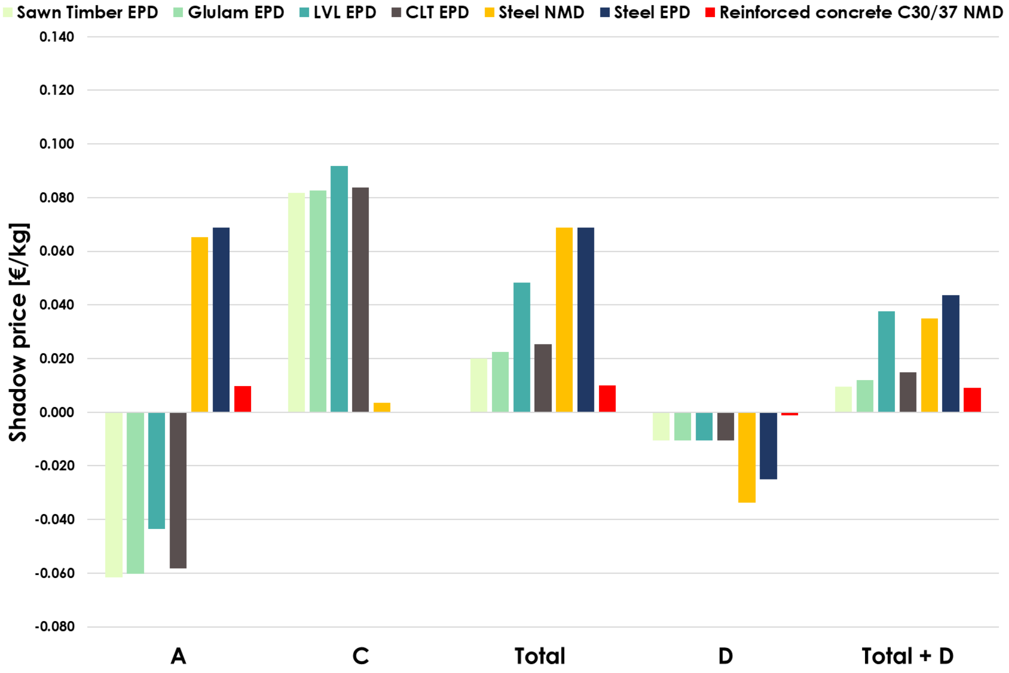


Figure 3.26: Environmental impact comparison of timber, steel and reinforced concrete

Structural steel data in the NMD is based on an outdated EPD by MRPI. The data has not been updated since its end of validity in January 2018. For the end of life scenario, it assumes 49% re-use and 51% recycling. This is inconsistent with the actual re-used fraction which is approximately 5-10% as found in literature [63], resulting in an overestimation of the benefits beyond the life cycle. Another deviation from current practice is the assumption for the fraction of recycled steel as input material. The NMD data uses 90% recycled steel and 10% virgin steel, while only 40% recycled steel is available in the market mix [62]. Correct assumptions for fractions of input material and end of life scenarios are available in EPDs and is therefore included in Figure 3.26.

Concrete data in the NMD is based on 75% blast furnace slag (CEM III) and 25% Portland cement (CEM I). For the end of life scenario 99% is assumed to be recycled and 1% landfilled. The data from the NMD has a comparable range when verified with literature and concrete EPDs with similar fractions of CEM III [104-106]. The data presented in Figure 3.26 assumes 100 kg of reinforcement per m^3 of concrete. Required formwork to cast the concrete is excluded from this data.

The default presentation of the data in the Netherlands is per kilogram material, resulting in a relatively low impact for concrete compared to timber due to difference in density. European EPDs typically present the data of timber and concrete per cubic meter, while steel data is presented per metric ton. The conversion of the environmental data from kilogram to cubic meter results in a relative increase of approximately 5 times for reinforced concrete compared to timber. The conversion to cubic meter is not representative for the comparison of steel since it is not applied as massive sections, but as slender structural profiles instead.

The data in Figure 3.27 extracts the global warming potential specifically for the manufacturing stage (LCA stage A1-A3) of timber and concrete, excluding the carbon sequestration of timber. The average impacts, as depicted by the bars in the chart, are significantly lower for timber products compared to reinforced concrete. The timber manufacturers with the highest contribution are also lower than the average reinforced concrete from the NMD, see the minimum and maximum variation range in Figure 3.27. The NMD data for Glulam, which is also used as base data for CLT in the NMD, has a 1.7 times higher impact than the highest manufacturer and 2.8 times higher than the average.

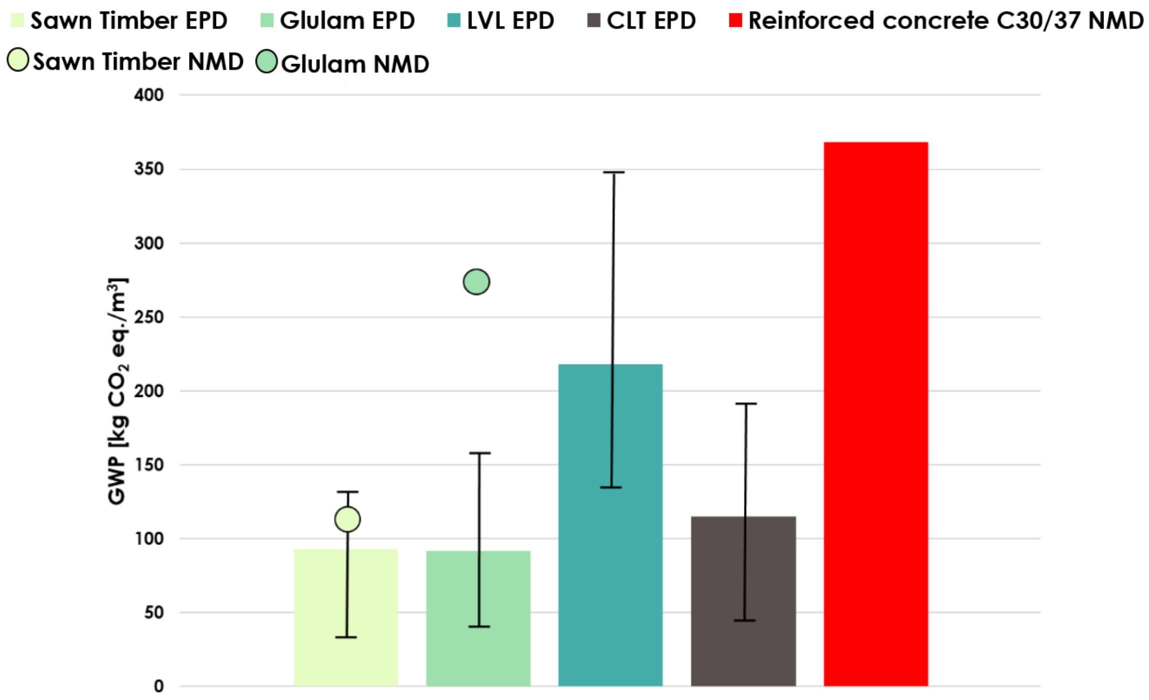


Figure 3.27: Global warming potential comparison of timber and concrete manufacturing (excluding carbon sequestration)

To make an accurate comparison for the environmental burden of structures it is crucial to evaluate the building as a whole, instead of only comparing the impact of materials per declared unit. Strength and stiffness variation of the materials and type of cross sections (massive or structural profiles) are the main parameters affecting the total material use in load bearing structures and thus the environmental impact. See chapter 6 for a comparison between a concrete case study and timber alternative.

3.7 Critical review

The previous sections of this chapter are reviewed, resulting in conclusions and recommendations.

NMD data and MPG methodology

The MPG calculation uses a ‘black box’ approach to quantify the environmental impact of buildings; by specifying input, the output score is obtained without questioning of the underlying data source (NMD database). Therefore, it is crucial for users to have correct and up to date data. In section 3.6.5 it was shown that the timber data in the NMD differs significantly from EPDs, resulting in too high impacts for timber products. By studying the data further, the timber NMD data proved to be derived from generic unverified processes (category 3 data). All category 3 data is increased by 30% to account for possible overlooked burdens [68]. Furthermore, section 3.6.6 showed that the NMD data for structural steel is outdated for over two years and uses inaccurate scenarios. These deficiencies raise serious concerns for the validity of the results, leading to incorrect conclusions.

Since the MPG methodology is prescribed by the government to obtain the required building permits, it should have sufficient reliable data sources. Nevertheless, the market is responsible for providing the data. It is costly to fund an LCA trajectory and include in the NMD, and therefore, not feasible for smaller manufacturers. For biobased products specifically, another issue is present. Because the Netherlands has a minor commercial forestry, around 95% of structural timber is imported [107]. These foreign manufacturers quantify the environmental impact of their products with EPDs, according to the European standards. The problem arises that the Dutch MPG methodology prescribes four additional environmental impact categories, not quantified in the European EPDs. To include these data sources in the NMD, an additional costly LCA trajectory is required. These manufacturers do not justify the costs, since the Netherlands currently has a relatively small structural timber market. This problem leads to a vicious circle in which the environmental impact of timber structures is overvalued; resulting in no increased market share since the traditional building materials score in most cases similar or better; resulting in no effort by manufacturers to include data in the NMD; and therefore the environmental impact still being overvalued.

Conclusions and recommendations:

- In the current situation, the interests to provide accurate and up to date data are conflicting between the government and the market. If the government prescribes the MPG methodology, they should be responsible for sufficient and reliable data, not the market.
- Better harmonization between the MPG methodology and European standards regarding environmental impact categories is beneficial to obtain more reliable data sources.

Issues with end of life scenarios in EPDs

Having looked at the end of life scenarios in EPDs in section 3.6.3, two errors in the assumed end of life scenarios can be observed depending on the programme operator. The first error is related to the modelling of re-use and recycling scenarios. By incorrectly modelling of the biogenic carbon content beyond the life cycle, an overestimation of the benefits occurs. The second error relates to the assumptions for energy and thermal recovery. It is assumed that the biomass substitutes fossil fuels predominantly. This is not allowed in the Dutch MPG methodology, stating that rules for material equivalency should be applied, i.e. biomass replacing biomass, not fossil fuels.

Another problem can occur when comparing the environmental burden of the original end of life scenarios in EPDs, see Table 3.8. Both re-using and recycling of timber scored worse than an energy recovery scenario. Observation of these results could lead to the incorrect conclusions that it is better to incinerate at the end of life than re-use or recycle. This has to do with the fact that only a single end of life scenario is considered. Energy recovery is still possible after a re-use or recycle scenario, yet excluded from the latter scenarios.

Conclusions and recommendations:

- Results of the data in LCA stage D is highly dependent on the interpretation of the LCA practitioner and should, therefore, be carefully analysed for assumed scenarios and comparability with other EPDs.
- LCA stage D contains data for an uncertain forecasted scenario. Hence, it should never be aggregated with data from other LCA stages but considered separately.

Crediting of carbon sequestration

The additional benefit of carbon sequestration (storage) is excluded in LCA, since LCA has a static reference timeframe on the building scale (meso-level), i.e. the biogenic carbon content is neutral over a building's lifespan. However, the carbon sequestration can be accounted for at the macro-scale by using DLCA, as discussed in section 3.4.2. Material passports could be used to monitor the increase in carbon sequestration in the timber buildings and structures of the industry as a whole. Using this approach, the benefits can be attributed to timber buildings until the market converges to the point where timber buildings are replaced by timber buildings and no additional benefits of carbon sequestration occur, as depicted in Figure 3.8.

Conclusions and recommendations:

- Carbon sequestration benefits are correctly excluded from LCAs on the building scale.
- By monitoring the total increase in timber pool across the industry, using material passports, the benefits of carbon sequestration can be attributed until market saturation. This results in an additional incentive for the biobased economy.

Re-use barriers

Barriers for a demountable re-use strategy have been identified in a study by van Maastrigt, resulting in six general barriers: the absence of client demand and the industry's resistance to innovate (attitudinal barrier); the lack of supporting data for potential risks and benefits of the investment (financial barrier); low awareness and responsibility regarding the structural sustainability (structural barrier); lack of facilities and infrastructure facilitating re-use (operational barrier); no guaranteed performance resulting in liability issues due to the lack of certification (technological barrier); the absence of incentives to strengthen the market position of re-used elements (legislative barrier) [63].

The current MPG requirement is easily achieved for traditional buildings without the need for additional measures. This creates the attitudinal barrier, simply because there is no need to innovate. By increasing the MPG requirements, as shown in Table 3.2, the government forces the building sector to lower the environmental burden. Effectively removing the attitudinal barrier and stimulating the circular economy, biobased economy, and innovations to develop materials with a low environmental burden.

Having looked at the present state of the circular economy in the building sector of the Netherlands in section 3.2, it showed the development of various initiatives and platforms such as material passports and marketplaces. Platform CB'23 develops a uniform framework, harmonizing the different initiatives. When these initiatives are successfully implemented on a larger scale, the risk of investment in circular solutions reduces since the investment represents a value at the end of life span. Thus, reducing the financial and operational barrier.

The main problem of the circular economy in the building sector is related to the residual properties, actual lifespan, and certification of re-used elements, forming a technological barrier. For timber products specifically, various studies recommend a common practice to deal with residual material properties, as discussed in section 3.5.3. These rules are derived from test samples, based on a one-time re-use. However, no agreed-upon rules exist for re-grading of used materials. By consulting professionals, involved in projects utilizing reclaimed elements, it was found that currently extensive physical testing in laboratories is required to prove the equivalent safety to new structures.

The general perception is that a CO_2-tax will change the market position of timber products compared to steel and concrete, creating an incentive to use biobased products (legislative barrier). Even though the carbon sequestration is not counted as previously discussed, the CO_2 emissions of timber products are lower than steel and concrete. However, when reviewing the CO_2-tax which the government will implement in 2021, it becomes clear that there will be no incentive to build bio-based. The tax is based on the European Emission Trading System (ETS), meaning that a benchmark is set by the 10% most efficient firms within their specific sector in Europe. All CO_2 emitted above the benchmark will be taxed and the benchmark will be gradually reduced over time [1, 108]. Since the benchmark is set per sector it will stimulate environmental impact reduction per sector, not changing market position between sectors. For instance, both the concrete and timber sector are stimulated to reduce their environmental impact to their respective benchmark, though not to each other.

Other types of incentives, promoting bio-based products, are increasing the previously discussed MPG requirement (by lowering the value). Alternatively, the suggested incentive for carbon sequestration in buildings can reduce the legislative barrier. This method is successfully implemented in the German state Hamburg [109].

Conclusions and recommendations:

- Various barriers for the circular economy in the built environment are present limiting the transition, being: attitudinal, financial, structural, operational, technological and legislative barriers.
- Increasing the MPG requirement removes the attitudinal barrier, stimulating circular solutions.
- Development of a material passports and marketplaces framework reduces the financial and operational barrier by creating an infrastructure facilitating circular use in the built environment.

- Standardisation of post-use certification is required to deal with residual properties and lifespan of reclaimed elements.
- An incentive to build with bio-based materials is missing in the Netherlands. Implementation of a carbon sequestration incentive can stimulate the market position.

Biomass

The recent discussion about biomass as (sustainable) energy source results in the following perspectives: On the one hand, it is a renewable source; on the other hand, it directly emits all stored CO_2 which took years to sequester and is relative inefficient. The scale up of biomass as energy source can lead to depravation of sustainable forestry due to the potential short-term economical gain, leading to additional deforestation.

By using timber in durable structural elements, the managed forest are regrown to their original level by the time the elements are released (section 3.4.3). As long as sustainably certified wood is used in the products the preservation of the forests is guaranteed. Contrary to biomass, this gives long term value to forests. After the intended use and possible cascading strategies (e.g. re-use and recycling), the elements will be used as biomass for energy and thermal recovery. However, excluding the negative aspects of direct use as biomass and being the better alternative to landfilling.

Conclusions and recommendations:

- Sustainability of biomass as energy source is questionable when directly incinerated after harvesting of the wood, possibly leading to additional deforestation due to short term economical gain.
- After a durable lifespan of bio-based products, energy and thermal recovery is a sustainable option as long as sustainably certified wood is used.
- A distinction should be made between biomass directly harvested from forests and biomass resulting as waste from durable bio-based products.

4

Structural parametric modelling of variant study

In this chapter, a description is given of the design process, characteristics, and assumptions of the variant study. The goal of this part is to obtain realistic material quantities which are used as input for Chapter 5. The level of detail is limited to the preliminary design phase, using hand calculations and manufacturers data to verify the structure. The models have been checked by cross-referencing results with a detailed design in Section 4.6 to verify the plausibility of the obtained material quantities.

4.1 Variants

The choices for the studied variants in this chapter are based on the analysis of reference projects from Chapter 2. The two main typologies, post & beam and mass timber, form the basis of the study. They are studied at 30, 50 and 70 meters high, which is within the current height domain of multi-storey timber structures.

For the floor systems the following options are studied: an LVL hollow box floor system and two types of CLT floor slabs, using either a dry screed or wet screed floor finishing.

Additionally, the impact of the two fire safety strategies is analysed by designing alternatives with gypsum encapsulated and exposed timber load-bearing structures. This is solely studied at a height of 50 meters for both the post & beam and mass timber typologies.

The cascading scenarios as discussed in Section 3.5.3 are included in the variant study, taking into account the effect of a flexible floor plan scenario for the post and beam typology and re-use scenario for both the post & beam and mass timber typology. Again, this is solely studied at a height of 50 meters.

See Figure 4.1 for an overview of the studied variants.

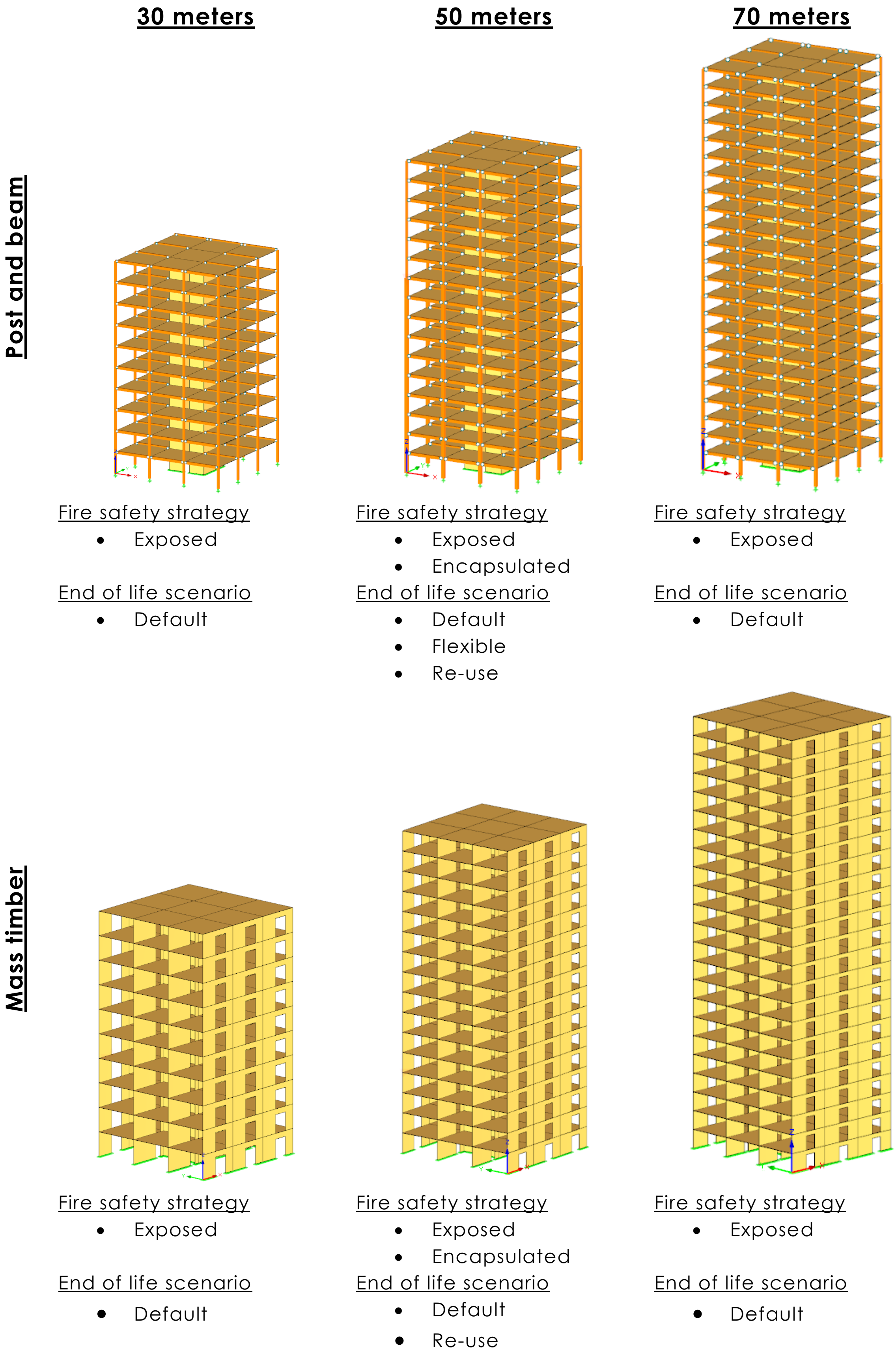


Figure 4.1: Overview of variants based on main typologies

4.2 Workflow

It was chosen to develop a parametric model to create the variants, the main reason being to speed up to the process of generating the models and going through design iterations. Dynamo by Autodesk is used as parametric environment for which the model data can be exported to the finite element software RFEM using the by Arcadis inhouse created Dynamo – RFEM tool.

The workflow is presented in Figure 4.2. Firstly, the model data is generated in Dynamo, after which the model data is exported to RFEM. In RFEM a linear static analysis is run. Using the output of this analysis, the structure is verified using hand calculations. When the design iteration satisfies the criteria for structural design, the material quantities are used to perform the life cycle assessment.

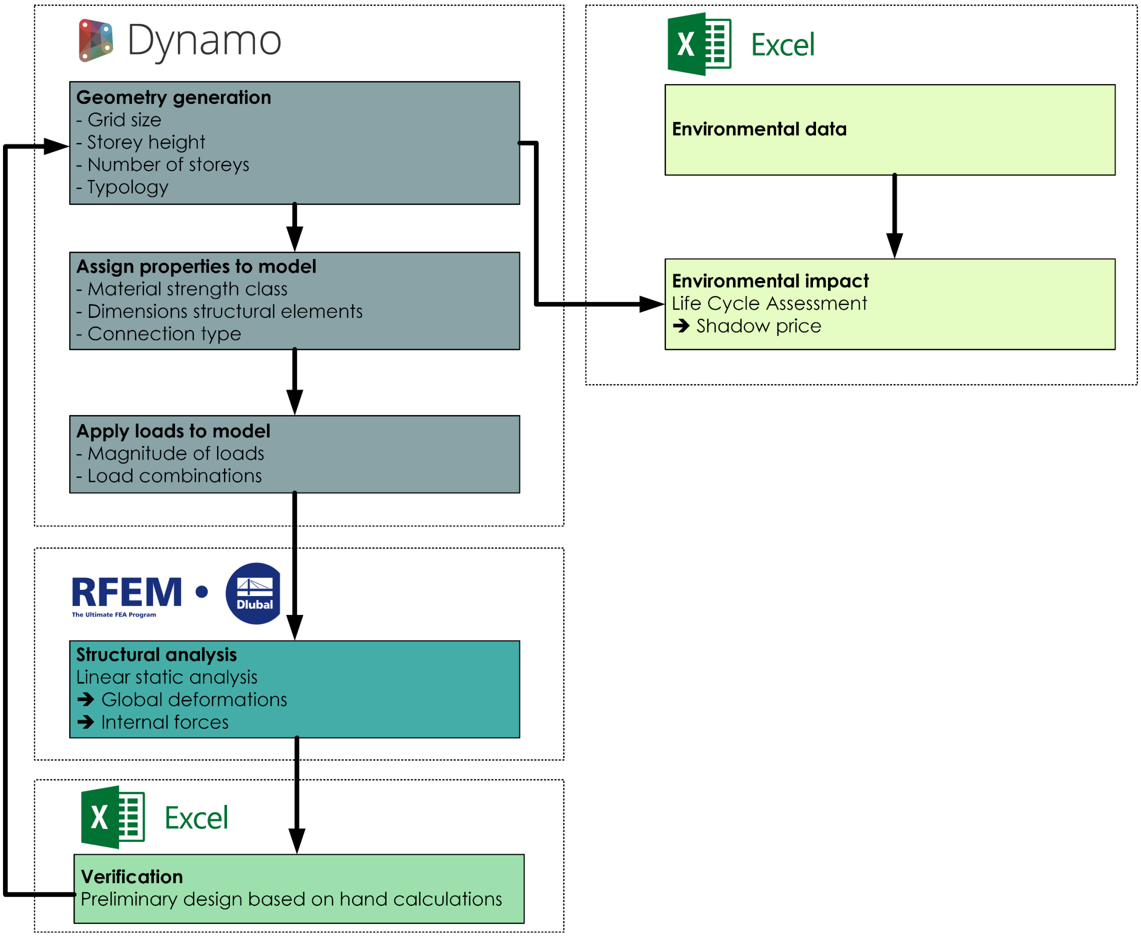


Figure 4.2: Graphical representation of workflow

4.3 Geometry of variants

Both the post & beam and mass timber variants utilize a central core as stability system. Besides the stabilizing core, the mass timber variants also gain stability by shear walls in one direction. Other stability systems, as discussed in Section 2.2, are only considered if the core proves to be insufficient to reach the lateral deformation criteria. This proved to be unnecessary, which is also according to the results of a study by van Rhijn that analysed the ultimate height limits of various stability systems [15].

Floorplans of several reference projects are analysed to estimate the minimum core size, which is based on the number of stairs, elevators and vertical ducting in the core. Figure 4.3 shows the results for the reference projects within the height range of the variant study.

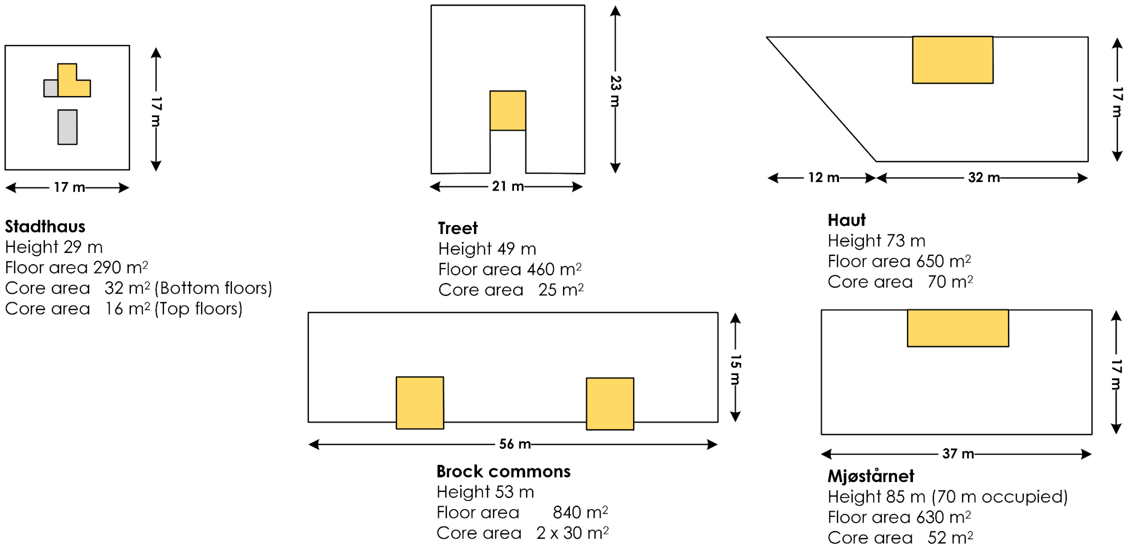


Figure 4.3: Core sizes in relation to floorplans of reference projects

The minimum core size for the variants are shown in Table 4.1. These values are also used for the grid spacing. Therefore, they are multiples of 0.9 meter, which is a common measurement in the Netherlands for floorplan grids. To determine the maximum core size, a rentable net floor area of at least 80% is used.

Table 4.1: Minimum core size

Variant height [m]	Minimum core size [m]
30	5.4 x 5.4
50	6.3 x 6.3
70	7.2 x 7.2

When increasing the building height, the members are designed in zones to account for the decreasing gravity loads towards the top. See Figure 4.4 for an impression of the geometry of the variants.

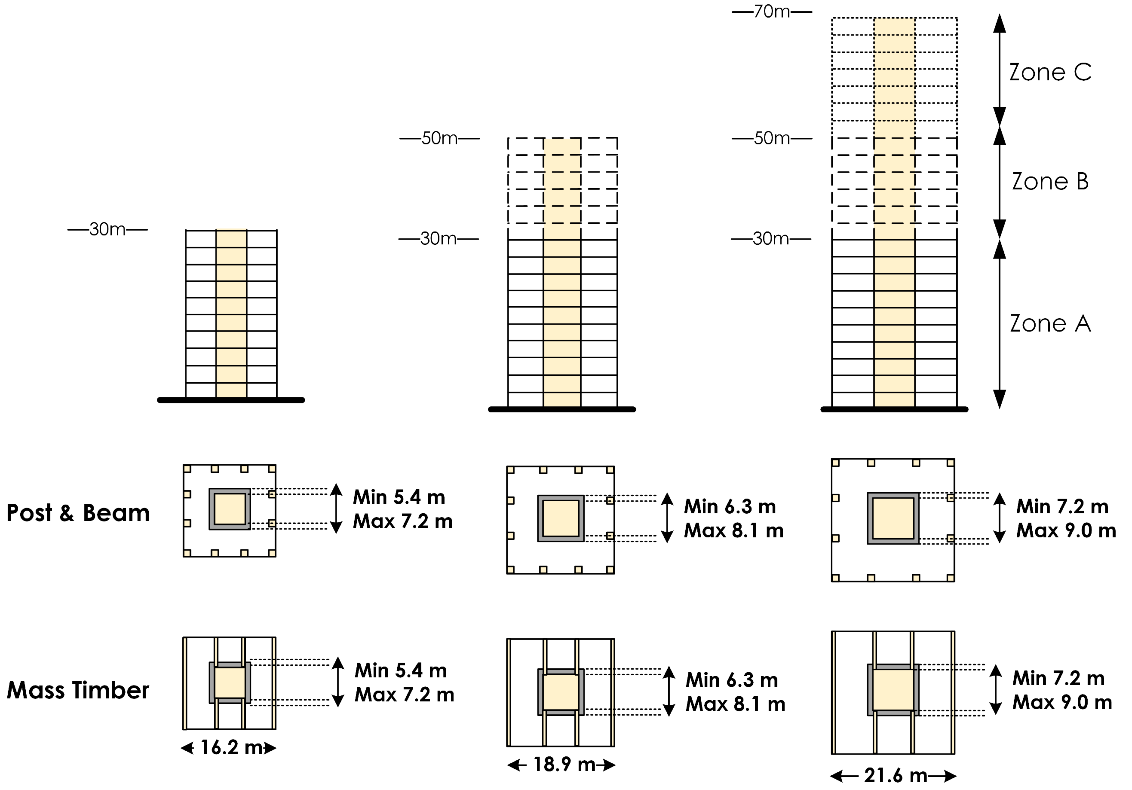


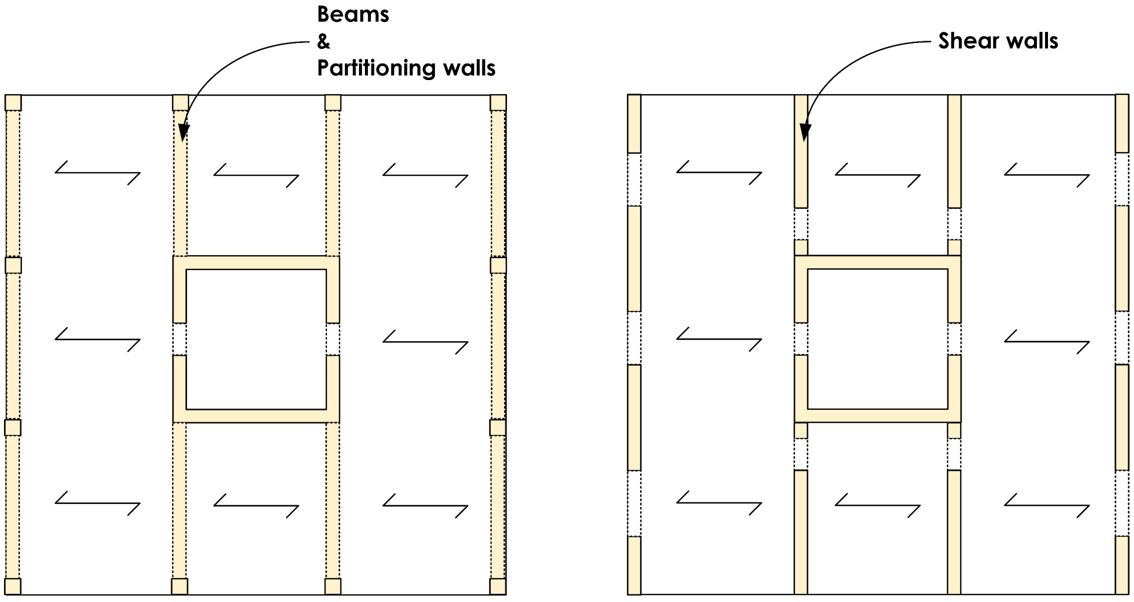
Figure 4.4: Geometry of variants

4.4 Structural design

As stated in the introduction of this chapter, the goal of the variant study is to obtain realistic material quantities. Therefore, the scope of this part has been set to the preliminary design phase, using hand calculations and manufacturers data. The structural verifications are optimised for a unity check of 0.8 instead of the regular 1.0 to account for later changes when converging to the detailed design. Detailed behaviour of the connections, for instance slip, is excluded from this design phase. The members are simply supported, using hinged nodes and line supports. Therefore, frame action does not contribute to the global stability. The stabilizing cores are assumed clamped. For the structural verification, see Appendix C.

4.4.1. Floors

The floors are designed as one-way spanning, see Figure 4.5. All floors are designed using manufacturers data. The LVL hollow box floor system is designed using an online tool by MetsäWood, for the CLT floors (wet and dry screed) the structural pre-analysis tables by KLH Massivholz are used. These sources take, besides structural requirements, also comfort (vibrations), fire and acoustical requirements into account. The LVL hollow box floor system results in a significant thicker floor packet compared to the CLT floors, even when integrating the ducting within the hollow sections. For the complete floor design see Appendix C.5; the floor build-up including floor finishing is included in Appendix C.12.



(A) Post and Beam (B) Mass timber

Figure 4.5: Floorplans

The floor system with the lowest impact can be identified by analysing the environmental impact of the three floor systems, including insulation and finishing. This proved to be the CLT dry screed floor system and is therefore applied to all the variants, see Section 5.3.1 for the results and interpretation of the floor analysis.

4.4.2. Walls

The main difference between the post & beam and mass timber variants are the walls. The post and beam typology uses columns and beams for the load transfer. Resulting in an open floorplan, which must be divided by partitioning walls. The mass timber typology has, besides partitioning walls, also load-bearing walls in one direction, see Figure 4.5.

To correctly account for the difference in the LCA, the equivalent partitioning walls (i.e. partitioning walls in the post and beam typology at the location of mass timber load-bearing walls) are designed for acoustical and fire safety requirements. See Appendix C.8 for the partitioning wall design.

The shear walls and core walls have a maximum thickness of 0.5 meters according to the capabilities of the manufacturer [110].

4.4.3. Cascading scenario

The effects of the two cascading scenarios, as presented in Section 3.5.3, on the material quantities and thus the environmental impact are included in the variant study. The first cascading scenario, the flexible floorplan layout, applies to the post and beam typology. While the second scenario of re-use can be applied to both the typologies. Both scenarios are assumed to elongate the lifespan of the building to 150 years, as discussed in Section 3.5.3.

The flexible scenario is verified by increasing the reference period of the variable loads to 150 years, to account for the increased chance that the maximum load occurs during the lifespan.

Since no agreed-upon rules for re-use design and verification exists, the theoretical re-use potential is used. This can be determined using the building circularity indicator (BCI), which represents the probability that a building can be (partly) re-used as presented in a study by Backx [111]. The BCI is derived based on concepts of Madaster and Alba Concepts. See Equation (6) and Table 4.2 for the method.

$$BCI = MI * RI \tag{5}$$

In which:

$$MI\ (Material\ index) = \ 1 - LFI * F(n)$$

$$LFI\ (Linear\ flow\ index) = \frac{\%\ virgin\ material + \%\ material\ loss}{2}$$

$$F(n)\ \ (use\ factor) = \frac{0.9}{n}$$

$$n = \frac{Technical\ service\ life}{Reference\ service\ life}$$

$$RI\ (Releasability\ index) = CT * CA$$

$$CT\ = Connection\ type$$

$$CA = Connection\ accessibility$$

Table 4.2: Connection type and accessibility factors[112]

Connection type (CT)		Connection accessibility (CA)	
Bolts	0.8	Accessible	1.0
Dowels	0.6	Accessible, extra actions, no damage	0.8
Screws	0.6	Accessible, extra actions, repairable damage	0.4
Nails	0.6	Accessible extra actions, irreparable damage	0.1
Glue	0.1	Inaccessible	0.1

Using this method, the additional required material per re-use cycle can be determined based on the probability that building parts cannot be re-used. To reach the lifespan of 150 years, two re-use cycles are required based on the default 50-year design lifespan. In the first cycle, the fraction virgin material is 100%; for the second cycle this fraction is based on the output results of the first cycle.

For CLT structures, the most common method is to apply screws or nail plates for the connections. Other possibilities are glued in rods or slotted-in steel plates using bolts or dowels, see Figure 4.6. Besides the traditional connection types, an innovative joint is developed for CLT panels by the manufacturer Rothoblaas. This connection is specifically designed for demountable structures using bolted connections, see Figure 4.7. For the re-use scenario, a demountable connection is assumed using bolted connections.

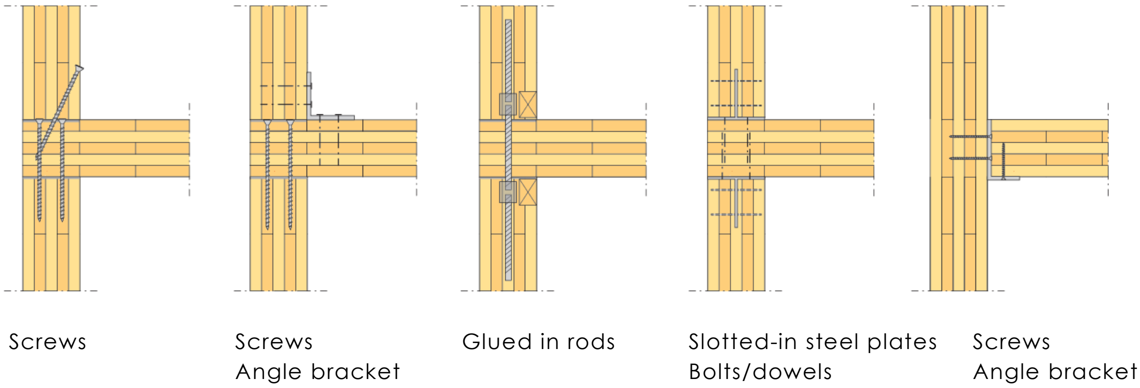


Figure 4.6: Examples of connection types

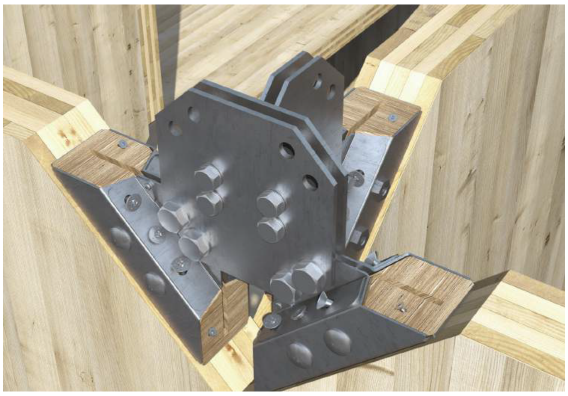


Figure 4.7: X-rad by Rothoblaas [113]

Table 4.3 presents the derivation of the building circularity indicator for both re-use cycles. Resulting in the following factor to determine the additional required material to reach 150 years using two re-use cycles:

$$Factor\ for\ additoinal\ material\ re-use\ scenario: \frac{1}{0.68 * 0.76} = 1.9$$

Table 4.3: Building circularity indicator for re-use cycles

First re-use cycle		Second re-use cycle	
CT	0.8	CT	0.8
CA	1.0	CA	1.0
n	150/50 = 3	n	150/50 = 3
F(n)	0.9/3 = 0.3	F(n)	0.9/3 = 0.3
LFI	(1-0)/2 = 0.5	LFI	(**0.32**-0)/2 = 0.16
MI	1-0.5*0.3 = 0.85	MI	1-0.16*0.3 = 0.95
BCI	0.85*0.8 = **0.68**	**BCI**	0.95*0.8 = **0.76**

4.5 Fire safety design

Two variants for the fire safety design are analysed: the exposed fire safety strategy and the gypsum encapsulated strategy. The first uses the reduced cross-section method from the Eurocode to account for structural safety during fire, see Appendix C.4.2. The latter uses the same method to determine the minimum thickness for which the wood itself will not char.

For larger element sizes, the exposed fire safety strategy does not increase the dimensions of the structural elements since it is not governing. In these cases, the encapsulated strategy will have a higher environmental impact by default since protective material is added without the reduction of material in the structural elements. However, this can be a design choice or requirement by the client to avoid (irreparable) damage to the building.

Besides the fire resistance of the load-bearing structure, the reaction to fire needs to be verified. The Building Decree specifies a fire class of at least D for living areas and at least B for escape routes. Additionally, a smoke reduction class of S2 is specified. The timber structural elements as used in this study have the following class: D-S2,d0 according to standard EN 14080 [114]. Therefore, additional measures are required for escape routes (i.e. the core). For the encapsulate fire safety strategy, the gypsum fireboards comply with the requirement of at least fire class B. The exposed fire safety strategy needs a fire-proofing coating. The single-component transparent fire-protection coating ‘Amotherm Wood WSB’ by AMONN is used since environmental data of the product is available. This varnish is rated class B-s1,d0 when applying 0.5 kg/m^2 [115]. See Figure 4.8 for the core surface to which the product is applied.

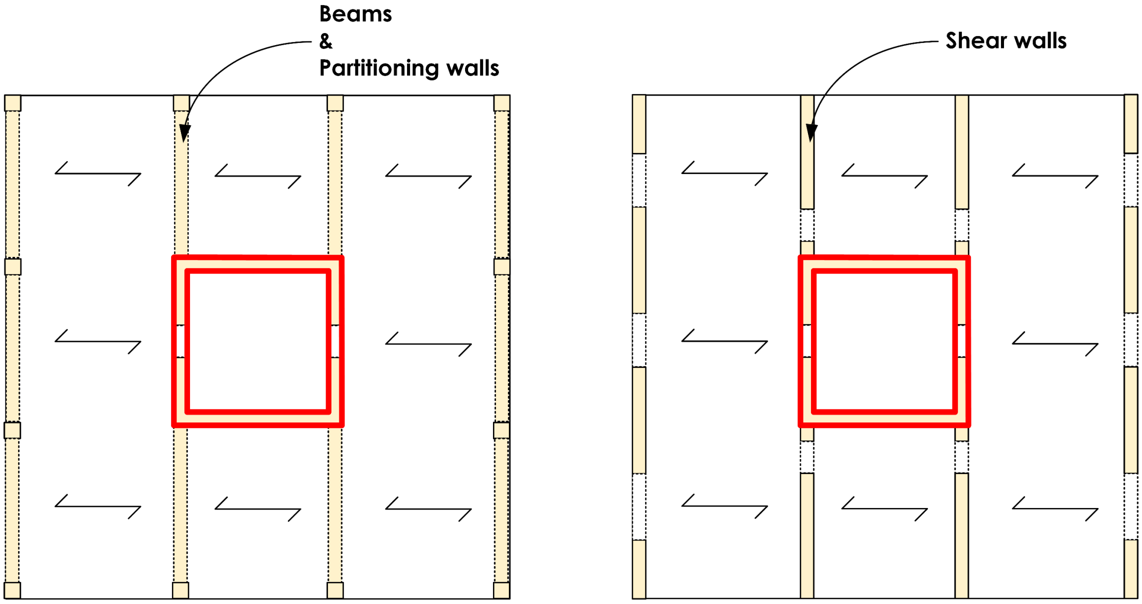


Figure 4.8: Fire protective coating to core

4.6 Model verification

Results are verified in Appendix C.11 by inputting the geometry of a detailed design in the model of this study. Relevant comparisons are the global lateral deformation, which is in most cases critical for timber structures, and the obtained material quantities. The detailed design includes modelling of connection behaviour and specifies the total steel mass of the connections. The mass is used in the next chapter to estimate the environmental impact of connections.

The same verification procedure from this variant study (described in Appendix C) is used to check the geometry of the detailed design. It results in a similar magnitude of material quantities, which are all higher than the detailed design. Therefore, the preliminary design verification is representative to obtain realist material quantities which are on the conservative side with a margin of 15%.

5

Life Cycle Assessment of variant study

In this chapter, the process and methodology of the LCA variant study are described and the results for the environmental impact discussed. For more information about the LCA framework, see Section 3.3.

5.1 Goal and scope definition

The goal of this LCA study is to determine the environmental impact of the variants, as described in Chapter 4. A comparative LCA using the fast track LCA method is performed to identify the differences between the two main timber typologies (post & beam and mass timber), different floor systems, fire safety strategies, effects of cascading scenarios and the relative contribution of the different elements to the total environmental impact of the variants.

5.1.1. Functional unit

The functional unit is described as residential buildings of the same size at the height of 30, 50 or 70 meter; with an energy and thermal recovery end of life scenario for a reference service lifespan of either the default 50 years or 150 years using cascading scenarios; which comply with the structural, acoustical and fire safety performance as described in Chapter 4 and Appendix C.

This includes:

- Cores
- Load-bearing walls (mass timber)
- Equivalent partitioning walls and interior façade leaves, see Section 4.4.2 (post and beam)
- Beams (post and beam)
- Columns (post and beam)
- Floors and floor finishing
- Fire-resistant materials (if applicable)
- Foundation

This excludes:

- Installations
- Façades
- Roof finishing
- Other building elements not mentioned in the previous list

5.1.2. System boundaries

The included life cycle stages of this LCA study are shown in Table 5.1. The construction stage is excluded since the construction installation process is inconsistently declared in the used environmental data. Most data sources exclude stage A5 completely; others include packaging waste. This leads to inconsistencies in the results if included. Furthermore, the actual construction and installation process is not included by the data sources since this is project and regional specific. Based on the equivalency of the construction installation process of the variants, this stage can be excluded from the study, avoiding a complex inventory of construction processes which is highly based on assumptions.

The building products do not have a contribution to the use stage and is, therefore, not declared in the data sources. The replacement of building products which do not meet the required service life of the building (50 or 150 years) is modelled as multiple life cycles instead of including this in the use stage, see Section 3.3.1 for a further explanation of the two principles.

As stated in the functional unit, the end of life stage and impact beyond the life cycle is assumed as energy and thermal recovery scenario. In case of the flexible floorplan cascading scenario, the variants are designed for the longer lifespan. Resulting in no changes besides the extended lifespan. For the re-use cascading scenario, the theoretical re-use potential is used to quantify the additional required material after each re-use cycle as described in Section 4.4.3.

Table 5.1: Included life cycle stages

Product stage			**Construction stage**		**Use stage**							**End of life stage**				**Impact beyond life cycle**
🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟥 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟩 C1	🟩 C2	🟩 C3	🟩 C4	🟩 D
Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Refurbishment	Replacement	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Re-use Recovery Recycling

🟩 **Stage included** 🟥 **Stage excluded**

5.1.3. Methodology

Based on the results from the data analysis of timber EPDs in Chapter 3 which proved to have a significantly lower impact than the generic data provided in the NMD, it is chosen to perform the assessment based on the average data from the studied timber EPDs. This implicates that this analysis includes the minimum seven environmental impact categories as specified by standard EN 15804, instead of the eleven impact categories as prescribed by the MPG and included in the NMD.

The chosen environmental impact categories are weighted using the CML2-baseline LCIA method, as described in Section 3.3.2. The results are monetized using the Dutch shadow prices, see Table 3.1. The results are aggregated to a single shadow price representing the total environmental burden of the variants. Additionally, the results are presented in the unit euro per gross floor area per year to compare variants with different heights and lifespans. These results should not be mistaken to be valid for the MPG requirement, which has the same unit. The LCA in this chapter has four impact categories less than required for the MPG and does not include all required building components for an MPG assessment.

The energy and thermal recovery scenario for the timber environmental data in Chapter 3 is modelled according to the rules for material equivalency as prescribed in the Dutch MPG methodology version 3.0, for background on the differences see Section 3.6.3 and for the derivation see Appendix B.4.

5.2 Life Cycle Inventory

Besides the environmental data from the timber EPD data analysis, the NMD is used for the environmental data of other materials if available. The NIBE EPD application and the NMD viewer v2.3 are selected to retrieve the data. The application by NIBE contains more up to date end of life scenarios according to MPG version 3.0 and is therefore prioritized. In case both the NIBE app and the NMD viewer do not contain applicable data, EPDs are used. The selected EPDs are third-party verified and in compliance with ISO 14025 and EN 15804. For the complete overview of used data see Appendix B.7.

The material quantities of the analysed variants are included in Appendix C.12. Using this data, together with the environmental data, the Life Cycle Impact Assessment is performed. The results of the LCIA are presented in the next section.

5.3 Interpretation of results

In this section, the results of the LCA study are presented and discussed. The graphs in this section are based on the numerical LCA results from Appendix C.12.

5.3.1. Floor comparison

The environmental impact of the three analysed floor systems (LVL, CLT dry screed and CLT wet screed) for both the exposed and encapsulated fire safety strategy and the varying spans are shown in Figure 5.1.

For the exposed fire safety strategy, the LVL hollow box floor has the highest environmental impact for all spans. Even though it is the lightest floor system, using the least amount of timber due to its hollow sections. The reason for this floor type scoring the worst environmental impact is the approximately twice higher burden of LVL compared to CLT and the need for more insulation materials to meet the acoustical demands. The reduction on other load-bearing elements due to lower dead load of the floor does not weight stronger than the higher impact of the floor system itself. The benefits of LCA stage D (i.e. the difference between the total shadow price and total shadow price + D bars in Figure 5.1) is smaller for the LVL floor system compared to CLT systems because of the relatively large contribution of insulation.

The difference between the dry and wet screed floor finishes for CLT is caused by the higher environmental burden of sand cement (wet screed) than the combined wood particleboard and insulation (dry screed). Besides the environmental impact, the dry screed floor system is more straightforward to disassemble than the wet screed system leading to a higher probability of the CLT slab being reused.

The used CLT panels in this study automatically reach the fire safety requirements without the need for additional thickness according to the manufacturer. This leads to an increase of the environmental burden due to gypsum fireboards without the reduction of timber in case the encapsulated fire safety strategy is chosen. For the LVL system, an encapsulated strategy does lead to a reduction of timber, resulting in the lowest environmental impact for the largest span of 7.2 meters.

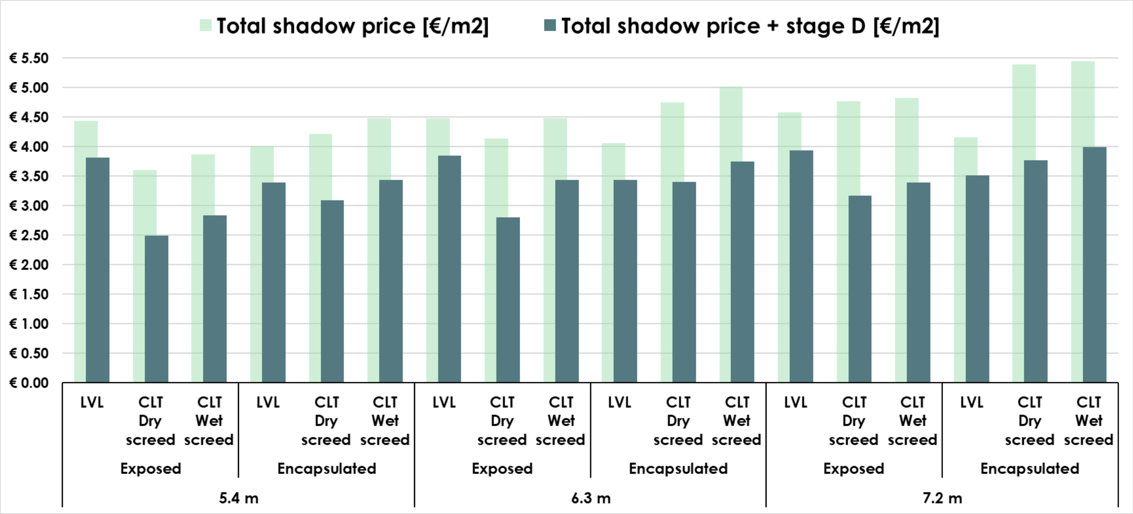


Figure 5.1: Environmental impact of floor systems [€/m2]

5.3.2. Typology comparison

Figure 5.2 and Figure 5.3 give the environmental impact and the relative contribution of the building components for the two main typologies, post & beam and mass timber, at the different heights.

For the default design lifespan of 50 years, the mass timber variants score marginally better (maximum of 5% difference) than the post and beam variants. The main difference between the two, are the contribution to the global stability of the timber shear walls where the equivalent partitioning walls in the post and beam variants do not contribute.

Figure 5.3 presents the normalised results for which the difference between the heights can be observed. The difference in environmental impact between the lowest and highest variants are 17% in favour of the lower variants. For higher timber structures, the global stability becomes critical, leading to a higher contribution of stabilizing elements. Furthermore, the contribution of the floors increases for higher variants. This effect can be related to the increased floor spans, leading to thicker floor packages which have a relatively higher contribution than the increased gross floor area.

For all variants, regardless of typology and height, the floors contribute the most (50-55% of total environmental impact) followed by walls (20-25% of total environmental impact) and foundation (13-20% of total environmental impact).

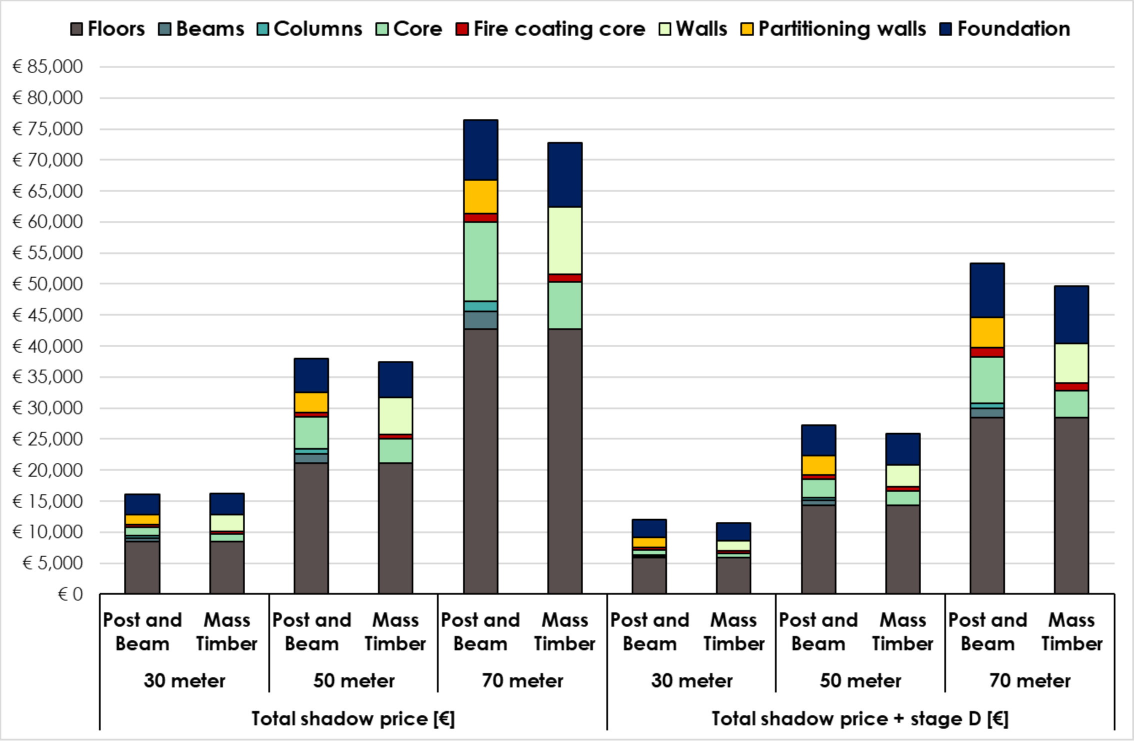


Figure 5.2: Environmental impact of variants[€]

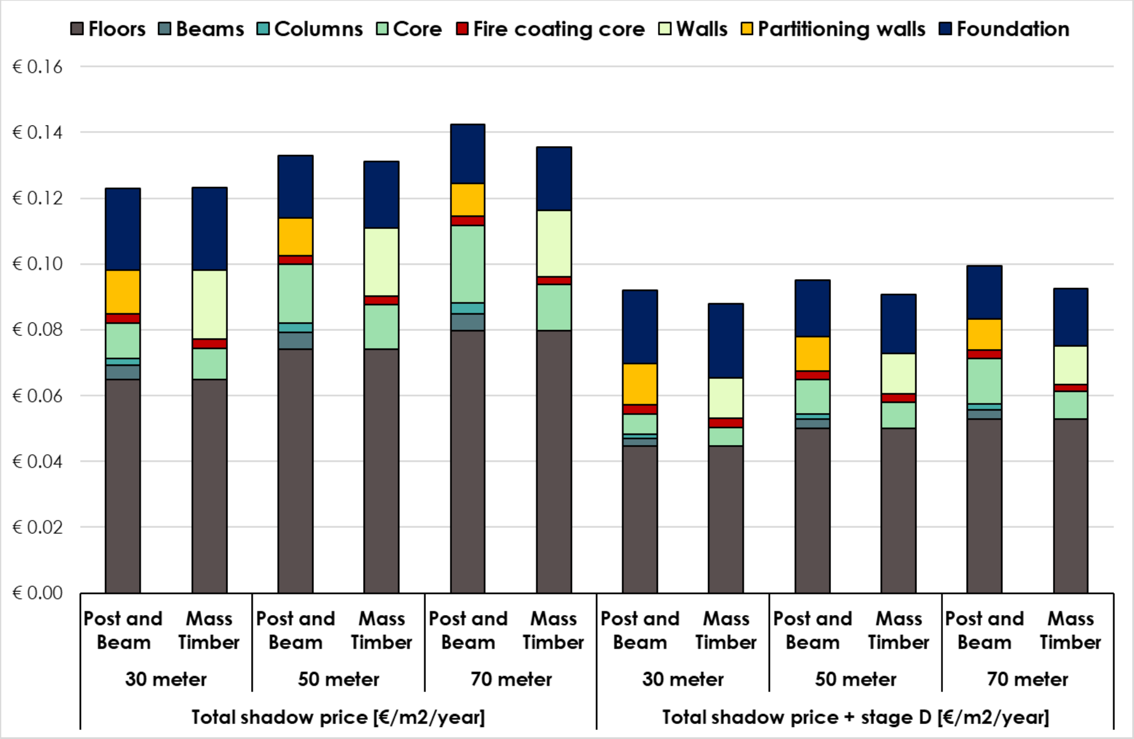


Figure 5.3: Environmental impact of variants [€/m²/year]

5.3.3. Fire safety strategy comparison

Figure 5.4 and Figure 5.5 give the comparison between the exposed and encapsulated fire safety strategies at the height of 50 meters and their relative contribution of the building components.

The choice for an encapsulated fire safety strategy increases the environmental impact of the post & beam and mass timber typology by 11% and 13% respectively. This is caused by the additional impact of the gypsum fireboards. The floor, core and shear wall encapsulation have the largest contribution as can be seen in Figure 5.4 since they have the largest surface area to cover. Note that gypsum encapsulation of the floor is included directly in the floor bars of the graph, see also Figure 5.1 for the difference between exposed and encapsulate fire safety effects of the floors.

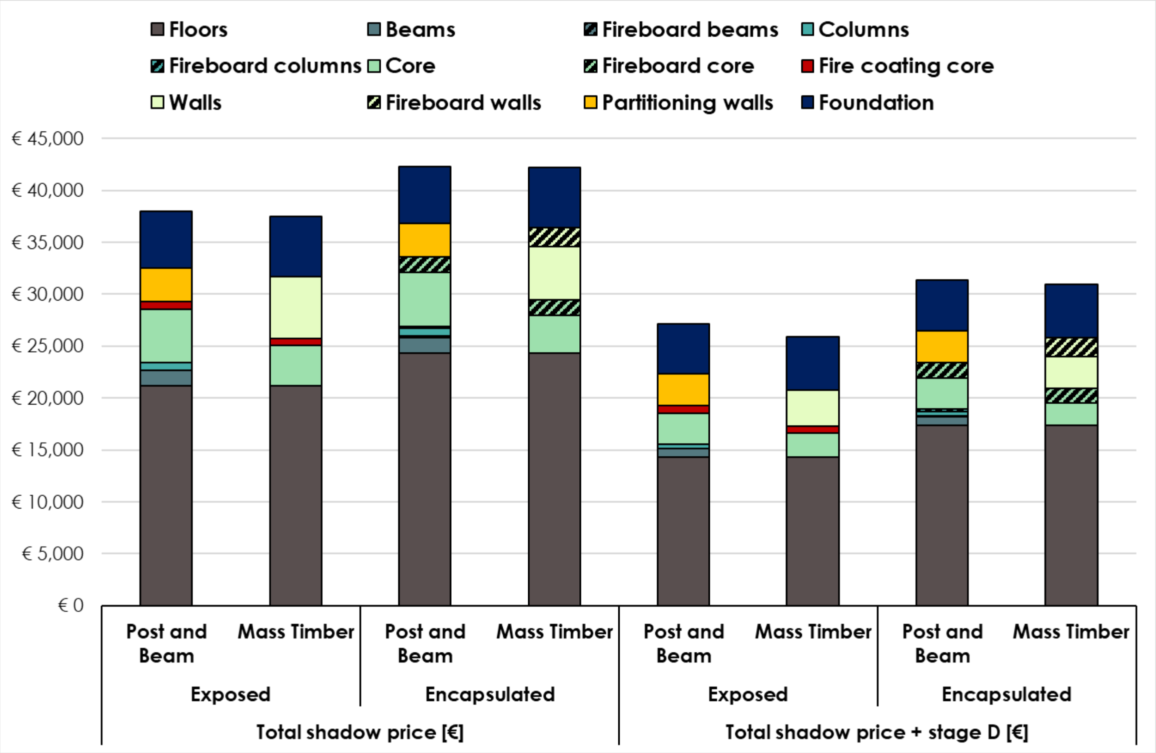


Figure 5.4: Environmental impact of fire safety strategies [€]

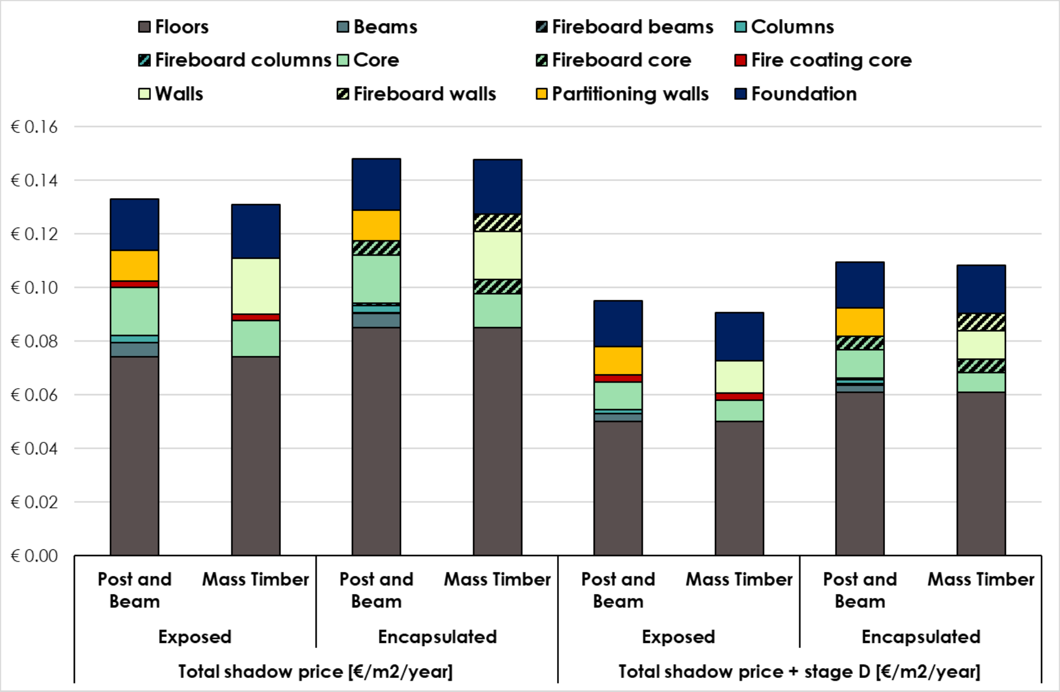


Figure 5.5: Environmental impact of fire safety strategies [€/m²/year]

5.3.4. Cascading scenario comparison

Figure 5.6 and Figure 5.7 give the environmental impact and the relative contribution of the building components for the default (50 years), flexible (150 years) and re-use (150 years) end of life scenarios at the height of 50 meters. Section 4.4.3 describes the cascading scenarios and how they are interpreted in this study.

Both the flexible and re-use scenario result in an increase of material use and have, therefore, a higher shadow price than the default scenario as shown in Figure 5.6. The design for a longer reference period by taking into account higher variable loading in case of the flexible design, together with the replacement of materials which have a shorter technical life span than 150 years, leads to a marginal increase of 8% compared to the default scenario. However, this scenario is only valid for the post and beam typology with the possibility of flexible floorplan layouts.

The material loss based on the re-use probability, derived with the building circularity indicator, leads to a significant increase of material used for the post & beam and mass timber typology by 91% and 81% respectively.

When the lifespan is considered in the determination of the environmental impact (see Figure 5.7), both the flexible and re-use scenario show a lower impact than the default scenario. The flexible scenario has the lowest impact, thus the post and beam typology has the best environmental reduction potential compared to mass timber.

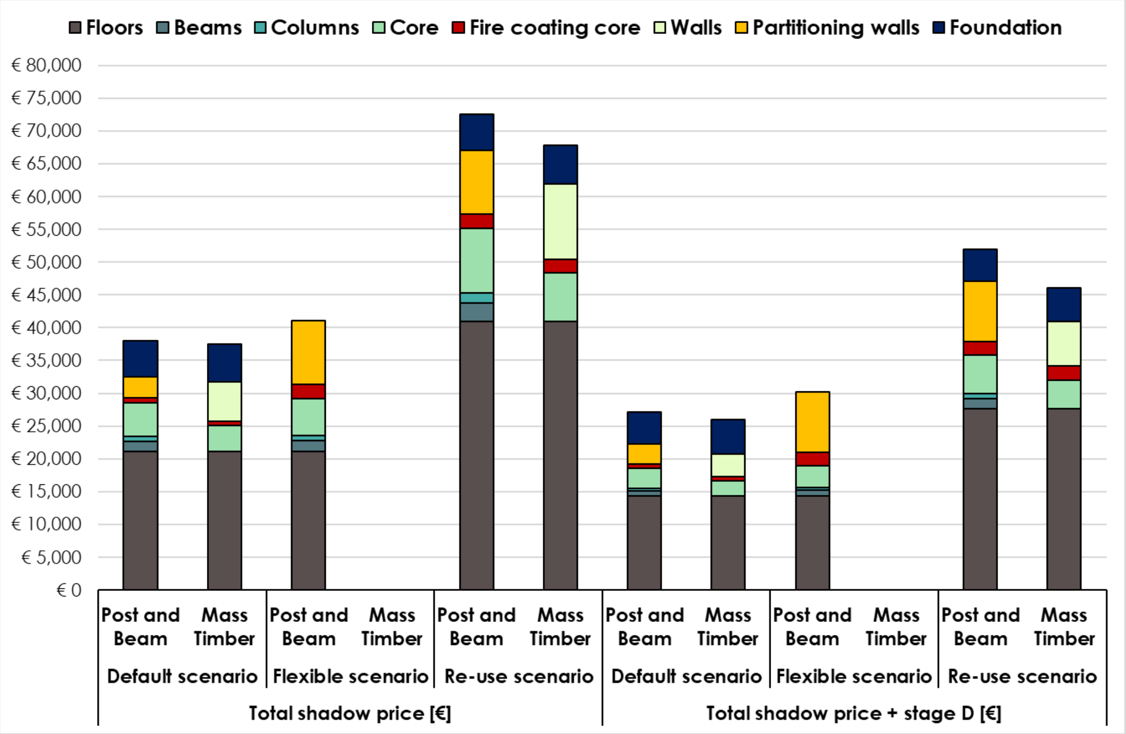


Figure 5.6: Environmental impact of cascading scenarios [€]

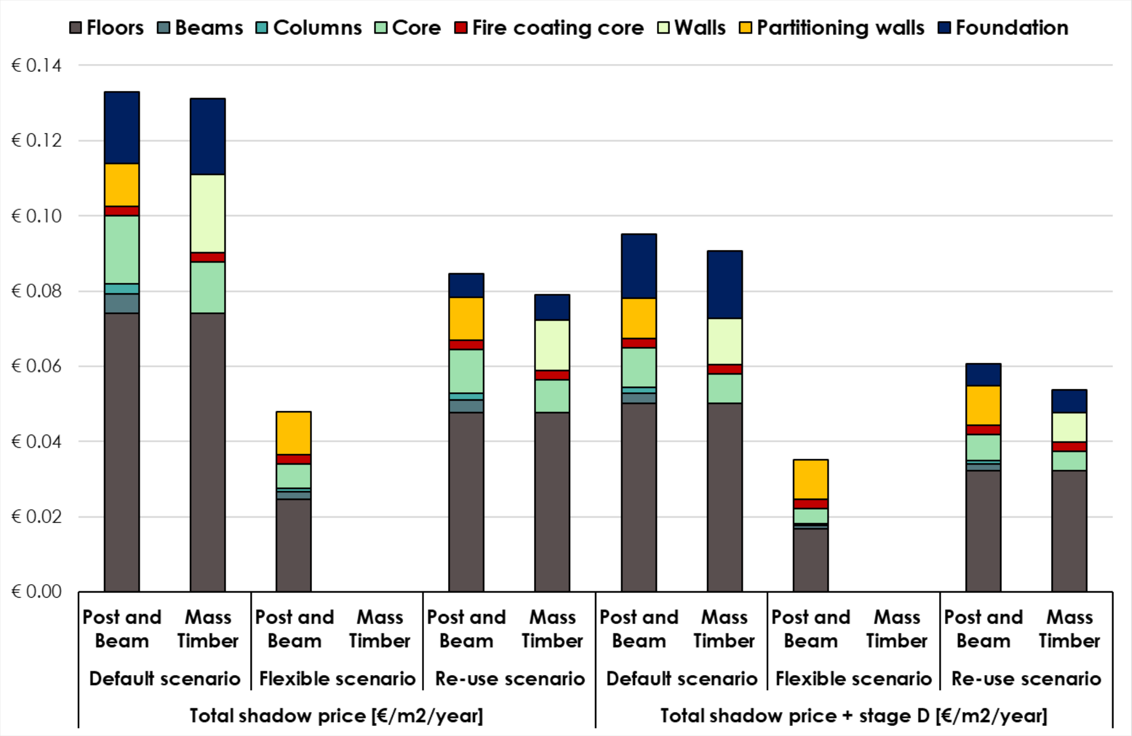


Figure 5.7: Environmental impact of cascading scenarios [€/m²/year]

5.3.5. Contribution of connections in a detailed design

Since the detailing of the connections is excluded from the scope of this study, the burden of the steel connections cannot be analysed. To get an approximation of how much the detailing can contribute to the environmental impact of timber buildings, the output of the detailed design as used for the model verification (see Section 4.6) is used. This leads to a maximum of 5.5% increase by the total steel mass of the connections compared to the total impact of timber elements, see Appendix C.12 for the derivation.

6

Timber vs Concrete, a case study: Bay House

In this chapter, a comparative fast track LCA between a concrete benchmark and timber alternative is performed to analyse the differences. The goal and scope definition from Chapter 5 is used with the addition of a transport analysis. For the timber alternative, the same design principles as in Chapter 4 are used. The chapter concludes with an estimation of the theoretical market potential.

6.1 Case study introduction

Bay House is an apartment complex, which is currently under development in the Rijnhaven district in Rotterdam (see Figure 6.1). It is part of a larger project, including a hotel and residential tower (Porter House). The building is a deck access flat (*Galerijflat*) with a two-level parking garage as basement. The front part of the building is the highest, reaching 40 meters. It uses a concrete design except for the multi-storey apartment in the middle (see the centre of Figure 6.1A), which has a timber structure.

(A) Impression [116] (B) Sitemap [117]

Figure 6.1: Bay House

6.2 Concrete benchmark

For the concrete benchmark, a simplification of a part of the building is used. The chosen part is the front section (highest part) as can be seen in Figure 6.1A. The low-rise at the back of the building is excluded. The structure is dilated in longitudinal direction. The complexity is further reduced by analysing one of the dilated sections.

The inventory used for the life cycle assessment is limited to the main load-bearing structure, excluding balconies. The floor finishing, fireproofing materials, and acoustical insulation is included similar to the variant study. Though, this is limited to the wet screed floor finishing since the concrete benchmark does not require additional fire safety and acoustical wall insulation measures.

The structure is design for the default lifespan of 50 years using cast-in-situ concrete of quality C30/37. For the floor system, a precast concrete lattice girder (*Breedplaatvloer*) is used. The stability in the transverse direction is provided by the apartment separating shear walls, the stability in the longitudinal direction by the core. See Appendix D for the complete simplification and material inventory.

6.3 Timber alternative

The timber alternative is designed using the same simplification as for the concrete benchmark. Based on the results from the variant study, the mass timber typology is chosen since it has the lowest environmental impact for the default lifespan of 50 years.

As discussed in Section 6.1, a small part of the building uses a timber load-bearing structure. The used design choices from the actual building are used for the timber alternative, which means that the walls use an encapsulated fire safety strategy and the ceilings (bottom of floor slabs) use an exposed fire safety strategy.

The basement is assumed to be the same as the concrete benchmark, though the reduction of the pile foundation is approximated due to the decrease of dead load. See Appendix D for the complete design verification and material inventory.

6.4 Transport analysis

For the comparison of the concrete benchmark and timber alternative, the transport from factory to construction site (LCA stage A4) is of relevance. Most engineered timber products, including Glulam, LVL and CLT, are not manufactured in the Netherlands contrary to concrete. Therefore, the environmental contribution of the transport of concrete (including reinforcement) and timber are analysed and compared.

According to the Dutch MPG methodology, the transport distance for bulk material, manufactured in the Netherlands, equals 50 kilometres [68]. To determine the average transportation distance of CLT, a transport analyses weighted by the production capacity of each factory (i.e. producers with a higher production capacity contribute more to the average transportation distance) is performed. In the analysis, the ten largest CLT manufacturers in Europe as of 2019 are included together with the remaining manufacturers from the EPD study, see Figure 6.2.

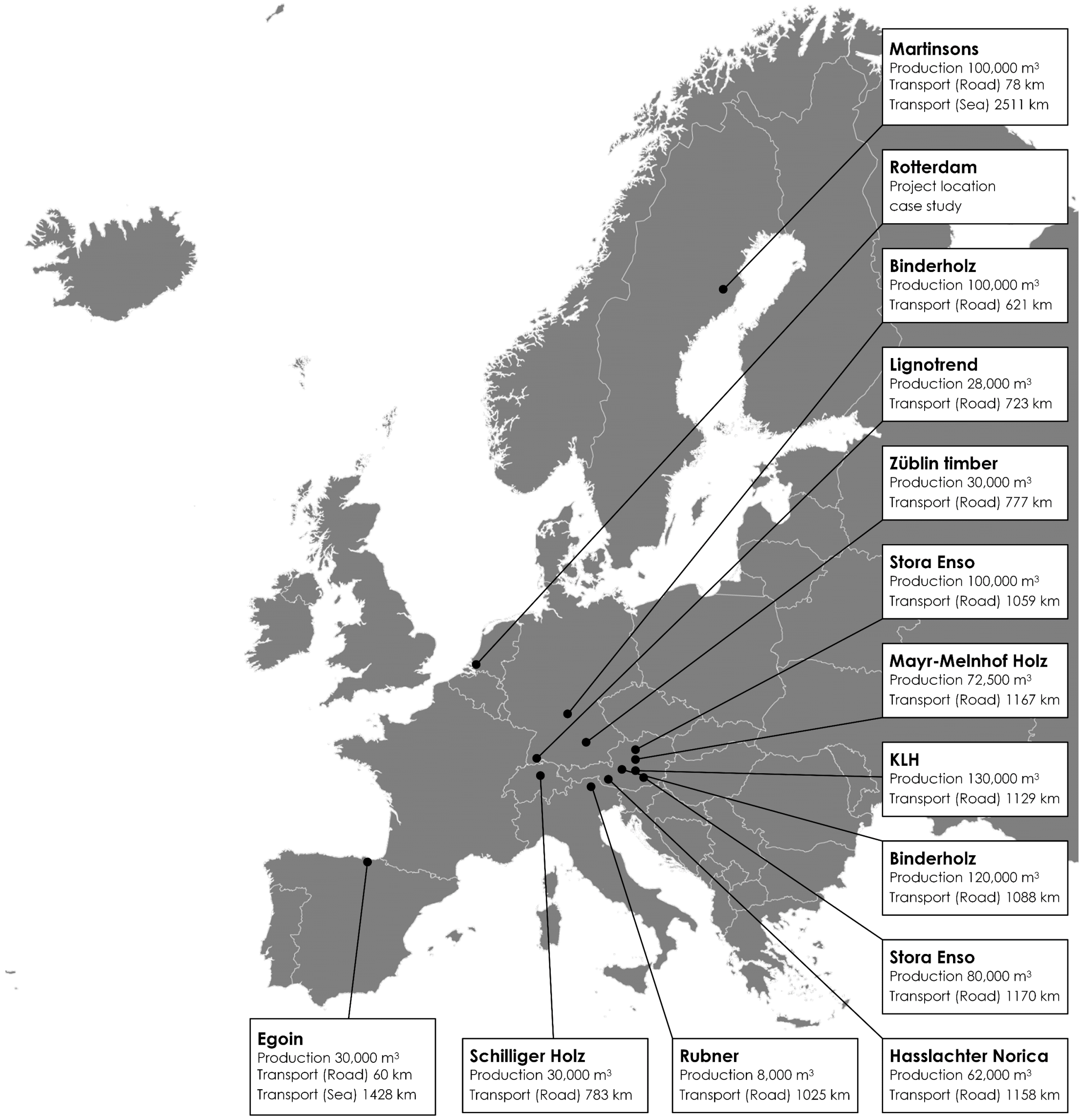


Figure 6.2: Weighted transport analysis (10 largest CLT manufacturers and CLT manufacturers from the EPD study)

The environmental impact of transportation is quantified per tonne per kilometre. The results for the superstructure, which is a direct comparison of CLT and reinforced concrete, is shown in Table 6.1. This is based on the minimum seven environmental impact categories as specified by standard EN 15804. See Appendix D for the complete transport analysis.

Table 6.1: Results of transportation analysis (based on reinforced concrete and CLT used in the superstructure)

Variant	Shadow price [€/tonne]	Shadow price [€]
Concrete benchmark	0.51	3,934
Timber alternative	9.90	15,334

6.5 Comparison of concrete benchmark and timber alternative

The same life cycle assessment goal and scope definition is used as described in Chapter 5 with the exception of the building height (40 metres) and the addition of transport of CLT and reinforced concrete (LCA stage A4). See Figure 6.3 for the results of the comparison between the concrete benchmark and timber alternative.

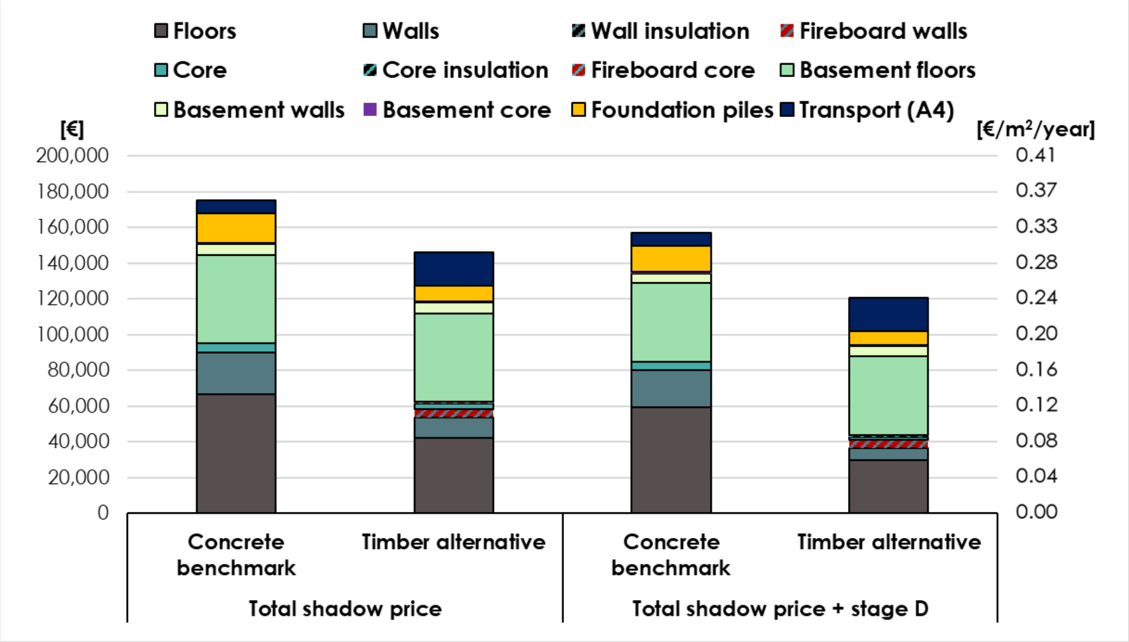


Figure 6.3: Environmental impact comparison case study

The largest difference in environmental impact between the two variants are caused by the floor system. Both the CLT and the precast concrete lattice girder use the same wet screed floor finishing, thus the difference is solely caused by the floor slabs themselves. The differences are shown in Table 6.2 for a CLT floor slab of 300 millimetre thickness and concrete floor slab of 250 millimetre thickness with reinforcement quantity of 100 kilograms per cubic meter. Both floor systems have a span of 7.8 metres. The benefits beyond the building's life cycle, quantified in LCA stage D, are larger for the CLT slab than precast concrete lattice girder.

Table 6.2: Environmental impact of floor systems

Floor system	Total shadow price [€/m²]	Total shadow price + stage D [€/m²]
CLT	5.37	3.81
Precast concrete lattice girder	8.46	7.54

The timber alternative requires additional fire safety measures and acoustical insulation, which is not the case for the concrete benchmark. However, the increase of the environmental impact of these measures is limited by 4% of the total timber alternative.

The impact of the foundation of the timber alternative is reduced by 48% compared to the concrete benchmark. This reduction is caused by the significantly lower dead load of the timber superstructure, which is roughly five times lower than the concrete equivalent.

The transportation impact of timber and reinforced concrete for the combined sub- and superstructure is 59% lower for the concrete benchmark. While the substructure is reduced for the timber alternative (concrete benchmark 12% higher impact), the substructure is increased (concrete benchmark 74% lower impact).

The environmental impact of the construction and installation stage (LCA stage A5) is excluded from this analysis, as discussed in the goal and scope definition (see Section 5.1). When included, this would have a positive relative contribution for the timber alternative compared to the concrete benchmark since less heavy construction equipment is required and arguably for a shorter period due to faster construction speed of timber structures. Another excluded aspect which is beneficial for the environmental impact of the timber alternative is the formwork used in the concrete variant. According to the Dutch MPG methodology, and therefore the NMD database, the formwork is excluded.

6.6 Sensitivity analysis

The selection of environmental data sources can have a significant impact on the results of a life cycle assessment, as previously discussed in Section 3.6.5. To determine the sensitivity of the results of this case study the same analysis is performed using timber data from the NMD. Figure 6.4 presents the differences between the analysis using average timber EPD data and timber NMD data. Again, the minimum seven environmental impact categories are used to be comparable with other data sources which do not include the four additional impact categories specified by the Dutch MPG methodology.

The total shadow price of the timber alternative increases by 26% using the NMD data compare to the EPD data. This increase makes it perform worse than the concrete benchmark, as indicated in Figure 6.4. The difference between the timber alternative and concrete benchmark would become even larger, in favour of the concrete benchmark, when considering the four additional impact categories specified by the MPG. However, the impact of these additional categories are also significantly higher for NMD data compared to EPD data, as shown in section 3.6.5 and derived in Appendix B.6.

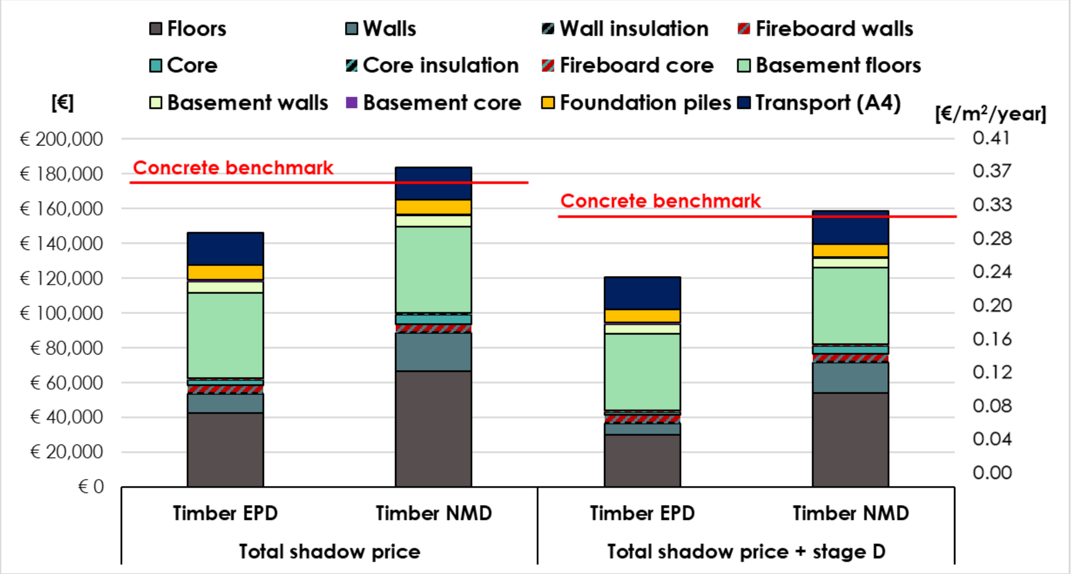


Figure 6.4: Sensitivity of data sources

6.7 Estimate of theoretical global warming reduction potential

In this section an estimation of the theoretical global warming reduction potential is given when timber is used instead of concrete for the load bearing structure. This theoretical potential is by no means an exact representation of the potential but gives an order of magnitude of the potential based on the results of the case study in this chapter.

To determine the reduction potential, the embodied carbon of both the concrete benchmark and timber alternative are extracted from the life cycle assessment. Additionally, the sequestered carbon of the timber is determined. The embodied carbon is used to determine the concrete substitution effect (i.e. the difference in GWP of both variants). See Table 6.3 for the data.

Table 6.3: GWP of case study

Variant		GWP [kg CO_2-eq]	GWP [kg CO_2-eq/m^2]
Concrete benchmark	Embodied carbon	2,347,841	239
Timber alternative	Embodied carbon	1,603,429	163
	Sequestered carbon (CLT volume: 3701 m^3)	-2,549,101	-259

The worked-out part of the case study has 84 apartments of 94 m^2 each. In the Netherlands, the average living area is 65 m^2, according to the Central Bureau of Statistics (CBS) [118]. To account for the difference, the GWP for the normalised apartment size has been determined, see Table 6.4.

Table 6.4: GWP of normalised case study

Variant		**GWP [kg CO_2-eq]**	**GWP [kg CO_2-eq/m^2]**
Concrete benchmark	Embodied carbon	1,630,455	166
Timber alternative	Embodied carbon	1,113,493	113
	Sequestered carbon (CLT volume: 2864 m^3)	-1,770,209	-180

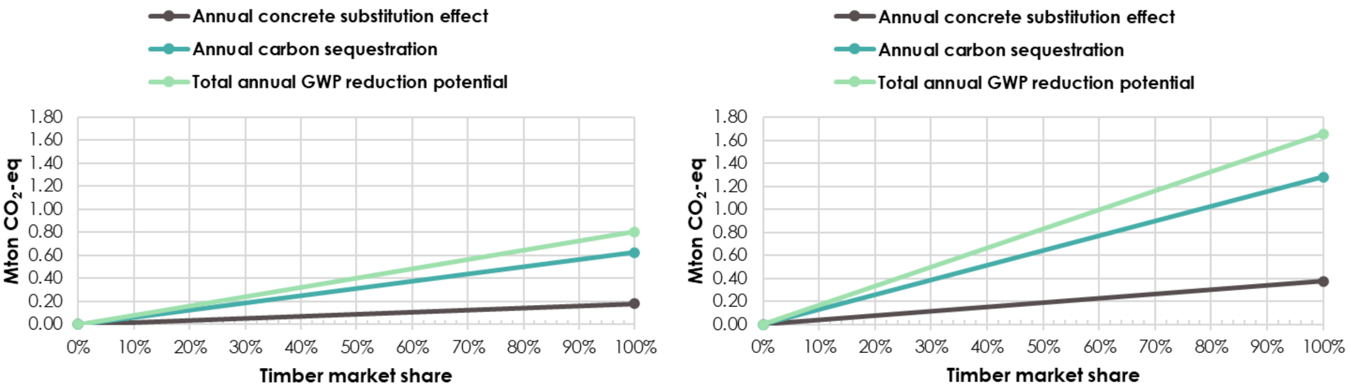
The annual net increase and replacement can be determined using the housing stock statistics by the CBS and TNO as shown in Table 6.5. It will take 250 years to replace the current housing stock with newly built houses based on the rate by TNO. This is longer than the default lifespan and requires renovation of the buildings to reach this lifespan.

Table 6.5: Housing stock statistics in the Netherlands

	Data	**Source**
Housing stock (2019)	7,814,911	CBS [119]
Average annual newly build houses (2019-2015)	60,869	CBS [120]
Annual housing replacement rate	0.4%	TNO [120]
Annual houses replaced	31,260	-
Annual net increase of housing stock	29,609	-

Based on these statistics, the annual global warming reduction potential can be determined. The results are shown in Figure 6.5 for the net increase of housing stock and the total newly build houses in the Netherlands. The latter is only valid for the initial 250 years after which timber buildings will replace timber buildings, resulting in no further increase of the GWP reduction potential. When this market saturation occurs, the reduction potential is solely caused by the net increase of housing stock (see also Section 3.4.2). The 250 years can be elongated by cascading strategies beyond the initial technical lifespan of timber by downcycling to particle-based products which can be further downcycled to fibre-based products in a third lifecycle before incinerating for thermal and energy recovery.

The annual reduction potential based on 100% market share in the housing sector is 1.6 Mton CO_2-eq for the initial 250 years after which it is reduced to 0.8 Mton CO_2-eq based on the current statistics. The annual greenhouse gas emission by the construction sector and production of construction materials in the Netherlands equalled 13.3 Mton in 2017 according to the CBS [121]. Thus, the annual global warming reduction potential by timber housing equals 12% and 6% of the national annual GWP emissions of the whole sector for respectively the initial 250 years and the years after.



(A) Net increase of housing stock

(B) Total newly build houses including replacement of demolished houses

Figure 6.5: Annual global warming reduction potential for timber housing in the Netherlands

In this calculation, it assumed that all build housing are apartments based on the case study. However, other types of housing (e.g. single-family houses) do not require engineered timber. When sawn timber is used, the concrete substitution effect will increase further. The same procedure can be performed for other functions such as offices, public and industrial buildings on top of the estimated potential for housing. This is done by NIBE, which quantified the maximum technical potential of 3.5 Mton CO_2-eq for exclusively the concrete substitution effect [122].

Currently, the bottleneck to reach the maximum global warming reduction potential is not the availability of roundwood since the current situation in Europe leads to afforestation as discussed in Section 3.4.3, but the production capacity of engineered timber. For CLT, the annual production capacity in Europe is 1.78 million m^3 [123]. However, to reach the maximum potential in the Dutch housing sector, an annual quantity of 2.07 million m^3 is required for 100% market share. This data indicates that for the coming years, it is a theoretical potential which in practice will not be realised regardless of the actual timber market share in the housing sector. The coming year the CLT production is expected to grow further to 2 million m^3, mainly by (new) manufacturers in Central Europe and Scandinavia [124]. As previously discussed, the data is based on the mass timber case study using CLT. Other engineered timber is available such as Glulam (used in post and beam typology) and LVL (used as alternative to CLT floors). This increases the available resources further, but not nearly enough to reach the potential. For instance, the European Glulam production equals around 3 million m^3. For other smaller types of housing which can be constructed using sawn timber, the available resources do not form a bottleneck since the sawn timber production in Europe equalled around 122 million m^3 according to Eurostat [125].

7

Final remarks

7.1 Conclusion

The current housing shortage in the Netherlands forms a major challenge due to set climate goals by the government to reduce greenhouse gas emissions to 95% in 2050 [1]. Therefore, alternative solutions to the status quo with lower impact on the environment should be considered, such as timber structures.

The objective of this study was to determine the environmental impact of multi-storey timber residential buildings. In this thesis, the trends in the timber construction sector were analysed by reference projects to determine timber typologies and used materials in these projects. Furthermore, the sustainability of timber on three different scales was analysed. Using the life cycle assessment methodology, the environmental impact was quantified based on multiple data sources. It was found that the selection of data sources has a significant impact on the results. Based on the identified timber typologies in this thesis, a variant study was performed to compare different design choices and the effect of cascading strategies; followed by a case study to compare the impact with concrete buildings which currently dominate the housing market. The formulated main research question at the start of the thesis was:

Which timber typologies have the lowest environmental impact for multi-storey buildings in the Netherlands at 30, 50 and 70 meters high and how does this compare to a concrete alternative?

The research has resulted in the following findings:

Timber typologies and products

- Two main structural typologies are present in the timber reference cases: the post & beam and mass timber typologies. The first has a flexible floorplan layout the latter a fixed floorplan layout.
- A variety of stability systems are used for timber structures: Timber frame, timber shear walls, timber core, concrete core, load-bearing façade (tube system), diagrid and bracings. Outriggers are currently not used but were proven to be feasible by several studies.
- For multi-storey timber structures, engineered wood products are used. Most commonly: glued laminated timber (Glulam), cross-laminated timber (CLT) and laminated veneer lumber (LVL). These products for the

European market are produced from softwood originating from European forests.
- Solid cross-laminated timber and hollow laminated veneer lumber floor slabs are dominating the market.
- Two types of structural fire safety strategies are available: Gypsum fireboard encapsulation and exposed timber whether or not with a sprinkler system.

Sustainability of timber on the macro-scale (Global level)

- A distinction should be made between fossil and biogenic carbon. The first can be classified as non-renewable, the latter as renewable due to the carbon formation time.
- Anthropogenic greenhouse gas emissions will be part of the biogenic carbon cycle for the foreseeable future, increasing the atmospheric greenhouse gas concentration.
- Forests are a natural carbon storage through the process of photosynthesis, thus a means of carbon sequestration. By using bio-based materials in the built environment, the total carbon sequestration potential increases to the point of market saturation in which timber buildings will replace timber buildings. Then the increase is governed by the net annual increase of the housing stock.
- Certified wood by the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) guarantee a sustainable harvesting rate. Approximately 55% of the total forest area in Europe is certified by either one. This leads to afforestation in Europe due to sustainable forestry since only 66% of the net annual increment is harvested.

Sustainability of timber on the meso-scale (Building level)

- Demolition of housing is for only 5% caused by reaching the technical lifespan of the structure. The “waste” materials have remaining technical lifespan in another functional context. The two main cascading scenarios to equalize the technical and functional lifespan are by using a flexible floorplan (valid for post & beam typology) or by re-use of the components (valid for both post & beam and mass timber typologies).
- The technical durability of timber depends on the biological durability (resistance to degradation mechanisms) and mechanical durability (time-dependent behaviour). For indoor dry applications, the biological durability is not a limiting factor. In practice when timber is re-used the

remaining mechanical properties are physically tested, no agreed-upon rules exist to determine the remaining technical lifespan.

Sustainability of timber on the micro-scale (Material level)

- On average, 50% of the original volume of roundwood ends up in the final product. The remaining offcuts are used for co-products and therefore not wasted.
- To quantify the environmental impact, a life cycle assessment can be used. For the building sector, this is prescribed by the European EN 15804 and the Dutch MPG methodology. The prescribed method by Dutch government includes four additional impact categories than the European standard. Therefore, foreign environmental product declarations are not accepted in the Dutch method.
- The contribution of carbon sequestration in timber products is completely neglected in the Dutch methodology while in the European standard it is assumed to be released at the end of life stage, leading in both cases to a neutral effect of carbon sequestration.
- Inconsistencies in the interpretation of re-use and recycling end of life scenarios of timber are present across multiple environmental product declarations. In some cases, leading to overestimating to the benefits.
- Disagreement in the field of life cycle assessment is present how to declare an energy and thermal recovery scenario. The scenarios in the environmental product declarations are based on the current electricity mixture and substitution of natural grass. On the contrary, the Dutch MPG methodology prescribes rules for material equivalency. Therefore, biomass will replace biomass (not partly fossil fuels). This leads to a reduction of this end of life scenario by 70%.
- The choice for timber environmental data source, either the Dutch NMD or European EPDs, results in a significant difference of 55% in shadow price based on the seven impact categories which are quantified for both sources. Choosing the EPDs results in lower results.
- The average total environmental impact (excluding LCA stage D) of timber products in increasing order is: sawn timber (0.020 €/kg), Glulam (0.022 €/kg), CLT (0.025 €/kg) and LVL (0.048 €/kg) based on the minimum seven environmental impact categories.

Environmental impact of timber variants

- For a default design lifespan of 50 years, the mass timber variant scores marginally better than the post and beam typology with a maximum of 5% difference. The main difference between the two typologies are the stabilizing and load-bearing walls in the mass timber typology versus the partitioning walls in the post and beam typology.

- Regardless of the height, the floors have the highest contribution to the environmental impact (50-55%), followed by walls (20-25%) and foundation (13-20%). The remaining impact is caused by beams and columns (for the post and beam system), fire safety measures and acoustical insulation.
- A CLT dry screed floor system generally has the lowest environmental impact, followed by a CLT wet screed floor system and LVL hollow box floor system. The maximum observed difference was a 50% higher impact for the LVL system compared to the CLT dry screed system.
- An encapsulated fire safety strategy increases the environmental impact with 11-13% compared to an exposed fire safety strategy due to the additional impact of gypsum fireboards.
- Using cascading scenarios to elongate a building's lifespan, an environmental impact reduction of 63% for a flexible floorplan scenario and 40% for a re-use scenario (2x re-use) can be achieved based on a lifespan of 150 years.

Timber versus Concrete case study

- The CLT floor system from the case study has a 37% lower environmental impact compared to the concrete precast lattice girder.
- The impact of transportation of construction materials from the factory to the construction site is 59% higher for the timber alternative due to the manufacturing abroad.
- The impact of the foundation is 48% lower for the timber alternative compared to the concrete benchmark.
- The timber alternative has a 17% lower shadow price compared to the concrete benchmark.
- When choosing the NMD as timber environmental data source instead of the average from the EPD study, the total shadow price is increased by 26%, which leads to worse performance than the concrete benchmark.

Estimate of theoretical global warming reduction potential timber versus concrete

- The global warming reduction potential of timber alternatives can be split in the concrete substitution effect and the carbon sequestration effect.
- It was estimated that the maximum total annual global warming reduction potential by timber housing equals 12% of the annual national emissions by the construction sector and production of construction materials in the Netherlands. This number is only valid during the initial phase, after which the market saturation occurs. Then the increase is governed by the

net annual increase of the housing stock with a reduction potential of approximately 6%.

- Currently, the production of engineered timber forms a bottleneck to reach the full reduction potential.

From this quantitative research, it was shown that the environmental impact of multi-storey timber residential buildings is lower than a concrete equivalent. However, the large-scale potential is limited by the current production capacity of engineered wood products. Furthermore, it was found that the choice for structural typology, either post and beam or mass timber, does not lead to significant differences for a default design lifespan of 50 years. Though, the choice for a certain floor system does result in large differences. A flexible floorplan cascading scenario can lead to a larger reduction of the post and beam typology than a re-use scenario for either post and beam or mass timber typologies. Overall, it can be concluded that a difference can be made to the environmental impact of the built environment by cascading scenarios, regardless of the choice of construction material. In case of timber structures, additional benefits occur due to the lower relative environmental impact and the carbon sequestration.

7.2 Discussion

A discussion of the factor of influences on the result of this thesis are discussed in this section. The results of the discussion of Chapter 3 are previously discussed in the critical review in Section 3.7.

Level of detail structural calculations and LCA methodology

The level of detail in this thesis for both the variant study and timber alternative in the case study are limited to the preliminary design phase. The structure is verified using manufacturers data and simplified hand calculations. When assumptions were necessary, a conservative approach was chosen. Additionally, the verification is optimized to a unity check of 0.8 to account for changes in the detailed design. This results in additional material than required in a final design. However, it is beneficial to do a life cycle assessment in the beginning of the design process so the environmental impact can influence the later design choices.

The results of the LCA are presented in euro per gross floor area per year. These results should not be mistaken to be valid for the MPG requirement, which has the same unit. The LCA in this chapter has four impact categories less than required for the MPG and does not include all required building components for an MPG assessment.

Sensitivity of data selection

As proved in this thesis, the choice of environmental data sources can change the output of a life cycle assessment significantly. A thorough review is required of the data sources to identify their validity and comparability.

Developments in sustainability of building materials

Where in the engineered timber industry developments are realised contributing to the sustainability of the products by replacing formaldehyde adhesives for more sustainable alternatives; manufacturers of other materials also innovate their product to have a lower environmental impact (e.g. replacement of cement by geopolymers and optimization of the production processes). Thus, the results of this thesis are only a snapshot based on the materials which are currently mostly used.

As of March 2020, a new EPD for CLT by Derix is declared according to the Dutch methodology version 3.0. Thus, includes all 11 impact categories as specified by the methodology. This data set is a better representation, relative to the European EPDs, than the previously available NMD data as used in this study. The data will be implemented in the newly version of the NMD v3.0.

Assumptions for re-use cascading scenario

The effects of a cascading scenario by re-using structural elements is derived by the building circularity indicator. This represents a theoretical value for the probability that a building can be (partly) re-used. Currently, the re-use of structural elements is not common practice. The prognosis is that this will change due to the promotion of the circular economy and the goals set by the government. When this strategy is embraced by a large scale of the industry, the actual re-used fractions can be determined.

Assumptions for market potential

The market potential is derived based on the current statistics of the housing market. The housing shortage is expected to remain unchanged in the coming years according to CBS. However, for a longer timeframe, these statistics can change based on changed demands. Furthermore, the assumption that the market potential is based on the case study results in an inaccurate representation of the housing market. Other types of housing require different quantities of construction material. To estimate the amounts for the average housing market, the data has been normalised to the average living area in the Netherlands.

The used annual housing replacement rate results in an average lifespan of 250 years, after which market saturation occurs. This can be elongated by cascading strategies beyond the initial lifespan by downcycling of the products. It was assumed that at the end of all life cycles, the product is incinerated using thermal and energy recovery. An alternative strategy for further carbon sequestration at the end of the final life cycle is available by storying biomass below ground. Due to the anaerobic condition below the soil, the decomposition of the wood is slowed, storing the sequestered carbon indefinitely [126]. In this case, no market saturation will occur since all added timber will lead to a direct increase of the timber. However, this concept is a carbon capture and storage technique proposed on paper which has not been tested in practice yet. Also, concerns are present for nutrient lock-up [126].

7.3 Recommendations for future research

During the research, several assumptions had to be made and the level of detail in certain topics minimized due to time constraints. Here follows a list for potential research topics:

- The construction stage (LCA stage A5) of the life cycle assessment is excluded from the scope of this research. Generally, it is assumed that for timber structures the impact of this stage is lower compared to concrete due to the faster erection times and less heavy equipment used during construction. However, limited quantitative studies have been performed to substantiate these claims and when this LCA stage is included in studies it is merely based on various assumptions.
- When the construction sector moves to a circular economy, the residual material properties are of relevance and rules for the remaining lifespan of the elements are required. Furthermore, the re-use potential in this thesis was based on a theoretical re-use potential. Validation of these assumptions are required based on examples from practice. Thus, more research to the implication of cascading strategies is required.
- The global warming reduction potential by carbon sequestration and the substitution effect of timber structures is limited by the production capacity of engineered timber. Various carbon capture and storage techniques for the industrial sector are proposed, of which many proved to be financially or technically unfeasible. An analysis of these artificial techniques versus an upscaling of the natural carbon sequestration in the biobased built environment by increasing engineered timber production is therefore of interest.

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Appendix A

Timber strength classes

A.1 Sawn timber (softwood)

Table A.1: Strength classes for softwood (NEN-EN 338) [127]

		C14	**C16**	**C18**	**C20**	**C22**	**C24**
Strength properties [N/mm^2]							
Bending	$f_{m,k}$	14	16	18	20	22	24
Tension //	$f_{t,0,k}$	7.2	8.5	10	11.5	13	14.5
Tension ⊥	$f_{t,90,k}$	0.4	0.4	0.4	0.4	0.4	0.4
Compression //	$f_{c,0,k}$	16	17	18	19	20	21
Compression ⊥	$f_{c,90,k}$	2.0	2.2	2.2	2.3	2.4	2.5
Shear	$f_{v,k}$	3.0	3.2	3.4	3.6	3.8	4.0
Stiffness properties [N/mm^2]							
Mean E-modulus //	$E_{0,mean}$	7000	8000	9000	9500	10000	11000
5% E-modulus //	$E_{0,05}$	4700	5400	6000	6400	6700	7400
Mean E-modulus ⊥	$E_{90,mean}$	230	270	300	320	330	370
Mean shear modulus	G_{mean}	440	500	560	590	630	690
Density [kg/m^3]							
5% density	ρ_k	290	310	320	330	340	350
Mean density	ρ_{mean}	350	370	380	400	410	420

		C27	**C30**	**C35**	**C40**	**C45**	**C50**
Strength properties [N/mm^2]							
Bending	$f_{m,k}$	27	30	35	40	45	50
Tension //	$f_{t,0,k}$	16.5	19	22.5	26	30	33.5
Tension ⊥	$f_{t,90,k}$	0.4	0.4	0.4	0.4	0.4	0.4
Compression //	$f_{c,0,k}$	22	23	24	27	29	30
Compression ⊥	$f_{c,90,k}$	2.5	2.7	2.7	2.8	2.9	3.0
Shear	$f_{v,k}$	4.0	4.0	4.0	4.0	4.0	4.0
Stiffness properties [N/mm^2]							
Mean E-modulus //	$E_{0,mean}$	11500	12000	13000	14000	15000	16000
5% E-modulus //	$E_{0,05}$	7700	8000	8700	9400	10000	10700
Mean E-modulus ⊥	$E_{90,mean}$	380	400	430	470	500	530
Mean shear modulus	G_{mean}	720	750	810	880	940	1000
Density [kg/m^3]							
5% density	ρ_k	360	380	390	400	410	430
Mean density	ρ_{mean}	430	460	470	480	490	520

A.2 Glued laminated timber

Table A.2: Strength classes for homogenous glulam (EN 14080) [114]

		GL20h	**GL22h**	**GL24h**	**GL26h**
Strength properties [N/mm^2]					
Bending	$f_{m,k}$	20	22	24	26
Tension //	$f_{t,0,k}$	16	17.6	19.2	20.8
Tension ⊥	$f_{t,90,k}$	0.5	0.5	0.5	0.5
Compression //	$f_{c,0,k}$	20	22	24	26
Compression ⊥	$f_{c,90,k}$	2.5	2.5	2.5	2.5
Shear	$f_{v,k}$	3.5	3.5	3.5	3.5
Stiffness properties [N/mm^2]					
Mean E-modulus //	$E_{0,mean}$	8400	10500	11500	12100
5% E-modulus //	$E_{0,05}$	7000	8800	9600	10100
Mean E-modulus ⊥	$E_{90,mean}$	300	300	300	300
Mean shear modulus	G_{mean}	650	650	650	650
Density [kg/m^3]					
5% density	ρ_k	340	370	385	405
Mean density	ρ_{mean}	370	410	420	445

		GL28h	**GL30h**	**GL32h**
Strength properties [N/mm^2]				
Bending	$f_{m,k}$	28	30	32
Tension //	$f_{t,0,k}$	22.3	24	25.6
Tension ⊥	$f_{t,90,k}$	0.5	0.5	0.5
Compression //	$f_{c,0,k}$	28	30	32
Compression ⊥	$f_{c,90,k}$	2.5	2.5	2.5
Shear	$f_{v,k}$	3.5	3.5	3.5
Stiffness properties [N/mm^2]				
Mean E-modulus //	$E_{0,mean}$	12600	13600	14200
5% E-modulus //	$E_{0,05}$	10500	11300	11800
Mean E-modulus ⊥	$E_{90,mean}$	300	300	300
Mean shear modulus	G_{mean}	650	650	650
Density [kg/m^3]				
5% density	ρ_k	425	430	440
Mean density	ρ_{mean}	460	480	490

Table A.3: Strength classes for combined glulam (EN 14080) [114]

		GL20c	GL22c	GL24c	GL26c
Strength properties [N/mm^2]					
Bending	$f_{m,k}$	20	22	24	26
Tension //	$f_{t,0,k}$	15	16	17	19
Tension ⊥	$f_{t,90,k}$	0.5	0.5	0.5	0.5
Compression //	$f_{c,0,k}$	18.5	20	21.5	23.5
Compression ⊥	$f_{c,90,k}$	2.5	2.5	2.5	2.5
Shear	$f_{v,k}$	3.5	3.5	3.5	3.5
Stiffness properties [N/mm^2]					
Mean E-modulus //	$E_{0,mean}$	10400	10400	11000	12000
5% E-modulus //	$E_{0,05}$	8600	8600	9100	10000
Mean E-modulus ⊥	$E_{90,mean}$	300	300	300	300
Mean shear modulus	G_{mean}	650	650	650	650
Density [kg/m^3]					
5% density	ρ_k	355	355	365	385
Mean density	ρ_{mean}	390	390	400	420

		GL28c	GL30c	GL32c
Strength properties [N/mm^2]				
Bending	$f_{m,k}$	28	30	32
Tension //	$f_{t,0,k}$	19.5	19.5	19.5
Tension ⊥	$f_{t,90,k}$	0.5	0.5	0.5
Compression //	$f_{c,0,k}$	24	24.5	24.5
Compression ⊥	$f_{c,90,k}$	2.5	2.5	2.5
Shear	$f_{v,k}$	3.5	3.5	3.5
Stiffness properties [N/mm^2]				
Mean E-modulus //	$E_{0,mean}$	12500	13000	13500
5% E-modulus //	$E_{0,05}$	10400	10800	11200
Mean E-modulus ⊥	$E_{90,mean}$	300	300	300
Mean shear modulus	G_{mean}	650	650	650
Density [kg/m^3]				
5% density	ρ_k	390	390	400
Mean density	ρ_{mean}	420	430	440

A.3 Laminated veneer lumber

Table A.4: Strength classes LVL [49]

		LVL32p	LVL35p	LVL48p	LVL50p	LVL80p
Strength properties [N/mm²]						
Bending	$f_{m,k}$	32	35	48	50	80
Tension //	$f_{t,0,k}$	22	22	35	36	60
Tension ⊥	$f_{t,90,k}$	0.5	0.5	0.8	0.9	1.5
Compression //	$f_{c,0,k}$	21	25	29	35	57
Compression ⊥	$f_{c,90,k}$	0.8	2.2	2.2	3.5	12
Shear	$f_{v,k}$	2.0	2.3	2.3	3.2	8
Stiffness properties [N/mm²]						
Mean E-modulus //	$E_{0,mean}$	9600	12000	13800	15200	16800
5% E-modulus //	$E_{0,05}$	8000	10000	11600	12600	14900
Mean E-modulus ⊥	$E_{90,mean}$	-	-	-	-	-
Mean shear modulus	G_{mean}	320	380	380	600	760
Density [kg/m³]						
5% density	ρ_k	410	510	510	580	800
Mean density	ρ_{mean}	410	480	480	550	730

LVL - p = without crossband veneers

		LVL22c	LVL25c	LVL32c	LVL36c	LVL70c	LVL75c
Strength properties [N/mm²]							
Bending	$f_{m,k}$	22	25	32	36	70	75
Tension //	$f_{t,0,k}$	14	15	18	22	45	51
Tension ⊥	$f_{t,90,k}$	4	4	5	5	16	18
Compression //	$f_{c,0,k}$	15	15	15	21	45	53
Compression ⊥	$f_{c,90,k}$	1.0	1.0	2.2	2.2	16	16
Shear	$f_{v,k}$	1.1	1.1	1.3	1.3	3.8	3.8
Stiffness properties [N/mm²]							
Mean E-modulus //	$E_{0,mean}$	6700	7200	10000	10500	11800	13200
5% E-modulus //	$E_{0,05}$	5500	6000	8300	8800	10900	12200
Mean E-modulus ⊥	$E_{90,mean}$	-	-	-	-	-	-
Mean shear modulus	G_{mean}	70	70	80	120	430	430
Density [kg/m³]							
5% density	ρ_k	410	410	480	480	730	730
Mean density	ρ_{mean}	440	440	510	510	800	800

LVL - c = with crossband veneers

A.4 Cross laminated timber

Table A.5: Characteristic material properties CLT [50]

		C24
Strength properties [N/mm²]		
Bending	$f_{m,k}$	24
Tension //	$f_{t,0,k}$	14.5
Tension ⊥	$f_{t,90,k}$	0.4
Compression //	$f_{c,0,k}$	21
Compression ⊥	$f_{c,90,k}$	2.5
Shear	$f_{v,k}$	4.0
Stiffness properties [N/mm²]		
Mean E-modulus //	$E_{0,mean}$	11000
5% E-modulus //	$E_{0,05}$	7400
Mean E-modulus ⊥	$E_{90,mean}$	400
Mean shear modulus	G_{mean}	690
Density [kg/m³]		
5% density	ρ_k	350
Mean density	ρ_{mean}	420

Appendix B

Environmental data

B.1 Studied EPDs

The environmental indicators are derived using the CML-2 LCIA method. All used data is third party verified and in compliance with ISO 14025 and EN 15804.

Table B.1: List of timber environmental product declarations

	EPD owner	Program operator	End of validity [dd-mm-yyyy]	Source
Sawn Timber	Stora Enso	Stora Enso	31-05-2023	[128]
	Swedish Wood	EPD International AB	27-06-2023	[129]
	Wood for Good	BRE Global	09-04-2022	[130]
Glulam	Binderholz GmbH	Institut Bauen und Umwelt e.V.	28-11-2024	[131]
	Martinsons Såg AB	The Norwegian EPD Foundation	08-09-2020	[132]
	Moelven Industrier ASA	The Norwegian EPD Foundation	13-06-2021	[133]
	Rubner Holding AG – S.p.A.	Institut Bauen und Umwelt e.V.	10-06-2023	[134]
	Schilliger Holz AG	Institut Bauen und Umwelt e.V.	27-05-2023	[135]
	Studiengemeinschaft Holzleimbau e.V.	Institut Bauen und Umwelt e.V.	12-08-2023	[136]
LVL	Stora Enso	EPD International AB	15-11-2024	[137]
	STEICO SE	Institut Bauen und Umwelt e.V.	07-02-2024	[138]
	METSÄ WOOD	METSÄ WOOD	31-01-2020	[139]
CLT	Binderholz GmbH	Institut Bauen und Umwelt e.V.	19-03-2024	[140]
	Egoin	EPD International AB	18-05-2023	[141]
	KLH Massivholz GmbH	Institut Bauen und Umwelt e.V.	05-05-2024	[142]
	Martinsons Såg AB	The Norwegian EPD Foundation	13-03-2024	[143]
	Studiengemeinschaft Holzleimbau e.V.	Institut Bauen und Umwelt e.V.	14-10-2020	[144]
	Rubner Holding AG – S.p.A.	Institut Bauen und Umwelt e.V.	10-06-2023	[145]
	Stora Enso	Stora Enso	31-05-2022	[146]

B.2 Assumptions and characteristics of EPDs

🟩 Module declared	🟨 Module declared, no contribution	🟥 Module not declared

Table B.2: Assumptions and characteristics of sawn timber EPDs

Stora Enso Wood Products Oy Ltd

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟥 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟩 C1	🟩 C2	🟩 C3	🟩 C4	🟩 D

Production site	Weighted average of 15 European production sites
Declared unit	1 m³ of sawn timber
End of life scenario(s)	100% re-use 100% recycling 100% Energy and Thermal recovery (75% efficiency) 100% Landfilling
Module A2 assumption	Not specified
Module A4 assumption	Module not declared
Module C2 assumption	50 km
Reference service life	Not specified
Wood species	Spruce, Pine
Packaging type	Not specified
Density	460 kg/m³
Wood moisture content	15%
Maximum application	T = 140 mm, W = 300 mm, L = 6.0 m

Swedish Wood

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟥 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟥 C2	🟥 C3	🟥 C4	🟥 D

Production site	Weighted average of 44 Swedish production sites
Declared unit	1 m³ of sawn timber
End of life scenario(s)	Module not declared
Module A2 assumption	100 km
Module A4 assumption	Module not declared
Module C2 assumption	Module not declared
Reference service life	Not specified
Wood species	Spruce, Pine
Packaging type	Plastic bands & caps or metal tapes
Density	455 kg/m³
Wood moisture content	16%
Maximum application	Not specified

Wood for Good

🟩 A1	🟩 A2	🟩 A3	🟩 A4	🟩 A5	🟨 B1	🟨 B2	🟨 B3	🟨 B4	🟨 B5	🟨 B6	🟨 B7	🟩 C1	🟩 C2	🟩 C3	🟩 C4	🟩 D

Production site	Earlston & Larbert & Naim, UK
Declared unit	1 m³ of sawn timber
End of life scenario(s)	Mix of 55% Recycling, 44% Thermal & Energy recovery ,1% landfilling
Module A2 assumption	Originating from UK forests (km not specified)
Module A4 assumption	292 km
Module C2 assumption	Recycling: 50 km, Recovery: 46 km, Landfilling: 21 km
Reference service life	60 years
Wood species	Spruce, Pine, Larch, Douglas Fir
Packaging type	Plastic film & strapping, steel banding, timber panels
Density	479 kg/m³
Wood moisture content	15%
Maximum application	Not specified

Table B.3: Assumptions and characteristics of Glulam EPDs (1)

Binderholz Bausysteme GmbH

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
🟩	🟩	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟩

Production site	Jenbach, Austria
Declared unit	1 m³ of Glulam
End of life scenario(s)	Energy (55% efficiency) & Thermal recovery (18% efficiency)
Module A4 assumption	Module not declared
Module C2 assumption	20 km
Reference service life	100+ years
Wood species	Spruce, Fir
Packaging type	Polyethylene films
Density	459 kg/m³
Wood moisture content	12.08%
Adhesive content	0.72% Melamine-urea-formaldehyde (MUF)
Maximum application	T = 480 mm, W = 2.0 m, L = 32.5 m

Martinsons Såg AB

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Production site	Bygdsiljum, Sweden
Declared unit	1 m³ of Glulam
End of life scenario(s)	Module not declared
Module A4 assumption	Module not declared
Module C2 assumption	Module not declared
Reference service life	60+ years
Wood species	Spruce
Packaging type	Not specified
Density	430 kg/m³
Wood moisture content	12%
Adhesive content	Not specified
Maximum application	Not specified

Moelven Industrier ASA

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Production site	Töreboda, Sweden
Declared unit	1 m³ of Glulam
End of life scenario(s)	Module not declared
Module A4 assumption	170 km
Module C2 assumption	Module not declared
Reference service life	Not specified
Wood species	Spruce
Packaging type	Not specified
Density	430 kg/m³
Wood moisture content	12%
Adhesive content	1% Melamine-urea-formaldehyde (MUF)
Maximum application	Not specified

Table B.4: Assumptions and characteristics of Glulam EPDs (2)

Rubner Holding AG – S.p.A.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Production site	Rohrbach & Ober-Grafendorf (Austria) Brixen & Calitri (Italy)
Declared unit	1 m^3 of Glulam
End of life scenario(s)	Energy & Thermal recovery (68% efficiency)
Module A4 assumption	Module not declared
Module C2 assumption	Module not declared
Reference service life	100+ years
Wood species	Spruce, Pine, Larch, Douglas Fir
Packaging type	Polyethylene films
Density	464 kg/m^3
Wood moisture content	12%
Adhesive content	0.4% Melamine-urea-formaldehyde (MUF) 0.2% Melamine 0.4% Emulsion polymer isocyanate (EPI)
Maximum application	T = 300 mm, W = 4 m, L = 50 m

Schilliger Holz AG

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Production site	Küssnacht, Switzerland
Declared unit	1 m^3 of Glulam
End of life scenario(s)	Energy (37% efficiency) & Thermal recovery (31% efficiency)
Module A4 assumption	90 km
Module C2 assumption	30 km
Reference service life	50+ years
Wood species	Spruce, Silver Fir
Packaging type	Polyethylene films
Density	420 kg/m3
Wood moisture content	12%
Adhesive content	0.9% Polyurethane (PUR)
Maximum application	T = 280 mm, W = 2 m, L = 18 m

Studiengemeinschaft Holzleimbau e.V.

A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Production site	-
Declared unit	1 m^3 of Glulam
End of life scenario(s)	Energy (18% efficiency) & Thermal recovery (55% efficiency)
Module A4 assumption	Not specified
Module C2 assumption	20 km
Reference service life	100+ years
Wood species	Spruce, Pine, Larch, Fir
Packaging type	Polyethylene films, wood, paper, cardboard
Density	480 kg/m3
Wood moisture content	12%
Adhesive content	0.03% Polyurethane (PUR) 2.04% Melamine-urea-formaldehyde (MUF) 0.1% Phenol-Resorcinol-Formaldehyde (PRF)
Maximum application	T = 240 mm, W = 2.4 m, L = 50 m

Table B.5: Assumptions and characteristics of LVL EPDs

Stora Enso Wood Products Oy Ltd

🟩 A1	🟩 A2	🟩 A3	🟩 A4	🟩 A5	🟨 B1	🟨 B2	🟨 B3	🟨 B4	🟨 B5	🟨 B6	🟨 B7	🟩 C1	🟩 C2	🟩 C3	🟩 C4	🟩 D

Production site	Varkaus, Finland
Declared unit	1 m^3 of LVL
End of life scenario(s)	100% Re-use 100% Recycling 100% Energy & Thermal recovery (75% Efficiency) 100% Landfilling
Module A4 assumption	Helsinki
Module C2 assumption	50 km
Reference service life	100+ years
Wood species	Spruce
Packaging type	Not specified
Density	510 kg/m^3
Wood moisture content	9%
Adhesive content	5.3% Phenol formaldehyde (PF), 0.1% Melamine-urea-formaldehyde (MUF), 0.3% Polyurethane (PUR)
Maximum application	T = 350 mm, W = 3.2 m, L = 19.9 m

Steico SE

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟩 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟩 C2	🟩 C3	🟥 C4	🟩 D

Production site	Czarna Woda, Poland
Declared unit	1 m^3 of LVL
End of life scenario(s)	Energy (18% efficiency) & Thermal recovery (55% efficiency)
Module A4 assumption	Module not declared
Module C2 assumption	20 km
Reference service life	50+ years
Wood species	Spruce, Pine
Packaging type	Not specified
Density	550 kg/m^3
Wood moisture content	9.15%
Adhesive content	4.5% Phenol formaldehyde (PF), 0.03% Melamine-urea-formaldehyde (MUF), 0.03% Hot-melt adhesive (HMA)
Maximum application	T = 90 mm, W = 2.5 m, L = 18.0 m

Metsä Wood

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟥 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟥 C2	🟥 C3	🟥 C4	🟥 D

Production site	Lohja & Punkaharju, Finland
Declared unit	1 m^3 of LVL
End of life scenario(s)	Module not declared
Module A4 assumption	Module not declared
Module C2 assumption	Module not declared
Reference service life	Not specified
Wood species	Not specified
Packaging type	Not specified
Density	440-510 kg/m^3
Wood moisture content	8-10%
Adhesive content	Phenol formaldehyde (PF), Melamine-urea-formaldehyde (MUF)
Maximum application	Not specified

Table B.6: Assumptions and characteristics of CLT EPDs (1)

Binderholz Bausysteme GmbH

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟩 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟩 C2	🟩 C3	🟥 C4	🟩 D

Production site	Unternberg, Austria & Burgbernheim, Germany
Declared unit	1 m^3 of CLT
End of life scenario(s)	Energy (18% efficiency) & Thermal recovery (55% efficiency)
Module A4 assumption	Module not declared
Module C2 assumption	20 km
Reference service life	100+ years
Wood species	Spruce, Fir, Pine, Larch & Stone Pine
Packaging type	Polyethylene films
Density	471 kg/m^3
Wood moisture content	12.1%
Adhesive content	5.3% Phenol formaldehyde (PF), 0.1% Melamine-urea-formaldehyde (MUF), 0.3% Polyurethane (PUR)
Maximum application	T = 350 mm, W = 3.5 m, L = 22.0 m

Egoin S.A.

🟩 A1	🟩 A2	🟩 A3	🟩 A4	🟩 A5	🟨 B1	🟨 B2	🟨 B3	🟨 B4	🟨 B5	🟨 B6	🟨 B7	🟩 C1	🟩 C2	🟩 C3	🟨 C4	🟩 D

Production site	Natxitua, Spain
Declared unit	1 m^3 of CLT
End of life scenario(s)	Recycling
Module A4 assumption	Average transportation to France
Module C2 assumption	Not specified
Reference service life	100 years
Wood species	Pine, Larch, Spruce & Fir
Packaging type	Not specified
Density	500-550 kg/m^3
Wood moisture content	12%
Adhesive content	0.71% Polyurethane (PUR)
Maximum application	T = 225 mm, W = 3.8 m, L = 14.0 m

KLH Massivholz GmbH

🟩 A1	🟩 A2	🟩 A3	🟩 A4	🟩 A5	🟨 B1	🟨 B2	🟥 B3	🟥 B4	🟥 B5	🟨 B6	🟨 B7	🟩 C1	🟩 C2	🟩 C3	🟨 C4	🟩 D

Production site	Teufenbach-Katsch, Austria
Declared unit	1 m^3 of CLT
End of life scenario(s)	Energy (17% efficiency) & Thermal recovery (75% efficiency)
Module A4 assumption	Average based on manufacturer's records
Module C2 assumption	50 km
Reference service life	100+ years
Wood species	Spruce, Pine, Fir & Arolla Pine
Packaging type	Polyethylene films
Density	480 kg/m^3
Wood moisture content	12%
Adhesive content	0.66% Polyurethane (PUR), 0.01% polyvinyl acetate (PVAC)
Maximum application	T = 500 mm, W = 2.95 m, L = 16.5 m

Table B.7: Assumptions and characteristics of CLT EPDs (2)

Martinsons Såg AB

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟥 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟥 C2	🟥 C3	🟥 C4	🟥 D

Production site	Bygdsiljum, Sweden
Declared unit	1 m^3 of CLT
End of life scenario(s)	Module not declared
Module A4 assumption	Module not declared
Module C2 assumption	Module not declared
Reference service life	Not specified
Wood species	Spruce
Packaging type	Cardboard and unspecified plastic
Density	430 kg/m^3
Wood moisture content	12%
Adhesive content	0.92% Polyurethane (PUR)
Maximum application	Not specified

Studiengmeinschaft Holzleimbau e.V.

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟩 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟩 C2	🟩 C3	🟥 C4	🟩 D

Production site	-
Declared unit	1 m^3 of CLT
End of life scenario(s)	Energy (18% efficiency) & Thermal recovery (55% efficiency)
Module A4 assumption	Module not declared
Module C2 assumption	20 km
Reference service life	100+ years
Wood species	Spruce, Fir, Pine, Larch, Douglas Fir
Packaging type	Polyethylene films
Density	470 kg/m^3
Wood moisture content	12%
Adhesive content	0.6% Polyurethane (PUR), 1.5% Melamine-urea-formaldehyde (MUF) 0.1% Emulsion polymer isocyanate (EPI)
Maximum application	T = 500 mm, W = 4.8 m, L = 20.0 m

Rubner Holding AG – S.p.A

🟩 A1	🟩 A2	🟩 A3	🟥 A4	🟥 A5	🟥 B1	🟥 B2	🟥 B3	🟥 B4	🟥 B5	🟥 B6	🟥 B7	🟥 C1	🟥 C2	🟩 C3	🟥 C4	🟩 D

Production site	Brixen, Italy
Declared unit	1 m^3 of CLT
End of life scenario(s)	Energy & Thermal recovery (68% efficiency)
Module A4 assumption	Module not declared
Module C2 assumption	Module not declared
Reference service life	100+ years
Wood species	Spruce, Pine, Larch, Fir
Packaging type	Polyethylene films
Density	461 kg/m^3
Wood moisture content	12%
Adhesive content	0.85-2.1% polyurethane (PUR), 0.15-0.4% melamine-urea-formaldehyde (MUF)
Maximum application	T = 300 mm, W = 4.3 m, L = 17.5 m

Table B.8: Assumptions and characteristics of CLT EPDs (3)

<table>
<tr><th colspan="17">Stora Enso Wood Products Oy Ltd</th></tr>
<tr><td>🟩 A1</td><td>🟩 A2</td><td>🟩 A3</td><td>🟥 A4</td><td>🟥 A5</td><td>🟥 B1</td><td>🟥 B2</td><td>🟥 B3</td><td>🟥 B4</td><td>🟥 B5</td><td>🟥 B6</td><td>🟥 B7</td><td>🟩 C1</td><td>🟩 C2</td><td>🟩 C3</td><td>🟩 C4</td><td>🟩 D</td></tr>
<tr><td colspan="6">Production site</td><td colspan="11">Ybbs an der Donau & Bad St. Leonhard, Austria</td></tr>
<tr><td colspan="6">Declared unit</td><td colspan="11">1 m³ of CLT</td></tr>
<tr><td colspan="6">End of life scenario(s)</td><td colspan="11">100% Re-use
100% Recycling
100% Energy & Thermal recovery (80% Efficiency)</td></tr>
<tr><td colspan="6">Module A4 assumption</td><td colspan="11">Module not declared</td></tr>
<tr><td colspan="6">Module C2 assumption</td><td colspan="11">50 km</td></tr>
<tr><td colspan="6">Reference service life</td><td colspan="11">Not specified</td></tr>
<tr><td colspan="6">Wood species</td><td colspan="11">Spruce & Pine</td></tr>
<tr><td colspan="6">Packaging type</td><td colspan="11">Not specified</td></tr>
<tr><td colspan="6">Density</td><td colspan="11">470 kg/m³</td></tr>
<tr><td colspan="6">Wood moisture content</td><td colspan="11">12%</td></tr>
<tr><td colspan="6">Adhesive content</td><td colspan="11">1% Mix of Polyurethane (PUR) & Emulsion polymer isocyanate (EPI)</td></tr>
<tr><td colspan="6">Maximum application</td><td colspan="11">T = 400 mm, W = 2.95 m, L = 16.0 m</td></tr>
</table>

B.3 EPD data

For the corresponding sources see Section B.1, for the assumptions and characteristics see Section B.2.

Table B.9: Parameters describing environmental impacts
Sawn timber – Stora Enso – Re-use

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.99E+02	6.24E-06	2.34E-01	1.12E-01	1.03E-02	2.98E-05	5.00E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.26E+00	0.00E+00	7.05E-03	1.83E-03	3.42E-05	0.00E+00	3.18E+01
	Waste processing	C3	7.32E+02	4.74E-08	8.46E-04	5.54E-03	2.73E-05	9.28E-08	5.91E+00
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	3.58E+01	6.87E-06	2.47E-01	1.20E-01	1.05E-02	3.01E-05	5.83E+02
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-7.61E+02	-1.18E-01	-2.24E-01	-1.04E-01	-1.03E-02	-2.18E-01	-4.19E+02
	Cradle to Cradle	**Total**	-7.25E+02	-1.18E-01	2.32E-02	1.62E-02	1.98E-04	-2.18E-01	1.64E+02

Table B.10: Parameters describing environmental impacts
Sawn timber – Stora Enso – Recycling

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.99E+02	6.24E-06	2.34E-01	1.12E-01	1.03E-02	2.98E-05	5.00E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.26E+00	0.00E+00	7.05E-03	1.83E-03	3.42E-05	0.00E+00	3.18E+01
	Waste processing	C3	7.36E+02	4.32E-07	3.17E-02	1.53E-02	3.53E-04	5.36E-06	5.64E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	3.98E+01	7.26E-06	2.78E-01	1.30E-01	1.08E-02	3.54E-05	6.33E+02
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-7.46E+02	-4.65E-06	-5.73E-02	-8.13E-02	-4.22E-03	-6.47E-07	-1.55E+02
	Cradle to Cradle	**Total**	-7.06E+02	2.61E-06	2.21E-01	4.87E-02	6.60E-03	3.48E-05	4.78E+02

Table B.11: Parameters describing environmental impacts
Sawn timber – Stora Enso – Recover

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.99E+02	6.24E-06	2.34E-01	1.12E-01	1.03E-02	2.98E-05	5.00E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.26E+00	0.00E+00	7.05E-03	1.83E-03	3.42E-05	0.00E+00	3.18E+01
	Waste processing	C3	7.36E+02	4.32E-07	3.17E-02	1.53E-02	3.53E-04	5.36E-06	5.64E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	3.98E+01	7.26E-06	2.78E-01	1.30E-01	1.08E-02	3.54E-05	6.33E+02
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.14E+02	-6.09E-05	5.41E-01	3.22E-01	3.93E-02	3.72E-05	-7.46E+03
	Cradle to Cradle	**Total**	-3.74E+02	-5.36E-05	8.19E-01	4.52E-01	5.01E-02	7.26E-05	-6.82E+03

Table B.12: Parameters describing environmental impacts
Sawn timber – Stora Enso – Landfill

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.99E+02	6.24E-06	2.34E-01	1.12E-01	1.03E-02	2.98E-05	5.00E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.26E+00	0.00E+00	7.05E-03	1.83E-03	3.42E-05	0.00E+00	3.18E+01
	Waste processing	C3	7.36E+02	4.32E-07	3.17E-02	1.53E-02	3.53E-04	5.36E-06	5.64E+01
	Disposal	C4	1.98E+01	1.30E-06	6.86E-02	1.08E+00	3.41E-03	8.85E-06	1.48E+02
	Cradle to Grave	**Total**	5.96E+01	8.56E-06	3.47E-01	1.21E+00	1.42E-02	4.43E-05	7.81E+02
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Cradle	**Total**	5.96E+01	8.56E-06	3.47E-01	1.21E+00	1.42E-02	4.43E-05	7.81E+02

Table B.13: Parameters describing environmental impacts
Sawn timber – Swedish Wood – End of life not declared

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-5.77E+02	MND	2.09E-01	5.02E-02	1.80E-02	1.16E-04	4.51E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	MND	MND	MND	MND	MND	MND	MND
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	MND	MND	MND	MND	MND	MND	MND
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	MND	MND	MND	MND	MND	MND	MND
	Cradle to Cradle	**Total**	MND	MND	MND	MND	MND	MND	MND

Table B.14: Parameters describing environmental impacts
Sawn timber – Wood for Good – Mix of recycling, recovery and landfill

LCA modules			**GWP**	**ODP**	**AP**	**EP**	**POCP**	**ADP-E**	**ADP-F**
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-7.12E+02	2.52E-09	6.44E-01	1.26E-01	4.53E-02	5.13E-06	1.42E+03
Construction process stage	Transport	A4	7.76E+00	5.26E-12	3.21E-02	7.86E-03	-1.32E-02	1.46E-07	1.07E+02
	Construction installation process	A5	4.15E+01	8.00E-11	2.41E-03	4.82E-04	3.08E-04	1.95E-07	5.71E+00
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Replacement	B4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Refurbishment	B5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	1.27E+01	7.52E-12	3.72E-03	3.72E-03	2.46E-03	1.75E-07	1.74E+02
	Transport	C2	7.38E+00	2.17E-11	1.10E-02	1.10E-02	-4.39E-03	2.89E-07	9.86E+01
	Waste processing	C3	7.75E+02	2.50E-10	6.48E-02	6.48E-02	3.51E-02	4.28E-07	6.40E+01
	Disposal	C4	9.19E+00	2.90E-12	9.91E-04	9.91E-04	2.27E-03	5.98E-08	4.87E+00
	Cradle to Grave	**Total**	1.42E+02	2.89E-09	7.59E-01	2.15E-01	6.78E-02	6.42E-06	1.87E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-2.51E+02	-5.89E-08	-5.52E-02	-5.52E-02	-4.18E-02	-3.42E-05	-3.29E+03
	Cradle to Cradle	**Total**	-1.09E+02	-5.60E-08	7.04E-01	1.60E-01	2.60E-02	-2.78E-05	-1.42E+03

Table B.15: Parameters describing environmental impacts
Glulam – Binderholz – Recovery

LCA modules			GWP kg CO_2 eq.	ODP kg CFC-11 eq.	AP kg. SO_2 eq.	EP kg PO_4 eq.	POCP kg C_2H_4 eq.	ADP-E kg Sb eq.	ADP-F MJ net calorific value
Product stage	Raw material supply	A1	-6.60E+02	1.58E-12	3.17E-01	7.46E-02	1.99E-02	2.11E-05	-6.60E+02
	Transport	A2	6.26E+00	1.05E-15	2.64E-02	6.73E-03	-1.09E-02	4.89E-07	6.26E+00
	Manufacturing	A3	1.44E+01	6.59E-13	6.04E-02	1.29E-02	3.57E-02	1.40E-05	1.44E+01
	Cradle to Gate	**Total**	-6.39E+02	2.24E-12	4.04E-01	9.42E-02	4.47E-02	3.56E-05	-6.39E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	4.42E+00	1.16E-15	6.73E-04	8.89E-05	3.05E-05	1.42E-07	4.42E+00
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	5.36E-01	8.99E-17	2.27E-03	5.77E-04	9.36E-04	4.19E-08	5.36E-01
	Waste processing	C3	7.49E+02	1.80E-13	6.64E-03	1.08E-03	4.39E-04	1.80E-06	7.49E+02
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	1.15E+02	2.42E-12	4.13E-01	9.60E-02	4.61E-02	3.76E-05	1.15E+02
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-3.95E+02	-9.20E-12	-3.61E-01	-5.61E-02	-3.18E-02	-9.38E-05	-3.95E+02
	Cradle to Cradle	**Total**	-2.80E+02	-6.78E-12	5.24E-02	3.99E-02	1.43E-02	-5.62E-05	-2.80E+02

Table B.16: Parameters describing environmental impacts
Glulam – Moelven – End of life not declared

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.56E+02	9.90E-07	3.80E-01	8.70E-02	4.20E-02	3.30E-05	8.67E+02
Construction process stage	Transport	A4	4.30E+00	1.90E-11	2.00E-02	4.00E-03	-6.00E-03	2.80E-07	5.80E+01
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	MND	MND	MND	MND	MND	MND	MND
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	MND	MND	MND	MND	MND	MND	MND
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	MND	MND	MND	MND	MND	MND	MND
	Cradle to Cradle	**Total**	MND	MND	MND	MND	MND	MND	MND

Table B.17: Parameters describing environmental impacts
Glulam – Martinsons – End of life not declared

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.79E+02	3.70E-06	2.90E-01	7.20E-02	4.60E-02	3.50E-05	5.63E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	MND	MND	MND	MND	MND	MND	MND
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	MND	MND	MND	MND	MND	MND	MND
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	MND	MND	MND	MND	MND	MND	MND
	Cradle to Cradle	**Total**	MND	MND	MND	MND	MND	MND	MND

Table B.18: Parameters describing environmental impacts
Glulam – Rubner – Recovery

LCA modules			GWP kg CO_2 eq.	ODP kg CFC-11 eq.	AP kg. SO_2 eq.	EP kg PO_4 eq.	POCP kg C_2H_4 eq.	ADP-E kg Sb eq.	ADP-F MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.46E+02	2.56E-05	8.40E-01	1.70E-01	1.03E-01	1.01E-04	1.34E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	7.67E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	1.21E+02	2.56E-05	8.40E-01	1.70E-01	1.03E-01	1.01E-04	1.34E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.12E+02	-1.08E-09	4.77E-01	1.29E-02	8.97E-02	-1.40E-04	-5.52E+03
	Cradle to Cradle	**Total**	-2.91E+02	2.56E-05	1.32E+00	1.83E-01	1.93E-01	-3.90E-05	-4.18E+03

Table B.19: Parameters describing environmental impacts Glulam – Schilliger – Recovery

LCA modules			**GWP**	**ODP**	**AP**	**EP**	**POCP**	**ADP-E**	**ADP-F**
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.15E+02	5.25E-06	3.94E-01	8.93E-02	1.23E-01	2.20E-05	1.10E+03
Construction process stage	Transport	A4	4.12E+00	1.35E-07	2.22E-01	5.02E-03	6.34E-04	4.88E-09	5.55E+01
	Construction installation process	A5	5.75E+00	5.22E-09	5.31E-04	1.80E-04	6.48E-06	2.61E-09	7.32E-01
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	1.37E+00	4.47E-08	7.36E-03	1.67E-03	2.10E-04	1.62E-09	1.84E+01
	Waste processing	C3	6.86E+02	1.93E-07	1.51E-02	1.97E-03	6.40E-04	1.18E-07	6.54E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	8.22E+01	5.63E-06	6.39E-01	9.81E-02	1.24E-01	2.21E-05	1.24E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-1.96E-02	-3.97E-05	-1.92E-01	3.13E-03	-1.28E-02	-1.04E-05	-3.15E+03
	Cradle to Cradle	**Total**	8.22E+01	-3.41E-05	4.47E-01	1.01E-01	1.12E-01	1.17E-05	-1.91E+03

Table B.20: Parameters describing environmental impacts
Glulam – Studiengemeinschaft – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-7.15E+02	7.14E-07	2.37E-01	6.59E-02	4.02E-02	5.53E-04	8.32E+02
	Transport	A2	3.21E+01	5.49E-08	1.32E-01	2.91E-02	9.83E-03	2.22E-06	4.38E+02
	Manufacturing	A3	6.82E+01	1.18E-07	3.48E-01	7.41E-02	7.38E-02	1.65E-04	7.66E+02
	Cradle to Gate	**Total**	-6.15E+02	8.87E-07	7.17E-01	1.69E-01	1.24E-01	7.20E-04	2.04E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	4.52E+00	4.31E-12	3.91E-04	8.23E-05	3.33E-05	5.31E-08	7.61E-01
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	4.85E-01	9.69E-10	2.08E-03	4.82E-04	1.85E-04	1.03E-08	7.61E-01
	Waste processing	C3	7.78E+02	1.75E-11	6.90E-03	1.10E-03	4.78E-04	2.34E-06	4.52E+01
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	1.68E+02	8.88E-07	7.26E-01	1.71E-01	1.25E-01	7.23E-04	2.08E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.15E+02	-9.27E-10	-4.30E-01	-6.42E-02	-4.38E-02	-1.26E-04	-5.52E+03
	Cradle to Cradle	**Total**	-2.47E+02	8.87E-07	2.96E-01	1.07E-01	8.07E-02	5.97E-04	-3.44E+03

Table B.21: Parameters describing environmental impacts LVL – Stora Enso – Re-use

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.64E+02	3.04E-05	8.80E-01	2.95E-01	8.44E-02	7.54E-04	2.94E+03
	Transport	A2	1.28E+01	2.54E-06	3.44E-02	7.41E-03	2.01E-03	2.75E-05	2.08E+02
	Manufacturing	A3	2.13E+01	3.15E-06	9.89E-02	4.85E-02	1.75E-02	8.47E-05	3.38E+02
	Cradle to Gate	**Total**	-6.30E+02	3.61E-05	1.01E+00	3.51E-01	1.04E-01	8.66E-04	3.49E+03
Construction process stage	Transport	A4	1.40E+01	2.82E-06	3.84E-02	8.23E-03	2.21E-03	2.75E-05	2.31E+02
	Construction installation process	A5	6.81E+00	4.61E-07	1.76E-02	7.98E-03	1.34E-03	2.28E-05	4.65E+01
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Replacement	B4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Refurbishment	B5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	5.36E-01	9.44E-08	5.06E-03	9.56E-04	1.12E-04	2.69E-07	7.68E+00
	Transport	C2	2.19E+00	4.40E-07	6.00E-03	1.29E-03	3.45E-04	4.29E-06	3.60E+01
	Waste processing	C3	8.04E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	1.98E+02	3.99E-05	1.08E+00	3.69E-01	1.08E-01	9.21E-04	3.81E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-1.72E+02	-3.55E-05	-1.00E+00	-3.49E-01	-1.04E-01	-8.62E-04	-3.44E+03
	Cradle to Cradle	**Total**	2.56E+01	4.41E-06	8.04E-02	2.04E-02	3.92E-03	5.91E-05	3.67E+02

Table B.22: Parameters describing environmental impacts LVL – Stora Enso – Recycling

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.64E+02	3.04E-05	8.80E-01	2.95E-01	8.44E-02	7.54E-04	2.94E+03
	Transport	A2	1.28E+01	2.54E-06	3.44E-02	7.41E-03	2.01E-03	2.75E-05	2.08E+02
	Manufacturing	A3	2.13E+01	3.15E-06	9.89E-02	4.85E-02	1.75E-02	8.47E-05	3.38E+02
	Cradle to Gate	**Total**	-6.30E+02	3.61E-05	1.01E+00	3.51E-01	1.04E-01	8.66E-04	3.49E+03
Construction process stage	Transport	A4	1.40E+01	2.82E-06	3.84E-02	8.23E-03	2.21E-03	2.75E-05	2.31E+02
	Construction installation process	A5	6.81E+00	4.61E-07	1.76E-02	7.98E-03	1.34E-03	2.28E-05	4.65E+01
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Replacement	B4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Refurbishment	B5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	5.36E-01	9.44E-08	5.06E-03	9.56E-04	1.12E-04	2.69E-07	7.68E+00
	Transport	C2	2.19E+00	4.40E-07	6.00E-03	1.29E-03	3.45E-04	4.29E-06	3.60E+01
	Waste processing	C3	8.10E+02	1.10E-06	5.87E-02	1.07E-02	1.21E-03	2.05E-06	8.78E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	2.04E+02	4.10E-05	1.14E+00	3.80E-01	1.09E-01	9.23E-04	3.89E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-6.24E+01	-7.58E-06	-4.03E-01	-1.51E-01	-5.40E-02	-2.83E-04	-1.03E+03
	Cradle to Cradle	**Total**	1.41E+02	3.34E-05	7.36E-01	2.29E-01	5.51E-02	6.40E-04	2.86E+03

Table B.23: Parameters describing environmental impacts LVL – Stora Enso – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.64E+02	3.04E-05	8.80E-01	2.95E-01	8.44E-02	7.54E-04	2.94E+03
	Transport	A2	1.28E+01	2.54E-06	3.44E-02	7.41E-03	2.01E-03	2.75E-05	2.08E+02
	Manufacturing	A3	2.13E+01	3.15E-06	9.89E-02	4.85E-02	1.75E-02	8.47E-05	3.38E+02
	Cradle to Gate	**Total**	-6.30E+02	3.61E-05	1.01E+00	3.51E-01	1.04E-01	8.66E-04	3.49E+03
Construction process stage	Transport	A4	1.40E+01	2.82E-06	3.84E-02	8.23E-03	2.21E-03	2.75E-05	2.31E+02
	Construction installation process	A5	6.81E+00	4.61E-07	1.76E-02	7.98E-03	1.34E-03	2.28E-05	4.65E+01
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Replacement	B4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Refurbishment	B5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	5.36E-01	9.44E-08	5.06E-03	9.56E-04	1.12E-04	2.69E-07	7.68E+00
	Transport	C2	2.19E+00	4.40E-07	6.00E-03	1.29E-03	3.45E-04	4.29E-06	3.60E+01
	Waste processing	C3	9.90E+02	2.68E-06	1.89E-01	1.03E-01	4.87E-03	2.46E-05	2.50E+02
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	3.84E+02	4.26E-05	1.27E+00	4.72E-01	1.13E-01	9.46E-04	4.06E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.28E+02	-6.35E-05	-1.86E-01	3.85E-02	-2.49E-02	1.07E-06	-8.25E+03
	Cradle to Cradle	**Total**	-4.44E+01	-2.09E-05	1.08E+00	5.11E-01	8.79E-02	9.47E-04	-4.19E+03

Table B.24: Parameters describing environmental impacts LVL – Stora Enso – Landfill

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO$_2$ eq.	kg CFC-11 eq.	kg. SO$_2$ eq.	kg PO$_4$ eq.	kg C$_2$H$_4$ eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.64E+02	3.04E-05	8.80E-01	2.95E-01	8.44E-02	7.54E-04	2.94E+03
	Transport	A2	1.28E+01	2.54E-06	3.44E-02	7.41E-03	2.01E-03	2.75E-05	2.08E+02
	Manufacturing	A3	2.13E+01	3.15E-06	9.89E-02	4.85E-02	1.75E-02	8.47E-05	3.38E+02
	Cradle to Gate	**Total**	-6.30E+02	3.61E-05	1.01E+00	3.51E-01	1.04E-01	8.66E-04	3.49E+03
Construction process stage	Transport	A4	1.40E+01	2.82E-06	3.84E-02	8.23E-03	2.21E-03	2.75E-05	2.31E+02
	Construction installation process	A5	6.81E+00	4.61E-07	1.76E-02	7.98E-03	1.34E-03	2.28E-05	4.65E+01
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Replacement	B4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Refurbishment	B5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	5.36E-01	9.44E-08	5.06E-03	9.56E-04	1.12E-04	2.69E-07	7.68E+00
	Transport	C2	2.19E+00	4.40E-07	6.00E-03	1.29E-03	3.45E-04	4.29E-06	3.60E+01
	Waste processing	C3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Disposal	C4	1.03E+03	2.42E-06	1.08E-01	1.41E+00	5.37E-02	8.16E-06	2.01E+02
	Cradle to Grave	**Total**	4.24E+02	4.23E-05	1.19E+00	1.78E+00	1.62E-01	9.29E-04	4.01E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-1.77E+01	-2.22E-06	-1.29E-02	-2.23E-03	-1.01E-03	-9.36E-07	-2.85E+02
	Cradle to Cradle	**Total**	4.06E+02	4.01E-05	1.18E+00	1.78E+00	1.61E-01	9.28E-04	3.72E+03

Table B.25: Parameters describing environmental impacts LVL – Steico – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-8.29E+02	2.53E-08	1.33E-01	2.49E-02	2.17E-02	9.78E-06	1.53E+03
	Transport	A2	1.38E+01	2.95E-13	5.58E-02	1.43E-02	-2.37E-02	1.38E-06	1.83E+02
	Manufacturing	A3	2.84E+02	1.87E-08	1.26E+00	1.57E-01	1.70E-01	3.68E-05	2.98E+03
	Cradle to Gate	**Total**	-5.31E+02	4.40E-08	1.45E+00	1.96E-01	1.68E-01	4.80E-05	4.69E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	1.86E+01	2.80E-13	2.94E-03	4.44E-04	1.33E-04	6.06E-07	4.81E+00
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	6.40E-01	1.77E-14	2.70E-03	6.93E-04	-1.12E-03	5.31E-08	8.80E+00
	Waste processing	C3	8.86E+02	6.58E-12	6.81E-03	1.11E-03	4.52E-04	3.05E-06	4.33E+01
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	3.74E+02	4.40E-08	1.46E+00	1.98E-01	1.67E-01	5.17E-05	4.75E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.43E+02	-4.12E-10	-4.55E-01	-7.15E-02	-4.04E-02	-1.87E-04	-6.38E+03
	Cradle to Cradle	**Total**	-6.90E+01	4.36E-08	1.01E+00	1.27E-01	1.27E-01	-1.35E-04	-1.63E+03

Table B.26: Parameters describing environmental impacts
LVL – MetsäWood – End of life not declared

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.72E+02	1.23E-09	1.01E+00	2.03E-01	1.11E-01	8.00E-04	2.36E+03
	Transport	A2	1.20E+01	5.03E-11	5.80E-02	1.50E-02	-2.20E-02	4.80E-07	1.69E+02
	Manufacturing	A3	5.00E+00	1.80E-08	1.40E-02	2.00E-03	3.00E-03	-1.69E-07	8.80E+01
	Cradle to Gate	**Total**	-6.55E+02	1.93E-08	1.08E+00	2.20E-01	9.20E-02	8.00E-04	2.61E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	MND	MND	MND	MND	MND	MND	MND
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	MND	MND	MND	MND	MND	MND	MND
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	MND	MND	MND	MND	MND	MND	MND
	Cradle to Cradle	**Total**	MND	MND	MND	MND	MND	MND	MND

Table B.27: Parameters describing environmental impacts
CLT – Binderholz – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.83E+02	3.57E-07	2.85E-01	6.54E-02	6.82E-02	8.01E-05	1.08E+03
	Transport	A2	7.56E+00	2.09E-13	3.19E-02	8.19E-03	-1.33E-02	6.28E-07	1.04E+02
	Manufacturing	A3	1.84E+01	8.38E-09	9.88E-02	2.07E-02	1.26E-02	2.47E-05	2.64E+02
	Cradle to Gate	**Total**	-6.57E+02	3.65E-07	4.16E-01	9.43E-02	6.75E-02	1.05E-04	1.45E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	4.08E+00	1.02E-13	9.74E-04	7.94E-05	3.38E-05	2.89E-07	1.42E+00
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	5.48E-01	1.51E-14	2.31E-03	5.93E-04	-9.62E-04	4.55E-08	7.53E+00
	Waste processing	C3	7.66E+02	6.58E-12	6.81E-03	1.11E-03	4.52E-04	3.05E-06	4.33E+01
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	1.14E+02	3.65E-07	4.26E-01	9.61E-02	6.70E-02	1.09E-04	1.50E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.12E+02	-3.46E-10	-3.89E-01	-6.04E-02	-3.41E-02	-1.63E-04	-5.35E+03
	Cradle to Cradle	**Total**	-2.98E+02	3.65E-07	3.68E-02	3.57E-02	3.29E-02	-5.42E-05	-3.85E+03

Table B.28: Parameters describing environmental impacts
CLT – Egoin – Recycling

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-7.16E+02	1.90E-05	9.20E-01	2.10E-01	1.40E-01	4.00E-04	1.90E+03
	Transport	A2	2.75E+01	5.20E-06	6.60E-02	1.40E-02	4.20E-03	8.50E-05	4.40E+02
	Manufacturing	A3	3.20E+00	4.30E-07	2.10E-02	4.70E-03	6.50E-04	1.20E-06	6.01E+01
	Cradle to Gate	**Total**	-6.86E+02	2.46E-05	1.01E+00	2.29E-01	1.45E-01	4.86E-04	2.40E+03
Construction process stage	Transport	A4	4.78E+01	9.00E-06	1.10E-01	2.40E-02	7.40E-03	1.50E-04	7.67E+02
	Construction installation process	A5	7.39E+00	1.20E-06	5.00E-02	1.30E-02	2.20E-03	3.40E-04	1.17E+02
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Replacement	B4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Refurbishment	B5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	4.99E+00	9.10E-07	3.80E-02	8.70E-03	1.00E-03	1.50E-06	7.68E+01
	Transport	C2	2.38E+00	4.50E-07	5.70E-03	1.20E-03	3.70E-04	7.30E-06	3.81E+01
	Waste processing	C3	8.59E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	2.36E+02	3.62E-05	1.21E+00	2.76E-01	1.56E-01	9.85E-04	3.40E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-5.65E+01	-6.22E-06	-3.77E-01	-9.55E-02	-3.60E-02	-1.55E-04	-8.40E+02
	Cradle to Cradle	**Total**	1.80E+02	3.00E-05	8.34E-01	1.80E-01	1.20E-01	8.30E-04	2.56E+03

Table B.29: Parameters describing environmental impacts
CLT – KLH – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.01E+02	1.93E-05	9.80E-01	3.30E-01	1.50E-01	6.19E-04	2.49E+03
Construction process stage	Transport	A4	7.04E+01	1.28E-05	2.30E-01	5.00E-02	3.00E-02	2.09E-04	1.05E+03
	Construction installation process	A5	2.07E+01	2.46E-06	1.10E-01	3.00E-02	2.00E-02	1.12E-03	2.35E+02
Use stage	Use	B1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Maintenance	B2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Operational water use	B7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of life	Deconstruction, demolition	C1	9.28E+00	1.67E-06	7.00E-02	2.00E-02	1.00E-02	3.16E-06	1.34E+02
	Transport	C2	4.02E+00	7.31E-07	1.00E-02	0.00E+00	0.00E+00	1.20E-05	6.01E+01
	Waste processing	C3	8.08E+02	5.66E-07	1.10E-01	1.40E-01	2.00E-02	9.68E-06	4.54E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	3.11E+02	3.75E-05	1.51E+00	5.70E-01	2.30E-01	1.97E-03	4.02E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-2.03E+02	-3.77E-05	-3.80E-01	-2.10E-01	-6.00E-02	-1.40E-04	-3.17E+03
	Cradle to Cradle	**Total**	1.08E+02	-1.73E-07	1.13E+00	3.60E-01	1.70E-01	1.83E-03	8.47E+02

Table B.30: Parameters describing environmental impacts CLT – Martinsons – End of life not declared

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.72E+02	4.50E-06	2.90E-01	6.10E-02	3.50E-02	7.70E-05	7.13E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	MND	MND	MND	MND	MND	MND	MND
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	MND	MND	MND	MND	MND	MND	MND
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	MND	MND	MND	MND	MND	MND	MND
	Cradle to Cradle	**Total**	MND	MND	MND	MND	MND	MND	MND

Table B.31: Parameters describing environmental impacts
CLT – Studiengemeinschaft – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-6.99E+02	6.52E-07	2.31E-01	6.05E-02	4.79E-02	5.11E-04	7.99E+02
	Transport	A2	7.56E+00	2.78E-09	3.16E-02	7.73E-03	-9.85E-03	7.14E-07	1.02E+02
	Manufacturing	A3	9.70E+01	7.64E-08	2.85E-01	5.58E-02	5.99E-02	1.28E-04	1.02E+03
	Cradle to Gate	**Total**	-5.94E+02	7.31E-07	5.48E-01	1.24E-01	9.80E-02	6.40E-04	1.92E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	1.76E+00	1.16E-12	1.09E-04	2.43E-05	1.14E-05	1.26E-08	1.96E-01
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	4.72E-01	9.42E-10	2.02E-03	4.69E-04	1.80E-04	1.00E-08	6.63E+00
	Waste processing	C3	7.58E+02	1.75E-11	6.90E-03	1.10E-03	4.78E-04	2.34E-06	4.52E+01
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	1.66E+02	7.32E-07	5.57E-01	1.26E-01	9.86E-02	6.42E-04	1.97E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.04E+02	-9.03E-10	-4.18E-01	-6.25E-02	-4.26E-02	-1.22E-04	-5.37E+03
	Cradle to Cradle	**Total**	-2.38E+02	7.31E-07	1.39E-01	6.31E-02	5.60E-02	5.20E-04	-3.40E+03

Table B.32: Parameters describing environmental impacts CLT – Rubner – Recovery

LCA modules			GWP kg CO_2 eq.	ODP kg CFC-11 eq.	AP kg. SO_2 eq.	EP kg PO_4 eq.	POCP kg C_2H_4 eq.	ADP-E kg Sb eq.	ADP-F MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.64E+02	3.18E-05	6.85E-01	1.34E-01	9.53E-02	8.24E-05	1.34E+03
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	MND	MND	MND	MND	MND	MND	MND
	Transport	C2	MND	MND	MND	MND	MND	MND	MND
	Waste processing	C3	7.59E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Disposal	C4	MND	MND	MND	MND	MND	MND	MND
	Cradle to Grave	**Total**	9.50E+01	3.18E-05	6.85E-01	1.34E-01	9.53E-02	8.24E-05	1.34E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.10E+02	-1.07E-09	4.75E-01	1.29E-02	8.92E-02	-1.39E-04	-5.49E+03
	Cradle to Cradle	**Total**	-3.15E+02	3.18E-05	1.16E+00	1.47E-01	1.85E-01	-5.66E-05	-4.15E+03

Table B.33: Parameters describing environmental impacts CLT – Stora Enso – Re-use

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.71E+02	8.14E-06	2.40E-01	3.47E-01	6.82E-03	3.70E-05	9.59E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.37E+00	0.00E+00	7.41E-03	1.92E-03	3.59E-05	0.00E+00	3.34E+01
	Waste processing	C3	7.31E+02	4.74E-08	8.46E-04	5.54E-03	2.73E-05	9.28E-08	5.91E+00
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	6.29E+01	8.77E-06	2.54E-01	3.55E-01	7.02E-03	3.73E-05	1.04E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-7.88E+02	-7.51E-06	-2.27E-01	-3.39E-01	-6.62E-03	-3.67E-05	-8.75E+02
	Cradle to Cradle	**Total**	-7.25E+02	1.26E-06	2.66E-02	1.63E-02	3.99E-04	6.42E-07	1.68E+02

Table B.34: Parameters describing environmental impacts
CLT – Stora Enso – Recycling

LCA modules			GWP kg CO_2 eq.	ODP kg CFC-11 eq.	AP kg. SO_2 eq.	EP kg PO_4 eq.	POCP kg C_2H_4 eq.	ADP-E kg Sb eq.	ADP-F MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.71E+02	8.14E-06	2.40E-01	3.47E-01	6.82E-03	3.70E-05	9.59E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.37E+00	0.00E+00	7.41E-03	1.92E-03	3.59E-05	0.00E+00	3.34E+01
	Waste processing	C3	7.35E+02	4.54E-07	3.32E-02	1.60E-02	3.71E-04	5.63E-06	5.92E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00
	Cradle to Grave	**Total**	6.69E+01	9.18E-06	2.86E-01	3.66E-01	7.36E-03	4.29E-05	1.10E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-7.44E+02	-4.63E-06	-5.53E-02	-8.05E-02	-4.20E-03	-3.79E-07	-1.50E+02
	Cradle to Cradle	**Total**	-6.77E+02	4.55E-06	2.31E-01	2.85E-01	3.16E-03	4.25E-05	9.47E+02

Table B.35: Parameters describing environmental impacts CLT – Stora Enso – Recovery

LCA modules			GWP	ODP	AP	EP	POCP	ADP-E	ADP-F
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ net calorific value
Product stage	Raw material supply	A1	-	-	-	-	-	-	-
	Transport	A2	-	-	-	-	-	-	-
	Manufacturing	A3	-	-	-	-	-	-	-
	Cradle to Gate	**Total**	-6.71E+02	8.14E-06	2.40E-01	3.47E-01	6.82E-03	3.70E-05	9.59E+02
Construction process stage	Transport	A4	MND	MND	MND	MND	MND	MND	MND
	Construction installation process	A5	MND	MND	MND	MND	MND	MND	MND
Use stage	Use	B1	MND	MND	MND	MND	MND	MND	MND
	Maintenance	B2	MND	MND	MND	MND	MND	MND	MND
	Repair	B3	MND	MND	MND	MND	MND	MND	MND
	Replacement	B4	MND	MND	MND	MND	MND	MND	MND
	Refurbishment	B5	MND	MND	MND	MND	MND	MND	MND
	Operation energy use	B6	MND	MND	MND	MND	MND	MND	MND
	Operational water use	B7	MND	MND	MND	MND	MND	MND	MND
End of life	Deconstruction, demolition	C1	5.51E-01	5.86E-07	5.30E-03	8.27E-04	1.36E-04	2.49E-07	4.49E+01
	Transport	C2	2.37E+00	0.00E+00	7.41E-03	1.92E-03	3.59E-05	0.00E+00	3.34E+01
	Waste processing	C3	7.35E+02	4.54E-07	3.32E-02	1.60E-02	3.71E-04	5.63E-06	5.92E+01
	Disposal	C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Cradle to Grave	**Total**	6.69E+01	9.18E-06	2.86E-01	3.66E-01	7.36E-03	4.29E-05	1.10E+03
Benefits and loads beyond the system boundaries	Re-use, recovery, recycling potential	D	-4.13E+02	-6.07E-05	5.97E-01	3.44E-01	4.24E-02	4.08E-05	-7.44E+03
	Cradle to Cradle	**Total**	-3.46E+02	-5.15E-05	8.83E-01	7.10E-01	4.98E-02	8.37E-05	-6.35E+03

B.4 Environmental data used in comparison of EPD vs NMD

Table B.36: Environmental data for comparison EPD vs NMD

Material or product	Unit	EOL	GWP	ODP	AP	EP	POCP	ADP-E	ADP-F	Shadow price	HTP	FAETP	MAETP	TETP	Shadow price	Source
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	kg Sb eq.	€/unit	kg 1,4 Db eq.	kg 1,4 Db eq.	kg 1,4 Db eq.	kg 1,4 Db eq.	€/unit	
			€ 0.05	€ 30.00	€ 4.00	€ 9.00	€ 2.00	€ 0.16	€ 0.16		€ 0.09	€ 0.03	€ 0.0001	€ 0.06		
Glulam total	kg	Recovery	2.93E-01	1.64E-08	1.19E-03	2.67E-04	1.87E-04	3.38E-07	1.40E-03	0.022	-	-	-	-	-	DA
Glulam total + D	kg	Recovery	2.49E-01	2.29E-09	3.82E-05	-1.07E-04	8.19E-06	2.44E-07	1.16E-03	0.012	-	-	-	-	-	DA
Glulam total	kg	Recovery	5.90E-01	6.83E-08	2.92E-03	6.84E-04	8.16E-04	1.30E-06	4.48E-03	0.050	2.93E-01	1.27E-02	3.57E+01	3.64E-03	0.080	NIBE
Glulam total + D	kg	Recovery	5.47E-01	5.41E-08	1.77E-03	3.10E-04	6.37E-04	1.21E-06	4.25E-03	0.039	1.96E-01	1.06E-02	3.35E+01	2.97E-03	0.061	NIBE

The environmental data as used in the comparison is presented in Table B.36. The timber data is used from the data analysis (DA) in Chapter 3 and previous sections of this appendix. All used EPDs are third party verified and in compliance with ISO 14025 and EN 15804.

Data sources from the NMD are retrieved from the NIBE EPD application.

- Stage A1-A3: NIBE EPD application
  423 | Laminated European softwood, from sustainable managed forest [NVL]
- Stage C1-C4: NIBE EPD application
  WPNL0026 | 0263-avC&Verbranden hout, verontreinigd (13,99 MJ/kg) (o.b.v. Waste building wood, chrome preserved {CH} | treatment of municipal incineration | Cut-off, U
- Stage D: NIBE EPD application
  E0081 | 0268-avD&Vermeden energieproductie AVI, o.b.v. HERNIEUWBARE grondstoffen, 18% elektrisch en 31% thermisch

B.5 Energy and Thermal recovery according to Dutch methodology

The Dutch MPG methodology, version 3.0, prescribes how the avoided energy production should be calculated when a thermal and energy recovery scenario is chosen as described in the report ‘Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken’ by Stichting Bouwkwaliteit [68]. This is based on material equivalency, meaning that biomass will replace biomass, not fossil fuels. The calculation is based on the lower heating value of wood (13.99 MJ/kg) and the net efficiency of Dutch incineration plants (18% electricity 31% thermal recovery). See Table B.37 for the data for avoided energy production.

Table B.37: Energy and thermal recovery scenario according to MPG and EPD (LCA stage D)

Environmental impact category	**Reference unit**	**MPG avoided energy production for renewable resources**[1] [MJ]	**MPG avoided energy production conversion for timber** [kg]	**EPD avoided energy production for average CLT** [kg]
GWP	kg CO_2 eq.	-3.06E-03	-4.34E-02	-7.85E-01
ODP	kg CFC-11 eq.	-1.01E-09	-1.41E-08	-4.15E-08
AP	kg SO_2 eq.	-8.20E-05	-1.15E-03	-4.13E-05
EP	kg PO_4^{3-} eq.	-2.68E-05	-3.74E-04	1.22E-05
POCP	kg C_2H_4 eq.	-1.28E-05	-1.79E-04	-8.70E-07
ADP-E	kg Sb eq.	-6.61E-09	-9.33E-08	-2.22E-07
ADP-F	kg Sb eq.	-1.68E-05	-2.36E-04	-5.50E-03
HTP	kg 1,4 Db eq.	-7.02E-03	-9.82E-02	-
FAETP	kg 1,4 Db eq.	-1.56E-04	-2.18E-03	-
MAETP	kg 1,4 Db eq.	-1.58E-01	-2.21E+00	-
TETP	kg 1,4 Db eq.	-4.78E-05	-6.69E-04	-

[1] Data source: NIBE EPD Application (Environmental profile E0081: 0268-avD&Vermeden energieproductie AVI, o.b.v. HERNIEUWBARE grondstoffen, 18% elektrisch en 31% thermisch)

Using the data from Table B.37 the following results are obtained for avoided energy production in LCA stage D (based on shadow prices from Table 3.1):

- -0.040 €/kg material based on European EPD data
- -0.011 €/kg material based on Dutch NMD data

The Dutch methodology, based on material equivalency, lowers the benefits of the recovery scenario compared to the European methodology (EN 15804) which is based on the current average substitution process of power mix [60]. The total benefit is lowered by:

$$\frac{-0.011 - -0.040}{-0.040} * 100 = -72.5\% \ (reduction)$$

B.6 Human toxicity potential verification

The verification of the HTP in the NMD is executed based on an LCA study of the Massiv-Holz-Mauer (MHM) wall system by the University of Padau and the University of Washington [147]. The wall system has a hybrid composition consisting of plasterboards, nine layers of spruce boards which uses nails instead of adhesives, geotextile, fibreboards, mortar, plaster mesh, and plaster. The specific environmental impact of solely the spruce boards have been extracted from the LCA in Table B.38:

Table B.38: Human toxicity potential of MHM wall system(LCA stage A1-A3)

Density	ρ	480	kg/m³
Total Spruce Boards per m² wall	V	0.207	m³
Total Spruce Boards per m² wall	$m = \rho * V$	99.36	kg
HTP Forest operation per m² wall	HTP_{Forest}	0.463	kg 1,4 Db eq.
HTP Sawmill process per m² wall	$HTP_{Sawmill}$	1.604	kg 1,4 Db eq.
HTP total per m² wall	$HTP_{Forest} + HTP_{Sawmill} = HTP_{Total}$	2.067	kg 1,4 Db eq.
HTP total per kg Spruce	$HTP = \frac{HTP_{Total}}{m}$	0.0208	kg 1,4 Db eq.

The HTP is compared to environmental data for sawn timber since no adhesives are used in the MHM wall system, see Table B.39.

Table B.39: Human toxicity potential of European softwood NMD(LCA stage A1-A3)

HTP per kg European softwood[1]	HTP	0.108	kg 1,4 Db eq.

[1] Data source: NIBE EPD Application (Environmental profile 442: European softwood, dried (n=15%, 496kg/m3), planed, from sustainable managed forest [VVNH])

Similar to the seven impact categories which are quantified for both the EPDs and the NMD (see Figure 3.25), the HTP based on the LCA study is significantly lower compared to the data from the NMD:

$$\frac{0.0208 - 0.108}{0.108} * 100 = -80.7\% \ (reduction)$$

B.7 Environmental data used in variant and case study

The environmental data as used in the variant and case study are presented in Table B.40. The timber data is used from the data analysis (DA) in Chapter 3 and previous sections of this appendix.

Data sources from the NMD are partly used from the NMD viewer v2.3 or the NIBE EPD application. The NIBE EPD application contains more up to date end of life scenarios according to MPG version 3.0 and is therefore prioritized. In case no applicable data was found in these databases an EPD is used. All used EPDs are third party verified and in compliance with ISO 14025 and EN 15804.

Sources:

- EPD1: [148]
- EPD2: [149]
- EPD3: [150]
- EPD4: [151]
- EPD5: [152]
- Concrete C30/37:
  - Stage A1-A3: NMD viewer v2.3
    SBK 847 Betonmortel C30/37 (o.b.v. 75% CEM III en 25% CEM I)
  - Stage C1-C4: NIBE EPD application
    070-reC&Breken, per kg steenachtig (o.b.v. SBK Breken steenachtigen MRPI)
  - Stage D: NIBE EPD application
    487 | Gravel, round (RoW)
- Reinforcement:
  - Stage A1-A3: NIBE EPD application
    257 | Steel, Reinforcement [VWN]
  - Stage C1-C4: NIBE EPD application
    Recycling steel [Steel federation NL] (SBK Bepalingsmethode)
  - Stage D: NMD viewer v2.3
    SBK 024r recycling metalen, overig
- Flax wool:
  - A1-A3: NMD viewer v2.3
    SBK 262 Vlas
  - C-D: NMD viewer v2.3
    SBK 025v verbranden organisch (via restmateriaal)
- Sand cement:
  - A1-A3: NMD viewer 2.3
    SBK 297 Zandcement
  - C-D: NMD viewer 2.3
    SBK 030s stort puin

Table B.40: Environmental data variant and case study

Material or product	Unit	EOL	Density	RSL	GWP	ODP	AP	EP	POCP	ADP-E	ADP-F	Shadow price	HTP	FAETP	MAETP	TETP	Shadow price	Source
			kg/m³	Years	kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	kg Sb eq.	€/unit	kg 1,4 Db eq.	kg 1,4 Db eq.	kg 1,4 Db eq.	kg 1,4 Db eq.	€/unit	
					€ 0.05	€ 30.00	€ 4.00	€ 9.00	€ 2.00	€ 0.16	€ 0.16		€ 0.09	€ 0.03	€ 0.0001	€ 0.06		
Glulam total	kg	Recovery	420	50+	2.93E-01	1.64E-08	1.19E-03	2.67E-04	1.87E-04	3.38E-07	1.40E-03	0.022	-	-	-	-	-	DA
Glulam total + D	kg	Recovery	420	50+	2.49E-01	2.29E-09	3.82E-05	-1.07E-04	8.19E-06	2.44E-07	1.16E-03	0.012	-	-	-	-	-	DA
LVL total	kg	Recovery	500	50+	6.25E-01	3.00E-08	2.57E-03	6.25E-04	2.41E-04	1.24E-06	3.65E-03	0.048	-	-	-	-	-	DA
LVL total + D	kg	Recovery	500	50+	5.81E-01	1.59E-08	1.42E-03	2.52E-04	6.14E-05	1.15E-06	3.41E-03	0.038	-	-	-	-	-	DA
CLT total	kg	Recovery	420	50+	2.80E-01	3.13E-08	1.49E-03	5.17E-04	2.30E-04	1.38E-06	1.90E-03	0.025	-	-	-	-	-	DA
CLT total + D	kg	Recovery	420	50+	2.37E-01	1.72E-08	3.38E-04	1.43E-04	5.05E-05	1.29E-06	1.66E-03	0.015	-	-	-	-	-	DA
Concrete C30/37 (75% CEM III, 25% CEM I) Total	kg	Recycling	2400	50+	9.79E-02	3.80E-09	2.63E-04	5.81E-05	2.49E-05	1.01E-07	3.06E-04	0.007	1.03E-02	2.51E-04	1.25E+00	1.95E-04	0.008	NMD
Concrete C30/37 (75% CEM III, 25% CEM I) Total + D	kg	Recycling	2400	50+	9.37E-02	3.42E-09	2.39E-04	5.39E-05	2.19E-05	7.75E-08	2.77E-04	0.006	8.45E-03	2.24E-04	1.13E+00	1.85E-04	0.007	NMD
Reinforcement total	kg	Recycling	7850	50+	1.39E+00	1.22E-08	2.10E-03	3.74E-04	4.91E-04	6.31E-07	7.77E-03	0.084	5.00E-02	1.60E-03	5.87E+00	1.89E-03	0.089	NMD
Reinforcement total + D	kg	Recycling	7850	50+	1.12E+00	2.19E-09	1.58E-03	2.82E-04	3.43E-04	-2.73E-06	6.37E-03	0.067	2.91E-02	-8.26E-04	8.71E-01	1.50E-03	0.069	NMD
Steel S235 total	kg	88% Recycling 11% re-use	7850	50+	1.13E+00	1.97E-12	2.17E-03	2.20E-04	4.02E-04	4.93E-07	4.92E-03	0.069	-	-	-	-	-	EPD1
Steel S235 total +D	kg	88% Recycling 11% re-use	7850	50+	7.19E-01	1.62E-09	1.36E-03	1.53E-04	2.24E-04	-3.99E-07	3.02E-03	0.044	-	-	-	-	-	EPD1
AMONN fire retardant coating total	m²	-	1300	10	1.18E+00	1.55E-07	8.35E-03	1.98E-03	4.68E-04	1.10E-05	1.15E-02	0.133	-	-	-	-	-	EPD2
Siniat Fireboards (t=12mm) total	m²	Recycling	700	50	2.85E+00	3.88E-07	7.40E-03	1.59E-03	9.37E-04	2.62E-05	2.32E-02	0.192	-	-	-	-	-	EPD3
Siniat Fireboards (t=12mm)total+D	m²	Recycling	700	50	2.80E+00	3.79E-07	7.05E-03	1.51E-03	9.07E-04	2.59E-05	2.29E-02	0.187	-	-	-	-	-	EPD3
Knauf mineral wool total	m³	Landfilling	70	50	9.08E+01	5.45E-10	5.04E-01	5.07E-02	3.86E-02	2.66E-05	6.00E-01	7.18	-	-	-	-	-	EPD4
Knauf mineral wool total + D	m³	Landfilling	70	50	8.73E+01	4.82E-10	4.99E-01	5.01E-02	3.81E-02	2.60E-05	5.77E-01	6.98	-	-	-	-	-	EPD4
Flax wool total	kg	Recovery	25	75	1.37E+00	1.35E-07	4.76E-03	1.36E-03	8.36E-04	4.61E-06	1.15E-02	0.10	-	-	-	-	-	NMD
Flax wool total+D	kg	Recovery	25	75	9.15E-01	9.81E-08	4.23E-03	1.26E-03	8.09E-04	4.51E-06	7.61E-03	0.08	-	-	-	-	-	NMD
Wood particle board (t=22mm) total	m²	Recycling	723	50	1.71E+01	1.36E-10	4.38E-02	1.24E-02	1.16E-02	1.12E-05	9.96E-02	1.18	-	-	-	-	-	EPD5
Wood particle board (t=22mm) total + D	m²	Recycling	723	50	1.40E+01	1.36E-10	2.09E-02	7.14E-03	2.16E-03	1.06E-05	8.13E-02	0.87	-	-	-	-	-	EPD5
Sand cement total	kg	Landfill	1650	75	1.55E-01	3.84E-09	3.07E-04	5.23E-05	3.21E-05	2.15E-07	1.54E-07	0.01	-	-	-	-	-	NMD
Sand cement total + D	kg	Landfill	1650	75	1.60E-01	5.54E-09	3.39E-04	5.90E-05	3.68E-05	2.20E-07	6.67E-05	0.01	-	-	-	-	-	NMD

Appendix C

Variant study

C.1 List of used Eurocodes

Table C.1 presents the used structural standards throughout this study. In the following sections of this appendix, the standards will be referenced by their abbreviated code as indicated by the bolted parts in Table C.1.

Table C.1: List of used Standards

Code	Title	Source
NEN-**EN 1990**+A1+A1/C2	Basis of structural design	[153]
NEN-**EN 1990**+A1+A1/C2/**NB**	National annex to Basis of structural design	[154]
NEN-**EN 1991-1-1**+C1	Actions on structures – Densities, self-weight, imposed loads for buildings	[155]
NEN-**EN 1991-1-1**+C1/**NB**	National annex to Actions on structures – Densities, self-weight, imposed loads for buildings	[156]
NEN-**EN 1991-1-3**+C1	Actions on structures – General actions – Snow loads	[157]
NEN-**EN 1991-1-3**+C1/**NB**	National annex to Actions on structures – General actions – Snow loads	[158]
NEN-**EN 1991-1-4**+A1+C2	Actions on structures – General actions – Wind actions	[159]
NEN-**EN 1991-1-4**+A1+C2/**NB**	National annex to Actions on structures – General actions – Wind actions	[160]
NEN-**EN 1995-1-1**+C1+A1	Design of timber structures – Common rules and rules for buildings	[161]
NEN-**EN 1995-1-1**+C1+A1/**NB**	National annex to Design of timber structures – Common rules and rules for buildings	[162]
NEN-**EN 1995-1-2**+C2	Design of timber structures – Structural fire design	[163]

C.2 Loads and load combinations

For the buildings in the variant study, ranging from 30 up to 70m, the following characteristics are prescribed according to EN 1990 and its national annex:

- Consequence class CC2
- Reliability class RC2
- Reference service life: 50 years (minimum)
- Use class A (residential)

C.2.1 Imposed loads

The national annex of EN 1991-1-1 prescribes an imposed load of 1.75 kN/m^2 for floors in residential buildings. Partitioning walls are accounted for by the additional load of 0.8 kN/m^2 according to EN 1991-1-1.

For the flexible cascading scenario (see section 3.5.3) this value is increased to account for longer design lifespan. The prescribed value is based on the reference service life of 50 years. In case of a longer design lifespan, the probability increases that the maximum load occurs. This is accounted for by the following equation from the national annex of EN 1990:

$$F_t = F_{t0}\left(1 + \frac{1-\psi_0}{9} * \ln\left(\frac{t}{t_0}\right)\right) \tag{6}$$

In which:

$F_t = \text{ imposed load for reference period } t$
$F_{t0} = \text{default imposed load}$
$\psi_0 = \text{combination factor}$
$t = \text{reference period}$
$t_0 = \text{default reference period } (50 \text{ years})$

Resulting in an imposed load for the flexible scenario (150 years) of:

$$F_t = 2.55\left(1 + \frac{1-0.4}{9} * \ln\left(\frac{150}{50}\right)\right) = 2.74\ kN/m^2$$

It was not chosen to take a higher load into account for a different function since the floor to ceiling height of residential buildings is insufficient for the requirement of offices. Because of the housing shortage in the Dutch market, it is more likely to adapt the configuration of the apartments for changed demands than a change to a completely different function (e.g. office).

C.2.2 Wind load

The wind pressure acting on the exterior of the building is determined by EN 1991-1-4 and the corresponding national annex. The following equation is used:

$$w_e = q_p(z_e) * c_{pe} \tag{7}$$

In which:

$w_e = \text{ wind pressure}$
$q_p(z_e) = \text{extreme thrust at reference height } z_e$
$c_{pe} = \text{pressure coefficient}$

The buildings in the variant study are assumed to be located in an urban area of wind area II, see Figure C.1.

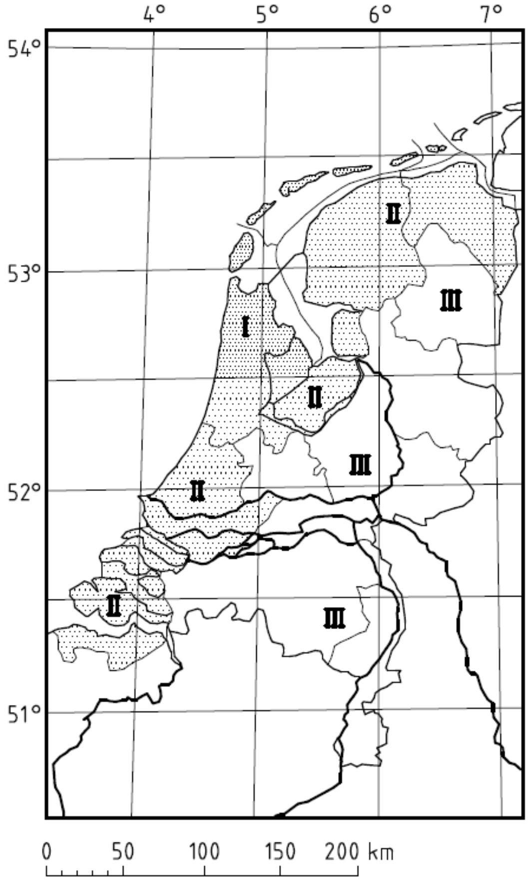


Figure C.1: Wind areas in the Netherlands according to the national annex of EN 1991-1-4 [160]

For this area, the values for the extreme thrust are determined using table NB.5 from the Dutch national annex, see Table C.2. The chance that the maximum wind load occurs for buildings with a longer reference service life increases, this is accounted for by the probability factor c_{prob}:

$$c_{prob} = \left(\frac{1 - K * \ln(-\ln(1-p))}{1 - K * \ln(-\ln(0.98))}\right)^{0.5} \tag{8}$$

In which:

$$c_{prob} = probability\,factor$$
$$K = shape\ parameter\ based\ on\ variation\ coefficient$$
$$p = probability = \frac{1}{reference\ period}$$

The national annex of EN 1991-1-4 prescribes a factor 0.234 for shape parameter K in wind area II. The probability for a reference period of 150 years equals 0.00667, resulting in a probability factor of:

$$c_{prob} = \left(\frac{1 - 0.234 * \ln(-\ln(1 - 1/150\,))}{1 - 0.234 * \ln(-\ln(0.98))}\right)^{0.5} = 1.065$$

Table C.2: Extreme thrust according to the national annex of EN 1991-1-4

Reference height z_e [m]	**Extreme thrust** $q_p(z_e)$ [kN/m^2] 50 years	**Extreme thrust** $q_p(z_e)$ [kN/m^2] 150 years
30	1.03	1.10
50	1.21	1.29
70	1.34	1.43

The pressure coefficients for the front and back façade are respectively +0.8 and -0.6, resulting in the wind pressures, as shown in Table C.3. It is chosen to use the conservative approach in which the wind load at the top of the building acts over the entire height of the building.

Table C.3: Wind pressures

Reference height z_e [m]	**Wind pressure** w_e [kN/m^2] 50 years		**Wind pressure** w_e [kN/m^2] 150 years	
	Front	Back	Front	Back
30	0.82	0.62	0.88	0.66
50	0.97	0.73	1.03	0.77
70	1.07	0.80	1.14	0.86

C.2.3 Snow load

The snow load acting on the roof of the building is determined by EN 1991-1-3 and the corresponding national annex. The following equation is used:

$$s = \mu_i * C_e * C_t * s_k \tag{9}$$

In which:

$s = \text{ snow load}$
$\mu_i = \text{shape coefficient}$
$C_e = \text{exposure coefficient}$
$C_t = \text{heat coefficient}$
$s_k = \text{characteristic snow load at ground level}$

The national annex of EN 1991-1-3 prescribes a factor 1 for both the exposure and heat coefficients. The characteristic snow load at ground level is 0.7 kN/m^2 for all locations in the Netherlands. The roof is assumed flat, which corresponds to a shape coefficient of 0.8. This results in the following snow load:

$$s = 0.8 * 1 * 1 * 0.7 = 0.56\ kN/m^2$$

The chance that the maximum snow load occurs for buildings with a longer reference service life increases, this is accounted for by the following equation from EN 1991-1-3 appendix D:

$$s_n = s_k \left(\frac{1 - V * \frac{\sqrt{6}}{\pi} (\ln(-\ln(1 - P_n)) + 0.57222)}{1 + 2.5923 * V} \right) \tag{10}$$

In which:

$s_n = \ snow\ load\ for\ reference\ period\ n$
$s_k = characterstic\ snow\ load\ at\ ground\ level$
$V = variation\ coefficient$
$P_n = probability = 1/n$

The Dutch national annex specifies a variation coefficient of 0.8, resulting in a snow load for the flexible scenario (150 years) of:

$$s_n = 0.7 \left(\frac{1 - 0.8 * \frac{\sqrt{6}}{\pi} (\ln(-\ln(1 - 1/150)) + 0.57222)}{1 + 2.5923 * 0.8} \right) = 0.86\ kN/m^2$$

C.2.4 List of loads

Table C.4 shows an overview of the loads which are used in the variant study and their corresponding combination factors.

Table C.4: List of characteristic loads

Load type	Load duration	Load [kN/m^2]		Combination factors		
		Reference period				
		50 years	150 years	Ψ_0	Ψ_1	Ψ_2
Dead load CLT floor (5.4m)	Permanent	1.44	-	-	-	-
Dead load CLT floor (6.3m)	Permanent	1.65	-	-	-	-
Dead load CLT floor (7.2m)	Permanent	1.90	-	-	-	-
Dead load LVL floor (5.4m)	Permanent	0.99	-	-	-	-
Dead load LVL floor (6.3m)	Permanent	1.00	-	-	-	-
Dead load LVL floor (7.2m)	Permanent	1.02	-	-	-	-
Dead load façade	Permanent	4.50 kN/m	-	-	-	-
Dead load other	Permanent	Generated in RFEM		-	-	-
Imposed load	Medium-term	2.55	2.74	0.4	0.5	0.3
Wind load 30m front	Short-term	0.82	0.88	0	0.2	0
Wind load 30m back	Short-term	0.62	0.66	0	0.2	0
Wind load 50m front	Short-term	0.97	1.03	0	0.2	0
Wind load 50m back	Short-term	0.73	0.77	0	0.2	0
Wind load 70m front	Short-term	1.07	1.14	0	0.2	0
Wind load 70m back	Short-term	0.80	0.86	0	0.2	0
Snow load	Short-term	0.56	0.86	0	0.2	0

C.2.5 Load combinations

The load combinations are derived using the following two equations from EN 1990:

$$\sum_{j\geq 1} \gamma_{G,j} * G_{k,j} + \sum_{i>1} \gamma_{Q,i} * \psi_{0,i} * Q_{k,i} \tag{11}$$

$$\sum_{j\geq 1} \gamma_{G,j} * G_{k,j} + \gamma_{Q,i} * Q_{k,1} + \sum_{i>1} \gamma_{Q,i} * \psi_{0,i} * Q_{k,i} \tag{12}$$

Table C.5 indicate the partial safety factors which are used in the load combinations as presented in Table C.6.

Table C.5: Partial safety factors (RC2) according to EN 1990

Limit state	**γ_G (permanent load)**		**γ_Q (variable load)**
	Unfavourable	Favourable	
Ultimate limit state	1.35 1.2	0.9	1.5
Ultimate limit state (fire)	1.0	1.0	1.0
Serviceability limit state	1.0	1.0	1.0

Table C.6: List of load combinations

	Load combination	**Notes**
ULS1	$1.35 * \boldsymbol{G}$	
ULS2	$1.35 * \boldsymbol{G} + 1.5 * 0.4 * \boldsymbol{Q}_{\boldsymbol{imposed}}$	
ULS3	$0.9 * \boldsymbol{G} + 1.5 * \boldsymbol{Q}_{\boldsymbol{wind}}$	Dead load favourable for tension in foundation
ULS4	$1.2 * \boldsymbol{G} + 1.5 * \boldsymbol{Q}_{\boldsymbol{imposed}}$	
ULS5	$1.2 * \boldsymbol{G} + 1.5 * \boldsymbol{Q}_{\boldsymbol{wind}} + 1.5 * 0.4 * \boldsymbol{Q}_{\boldsymbol{imposed}}$	
ULS6	$1.2 * \boldsymbol{G} + 1.5 * \boldsymbol{Q}_{\boldsymbol{snow}} + 1.5 * 0.4 * \boldsymbol{Q}_{\boldsymbol{imposed}}$	
ULS7	$1.0 * \boldsymbol{G} + 1.0 * 0.2 * \boldsymbol{Q}_{\boldsymbol{wind}} + 1.0 * 0.3 * \boldsymbol{Q}_{\boldsymbol{imposed}}$	Exceptional load case (Fire)
SLS1	$1.0 * \boldsymbol{G} + 1.0 * \boldsymbol{Q}_{\boldsymbol{wind}} + 1.0 * 0.4 * \boldsymbol{Q}_{imposed}$	
SLS2	$1.0 * \boldsymbol{G} + 1.0 * 0.3 * \boldsymbol{Q}_{imposed}$	Dynamic (quasi permanent)

In case the imposed load is the leading variable load (ULS4 and SLS2), the entire load is applied to the top two floors while the loads on the other floors are reduced using the ψ_0-factor according to the national annex of EN 1991 clause 6.3.1.2(11).

C.3 Material characteristics

For the one-dimensional members (beams and columns), the RFEM Glulam material for strength class GL24h is used. For the properties, see Appendix A.2. RFEM uses an isotropic linear elastic material model for glued laminated timber.

For the two-dimensional members (floors and walls), a user-defined orthotropic elastic 2D RFEM material is defined using the parameters from Appendix A.4 and a Poisson's ratio of 0.4. These values correspond to the longitudinal direction of the boards since they are derived from the material properties of sawn timber strength class C24. However, the lamellas in the CLT are bi-directional oriented; thus, the indicated values are not applicable over the full thickness.

To take this into account, the equivalent stiffness can be derived using the following expressions [15]:

$$E_{eq,1} = \frac{E_0 * t_1 * n_1 + E_{90} * t_2 * n_2}{t_{total}} \tag{13}$$

$$E_{eq,2} = \frac{E_0 * t_2 * n_2 + E_{90} * t_1 * n_1}{t_{total}} \tag{14}$$

In which:

$E_{eq,1} = equivalent\ stiffness\ in\ first\ direction$
$E_{eq,2} = equivalent\ stiffness\ in\ second\ direction$
$E_0 = E - modulus\ //$
$E_{90} = E - modulus\ \perp$
$t_1 = lamella\ thickness\ in\ first\ direction$
$t_2 = lamella\ thickness\ in\ second\ direction$
$t_{total} = total\ lamella\ thickness$
$n_1 = number\ of\ lammellae\ in\ first\ direction$
$n_2 = number\ of\ lammellae\ in\ second\ direction$

C.4 Performance criteria

For the verification in the variant study, the Unity Checks (i.e. the design action divided by the design resistance) are optimized for 0.8 instead of the usual 1.0 to account for the limited level of detail for the preliminary design calculations.

C.4.1 Partial safety and modification factors

To verify the resistance properties of timber in the ultimate limit state, the following expression from EN 1995-1-1 should be used:

$$X_d = k_{mod} * \frac{X_k}{\gamma_M} \tag{15}$$

In which:

$X_d = \text{design value of strength property}$
$X_k = \text{characteristic value of strength property}$
$k_{mod} = \text{modification factor for load duration and moisture content}$
$\gamma_M = \text{partial safety factor for material properties}$

See Table C.7 and Table C.8 for the relevant partial safety and k_{mod} values. For load combinations with loads of different time duration, the shortest load duration class should be chosen. See Table C.4 for the loads and their corresponding load durations.

Table C.7: Partial safety factors timber according to EN 1995-1-1

Material	γ_M
Sawn timber	1.3
Glulam	1.25
CLT	1.25
LVL	1.2

Table C.8: k_{mod} factors for sawn timber, Glulam, CLT and LVL according to EN 1995-1-1 (service class 1 and 2)

Load duration class	Duration	k_{mod}
Permanent	> 10 years	0.6
Long-term	6 months – 10 years	0.7
Medium-term	1 week – 6 months	0.8
Short-term	< 1 week	0.9
Instantaneous		1.1

Time-dependent behaviour (creep) and moisture content will affect the final deformations of the structure. To verify the deformations in the serviceability limit state, the following expressions from EN 1995-1-1 should be used for the modulus of elasticity and the shear modulus:

$$E_{mean,fin} = \frac{E_{mean}}{1 + k_{def}} \tag{16}$$

$$G_{mean,fin} = \frac{G_{mean}}{1 + k_{def}} \tag{17}$$

In which:

$E_{mean} = mean\ modulus\ of\ elasticity$
$G_{mean} = mean\ shear\ modulus$
$k_{def} = creep\ factor$

The k_{def} factor for sawn timber, Glulam, CLT and LVL is 0.6 (service class 1).

C.4.2 Ultimate limit state criteria

To determine element sizes for the structure, and ultimately the material quantities of the variants, the governing resistance properties of the timber are verified according to the criteria as discussed in this section. These criteria are prescribed by the standard: EN 1995-1-1.

Compression and tension parallel to the grain

$$\sigma_{c,0,d} \leq f_{c,0,d} \tag{18}$$
$$\sigma_{t,0,d} \leq f_{t,0,d} \tag{19}$$

In which:

$\sigma_{0,d} = \frac{N_d}{A} = design\ compressive\ or\ tensile\ stress\ parallel\ to\ the\ grain$
$N_d = design\ normal\ force$
$A = cross\ sectional\ area$
$f_{c,0,d} = design\ compressive\ or\ tensilte\ strength\ parallel\ to\ the\ grain$

The compression verification is applied to the columns and walls. For the CLT wall elements, the stress is determined by the effective net cross-sectional area, i.e. the lamellae in the loaded direction. For core walls loaded by wind, also the tension is verified.

Buckling

$$\sigma_{c,0,d} \leq f_{c,0,d} * k_c \tag{20}$$

$$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} \tag{21}$$

$$k = 0.5 * (1 + \beta_c * (\lambda_{rel} - 0.3) + \lambda_{rel}^2 \tag{22}$$

$$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}} \tag{23}$$

In which:

$\beta_c = 0.1\ (for\ laminated\ timber\ and\ LVL)$
$\lambda = \frac{l_{eff}}{i} = slenderness\ factor$
$l_{eff} = buckling\ length$
$i = \sqrt{\frac{I}{A}} = radius\ of\ gyration$
$I = moment\ of\ inertia$
$A = cross\ sectional\ area$
$E_{0.05} =\ 5\%\ value\ of\ modulus\ of\ elasticity$

This verification is applied to the columns and walls. Contribution of out of plane bending is excluded. It is assumed that the horizontal wind loads have a load transfer directly to the floors, resulting in no bending moment in the columns.

For CLT walls, the net cross-sectional area and net moment of inertia (excluding the shear flexibility of the transverse layers) of one-meter strip is used according to the method from the CLT Handbook [164]:

$$I_{net} = b * \sum_{i=1}^{n} \left(\frac{t_i^3}{12} + t_i * a_i^2 \right) \tag{24}$$

In which:

$n = number\ of\ lamellae\ in\ loaded\ direction$
$b = 1\ meter\ strip$
$t_i = thickness\ of\ lamellae\ i$
$a_i = distance\ of\ middle\ of\ lamellae\ to\ centre\ of\ gravity\ cross\ sectoin$

Bending

$$\sigma_{m,d} \leq f_{m,d} \tag{25}$$

In which:

$\sigma_{m,d} = \frac{M_d}{W} =\ design\ bending\ stress$
$M_d = design\ bending\ moment$
$W = moment\ of\ resistance$
$f_{m,d} = design\ bending\ strength$

This verification is applied to beams.

Shear

$$\tau_d \leq f_{v,d} \tag{26}$$

In which:

$$\tau_d = \frac{3}{2} * \frac{V_d}{A} = \text{ design shear stress}$$
$$V_d = \text{design shear force}$$
$$A = \text{cross sectional area}$$
$$f_{m,d} = \text{design bending strength}$$

This verification is applied to beams. The effect of cracks in member should be accounted for by the factor k_{cr} to reduce the effective width of the member. However, the national annex of EN 1995 prescribes a factor k_{cr} of 1.0 for a prismatic cross-section, leading to no further reduction.

Reduced cross-section method

Standard EN 1995-1-2 for structural fire safety of timber structures prescribes two methods to access the fire safety of the structural elements: The reduced cross-section method and the reduced properties method. The first method is used in this study.

The reduced cross-section method verifies the structural elements when the effective cross-section is reduced due to charring of the timber. The original cross-section should be reduced at all exposed fire sides, see Figure C.2, using Equation (27).

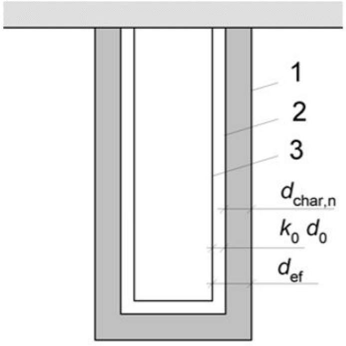


Figure C.2: Reduced cross section[163]

$$d_{ef} = d_{char,n} + k_0 * d_0 \tag{27}$$

In which:

$$d_{ef} = \text{effective burn in depth}$$
$$d_{char,n} = \beta_n * t$$
$$\beta_n = \text{burn in speed (including corner effects and cracks)}$$
$$t = \text{time of fire exposure}$$
$$k_0 = 1.0 \ (\text{for } t \geq 20 \text{ minutes})$$
$$d_0 = 7\ mm$$

For residential buildings in the range of 30 to 70 meters, the Building Decree prescribes a time of fire exposure of 120 minutes. Since it is assumed that the buildings have a sprinkler installation, this requirement can be reduced to 90 minutes based on a study for steel structures [165]. This is also valid for timber structures based on equivalency. In practice, this rule was for example applied to the reference project Hotel Jakarta (Section 2.1.6).

In the verification, it is assumed that columns and beams are exposed at three sides, while walls are one-sided fire exposure. The burn-in speed (β_n) for laminated softwood and LVL is 0.7 mm/min according to EN 1995-1-2.

The design value for the resistance is adapted during a fire, using the following expression:

$$f_{d,fi} = k_{mod,fi} * \frac{f_{20}}{\gamma_{M,fi}} \tag{28}$$

In which:

$f_{d,fi} = design\ value\ of\ strength\ property\ during\ fire$
$f_{20} = k_{fi} * f_k = 20\%\ fractile\ value\ of\ resistance\ at\ room\ temperature$
$k_{mod,fi} = modification\ factor\ for\ fire$
$\gamma_{M,fi} = partial\ safety\ factor\ for\ material\ properties\ during\ fire$

The relevant k_{fi} factors are shown in Table C.9. For the verification of fire safety, the modification factor ($k_{mod,fi}$) and the partial safety factor (γ_M) are both set to 1.0 according to EN 1995-1-2. Besides the change of the design resistance during fire, the design actions are also changed using different partial safety factors during fire. This is accounted for in load combination ULS7, see Table C.5 and Table C.6.

Table C.9: k_{fi} factors

Material	k_{fi}
Sawn timber	1.25
Glulam	1.15
CLT	1.15
LVL	1.10

For variants with an encapsulated fire safety strategy, using gypsum boards (type A, F or H), the following expression can be used according to EN 1995-1-2 to determine the moment when the charring of the protected timber starts:

$$t_{ch} = 2.8 * h_p - 14 \tag{29}$$

In which:

$$t_{ch} = starting\ time\ of\ charring\ protected\ timber\ [min]$$
$$h_p = thickness\ of\ gypsum\ boards\ [mm]$$

By reversing Expression (29), the required thickness of the protective boards can be determined for which no charring of the protected timber occurs during the required 90-minute fire resistance requirement:

$$h_p = \frac{t_{ch} + 14}{2.8} = \frac{90 + 14}{2.8} = 37\ mm \approx 40\ mm$$

Thus, for all variants using the encapsulated fire safety strategy, 40-millimetre-thick gypsum boards are applied at the exposed sides of the structural elements.

C.4.3 Serviceability limit state criteria

Global deformations

The national annex of EN 1990 prescribes a maximal horizontal deformation for buildings of:

$$u_{max} = \frac{h}{500} \qquad (30)$$

In which:

$$h = height\ of\ the\ building$$

The influence of the rotational stiffness of the foundation is excluded in the structural model. Though this contributes to the total horizontal deformation of the building. To account for the contribution of the foundation, the criteria from Equation (30) can be changed to the following rule of thumb for the preliminary design phase [166]:

$$u_{max} = \frac{h}{750} \qquad (31)$$

Local deformations

For the local beam deformations, the instantaneous and final deformations due to creep are verified according to the criteria specified in EN 1995-1-1. See Figure C.3 and Equations (32) & (33).

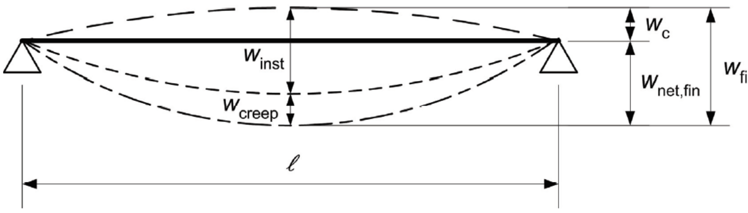


Figure C.3: Deformation criteria [161]

$$w_{inst} = \frac{l}{300} \tag{32}$$

$$w_{net,fin} = \frac{l}{250} \tag{33}$$

The final deformation, including creep, can be determined using the creep factor k_{def} and Equation (16).

Dynamic behaviour

Limitations of wind-induced vibrations are prescribed in the national annex of EN 1990, see Figure C.4. For residential buildings, the second line (gebruik 2) should be used as criteria for dynamic behaviour.

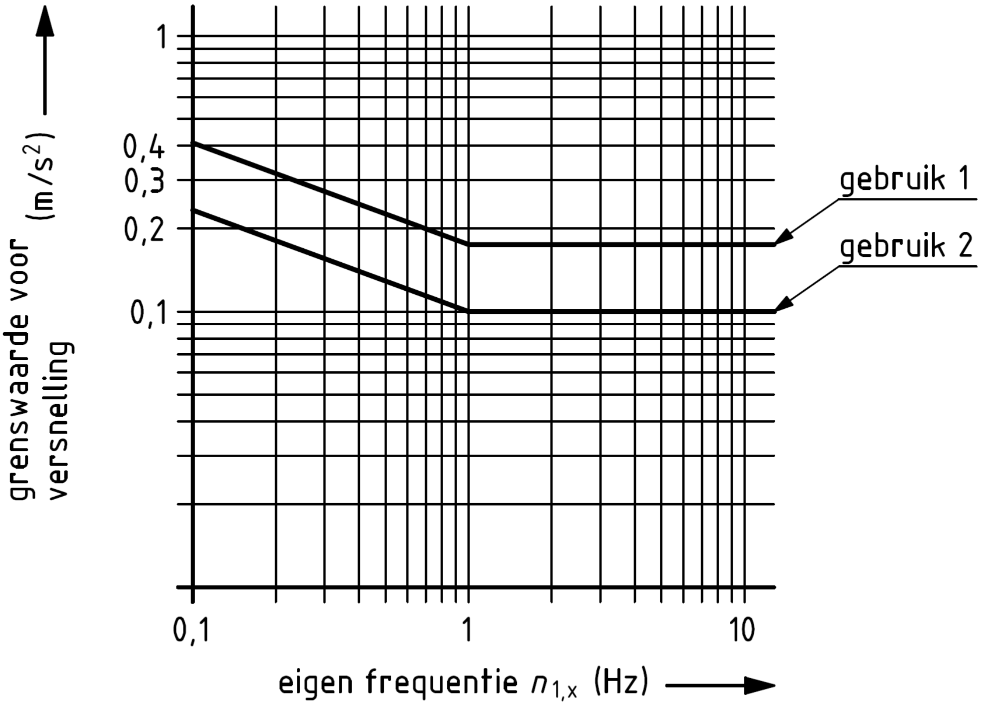


Figure C.4: Maximum values of wind-induced building accelerations [154]

The first fundamental frequency can be determined by the following expression according to the national annex of EN 1991-1-4:

$$n_1 = \frac{46}{h} \tag{34}$$

In which:

$n_1 = fundamental\ frequency\ [Hz]$
$h = height\ of\ the\ building\ [m]$

The acceleration of buildings can be approximated by the following expressions according to EN 1990:

$$a_{wind} = 1.6 * \frac{\phi_2 * p_{vw} * c_{pe} * b_m}{\rho_l} \tag{35}$$

$$\phi_2 = \sqrt{\frac{0.0344(n_1)^{-\frac{2}{3}}}{D(1 + 0.12 * n_1 * h)(1 + 0.2 * n_1 * b_m)}} \tag{36}$$

$$p_{vw} = 100 * \ln\left(\frac{h}{0.2}\right) \tag{37}$$

In which:

$\phi_2 = dynamic\ facotor$
$p_{vw} = variable\ part\ of\ wind\ pressure$
$c_{pe} = sum\ of\ external\ wind\ pressure\ coefficients$
$b_m = average\ width\ of\ the\ building\ [m]$
$\rho_l = mass\ of\ building\ and\ quasi\ permanent\ imposed\ load\ over\ building\ height\ \left[\frac{kg}{m}\right]$
$n_1 = fundamental\ frequency\ [Hz]$
$D = damping\ coefficient$
$h = building\ height\ [m]$

The damping coefficient (D) depends on the fundamental frequency n_1. For fundamental frequencies lower than one hertz, the damping coefficient is 0.01; for fundamental frequencies higher than two hertz, the damping coefficient is 0.02; for values in between one and two hertz, linear interpolation should be used.

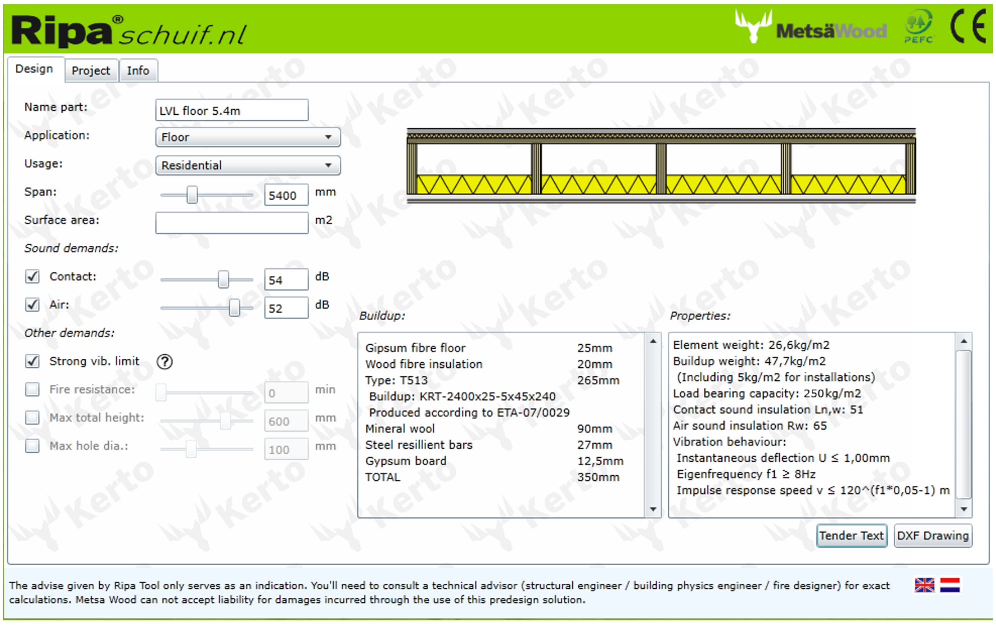
C.5 Floor design

The floors are designed using manufacturers data. MetsäWood, the producer of LVL box floors, published an online tool to determine the required floor build-up. For CLT floors, the structural pre-analysis tables of manufacturer KLH Massivholz are used. Besides structural design, the floor slabs are designed for the required vibration, fire, and acoustical requirements. Acoustical requirements are prescribed in the Building Decree:

$$Contact\ sound: L_{n,T,A} \leq 54\ dB$$
$$Airborn\ sound: D_{nT,A,k} \geq 52\ dB$$

C.5.1 LVL

Figure C.5 shows an example of the Ripaschuif tool by MetsäWood. It can account for vibration criteria from the Eurocode and user-defined acoustical demands. Ducting and installations are assumed to be internal within the hollow sections of the box profile according to the tool.



Name part: LVL floor 5.4m
Application: Floor
Usage: Residential
Span: 5400 mm
Surface area: m2

Sound demands:

☑ Contact: 54 dB
☑ Air: 52 dB

Other demands:

☑ Strong vib. limit ?
☐ Fire resistance: 0 min
☐ Max total height: 600 mm
☐ Max hole dia.: 100 mm

Buildup:

Gipsum fibre floor	25mm
Wood fibre insulation	20mm
Type: T513	265mm
Buildup: KRT-2400x25-5x45x240	
Produced according to ETA-07/0029	
Mineral wool	90mm
Steel resillient bars	27mm
Gypsum board	12,5mm
TOTAL	350mm

Properties:

Element weight: 26,6kg/m2
Buildup weight: 47,7kg/m2
(Including 5kg/m2 for installations)
Load bearing capacity: 250kg/m2
Contact sound insulation Ln,w: 51
Air sound insulation Rw: 65
Vibration behaviour:
Instantaneous deflection U ≤ 1,00mm
Eigenfrequency f1 ≥ 8Hz
Impulse response speed v ≤ 120^(f1*0,05-1) m

The advise given by Ripa Tool only serves as an indication. You'll need to consult a technical advisor (structural engineer / building physics engineer / fire designer) for exact calculations. Metsa Wood can not accept liability for damages incurred through the use of this predesign solution.

Figure C.5: Ripaschuif online tool for LVL box floors [167]

Fire safety is manually checked. For the encapsulated strategy, the derived minimum gypsum board thickness from Section C.4.2 has been used (40mm). For the exposed fire safety strategy, the required LVL thickness of the bottom panel is determined using the LVL handbook [168]:

$$h_p = \beta_0 * (t + 4) + 7\,mm = 0.65 * 94 + 7 = 68\,mm$$

The 68 mm LVL bottom panel replaces the bottom gypsum board as indicated by the tool. See Table C.10 for the results.

Table C.10: LVL floor characteristics

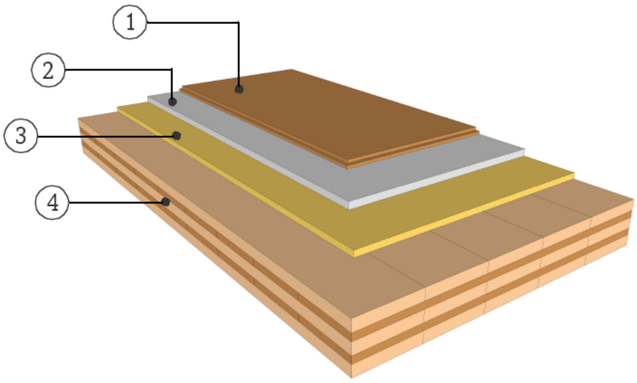
Fire safety strategy		Span [m]		
		5.4	6.3	7.2
Encapsulated	Floor height [mm]	378	398	438
	Dead load [kN/m²]	0.97	0.98	1.00
Exposed	Floor height [mm]	379	399	439
	Dead load [kN/m²]	0.99	1.00	1.02

C.5.2 CLT

Two types of CLT floor build-ups have been considered in this study: using a wet screed and dry screed floor finishing. See Table C.11 and Table C.13 for the used KLH structural pre-analysis tables. These tables include verification of load-bearing capacity, structural fire safety design, deflections, and vibrations according to the Eurocodes.

The used CLT panels automatically reach the fire safety requirement of R90 (single-sided fire exposure) without the need for additional thickness since this design situation is not governing. However, for the encapsulated strategy, the derived minimum gypsum board thickness from Section C.4.2 has been used (40mm). Resulting in an additional load of 0.28 kN/m^2.

To meet the acoustical demands, KLH specifies a minimum thickness of 6 cm wet screed floating on top of filler. For the dry screed system, the build-up as presented in Figure C.6 has been used.



FIRE RESISTANCE

Pre-dimensioning one-sided fire attack

R*EI 30	> 3s 80 TL
R*EI 60	> 5s 120 TL
R*EI 90	> 5s 150 TL

*For residual load capacity or alternative design see https://www.klhdesigner.at/

SOUND INSULATION

R_w (C;C_{tr})	56 (-1;-5)	[dB]
$L_{n,w}$ (C_I)	53 (1)	[dB]

https://www.klh.at/online-bauteilkatalog/

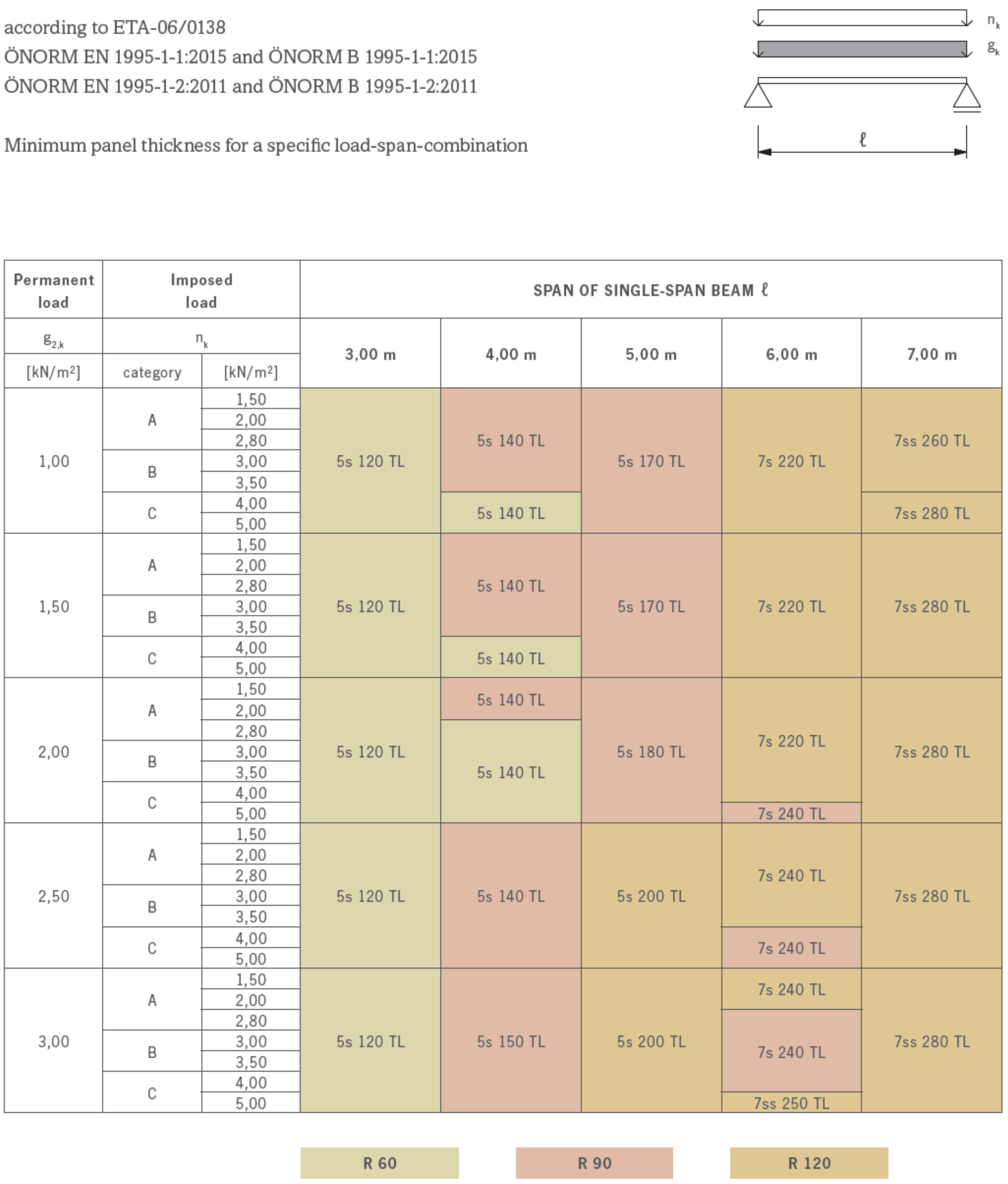
THERMAL PROTECTION

U	0,47	[W/m²K]
$m_{w,B,A}$	36/63	[kg/m²]

Figure C.6: Dry screed floor finishing according to KLH [169]
1 = Gypsum board, 2 = Wood particle board, 3 = Insulation layer, 4 = CLT slab

See Table C.12 for the results of the wet screed system and Table C.14 for the results of the dry screed system.

Table C.11: KLH structural pre-analysis table for single-span beam (wet screed) [110]



according to ETA-06/0138
ÖNORM EN 1995-1-1:2015 and ÖNORM B 1995-1-1:2015
ÖNORM EN 1995-1-2:2011 and ÖNORM B 1995-1-2:2011

Minimum panel thickness for a specific load-span-combination

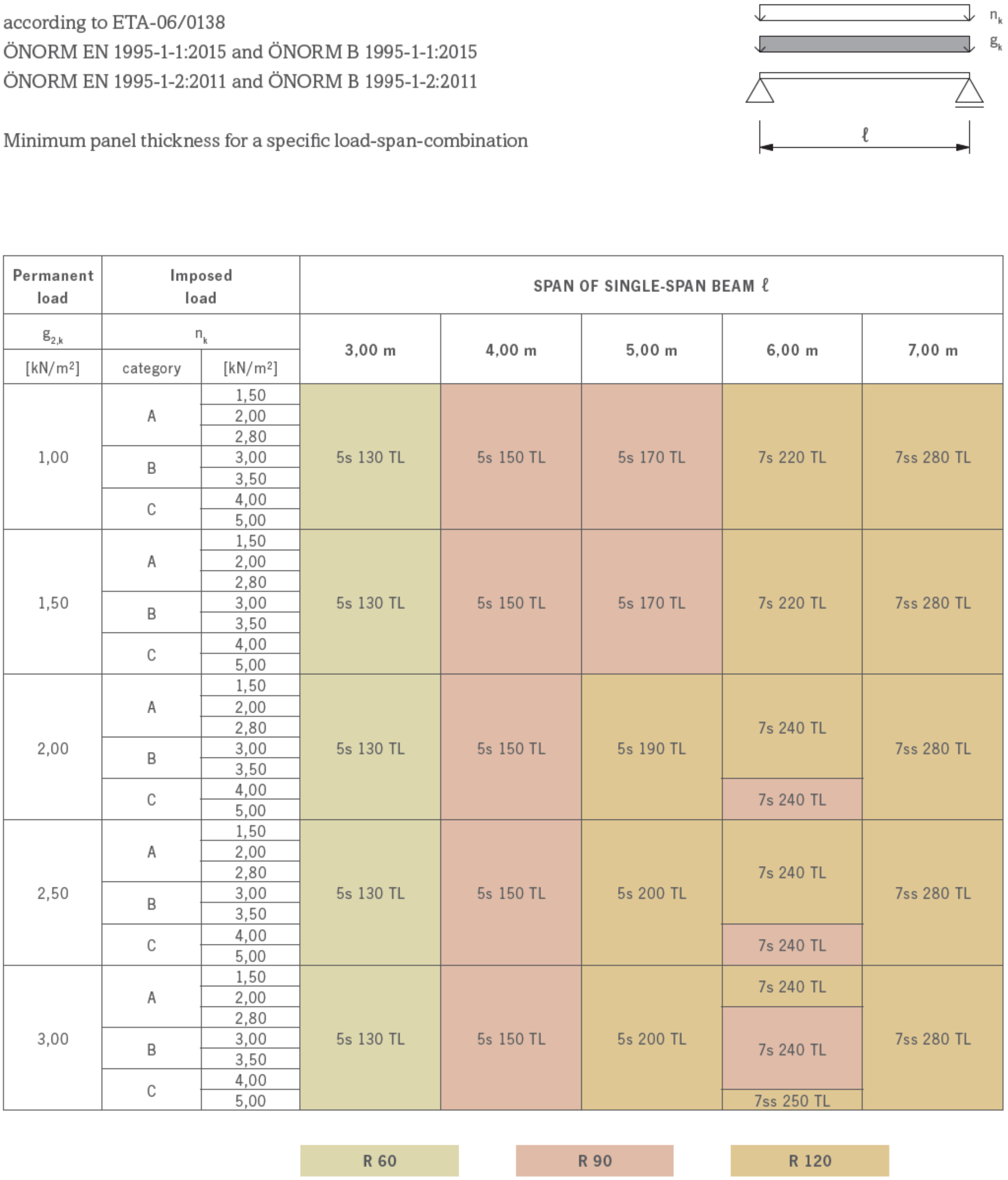
Permanent load $g_{2,k}$ [kN/m²]	Imposed load n_k category	Imposed load n_k [kN/m²]	SPAN OF SINGLE-SPAN BEAM ℓ 3,00 m	4,00 m	5,00 m	6,00 m	7,00 m
1,00	A	1,50	5s 120 TL	5s 140 TL	5s 170 TL	7s 220 TL	7ss 260 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00		5s 140 TL			7ss 280 TL
		5,00					
1,50	A	1,50	5s 120 TL	5s 140 TL	5s 170 TL	7s 220 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00		5s 140 TL			
		5,00					
2,00	A	1,50	5s 120 TL	5s 140 TL	5s 180 TL	7s 220 TL	7ss 280 TL
		2,00					
		2,80		5s 140 TL			
	B	3,00					
		3,50					
	C	4,00					
		5,00				7s 240 TL	
2,50	A	1,50	5s 120 TL	5s 140 TL	5s 200 TL	7s 240 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00				7s 240 TL	
		5,00					
3,00	A	1,50	5s 120 TL	5s 150 TL	5s 200 TL	7s 240 TL	7ss 280 TL
		2,00					
		2,80				7s 240 TL	
	B	3,00					
		3,50					
	C	4,00					
		5,00				7ss 250 TL	

R 60 R 90 R 120

Table C.12: CLT wet screed floor characteristics

Fire safety strategy		Span [m] 5.4	6.3	7.2
Exposed	CLT floor height [mm]	170	220	260
	CLT dead load [kN/m²]	0.71	0.92	1.09
	Wet screed dead load [kN/m²]	1.00	1.00	1.00
	Ducting dead load [kN/m²]	0.2	0.2	0.2
	Total dead load [kN/m²]	2.19	2.20	2.22

Table C.13: KLH structural pre-analysis table for single-span beam (dry screed) [110]



according to ETA-06/0138
ÖNORM EN 1995-1-1:2015 and ÖNORM B 1995-1-1:2015
ÖNORM EN 1995-1-2:2011 and ÖNORM B 1995-1-2:2011

Minimum panel thickness for a specific load-span-combination

Permanent load	Imposed load		SPAN OF SINGLE-SPAN BEAM ℓ				
$g_{2,k}$	n_k		3,00 m	4,00 m	5,00 m	6,00 m	7,00 m
[kN/m²]	category	[kN/m²]					
1,00	A	1,50	5s 130 TL	5s 150 TL	5s 170 TL	7s 220 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00					
		5,00					
1,50	A	1,50	5s 130 TL	5s 150 TL	5s 170 TL	7s 220 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00					
		5,00					
2,00	A	1,50	5s 130 TL	5s 150 TL	5s 190 TL	7s 240 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00				7s 240 TL	
		5,00					
2,50	A	1,50	5s 130 TL	5s 150 TL	5s 200 TL	7s 240 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00					
		3,50					
	C	4,00				7s 240 TL	
		5,00					
3,00	A	1,50	5s 130 TL	5s 150 TL	5s 200 TL	7s 240 TL	7ss 280 TL
		2,00					
		2,80					
	B	3,00				7s 240 TL	
		3,50					
	C	4,00					
		5,00				7ss 250 TL	

R 60 R 90 R 120

Table C.14: CLT dry screed floor characteristics

Fire safety strategy		Span [m]		
		5.4	6.3	7.2
Exposed	CLT floor height [mm]	170	220	280
	CLT dead load [kN/m²]	0.71	0.92	1.17
	Dry screed dead load [kN/m²]	0.53	0.53	0.53
	Ducting dead load [kN/m²]	0.2	0.2	0.2
	Total dead load [kN/m²]	1.44	1.65	1.90

C.6 Façade loads

Table C.15 shows the used façade loads. In case of the mass timber variants, where façade walls have a load-bearing function, the load by the interior façade leaf is excluded since this is automatically accounted for by the dead load of the load-bearing CLT wall in RFEM.

Table C.15: Façade loads

Façade element	Load [kN/m²]
Interior façade leaf (timber frame construction)	0.5
Windows and exterior cladding	1.0
Total regular façade	1.5
Total load-bearing façade	1.0

C.7 Estimation of foundation volume

An estimation of the required concrete volume of the foundation is based on the foundation characteristics of the case study in Chapter 6, see Table C.16. The variant study does not include a basement. Therefore, a single concrete raft is assumed (thickness 0.25m) to transfer the loads of the superstructure to the foundation piles and separate the superstructure from the soil. A minimum of 16 piles is assumed, located below each column and at the corners of the core.

Table C.16: Pile foundation characteristics

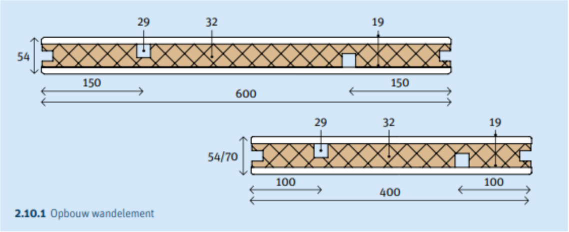
Soil conditions	Rotterdam
Pile type	Prefabricated concrete pile
Pile size (square)	450 mm
Pile length	20 m
Pile capacity compression	1900 kN
Pile capacity tension	450 kN

C.8 Partitioning wall design

For the partitioning walls, which are used in the post and beam variants at the locations of load-bearing walls in the mass timber variants, the required build-up to meet the fire safety and acoustical demands are determined using datasheets of the manufacturer Faay.

To meet the requirements, an IW200/54 wall system is required according to the manufacturer. This build-up consists of two VP54 panels (flax wool boards encapsulated in two gypsum panels), a cavity and mineral wool. See Figure C.7 for the characteristics of the partitioning wall.

VP54



2.10.1 Opbouw wandelement

Technische gegevens VP54

Lengte
2400, 2600, 2800, 3000, 3200, 3600 mm

Breedte
40 cm (60 cm op aanvraag)

Dikte
54 mm

Gewicht
28,12 kg/m²

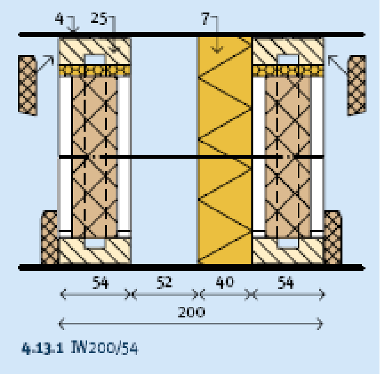
Brandwerendheid
EI30 (EN 1364)

Isolatie
0,42 m² K/W (Rc)
1.54 W/m²K (U)

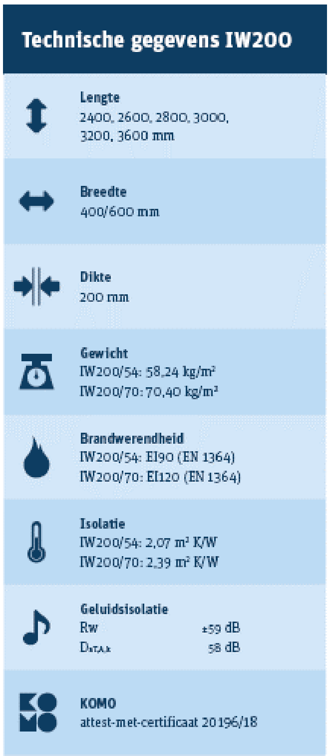
Geluidsisolatie
Rw 30 dB
$D_{nT,A,k}$ 28 dB

KOMO
attest-met-certificaat 20196/18

IW200



4.13.1 IW200/54



Technische gegevens IW200

Lengte
2400, 2600, 2800, 3000, 3200, 3600 mm

Breedte
400/600 mm

Dikte
200 mm

Gewicht
IW200/54: 58,24 kg/m²
IW200/70: 70,40 kg/m²

Brandwerendheid
IW200/54: EI90 (EN 1364)
IW200/70: EI120 (EN 1364)

Isolatie
IW200/54: 2,07 m² K/W
IW200/70: 2,39 m² K/W

Geluidsisolatie
Rw ±59 dB
$D_{nT,A,k}$ 58 dB

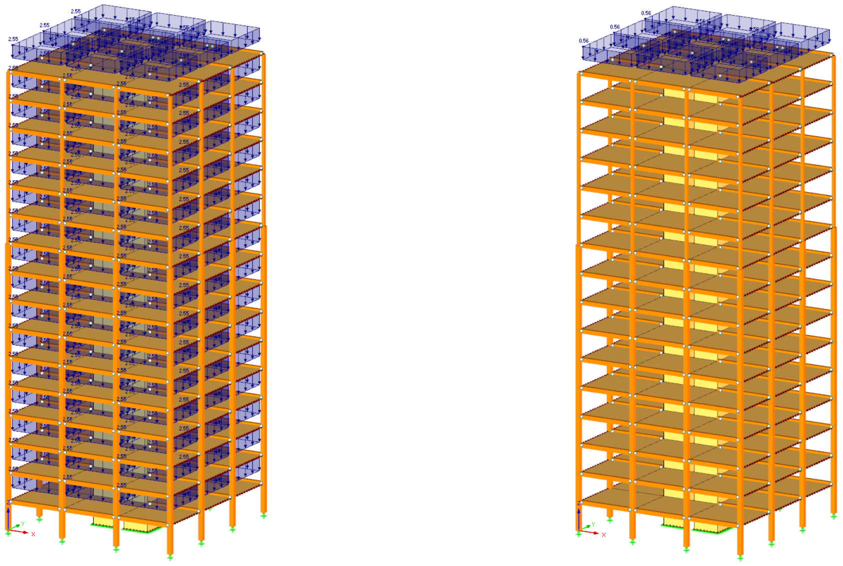
KOMO
attest-met-certificaat 20196/18

Figure C.7: Partitioning wall characteristics[170]

C.9 Example verification

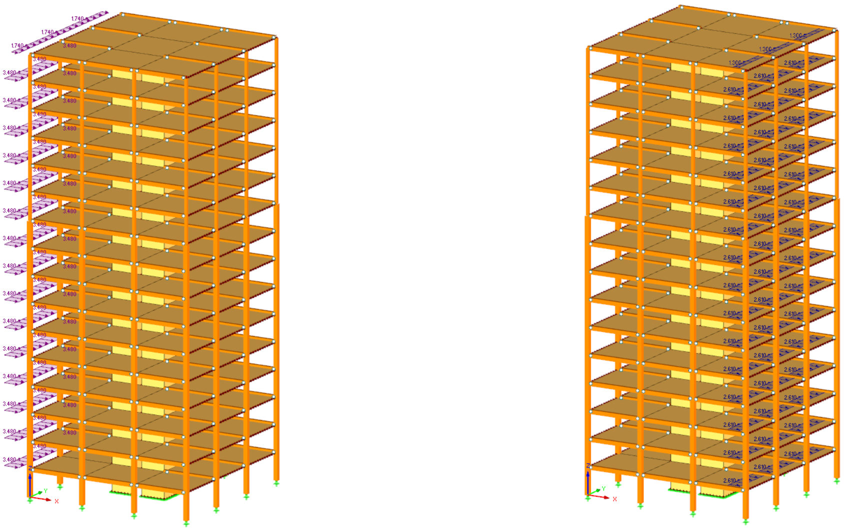
This section presents a worked-out example of the structural design verification using the RFEM output and the checking procedure as described in Section C.4. The chosen variant for this verification is the post and beam, 50-meter-high, variant with an exposed fire safety strategy. The other variants are verified using the same procedures.

The way of application of the loads to the structure is shown in Figure C.8 and Figure C.9.



(A) Imposed load

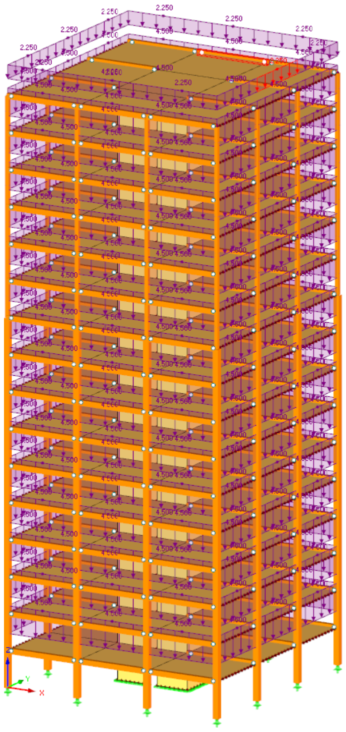
(B) Snow load



(C) Wind load (front)

(D) Wind load (back)

Figure C.8: Load overview (1)



Façade load

Figure C.9: Load overview (2)

Using the results from the linear static analysis in RFEM the structural elements are verified, see Table C.17, Table C.18, Table C.19 and Table C.20 for the worked-out verifications.

For the CLT wall panels, the double lamella layout in the strong direction is chosen, as presented in the KLH structural pre-analysis data [110]. Instead of the regular alternating orientation, this configuration alternates two lamellae in vertical direction with one lamella in the horizontal direction:

$$(//, //, \perp, //, //, \perp, //, //)$$

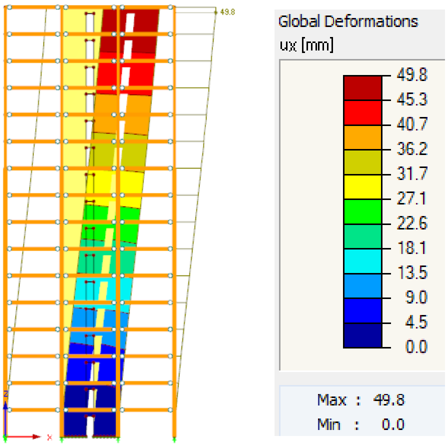


Figure C.10: Global deformations

Table C.17: Global verification

Global verification - Building geometry				
Building height	$h_{building}$		48	m
Number of storeys	$n_{storeys}$		16	m
Grid size	w_{grid}		6.3	m
Core size	w_{core}		6.3	m
Floor to floor height	h_{storey}		3	m
Global verification – Equivalent stiffness CLT walls				
Mean E-modulus // CLT C24	$E_{0,mean}$		11000	N/mm^2
Mean E-modulus ⊥ CLT C24	$E_{90,mean}$		370	N/mm^2
Vertical lamella thickness	$t_{lam,v}$		50	mm
Horizontal lamella thickness	$t_{lam,h}$		50	mm
Number of vertical lamellae	$n_{lam,v}$		6	-
Number of horizontal lamellae	$n_{lam,h}$		2	-
Number of total lamellae	$n_{lam,total}$	$n_{lam,total} = n_{lam,v} + n_{lam,h}$	8	-
Wall thickness	t_{wall}	$t_{wall} = t_{lam,v} * n_{lam,v} + t_{lam,h} * n_{lam,h}$	400	mm
Vertical equivalent stiffness	$E_{eq,1}$	$E_{eq,1} = \frac{E_0 * t_1 * n_1 + E_{90} * t_2 * n_2}{t_{total}}$	8342.5	N/mm^2
Horizontal equivalent stiffness	$E_{eq,2}$	$E_{eq,2} = \frac{E_0 * t_2 * n_2 + E_{90} * t_1 * n_1}{t_{total}}$	3027.5	N/mm^2
Global verification - RFEM results				
Governing load combination for global deformation			SLS1	-
Global deformation	u_d	Figure C.10	49.8	mm
Governing load combination for dynamics			SLS2	
Total vertical force	$F_{d,dynamic}$		37681	kN
Governing load combination foundation			ULS5	
Total vertical force	$F_{d,foundation}$		60217	kN
Global verification – horizontal deformation				
Maximum deformation	u_{max}	$u_{max} = \frac{h_{building}}{750}$	64	mm
Unity check	UC	$UC = \frac{u_d}{u_{max}}$	**0.78**	-
Global verification – dynamic behaviour				
Fundamental frequency	n_1	$n_1 = \frac{46}{h_{building}}$	**0.96**	Hz
Building mass	ρ_l	$\rho_l = \frac{F_{d,dynamic}}{h_{building}}$	78502	kg/m
Building width	b_m	$b_m = w_{grid} * 3$	18.9	m
Sum of external wind pressure coefficients	c_{pe}		1.4	-
Dynamic factor	ϕ_2	$\phi_2 = \sqrt{\frac{0.0344(n_1)^{-\frac{2}{3}}}{D(1 + 0.12 * n_1 * h)(1 + 0.2 * n_1 * b_m)}}$	0.34	-
Damping	D		0.01	-
Varying part of wind vibrations	p_{vw}	$p_{vw} = 100 * \ln\left(\frac{h}{0.2}\right)$	548.06	N/m^2
Acceleration due to wind induced vibrations	a_{wind}	$a_{wind} = 1.6 * \frac{\phi_2 * p_{vw} * c_{pe} * b_m}{\rho_l}$	**0.101**	m/s^2

Global verification – estimation of foundation volume				
Pile capacity	$F_{d,pile}$		1900	kN
Required number of piles	n_{piles}	$n_{piles} = \frac{F_{d,foundation}}{F_{d,pile}}$	32	-
Pile size (square)	w_{pile}		450	mm
Pile length	l_{pile}		20	m
Raft thickness	t_{raft}		250	mm
Pile foundation volume	V_{piles}	$V_{piles} = (w_{pile})^2 * l_{pile} * n_{piles}$	134	m³
Raft foundation volume	V_{raft}	$V_{raft} = (w_{grid} * 3)^2 * t_{raft}$	89	m³
Total foundation volume	V_{total}	$V_{total} = V_{piles} + V_{raft}$	**218**	m³

The vertical load transfer to the core is depicted in Figure C.11. This is used to determine the total vertical force on the core:

$$Load\ transfer\ floors\ to\ core\ [kN]\colon n_{storeys} * w_{grid} * q_{floor} * w_{core}$$

$$Load\ transfer\ beams\ to\ core\ [kN]\colon 4\left(n_{storeys} * q_{beam} * \frac{w_{grid}}{2}\right)$$

$$Dead\ load\ core\ [kN]\colon 4(h_{building} * t_{core} * w_{core} * \rho_{mean})$$

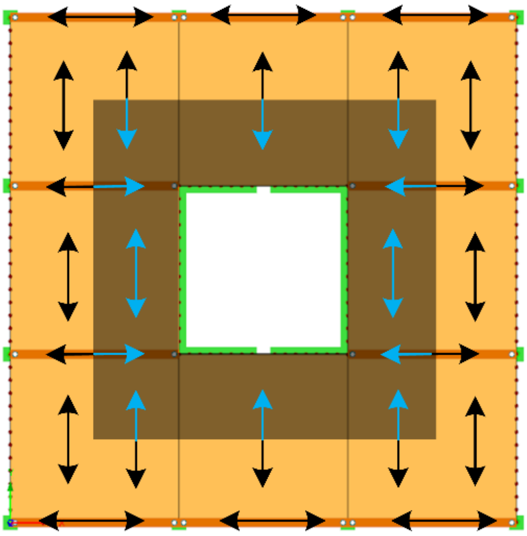


Figure C.11: Vertical load transfer to core for post and beam variants

The contribution of the wind load can be determined using:

$$Bending\ moment\ core\ [kNm]\colon \frac{1}{2} * q_{wind} * h_{building}^2$$

Table C.18: Wall verification

Wall verification (core) – Geometry and other properties				
Core thickness	t_{core}		400	mm
Core storey height	h_{core}		3	m
Material			C24	-
Material factor	γ_M		1.25	-
Material factor during fire	$\gamma_{M,fi}$		1.0	-

Wall verification (core) – Loading				
Governing load combination for compression and buckling			ULS5	-
Vertical force	N_d		6928	kN
Moment	M_d		55325	kNm
Governing load combination for compression and buckling (fire)			ULS7	-
Vertical force	$N_{d,fi}$		4802	kN
Moment	$M_{d,fi}$		7377	kNm
Governing load combination for tension			ULS3	-
Vertical force	N_d		3010	kN
Moment	M_d		55325	kNm
Wall verification (core) – Compression parallel to the grain				
Modification factor	k_{mod}	(short-term)	0.9	-
Characteristic compressive strength //	$f_{c,o,k}$		21	N/mm²
Design compressive strength //	$f_{c,o,d}$	$f_{c,o,d} = k_{mod} * \frac{f_{c,o,k}}{\gamma_M}$	15.1	N/mm²
Thickness of vertical lamellae	$t_{core,ef}$	$t_{core,ef} = t_{lam,v} * n_{lam,v}$	300	mm
Effective cross section	$A_{core,ef}$	$A_{core,ef} = w_{grid}^2 - (w_{grid} - t_{core,ef})^2$	3690000	mm²
Effective moment of resistance	$W_{core,ef}$	$W_{core,ef} = \frac{w_{grid}^3}{6} - \frac{(w_{grid} - t_{core,ef})^3}{6}$	5.7E+9	mm³
Design compressive stress	$\sigma_{c,o,d}$	$\sigma_{c,o,d} = \frac{N_d}{A_{core,ef}} + \frac{M_d}{W_{core,ef}}$	11.6	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{f_{c,o,d}}$	0.77	-
Wall verification (core) – Compression parallel to the grain during fire				
Modification factor	$k_{mod,fi}$		1.0	-
Fire duration	t		90	min
Charring rate	β_n		0.7	mm/min
Heat affected zone	k_0*d_0		7	mm
Notional charring	d_{char}	$d_{char,n} = \beta_n * t$	63	mm
Effective burn-in depth	d_{ef}	$d_{ef} = d_{char,n} + k_0 * d_0$	70	mm
Effective thickness	$t_{core,ef,fi}$	$t_{core,ef,fi} = t_{core,ef} - d_{ef}$	230	mm
k_{fi} factor	k_{fi}		1.15	-
Design compressive strength //	$f_{c,o,d,fi}$	$f_{c,o,d,fi} = k_{mod,fi} * \frac{k_{fi} * f_{c,o,k}}{\gamma_{M,fi}}$	24.15	N/mm²
Design compressive stress	$\sigma_{c,o,d,fi}$	$\sigma_{c,o,d,fi} = \frac{N_{d,fi}}{A_{core,eff,fi}} + \frac{M_{d,fi}}{W_{core,eff,fi}}$	3.36	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d,fi}}{f_{c,o,d,fi}}$	0.14	-

Wall verification (core) – Tension parallel to the grain				
Modification factor	k_{mod}	(short-term)	0.9	-
Characteristic compressive strength //	$f_{t,o,k}$		14.5	N/mm²
Design compressive strength //	$f_{t,o,d}$	$f_{t,o,d} = k_{mod} * \frac{f_{t,o,k}}{\gamma_M}$	10.5	N/mm²
Thickness of vertical lamellae	$t_{core,ef}$	$t_{core,ef} = t_{lam,v} * n_{lam,v}$	360	mm
Design compressive stress	$\sigma_{t,o,d}$	$\sigma_{t,o,d} = \frac{N_d}{A_{core,eff}} - \frac{M_d}{W_{core,eff}}$	7.99	N/mm²
Unity check	UC	$UC = \frac{\sigma_{t,o,d}}{f_{t,o,d}}$	0.76	-
Wall verification (core) – Buckling (for 1m strip)				
5% value of modulus of elasticity	$E_{0.05}$		7400	N/mm²
Centre of gravity	z	$z = \frac{t_{core}}{2}$	200	mm
Strip width	b		1000	mm
Net cross section	A_{net}	$A_{net} = t_{core,eff} * b$	300000	mm²
Net moment of inertia	I_{net}	$I_{net} = b * \sum_{i=1}^{n} \left(\frac{t_i^3}{12} + t_i * a_i^2 \right)$	$4.56*10^9$	mm⁴
Radius of gyration	i	$i = \sqrt{I_{net}/A_{net}}$	123.3	mm
Buckling length	l_{eff}		3000	mm
Slenderness factor	λ	$\lambda = \frac{l_{eff}}{i}$	24.3	-
Relative slenderness	λ_{rel}	$\lambda_{rel} = \frac{\lambda}{\pi} \sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	0.4	-
β factor	β_c		0.1	-
k factor	k	$k = 0.5 * (1 + \beta_c * (\lambda_{rel} - 0.3) + \lambda_{rel}^2$	0.59	-
Reduction factor	k_c	$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}}$	0.99	-
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{k_{fi} * f_{c,o,d}}$	**0.78**	-

Table C.19: Beam verification

Beam verification – Geometry and other properties				
Beam length	l_{beam}		6.3	m
Beam height	h_{beam}		450	mm
Beam width	w_{beam}		350	mm
Material			GL24h	-
Material factor	γ_M		1.25	-
Material factor during fire	$\gamma_{M,fi}$		1.0	-
Beam verification – Loading				
Dead load beam	G_{beam}	$G_{beam} = h_{beam} * w_{beam} * \rho$	0.66	kN/m
Dead load floor	G_{floor}		1.65	kN/m^2
Dead load floor	$G_{floor,line}$	$G_{floor,line} = G_{floor} * w_{grid}$	5.20	kN/m
Dead load façade	G_{facade}		4.50	kN/m
Imposed load	$Q_{imposed}$		2.55	kN/m^2
Imposed load	$Q_{imposed,line}$	$G_{imposed,line} = G_{imposed} * w_{grid}$	8.03	kN/m
Governing load combination for bending and shear			ULS4	-
Design load	q_d	$1.2 * G + 1.5 * Q$	24.5	kN/m
Governing load combination for bending and shear (fire)			ULS7	-
Design load	$q_{d,fi}$	$1.0 * G + 1.0 * 0.3 * Q$	12.8	kN/m
Governing load combination for deformation			SLS2	-
Design load	q_d	$1.0 * G + 1.0 * Q$	18.4	kN/m
Beam verification – Bending				
Modification factor	k_{mod}	(medium-term)	0.8	
Characteristic bending strength	$f_{m,k}$		24	N/mm^2
Design bending strength	$f_{m,d}$	$f_{m,d} = k_{mod} * \frac{f_{m,k}}{\gamma_M}$	15.4	N/mm^2
Moment of resistance	W	$W = \frac{1}{6} * w_{beam} * h_{beam}^2$	$1.18*10^7$	mm^3
Design bending moment	M_d	$M_d = \frac{1}{8} * q_d * l_{beam}^2$	121.4	kNm
Design bending stress	$\sigma_{m,d}$	$\sigma_{m,d} = \frac{M_d}{W}$	10.28	N/mm^2
Unity check	UC	$UC = \frac{\sigma_{m,d}}{f_{m,d}}$	0.67	-
Beam verification – Shear				
Modification factor	k_{mod}	(medium-term)	0.8	
Characteristic shear strength	$f_{v,k}$		3.5	N/mm^2
Design shear strength	$f_{v,d}$	$f_{v,d} = k_{mod} * \frac{f_{v,k}}{\gamma_M}$	2.2	N/mm^2
Cross sectional area	A_{ef}	$A = h_{beam} * w_{beam,ef}$	157500	mm^2
Design shear force	V_d	$V_d = \frac{1}{2} * q_d * l_{beam}$	77.1	kN
Design shear stress	τ_d	$\tau_d = \frac{3}{2} * \frac{V_d}{A_{ef}}$	0.7	N/mm^2
Unity check	UC	$UC = \frac{\tau_d}{f_{v,d}}$	0.33	-

Beam verification – deformation				
Modification factor	k_{def}		0.6	
Mean modulus of elasticity	E_{mean}		11500	N/mm^2
Mean modulus of elasticity including creep correction	$E_{mean,fin}$	$E_{mean,fi} = \frac{E_{mean}}{1 + k_{def}}$	7188	N/mm^2
Moment of inertia	I	$I = \frac{1}{12} * w_{beam} * h_{beam}^3$	$2.66*10^9$	mm^4
Instantaneous deflection	w_{inst}	$w_{inst} = \frac{5}{384} * \frac{q_d * l_{beam}^4}{E_{mean} * I}$	12.3	mm
Maximum instantaneous deflection	$w_{max,inst}$	$w_{max,inst} = \frac{l}{300}$	21	mm
Unity check	UC	$UC = \frac{w_{inst}}{w_{max,inst}}$	0.59	-
Final deflection	w_{fin}	$w_{fin} = \frac{5}{384} * \frac{q_d * l_{beam}^4}{E_{mean,fin} * I}$	19.7	mm
Maximum Final deflection	$w_{max,fin}$	$w_{max,fin} = \frac{l}{300}$	25.2	mm
Unity check	UC	$UC = \frac{w_{fin}}{w_{max,fin}}$	**0.78**	-
Beam verification – Bending during fire				
Modification factor	$k_{mod,fi}$		1.0	
Fire duration	t		90	min
Charring rate	β_n		0.7	mm/min
Heat affected zone	k_0*d_0		7	mm
Notional charring	d_{char}	$d_{char,n} = \beta_n * t$	63	mm
Effective burn-in depth	d_{ef}	$d_{ef} = d_{char,n} + k_0 * d_0$	70	mm
Moment of resistance	W_{fi}	$W_{fi} = \frac{1}{6} * (w_{beam} - 2 * d_{ef})(h_{beam} - d_{ef})^2$	$5.05*10^6$	mm^3
k_{fi} factor	k_{fi}		1.15	-
Design bending strength	$f_{m,d,fi}$	$f_{m,d,fi} = k_{mod,fi} * \frac{k_{fi} * f_{m,k}}{\gamma_{M,fi}}$	27.6	N/mm^2
Design bending moment	$M_{d,fi}$	$M_{d,fi} = \frac{1}{8} * q_{d,fi} * l_{beam}^2$	63.3	kNm
Design bending stress	$\sigma_{m,d,fi}$	$\sigma_{m,d} = \frac{M_{d,fi}}{W_{fi}}$	12.53	N/mm^2
Unity check	UC	$UC = \frac{\sigma_{m,d,fi}}{f_{m,d,fi}}$	0.45	-
Beam verification – Shear during fire				
Modification factor	$k_{mod,fi}$		1.0	
Effective cross section	A_{fi}	$A_{fi} = (h_{beam} - d_{ef})(w_{beam} - 2 * d_{ef})$	79800	mm^2
Design shear strength	$f_{v,d,fi}$	$f_{v,d,fi} = k_{mod,fi} * \frac{k_{fi} * f_{v,k}}{\gamma_{M,fi}}$	4.0	N/mm^2
Design shear force	$V_{d,fi}$	$V_{d,fi} = \frac{1}{2} * q_{d,fi} * l_{beam}$	40.2	kN
Design shear stress	$\tau_{d,fi}$	$\tau_{d,fi} = \frac{3}{2} * \frac{V_{d,fi}}{A_{fi}}$	1.1	N/mm^2
Unity check	UC	$UC = \frac{\tau_{d,fi}}{f_{v,d,fi}}$	0.19	-

Table C.20: Column verification

Column verification – Geometry and other properties					
		Columns in range:	**0-30m**	**30-50m**	
Column length	l_{column}		3	3	m
Column size (square)	w_{column}		420	280	mm
Material			GL24h	GL24h	-
Material factor	γ_M		1.25	1.25	-
Material factor during fire	$\gamma_{M,fi}$		1.0	1.0	-
Column verification – RFEM results					
Governing load combination for compression and buckling			ULS4	ULS4	-
Maximum compressive force	N_d		1873	759	kN/m
Governing load combination for compression and buckling (fire)			ULS7	ULS7	-
Total vertical force	$N_{d,fi}$		1302	489	kN/m
Column verification – Compression parallel to the grain					
Modification factor	k_{mod}	(medium-term)	0.8	0.8	-
Characteristic compressive strength //	$f_{c,o,k}$		21	21	N/mm²
Design compressive strength //	$f_{c,o,d}$	$f_{c,o,d} = k_{mod} * \frac{f_{c,o,k}}{\gamma_M}$	13.4	13.4	N/mm²
Design compressive stress	$\sigma_{c,o,d}$	$\sigma_{c,o,d} = \frac{N_d}{A}$	10.6	9.9	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{f_{c,o,d}}$	**0.79**	0.72	-
Column verification – Buckling					
5% value of modulus of elasticity	$E_{0.05}$		9600	9600	N/mm²
Moment of inertia	I_{net}	$I = \frac{1}{12} * w_{colum}^4$	$2.59*10^9$	$5.12*10^8$	mm⁴
Radius of gyration	i	$i = \sqrt{I/A}$	121.2	80.8	mm
Buckling length	l_{eff}		3000	3000	mm
Slenderness factor	λ	$\lambda = \frac{l_{eff}}{i}$	24.7	37.1	-
Relative slenderness	λ_{rel}	$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	0.37	0.55	-
β factor	β_c		0.1	0.1	-
k factor	k	$k = 0.5 * (1 + \beta_c * (\lambda_{rel} - 0.3) + \lambda_{rel}^2$	0.57	0.67	-
Reduction factor	k_c	$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}}$	0.99	0.97	-
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{k_{fi} * f_{c,o,d}}$	**0.80**	**0.75**	-
Column verification – Compression parallel to the grain during fire					
Modification factor	$k_{mod,fi}$		1.0	1.0	-
Fire duration	t		90	90	min
Charring rate	β_n		0.7	0.7	mm/min
Heat affected zone	$k_0 * d_0$		7	7	mm
Notional charring	d_{char}	$d_{char,n} = \beta_n * t$	63	63	mm
Effective burn-in depth	d_{ef}	$d_{ef} = d_{char,n} + k_0 * d_0$	70	70	mm

Effective cross section	A_{fi}	$A_{fi} = (w_{columm} - d_{ef})(w_{column} - 2 * d_{ef})$	98000	29400	mm^2
k_{fi} factor	k_{fi}		1.15	1.15	-
Design compressive strength //	$f_{c,o,d,fi}$	$f_{c,o,d,fi} = k_{mod,fi} * \frac{k_{fi} * f_{c,o,k}}{\gamma_{M,fi}}$	24.15	24.15	N/mm^2
Design compressive stress	$\sigma_{c,o,d,fi}$	$\sigma_{c,o,d,fi} = \frac{N_{d,fi}}{A_{fi}}$	13.29	16.62	N/mm^2
Unity check	UC	$UC = \frac{\sigma_{c,o,d,fi}}{f_{c,o,d,fi}}$	0.55	0.69	-

C.10 Obtained member sizes per variant

Table C.21: Obtained member sizes per variant

Variant	Storeys	Height [m]	Core width [m]	Core thickness [mm]	Beam size [mm]		Column size [mm]			Wall thickness [mm]		
					w_{beam}	h_{beam}	0-30m	30-50m	50-70m	0-30m	30-50m	50-70m
P&B – 30 – RSL 50	10	30	5.4	200	290	390	290	-	-	-	-	-
P&B – 50 – RSL 50	16	48	6.3	400	350	450	420	280	-	-	-	-
P&B – 50 – RSL 150	16	48	6.3	440	370	450	430	290	-	-	-	-
P&B – 70 – RSL 50	23	69	9.0	480	380	480	580	420	280	-	-	-
MT – 30 – RSL 50	10	30	5.4	200*	-	-	-	-	-	160	-	-
MT – 50 – RSL 50	16	48	6.3	400*	-	-	-	-	-	200	160	-
MT – 70 – RSL 50	23	69	7.2	480*	-	-	-	-	-	240	200	160

* Core thickness for Mass timber variant is exclusively applied in weak direction (without load-bearing walls). For the strong direction, the thickness from the wall thickness columns are applied.

C.11 Results verification by detailed design study

To verify the plausibility of the obtained material quantities, the geometry of a detailed design has been inputted in the model to analyse the differences in results between the preliminary design from this study and results of a detailed design. The detailed design is used from a study by van Rhijn: Possibilities of timber high-rise – A parametric study on the possibilities of timber high-rise in the Netherlands [15]. This study analyses the ultimate structural capabilities of timber structures in detail. Specifically, the post and beam typology with CLT stability core is used for the comparison. Instead of the residential function in this report, the study by van Rhijn analyses buildings with an office function. To take this into account, the floor to floor height and imposed load are changed to make a correct comparison, see Table C.22 for the parameters. The verification is performed for three building heights similar to the heights studied in this report, see Table C.23 and Table C.24. By inputting this data in the preliminary design model as described in this appendix, the obtained material quantities are verified in Table C.25. It results that the conservative approach to optimize the unity checks to 0.8 and other conservative assumptions (e.g. maximum wind load over the full height), result in good material quantities which are representative for reality.

Table C.22: General data of the variants by van Rhijn

Geometry and loads			
Width	$w_{building}$	32.4	m
Depth	$d_{building}$	28.8	m
Storey height	h_{storey}	3.6	m
Columns in width	n_w	7	-
Columns in depth	n_d	5	-
Floor thickness	t_{floor}	255	mm
Floor span	l_{floor}	5.4	m
Beam span	l_{beam}	7.2	m
Number of lamellae core	n_{core}	11	
Lamella thickness core	$t_{lamella}$	45	mm
Fire duration	t	120	min
Imposed load (office)	q_k	2.5	kN/m²
Imposed load (separating walls)	q_k	0.5	kN/m²

Table C.23: Results by van Rhijn (1)

Storeys	Height [m]	Core thickness [mm]	Column size [mm]	Beam size [mm]	
				w_{beam}	h_{beam}
8	28.8	495	400	400	700
14	50.4	495	500	400	700
20	72	495	600	400	700

Table C.24: Results by van Rhijn (2)

Storeys	Core size [mm]		Unity check		U_{max} [mm]		U [mm]	
	X (width)	Y (depth)	X (width)	Y (depth)	X (width)	Y (depth)	X (width)	Y (depth)
8	9	5	0.8	0.71	28.8	28.8	23.0	20.4
14	13	7	0.95	1	50.4	50.4	48.4	50.4
20	17	10	0.94	0.94	72	72	69.1	67.7

Table C.25: Verification of obtained material quantities

	van Rhijn (detailed design)		This study (preliminary design)
Storeys	Timber volume [m^3]	Steel mass [kg]	Timber volume [m^3]
8	**2178**	10431	**2217**
14	**4266**	26781	**4900**
20	**6862**	58465	**7884**

C.12 Life Cycle Impact Assessment

Table C.26: Build-up and shadow price of LVL floor assembly, 5.4m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m^2]**	**Total [€/m^2]**	**Total + D [€/m^2]**
Gypsum board	25		0.38	0.37
Wood fibre	20		1.07	0.79
LVL		26.6	1.28	1.00
Mineral wool	90		0.65	0.63
Gypsum board	40		0.61	0.60
		Σ	**4.00**	**3.39**

Table C.27: Build-up and shadow price of LVL floor assembly, 5.4m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m^2]**	**Total [€/m^2]**	**Total + D [€/m^2]**
Gypsum board	25		0.38	0.37
Wood fibre	20		1.07	0.79
LVL		26.6	1.28	1.00
Mineral wool	90		0.65	0.63
LVL	68		1.04	1.02
		Σ	**4.43**	**3.81**

Table C.28: Build-up and shadow price of LVL floor assembly, 6.3m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m^2]**	**Total [€/m^2]**	**Total + D [€/m^2]**
Gypsum board	25		0.38	0.37
Wood fibre	20		1.07	0.79
LVL		27.7	1.34	1.04
Mineral wool	90		0.65	0.63
Gypsum board	40		0.61	0.60
		Σ	**4.06**	**3.43**

Table C.29: Build-up and shadow price of LVL floor assembly, 6.3m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m^2]**	**Total [€/m^2]**	**Total + D [€/m^2]**
Gypsum board	25		0.38	0.37
Wood fibre	20		1.07	0.79
LVL		27.7	1.34	1.04
Mineral wool	90		0.65	0.63
LVL	68		1.04	1.02
		Σ	**4.49**	**3.85**

Table C.30: Build-up and shadow price of LVL floor assembly, 7.2m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	25		0.38	0.37
Wood fibre	20		1.07	0.79
LVL		29.8	1.44	1.12
Mineral wool	90		0.65	0.63
Gypsum board	40		0.61	0.60
		Σ	**4.16**	**3.51**

Table C.31: Build-up and shadow price of LVL floor assembly, 7.2m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	25		0.38	0.37
Wood fibre	20		1.07	0.79
LVL		29.8	1.44	1.12
Mineral wool	90		0.65	0.63
LVL	68		1.04	1.02
		Σ	**4.59**	**3.93**

Table C.32: Build-up and shadow price of CLT (Dry screed) floor assembly, 5.4m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	31		0.48	0.46
Wood fibre	24		1.29	0.94
Flax wool	10		0.03	0.02
CLT	170		1.81	1.06
Gypsum board	40		0.61	0.60
		Σ	**4.22**	**3.09**

Table C.33: Build-up and shadow price of CLT (Dry screed) floor assembly, 5.4m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	31		0.48	0.46
Wood fibre	24		1.29	0.94
Flax wool	10		0.03	0.02
CLT	170		1.81	1.06
		Σ	**3.60**	**2.49**

Table C.34: Build-up and shadow price of CLT (Dry screed) floor assembly, 6.3m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	31		0.48	0.46
Wood fibre	24		1.29	0.94
Flax wool	10		0.03	0.02
CLT	220		2.34	1.37
Gypsum board	40		0.61	0.60
		Σ	**4.75**	**3.40**

Table C.35: Build-up and shadow price of CLT (Dry screed) floor assembly, 6.3m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	31		0.48	0.46
Wood fibre	24		1.29	0.94
Flax wool	10		0.03	0.02
CLT	220		2.34	1.37
		Σ	**4.14**	**2.80**

Table C.36: Build-up and shadow price of CLT (Dry screed) floor assembly, 7.2m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	31		0.48	0.46
Wood fibre	24		1.29	0.94
Flax wool	10		0.03	0.02
CLT	280		2.98	1.75
Gypsum board	40		0.61	0.60
		Σ	**5.39**	**3.77**

Table C.37: Build-up and shadow price of CLT (Dry screed) floor assembly, 7.2m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Gypsum board	31		0.48	0.46
Wood fibre	24		1.29	0.94
Flax wool	10		0.03	0.02
CLT	280		2.98	1.75
		Σ	**4.77**	**3.17**

Table C.38: Build-up and shadow price
of CLT (Wet screed) floor assembly, 5.4m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Sand cement	60		0.99	0.99
Separating layer				
Wood fibre	20		1.07	0.79
CLT	170		1.81	1.06
Gypsum board	40		0.61	0.60
		Σ	**4.49**	**3.43**

Table C.39: Build-up and shadow price
of CLT (Wet screed) floor assembly, 5.4m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Sand cement	60		0.99	0.99
Separating layer				
Wood fibre	20		1.07	0.79
CLT	170		1.81	1.06
		Σ	**3.87**	**2.83**

Table C.40: Build-up and shadow price
of CLT (Wet screed) floor assembly, 6.3m, encapsulated fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Sand cement	60		0.99	0.99
Separating layer				
Wood fibre	20		1.07	0.79
CLT	220		2.34	1.37
Gypsum board	40		0.61	0.60
		Σ	**5.02**	**3.74**

Table C.41: Build-up and shadow price
of CLT (Wet screed) floor assembly, 6.3m, exposed fire safety strategy

			Shadow price	
Build-up	**Thickness [mm]**	**Weight [kg/m²]**	**Total [€/m²]**	**Total + D [€/m²]**
Sand cement	60		0.99	0.99
Separating layer				
Wood fibre	20		1.07	0.79
CLT	220		2.34	1.37
		Σ	**4.40**	**3.14**

Table C.42: Build-up and shadow price of CLT (Wet screed) floor assembly, 7.2m, encapsulated fire safety strategy

Build-up	Thickness [mm]	Weight [kg/m²]	Shadow price Total [€/m²]	Shadow price Total + D [€/m²]
Sand cement	60		0.99	0.99
Separating layer				
Wood fibre	20		1.07	0.79
CLT	260		2.77	1.62
Gypsum board	40		0.61	0.60
		Σ	**5.44**	**3.99**

Table C.43: Build-up and shadow price of CLT (Wet screed) floor assembly, 7.2m, exposed fire safety strategy

Build-up	Thickness [mm]	Weight [kg/m²]	Shadow price Total [€/m²]	Shadow price Total + D [€/m²]
Sand cement	60		0.99	0.99
Separating layer				
Wood fibre	20		1.07	0.79
CLT	260		2.77	1.62
		Σ	**4.83**	**3.39**

Table C.44: Build-up and shadow price of IW200/54 partitioning wall

Build-up	Thickness [mm]	Weight [kg/m²]	Shadow price Total [€/m²]	Shadow price Total + D [€/m²]
Gypsum board	10		0.15	0.15
Flax wool	34		0.09	0.07
Gypsum board	10		0.15	0.15
Mineral wool	40		0.29	0.28
Gypsum board	10		0.15	0.15
Flax wool	34		0.09	0.07
Gypsum board	10		0.15	0.15
		Σ	**1.08**	**1.01**

Table C.45: Material quantities and shadow price
post and beam, 30m, 50 year, exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**
Floors	CLT (Hybrid)	2362	m^2	8510	5875	0.065	0.045
Beams	Glulam	61	m^3	574	304	0.004	0.002
Fireboard beams	Gypsum	0	m^2	0	0	0.000	0.000
Columns	Glulam	30	m^3	285	151	0.002	0.001
Fireboard columns	Gypsum	0	m^2	0	0	0.000	0.000
Core	CLT	130	m^3	1381	808	0.011	0.006
Fireboard core	Gypsum	0	m^2	0	0	0.000	0.000
Fire coating core	AMONN	1296	m^2	377	377	0.003	0.003
Walls	CLT	0	m^3	0	0	0.000	0.000
Fireboard walls	Gypsum	0	m^2	0	0	0.000	0.000
Partitioning walls	Hybrid	1620	m^2	1746	1635	0.013	0.012
Foundation	Concrete	130	m^3	3277	2924	0.025	0.022
			Σ	**16150**	**12074**	**0.123**	**0.092**

Table C.46: Material quantities and shadow price
mass timber, 30m, 50 year, exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**
Floors	CLT (Hybrid)	2362	m^2	8510	5875	0.065	0.045
Beams	Glulam	0	m^3	0	0	0.000	0.000
Fireboard beams	Gypsum	0	m^2	0	0	0.000	0.000
Columns	Glulam	0	m^3	0	0	0.000	0.000
Fireboard columns	Gypsum	0	m^2	0	0	0.000	0.000
Core	CLT	117	m^3	1243	727	0.009	0.006
Fireboard core	Gypsum	0	m^2	0	0	0.000	0.000
Fire coating core	AMONN	1296	m^2	377	377	0.003	0.003
Walls	CLT	259	m^3	2761	1615	0.021	0.012
Fireboard walls	Gypsum	0	m^2	0	0	0.000	0.000
Partitioning walls	Hybrid	0	m^2	0	0	0.000	0.000
Foundation	Concrete	130	m^3	3277	2924	0.025	0.022
			Σ	**16168**	**11519**	**0.123**	**0.088**

Table C.47: Material quantities and shadow price
post and beam, 50m, 50 year, exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**
Floors	CLT (Hybrid)	5120	m^2	21175	14331	0.074	0.050
Beams	Glulam	159	m^3	1492	791	0.005	0.003
Fireboard beams	Gypsum	0	m^2	0	0	0.000	0.000
Columns	Glulam	80	m^3	756	401	0.003	0.001
Fireboard columns	Gypsum	0	m^2	0	0	0.000	0.000
Core	CLT	484	m^3	5155	3016	0.018	0.011
Fireboard core	Gypsum	0	m^2	0	0	0.000	0.000
Fire coating core	AMONN	2419	m^2	704	704	0.002	0.002
Walls	CLT	0	m^3	0	0	0.000	0.000
Fireboard walls	Gypsum	0	m^2	0	0	0.000	0.000
Partitioning walls	Hybrid	3024	m^2	3259	3053	0.011	0.011
Foundation	Concrete	218	m^3	5469	4880	0.019	0.017
			Σ	**38010**	**27174**	**0.133**	**0.095**

Table C.48: Material quantities and shadow price
mass timber, 50m, 50 year, exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**
Floors	CLT (Hybrid)	5120	m^2	21175	14331	0.074	0.050
Beams	Glulam	0	m^3	0	0	0.000	0.000
Fireboard beams	Gypsum	0	m^2	0	0	0.000	0.000
Columns	Glulam	0	m^3	0	0	0.000	0.000
Fireboard columns	Gypsum	0	m^2	0	0	0.000	0.000
Core	CLT	363	m^3	3866	2262	0.014	0.008
Fireboard core	Gypsum	0	m^2	0	0	0.000	0.000
Fire coating core	AMONN	2419	m^2	704	704	0.002	0.002
Walls	CLT	559	m^3	5960	3487	0.021	0.012
Fireboard walls	Gypsum	0	m^2	0	0	0.000	0.000
Partitioning walls	Hybrid	0	m^2	0	0	0.000	0.000
Foundation	Concrete	229	m^3	5765	5144	0.020	0.018
			Σ	**37470**	**25927**	**0.131**	**0.091**

Table C.49: Material quantities and shadow price
post and beam, 70m, 50 year, exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m²/year]**	**Total + D [€/m²/year]**
Floors	CLT (Hybrid)	8949	m^2	42730	28394	0.080	0.053
Beams	Glulam	302	m^3	2839	1504	0.005	0.003
Fireboard beams	Gypsum	0	m^2	0	0	0.000	0.000
Columns	Glulam	179	m^3	1682	891	0.003	0.002
Fireboard columns	Gypsum	0	m^2	0	0	0.000	0.000
Core	CLT	1192	m^3	12703	7431	0.024	0.014
Fireboard core	Gypsum	0	m^2	0	0	0.000	0.000
Fire coating core	AMONN	4968	m^2	1446	1446	0.003	0.003
Walls	CLT	0	m^3	0	0	0.000	0.000
Fireboard walls	Gypsum	0	m^2	0	0	0.000	0.000
Partitioning walls	Hybrid	4968	m^2	5354	5015	0.010	0.009
Foundation	Concrete	383	m^3	9626	8589	0.018	0.016
			Σ	**76381**	**53271**	**0.142**	**0.099**

Table C.50: Material quantities and shadow price
mass timber, 70m, 50 year, exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m²/year]**	**Total + D [€/m²/year]**
Floors	CLT (Hybrid)	8949	m^2	42730	28394	0.080	0.053
Beams	Glulam	0	m^3	0	0	0.000	0.000
Fireboard beams	Gypsum	0	m^2	0	0	0.000	0.000
Columns	Glulam	0	m^3	0	0	0.000	0.000
Fireboard columns	Gypsum	0	m^2	0	0	0.000	0.000
Core	CLT	715	m^3	7622	4459	0.014	0.008
Fireboard core	Gypsum	0	m^2	0	0	0.000	0.000
Fire coating core	AMONN	3974	m^2	1157	1157	0.002	0.002
Walls	CLT	1020	m^3	10862	6354	0.020	0.012
Fireboard walls	Gypsum	0	m^2	0	0	0.000	0.000
Partitioning walls	Hybrid	0	m^2	0	0	0.000	0.000
Foundation	Concrete	413	m^3	10376	9258	0.019	0.017
			Σ	**72746**	**49622**	**0.136**	**0.092**

Table C.51: Material quantities and shadow price post and beam, 50m, 50 year, encapsulated fire safety strategy

Element type	Material type	Quantity	Unit	Shadow price Total [€]	Total + D [€]	Total [€/m²/year]	Total + D [€/m²/year]
Floors	CLT (Hybrid)	5120	m²	24321	17401	0.085	0.061
Beams	Glulam	159	m³	1492	791	0.005	0.003
Fireboard beams	Gypsum	200	m²	123	120	0.000	0.000
Columns	Glulam	80	m³	756	401	0.003	0.001
Fireboard columns	Gypsum	358	m²	220	215	0.001	0.001
Core	CLT	484	m³	5155	3016	0.018	0.011
Fireboard core	Gypsum	2419	m²	1486	1451	0.005	0.005
Fire coating core	AMONN	0	m²	0	0	0.000	0.000
Walls	CLT	0	m³	0	0	0.000	0.000
Fireboard walls	Gypsum	0	m²	0	0	0.000	0.000
Partitioning walls	Hybrid	3024	m²	3259	3053	0.011	0.011
Foundation	Concrete	218	m³	5469	4880	0.019	0.017
			Σ	**42282**	**31325**	**0.148**	**0.110**

Table C.52: Material quantities and shadow price mass timber, 50m, 50 year, encapsulated fire safety strategy

Element type	Material type	Quantity	Unit	Shadow price Total [€]	Total + D [€]	Total [€/m²/year]	Total + D [€/m²/year]
Floors	CLT (Hybrid)	5120	m²	24321	17401	0.085	0.061
Beams	Glulam	0	m³	0	0	0.000	0.000
Fireboard beams	Gypsum	0	m²	0	0	0.000	0.000
Columns	Glulam	0	m³	0	0	0.000	0.000
Fireboard columns	Gypsum	0	m²	0	0	0.000	0.000
Core	CLT	339	m³	3608	2111	0.013	0.007
Fireboard core	Gypsum	384	m²	236	230	0.001	0.001
Fire coating core	AMONN	0	m²	0	0	0.000	0.000
Walls	CLT	484	m³	5155	3016	0.018	0.011
Fireboard walls	Gypsum	3024	m²	1858	1813	0.007	0.006
Partitioning walls	Hybrid	0	m²	0	0	0.000	0.000
Foundation	Concrete	229	m³	5765	5144	0.020	0.018
			Σ	**40943**	**29714**	**0.143**	**0.104**

Table C.53: Material quantities and shadow price
post and beam, 50m, 150 year (re-use scenario), exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m²/year]**	**Total + D [€/m²/year]**
Floors	CLT (Hybrid)	9886	m²	40887	27672	0.048	0.032
Beams	Glulam	307	m³	2882	1526	0.003	0.002
Fireboard beams	Gypsum	0	m²	0	0	0.000	0.000
Columns	Glulam	155	m³	1460	773	0.002	0.001
Fireboard columns	Gypsum	0	m²	0	0	0.000	0.000
Core	CLT	934	m³	9953	5823	0.012	0.007
Fireboard core	Gypsum	0	m²	0	0	0.000	0.000
Fire coating core	AMONN	4671	m²	2113	2113	0.002	0.002
Walls	CLT	0	m³	0	0	0.000	0.000
Fireboard walls	Gypsum	0	m²	0	0	0.000	0.000
Partitioning walls	Hybrid	5839	m²	9777	9158	0.011	0.011
Foundation	Concrete	420	m³	5469	4880	0.006	0.006
			Σ	**72541**	**51945**	**0.085**	**0.061**

Table C.54: Material quantities and shadow price
mass timber, 50m, 150 year (re-use scenario), exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m²/year]**	**Total + D [€/m²/year]**
Floors	CLT (Hybrid)	9886	m²	40887	27672	0.048	0.032
Beams	Glulam	0	m³	0	0	0.000	0.000
Fireboard beams	Gypsum	0	m²	0	0	0.000	0.000
Columns	Glulam	0	m³	0	0	0.000	0.000
Fireboard columns	Gypsum	0	m²	0	0	0.000	0.000
Core	CLT	701	m³	7465	4367	0.009	0.005
Fireboard core	Gypsum	0	m²	0	0	0.000	0.000
Fire coating core	AMONN	4671	m²	2113	2113	0.002	0.002
Walls	CLT	1080	m³	11509	6733	0.013	0.008
Fireboard walls	Gypsum	0	m²	0	0	0.000	0.000
Partitioning walls	Hybrid	0	m²	0	0	0.000	0.000
Foundation	Concrete	9886	m³	5765	5144	0.007	0.006
			Σ	**67738**	**46028**	**0.079**	**0.054**

Table C.55: Material quantities and shadow price post and beam, 50m, 150 year (flexible scenario), exposed fire safety strategy

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m²/year]**	**Total + D [€/m²/year]**
Floors	CLT (Hybrid)	5120	m²	21175	14331	0.025	0.017
Beams	Glulam	168	m³	1578	836	0.002	0.001
Fireboard beams	Gypsum	0	m²	0	0	0.000	0.000
Columns	Glulam	85	m³	796	422	0.001	0.000
Fireboard columns	Gypsum	0	m²	0	0	0.000	0.000
Core	CLT	532	m³	5670	3317	0.007	0.004
Fireboard core	Gypsum	0	m²	0	0	0.000	0.000
Fire coating core	AMONN	2419	m²	2113	2113	0.002	0.002
Walls	CLT	0	m³	0	0	0.000	0.000
Fireboard walls	Gypsum	0	m²	0	0	0.000	0.000
Partitioning walls	Hybrid	3024	m²	9777	9158	0.011	0.011
Foundation	Concrete	0	m³	0	0	0.000	0.000
			Σ	**41109**	**30176**	**0.048**	**0.035**

Table C.56: Material quantities and shadow price for 8 storey detailed design by van Rhijn

				Shadow price	
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**
Total Timber volume	CLT	2178	m³	23204	13575
Steel mass of connections	Steel	10431	kg	720	365
	% increase by connections			**3.1**	**2.7**

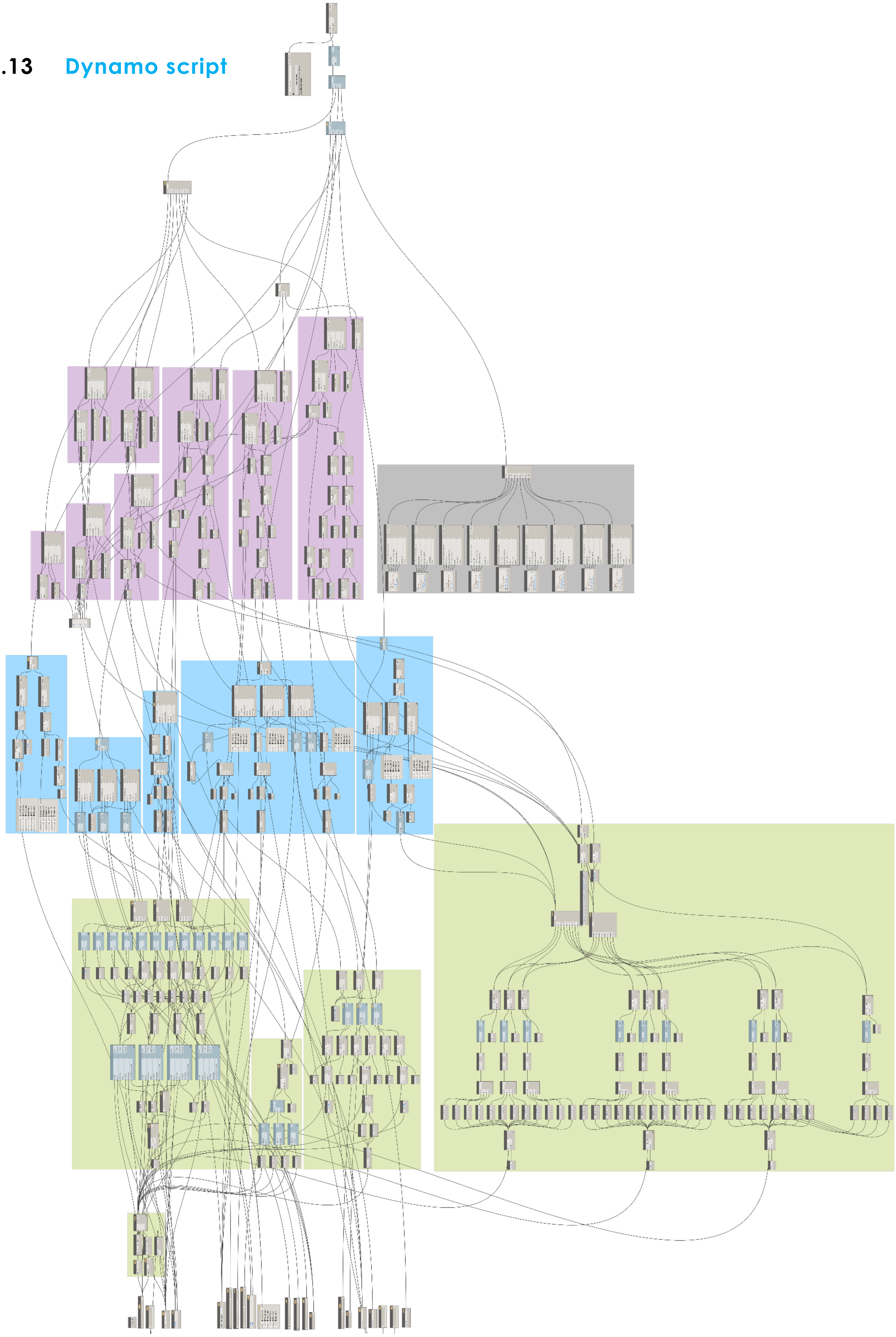
Table C.57: Material quantities and shadow price for 14 storey detailed design by van Rhijn

				Shadow price	
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**
Total Timber volume	CLT	4266	m³	45499	26588
Steel mass of connections	Steel	26781	kg	1848	937
	% increase by connections			**4.1**	**3.5**

Table C.58: Material quantities and shadow price for 20 storey detailed design by van Rhijn

				Shadow price	
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**
Total Timber volume	CLT	6862	m³	73106	42768
Steel mass of connections	Steel	58465	kg	4034	2046
	% increase by connections			**5.5**	**4.8**

C.13 Dynamo script



Appendix D
Case study

The following internal Arcadis documents have been used:

1. The View Rotterdam – Gewichtsberekening Westgebouw, 28-11-2018
2. The View Rotterdam – Stabiliteitsberekening Westgebouw, 28-11-2018
3. 16035 Constructieve uitgangspunten t.b.v. bestek, 22-05-2017
4. CON-16035 Plattegronden West, N.D.

D.1 Simplification of case study

Figure D.1 and Figure D.2 show the analysed part of the structure. This part includes axes 9-16 of the highest part. In practice the geometry of each of the axis is different. The complexity is further reduced by the simplification as shown in Figure D.3. Two configurations are considered for an axis, one fully closed wall and one with partly opened-up ground and first floor. Figure D.3 indicates which axis uses which geometry. Note that balconies are excluded from the simplification. Also, the basement is assumed to be the same for the timber alternative and concrete benchmark.

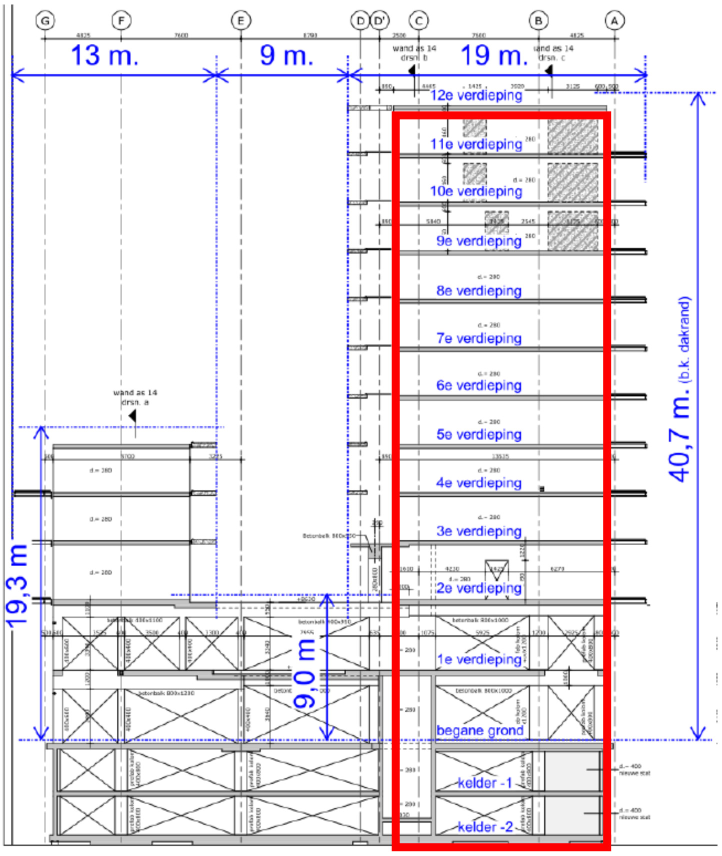


Figure D.1: Analysed part of case study (1)

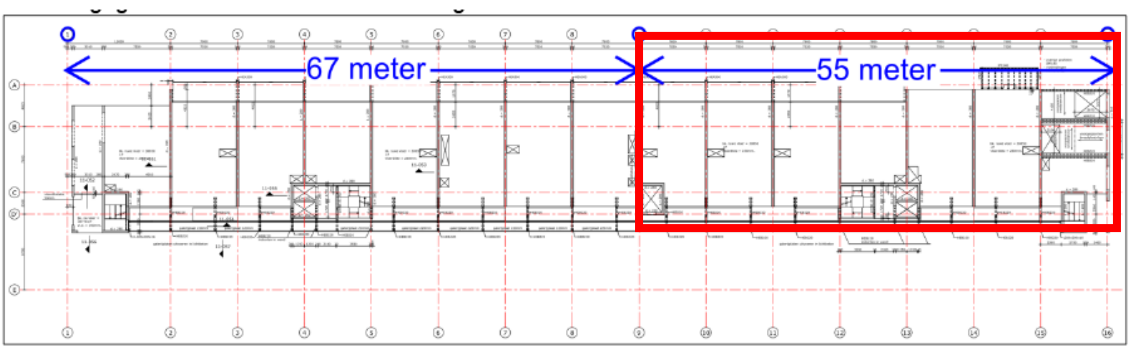


Figure D.2 Analysed part of case study (2)

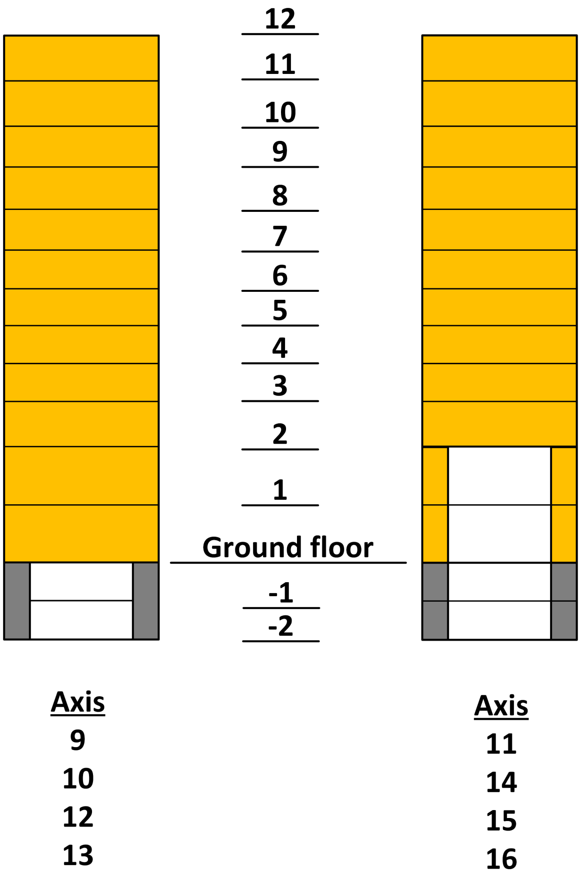


Figure D.3: Geometry simplification of main axes

D.2 Design of timber alternative

The same verification workflow as in Appendix C has been used to determine the material quantities for the timber alternative. For the CLT floor, the same thickness (300mm for 7.8m span) is used as the part of the case study which has a timber load-bearing structure. Furthermore, the same external loads (e.g. wind and live load) are applied from the documents of the concrete benchmark. The maximum wind load (present at axis 9) is applied to all axes, see Table D.1 for the values.

Table D.1: Wind loads

Storeys	Storey height [m]	Total height [m]	Governing characteristic wind load [kN]	Characteristic bending moment [kNm]
Roof edge		40.7	48	1954
12 (Roof)	0.67	40.03	-	
11	3.06	36.97	51	1885
10	3.06	33.91	51	1729
9	3.06	30.85	51	1573
8	3.06	27.79	51	1417
7	3.06	24.73	51	1261
6	3.06	21.67	51	1105
5	3.06	18.61	51	949
4	3.06	15.55	51	793
3	3.06	12.49	57	712
2	3.71	8.78	-53	-465
1	4.44	4.34	49	213
Ground floor	4.64	-0.3		
-1	3.03	-3.33		
-2	2.775	-6.105		
			Total characteristic	13127
			Total design	19690

Table D.2: Wall verification (axis 9, 10, 12, 13)

Wall verification - Building geometry				
Building height	$h_{building}$		40.7	m
Building width	$w_{building}$		12	m
Building length	$l_{building}$		54.6	m
Grid size	w_{grid}		7.8	m
Wall verification – Equivalent stiffness CLT walls				
Mean E-modulus // CLT C24	$E_{0,mean}$		11000	N/mm²
Mean E-modulus ⊥ CLT C24	$E_{90,mean}$		370	N/mm²
Vertical lamella thickness	$t_{lam,v}$		35	mm
Horizontal lamella thickness	$t_{lam,h}$		35	mm
Number of vertical lamellae	$n_{lam,v}$		5	-
Number of horizontal lamellae	$n_{lam,h}$		4	-
Number of total lamellae	$n_{lam,total}$	$n_{lam,total} = n_{lam,v} + n_{lam,h}$	9	-
Wall thickness	t_{wall}	$t_{wall} = t_{lam,v} * n_{lam,v} + t_{lam,h} * n_{lam,h}$	315	mm
Vertical equivalent stiffness	$E_{eq,1}$	$E_{eq,1} = \frac{E_0 * t_1 * n_1 + E_{90} * t_2 * n_2}{t_{total}}$	6275.6	N/mm²
Horizontal equivalent stiffness	$E_{eq,2}$	$E_{eq,2} = \frac{E_0 * t_2 * n_2 + E_{90} * t_1 * n_1}{t_{total}}$	5094.4	N/mm²
Wall verification – Geometry and other properties				
Wall thickness	t_{wall}		315	mm
Wall length	l_{wall}		12	m
Material			C24	-
Material factor	γ_M		1.25	-
Material factor during fire	$\gamma_{M,fi}$		1.0	-
Wall verification – Loading from floor				
Characteristic imposed load	$Q_{imposed}$		2.55	kN/m²
Characteristic floor finishing load	G_{finish}		1.60	kN/m²
Characteristic dead load	G		1.26	kN/m²
Governing load combination for compression and buckling at ground level	n_d	$ULS5$: $1.2 * \boldsymbol{G} + 1.5 * \boldsymbol{Q_{wind}} + 1.5 * 0.4 * \boldsymbol{Q_{imposed}}$	579	kN/m
Governing load combination for compression and buckling (fire) at ground level	n_d	$ULS7$: $1.0 * \boldsymbol{G} + 1.0 * 0.2 * \boldsymbol{Q_{wind}} + 1.0 * 0.3 * \boldsymbol{Q_{imposed}}$	435	kN/m
Governing load combination for tension at ground level	n_d	$ULS3$: $0.9 * \boldsymbol{G} + 1.5 * \boldsymbol{Q_{wind}}$	290	kN/m
Wall verification – Compression parallel to the grain				
Modification factor	k_{mod}	(medium-term)	0.8	-
Characteristic compressive strength //	$f_{c,o,k}$		21	N/mm²
Design compressive strength //	$f_{c,o,d}$	$f_{c,o,d} = k_{mod} * \frac{f_{c,o,k}}{\gamma_M}$	13.4	N/mm²
Thickness of vertical lamellae	$t_{wall,ef}$	$t_{wall,ef} = t_{lam,v} * n_{lam,v}$	175	mm
Effective moment of resistance	$W_{wall,ef}$	$W_{wall,ef} = \frac{1}{6} * l_{wall} * t_{wall,ef}^2$	4.2E+09	mm³
Design compressive stress	$\sigma_{c,o,d}$	$\sigma_{c,o,d} = \frac{n_d}{t_{wall,ef}} + \frac{M_d}{W_{wall,ef}}$	8.0	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{f_{c,o,d}}$	0.59	-

Wall verification – Compression parallel to the grain during fire				
Modification factor	$k_{mod,fi}$		1.0	-
Fire duration	t		90	min
Charring rate	β_n		0.7	mm/min
Heat affected zone	$k_0 * d_0$		7	mm
Notional charring	d_{char}	$d_{char,n} = \beta_n * t$	63	mm
Effective burn-in depth	d_{ef}	$d_{ef} = d_{char,n} + k_0 * d_0$	70	mm
Effective thickness	$t_{wall,ef,fi}$	$t_{wall,ef,fi} = t_{wall,ef} - d_{ef}$	105	mm
k_{fi} factor	k_{fi}		1.15	-
Design compressive strength //	$f_{c,o,d,fi}$	$f_{c,o,d,fi} = k_{mod,fi} * \frac{k_{fi} * f_{c,o,k}}{\gamma_{M,fi}}$	24.15	N/mm²
Effective moment of resistance	$W_{wall,ef,fi}$	$W_{wall,ef,fi} = \frac{1}{6} * l_{wall} * t_{wall,ef,fi}^2$	2.5E+09	mm³
Design compressive stress	$\sigma_{c,o,d,fi}$	$\sigma_{c,o,d,fi} = \frac{n_{d,fi}}{A_{wall,ef,fi}} + \frac{M_{d,fi}}{W_{wall,ef,fi}}$	9.57	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d,fi}}{f_{c,o,d,fi}}$	0.40	-

Wall verification – Tension parallel to the grain				
Modification factor	k_{mod}	(medium-term)	0.8	-
Characteristic compressive strength //	$f_{t,o,k}$		14.5	N/mm²
Design compressive strength //	$f_{t,o,d}$	$f_{t,o,d} = k_{mod} * \frac{f_{t,o,k}}{\gamma_M}$	9.3	N/mm²
Design compressive stress	$\sigma_{t,o,d}$	$\sigma_{t,o,d} = \frac{n_d}{A_{wall,ef}} - \frac{M_d}{W_{wall,ef}}$	7.99	N/mm²
Unity check	UC	$UC = \frac{\sigma_{t,o,d}}{f_{t,o,d}}$	0.33	-

Wall verification – Buckling (for 1m strip)				
5% value of modulus of elasticity	$E_{0.05}$		7400	N/mm²
Centre of gravity	z	$z = \frac{t_{wall}}{2}$	157.5	mm
Strip width	b		1000	mm
Net cross section	A_{net}	$A_{net} = t_{wall,eff} * b$	175000	mm²
Net moment of inertia	I_{net}	$I_{net} = b * \sum_{i=1}^{n}\left(\frac{t_i^3}{12} + t_i * a_i^2\right)$	$1.73*10^9$	mm⁴
Radius of gyration	i	$i = \sqrt{I_{net}/A_{net}}$	99.5	mm
Buckling length	l_{eff}		4640	mm
Slenderness factor	λ	$\lambda = \frac{l_{eff}}{i}$	46.6	-
Relative slenderness	λ_{rel}	$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	0.79	-
β factor	β_c		0.1	-
k factor	k	$k = 0.5 * (1 + \beta_c * (\lambda_{rel} - 0.3) + \lambda_{rel}^2$	0.84	-
Reduction factor	k_c	$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}}$	0.90	-
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{k_{fi} * f_{c,o,d}}$	**0.66**	-

Global verification – horizontal deformation				
Distributed design load	Q_{wind}		16.7	kN/m
Moment of inertia	I	$I = \frac{1}{12} * t_{wall} * l_{wall}^3$	4.54E+13	mm⁴
Surface area	A	$A = t_{wall} * l_{wall}$	3780000	mm²
Shear modulus	G		690	N/mm²
Deformation	u_d	$u_d = \frac{q * h_{building}^4}{8 * E_{eq,1} * I} + \frac{q * h_{building}}{2 * G * A}$	25.4	mm
Maximum deformation	u_{max}	$u_{max} = \frac{h_{building}}{750}$	54.2	mm
Unity check	UC	$UC = \frac{u_d}{u_{max}}$	0.47	-

Global verification (U-shaped Core) – horizontal deformation (longitudinal direction)				
Distributed design load	Q_{wind}		50.3	kN/m
Core thickness	t_{core}		380	mm
Core length	l_{core}		9.5	m
Core width	w_{core}		4	m
Moment of inertia	I	$I = \frac{w_{core} * l_{core}^3}{12} - \frac{(w_{core} - t_{core})(l_{core} - 2 * t_{core})^3}{12}$	8.44E+13	mm⁴
Surface area	A	$A = t_{core} * (l_{core} + w_{core})$	6650000	mm²
Shear modulus	G		690	N/mm²
Deformation	u_d	$u_d = \frac{q * h_{building}^4}{8 * E_{eq,1} * I} + \frac{q * h_{building}}{2 * G * A}$	41.7	mm
Maximum deformation	u_{max}	$u_{max} = \frac{h_{building}}{750}$	54.2	mm
Unity check	UC	$UC = \frac{u_d}{u_{max}}$	**0.77**	-

Table D.3: Column verification (axis 11, 14, 15, 16)

Column verification - Building geometry				
Building height	$h_{building}$		40.7	m
Building width	$w_{building}$		12	m
Building length	$l_{building}$		54.6	m
Grid size	w_{grid}		7.8	m
Column verification – Equivalent stiffness CLT walls				
Mean E-modulus // CLT C24	$E_{0,mean}$		11000	N/mm²
Mean E-modulus ⊥ CLT C24	$E_{90,mean}$		370	N/mm²
Vertical lamella thickness	$t_{lam,v}$		50	mm
Horizontal lamella thickness	$t_{lam,h}$		50	mm
Number of vertical lamellae	$n_{lam,v}$		5	-
Number of horizontal lamellae	$n_{lam,h}$		4	-
Number of total lamellae	$n_{lam,total}$	$n_{lam,total} = n_{lam,v} + n_{lam,h}$	9	-
Wall thickness	t_{wall}	$t_{wall} = t_{lam,v} * n_{lam,v} + t_{lam,h} * n_{lam,h}$	450	mm
Vertical equivalent stiffness	$E_{eq,1}$	$E_{eq,1} = \frac{E_0 * t_1 * n_1 + E_{90} * t_2 * n_2}{t_{total}}$	6275.6	N/mm²
Horizontal equivalent stiffness	$E_{eq,2}$	$E_{eq,2} = \frac{E_0 * t_2 * n_2 + E_{90} * t_1 * n_1}{t_{total}}$	5094.4	N/mm²

Column verification – Geometry and other properties				
Column thickness	t_{column}		450	mm
Column width	w_{column}		2	m
Material			C24	-
Material factor	γ_M		1.25	-
Material factor during fire	$\gamma_{M,fi}$		1.0	-
Column verification – Loading from floor				
Characteristic imposed load	$Q_{imposed}$		2.55	kN/m²
Characteristic floor finishing load	G_{finish}		1.60	kN/m²
Characteristic dead load	G		1.26	kN/m²
Governing load combination for compression and buckling at ground level (including load due to wind)	N_d	$ULS5$: $1.2 * \boldsymbol{G} + 1.5 * \boldsymbol{Q_{wind}} + 1.5 * 0.4 * \boldsymbol{Q_{imposed}}$	5113	kN
Governing load combination for compression and buckling (fire) at ground level (including load due to wind)	N_d	$ULS7$: $1.0 * \boldsymbol{G} + 1.0 * 0.2 * \boldsymbol{Q_{wind}} + 1.0 * 0.3 * \boldsymbol{Q_{imposed}}$	3701	kN
Governing load combination for tension at ground level (including load due to wind)	N_d	$ULS3$: $0.9 * \boldsymbol{G} + 1.5 * \boldsymbol{Q_{wind}}$	3379	kN
Column verification – Compression parallel to the grain				
Modification factor	k_{mod}	(medium-term)	0.8	-
Characteristic compressive strength //	$f_{c,o,k}$		21	N/mm²
Design compressive strength //	$f_{c,o,d}$	$f_{c,o,d} = k_{mod} * \frac{f_{c,o,k}}{\gamma_M}$	13.4	N/mm²
Thickness of vertical lamellae	$t_{column,ef}$	$t_{column,ef} = t_{lam,v} * n_{lam,v}$	250	mm
Effective cross section	$A_{column,ef}$	$A_{column,ef} = w_{column} * t_{wall,ef}$	500000	mm²
Design compressive stress	$\sigma_{c,o,d}$	$\sigma_{c,o,d} = \frac{N_d}{A_{column,ef}}$	10.2	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{f_{c,o,d}}$	0.76	-
Column verification – Compression parallel to the grain during fire				
Modification factor	$k_{mod,fi}$		1.0	-
Fire duration	t		90	min
Charring rate	β_n		0.7	mm/min
Heat affected zone	$k_0 * d_0$		7	mm
Notional charring	d_{char}	$d_{char,n} = \beta_n * t$	63	mm
Effective burn-in depth	d_{ef}	$d_{ef} = d_{char,n} + k_0 * d_0$	70	mm
Effective thickness	$t_{column,ef,fi}$	$t_{column,ef,fi} = t_{column,ef} - d_{ef}$	180	mm
k_{fi} factor	k_{fi}		1.15	-
Design compressive strength //	$f_{c,o,d,fi}$	$f_{c,o,d,fi} = k_{mod,fi} * \frac{k_{fi} * f_{c,o,k}}{\gamma_{M,fi}}$	24.15	N/mm²
Effective cross section	$A_{column,ef,fi}$	$A_{column,ef,fi} = w_{column} * t_{column,ef,fi}$	360000	mm²
Design compressive stress	$\sigma_{c,o,d,fi}$	$\sigma_{c,o,d,fi} = \frac{N_{d,fi}}{A_{column,ef,fi}}$	10.28	N/mm²
Unity check	UC	$UC = \frac{\sigma_{c,o,d,fi}}{f_{c,o,d,fi}}$	0.43	-

Column verification – Tension parallel to the grain				
Modification factor	k_{mod}	(medium-term)	0.8	-
Characteristic compressive strength //	$f_{t,o,k}$		14.5	N/mm²
Design compressive strength //	$f_{t,o,d}$	$f_{t,o,d} = k_{mod} * \frac{f_{t,o,k}}{\gamma_M}$	9.3	N/mm²
Design compressive stress	$\sigma_{t,o,d}$	$\sigma_{t,o,d} = \frac{N_d}{A_{column,ef}}$	6.8	N/mm²
Unity check	UC	$UC = \frac{\sigma_{t,o,d}}{f_{t,o,d}}$	0.73	-

Column verification – Buckling (for 1m strip)				
5% value of modulus of elasticity	$E_{0.05}$		7400	N/mm²
Centre of gravity	z	$z = \frac{t_{wall}}{2}$	225	mm
Strip width	b		1000	mm
Net cross section	A_{net}	$A_{net} = t_{column,ef} * b$	250000	mm²
Net moment of inertia	I_{net}	$I_{net} = b * \sum_{i=1}^{n} \left(\frac{t_i^3}{12} + t_i * a_i^2 \right)$	5.05E+09	mm⁴
Radius of gyration	i	$i = \sqrt{I_{net}/A_{net}}$	142.2	mm
Buckling length	l_{eff}		4640	mm
Slenderness factor	λ	$\lambda = \frac{l_{eff}}{i}$	32.6	-
Relative slenderness	λ_{rel}	$\lambda_{rel} = \frac{\lambda}{\pi} \sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$	0.55	-
β factor	β_c		0.1	-
k factor	k	$k = 0.5 * (1 + \beta_c * (\lambda_{rel} - 0.3) + \lambda_{rel}^2$	0.67	-
Reduction factor	k_c	$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}}$	0.97	-
Unity check	UC	$UC = \frac{\sigma_{c,o,d}}{k_{fi} * f_{c,o,d}}$	**0.79**	-

The reduction of the pile foundation is approximated due to the decrease of dead load for the timber alternative. The reduction factor for the timber alternative equals 0.45. See Table D.4 and Table D.5 for the difference between the concrete benchmark and timber alternative. Figure D.4 gives an overview of the pile groups as referred to in the tables.

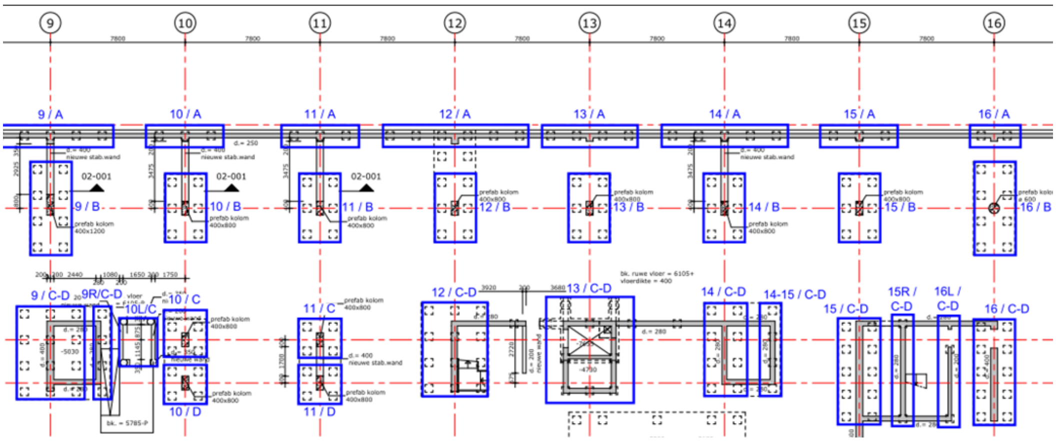


Figure D.4: Pile plan(Source: internal Arcadis document 1)Table D.4: Pile foundation concrete benchmark(Source: internal Arcadis document 1)

Pile group	Dead load [kN]	Imposed load [kN]	Ground water load [kN]	Wind load [kN]	Total load [kN]	Number of piles	Design load per pile [kN]	Pile capacity	Unity Check
Load factor	*1.2*	*1.5*	*1*	*1.5*					
9A	5315	616	-505	1484	9023	5	1805	2080	0.87
9B	7813	918	-977	590	10661	8	1333	2080	0.64
9C-D	10424	1345	-1562	-1145	14682	12	1223	2290	0.53
10A	4124	440	-391	410	5833	3	1944	2080	0.93
10B	7976	957	-981	275	10438	6	1740	2080	0.84
10C	5512	815	-795	-337	7547	4	1887	2290	0.82
10D	5442	901	-885	-347	7517	4	1879	2290	0.82
11A	4121	440	-391	669	6218	3	2073	2080	1.00
11B	7976	957	-981	95	10168	6	1695	2080	0.81
11C	5512	815	-795	-159	7280	4	1820	2290	0.79
11D	5442	901	-885	-634	7948	4	1987	2290	0.87
12A	5091	529	-445	1478	8675	5	1735	2080	0.83
12B	5451	621	-797	545	7493	6	1249	2080	0.60
12C-D	13739	1786	-1726	-3098	22087	12	1841	2165	0.85
13A	4437	408	-343	1300	7543	4	1886	2080	0.91
13B	6327	669	-811	526	8574	6	1429	2080	0.69
13C-D	14976	1926	-1981	-1826	21618	10	2162	2170	1.00
14A	4961	548	-414	424	6997	5	1399	2080	0.67
14B	6604	820	-842	220	8643	6	1440	2080	0.69
14C-D	11877	1625	-1828	-756	15996	8	1999	2170	0.92
15A	4477	577	-337	515	6673	3	2224	2340	0.95
15B	6917	916	-936	339	9247	6	1541	2170	0.71
15C-D	11082	1762	-1867	-1372	16132	10	1613	2170	0.74
16A	2444	240	-250	15	3065	2	1533	2430	0.63
16B	5934	595	-1050	-5	6971	8	871	2430	0.36
16C-D	8481	811	-1918	-995	10968	10	1097	2430	0.45
					Total	160			

Table D.5: Pile foundation timber alternative

Pile group	Dead load [kN]	Imposed load [kN]	Ground water load [kN]	Wind load [kN]	Total load [kN]	Number of piles	Design load per pile [kN]	Pile capacity	Unity Check
Load factor	*1.2*	*1.5*	*1*	*1.5*					
9A	**2404**	616	-505	1484	5530	3	1843	2080	0.89
9B	**3534**	918	-977	590	5526	4	1381	2080	0.66
9C-D	**4715**	1345	-1562	-1145	7831	6	1305	2290	0.57
10A	**1865**	440	-391	410	3122	2	1561	2080	0.75
10B	**3608**	957	-981	275	5196	3	1732	2080	0.83
10C	**2493**	815	-795	-337	3925	2	1962	2290	0.86
10D	**2462**	901	-885	-347	3941	2	1970	2290	0.86
11A	**1864**	440	-391	669	3509	2	1755	2080	0.84
11B	**3608**	957	-981	95	4926	3	1642	2080	0.79
11C	**2493**	815	-795	-159	3658	2	1829	2290	0.80
11D	**2462**	901	-885	-634	4371	2	2186	2290	0.95
12A	**2303**	529	-445	1478	5329	3	1776	2080	0.85
12B	**2466**	621	-797	545	3911	3	1304	2080	0.63
12C-D	**6215**	1786	-1726	-3098	13057	7	1865	2165	0.86
13A	**2007**	408	-343	1300	4627	3	1542	2080	0.74
13B	**2862**	669	-811	526	4416	3	1472	2080	0.71
13C-D	**6774**	1926	-1981	-1826	11776	6	1963	2170	0.90
14A	**2244**	548	-414	424	3737	2	1868	2080	0.90
14B	**2987**	820	-842	220	4303	3	1434	2080	0.69
14C-D	**5372**	1625	-1828	-756	8190	4	2048	2170	0.94
15A	**2025**	577	-337	515	3731	2	1866	2340	0.80
15B	**3129**	916	-936	339	4701	3	1567	2170	0.72
15C-D	**5013**	1762	-1867	-1372	8849	5	1770	2170	0.82
16A	**1105**	240	-250	15	1459	1	1459	2430	0.60
16B	**2684**	595	-1050	-5	3071	3	1024	2430	0.42
16C-D	**3836**	811	-1918	-995	5394	5	1079	2430	0.44
					Total	84			

D.3 Obtained member sizes

Table D.6: Obtained member sizes per variant

Variant	Concrete benchmark	Timber alternative
Floor thickness [mm]	250	300
Wall thickness [mm]	280	315
Core thickness [mm]	280	380
Column thickness [mm] (ground floor + first floor of axis 11, 14, 15, 16)	280	450
Column width [m] (ground floor + first floor of axis 11, 14, 15, 16)	2	2
Basement floor thickness [mm]	300	300 (concrete)
Basement wall thickness [mm]	400	400 (concrete)
Basement core thickness [mm]	280	280 (concrete)
Number of foundation piles	160	84

D.4 Transport analysis

To determine the average transportation distance of CLT, a transport analyses weighted by the production capacity of each factory (i.e. producers with a higher production capacity contribute more to the average transportation distance) is performed. The environmental impact of transportation is quantified per tonne per kilometre, see Table D.7 for the data. In the analysis, the ten largest CLT manufacturers in Europe as of 2019 are included together with the remaining manufacturers from the EPD study. The road distances are determined using Google Maps; the sea distances with https://sea-distances.org/.

Table D.7: Environmental transport data(LCA Stage A4)

Transportation type	Unit	Source	GWP	ODP	AP	EP	POCP	ADP-E	ADP-F	Shadow price
			kg CO_2 eq.	kg CFC-11 eq.	kg. SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	kg Sb eq.	€/unit
			€ 0.05	€ 30.00	€ 4.00	€ 9.00	€ 2.00	€ 0.16	€ 0.16	
Truck	tkm	NIBE t001	1.31E-01	2.44E-08	5.66E-04	1.14E-04	7.75E-05	3.72E-07	9.77E-04	0.010
Transoceanic ship	tkm	NIBE t008	1.13E-02	1.80E-09	2.37E-04	2.13E-05	1.23E-05	2.51E-09	7.80E-05	0.002

Table D.8: Transport analysis

Producer	Production capacity	Location	Distance road [km]	Distance sea [nautical miles]	Distance sea [km]	Port	Environmental impact [€ per ton]
Bulkmaterial produced in NL	-	-	50	-	-	-	**0.51**
Binderholz	120000	Unternberg, AT	1088	-	-	-	11.0
Binderholz	100000	Burgbernheim, DE	621	-	-	-	6.3
Egoin	30000	Natxitua, ES	60	771	1428	Bilbao	3.1
KLH	130000	Teufenbach-Katsch, AT	1129	-	-	-	11.5
Martinsons	25000	Bygdsijum, SE	78	1356	2511	Skelleftea	5.2
Rubner	8000	Brixen, It	1025	-	-	-	10.4
Stora Enso	100000	Ybbs, AT	1059	-	-	-	10.8
Stora Enso	80000	Bad St. Leonhard, AT	1170	-	-	-	11.9
Mayr-Melnhof Holz	72500	Gaishorn, AT	1167	-	-	-	11.8
Hasslachter Norica Timber	62000	Stall im Mölltal, AT	1158	-	-	-	11.8
Schilliger Holz	30000	Küssnacht, CH	783	-	-	-	7.9
Züblin timber	30000	Aichach, DE	777	-	-	-	7.9
Lignotrend	28000	Weilheim-Bannholz, DE	723	-	-	-	7.3
						Weighted average	**9.9**

D.5 Life cycle Impact assessment

Table D.9: Build-up and shadow price (EPD)
of CLT (Wet screed) floor assembly, 7.8m, exposed fire safety strategy

		Shadow price		Embodied carbon	Carbon sequestration
Build-up	**Thickness [mm]**	**Total [€/m^2]**	**Total + D [€/m^2]**	**Kg CO_2 eq.**	**Kg CO_2 eq.**
Sand cement	70	1.10	1.15	18.44	
Separating layer					
Wood fibre	20	1.07	0.79	12.73	
CLT	300	3.20	1.87	29.82	-206.64
	Σ	**5.37**	**3.81**	**60.99**	**-206.64**

Table D.10: Build-up and shadow price (NMD)
of Concrete (Wet screed) floor assembly, 7.8m

		Shadow price		Embodied carbon	Carbon sequestration
Build-up	**Thickness [mm]**	**Total [€/m^2]**	**Total + D [€/m^2]**	**Kg CO_2 eq.**	**Kg CO_2 eq.**
Sand cement	70	1.10	1.15	18.44	
Separating layer					
Wood fibre	20	1.07	0.79	12.73	
Reinforced concrete	250	6.28	5.60	87.71	
	Σ	**8.46**	**7.54**	**118.88**	**0**

Table D.11: Build-up and shadow price (timber from NMD)
of CLT (Wet screed) floor assembly, 7.8m, exposed fire safety strategy

		Shadow price	
Build-up	**Thickness [mm]**	**Total [€/m^2]**	**Total + D [€/m^2]**
Sand cement	70	1.10	1.15
Separating layer			
Wood fibre	20	1.07	0.79
CLT	300	6.26	4.94
	Σ	**8.44**	**6.87**

Table D.12: Material quantities and shadow price
timber alternative, encapsulated walls and exposed ceiling

				Shadow price				Embodied carbon	Carbon seq.
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**	**Kg CO_2 eq.**	**Kg CO_2 eq.**
Floors	CLT (hybrid)	7862	m^2	42236	29924	0.086	0.061	479528	-1624686
Walls	CLT	1071	m^3	11415	6678	0.023	0.014	106501	-737987
Wall insulation	Mineral wool (15mm)	6678	m^2	720	699	0.001	0.001	8747	
Fireboard walls	Gypsum	6678	m^2	4103	4004	0.008	0.008	59866	
Core	CLT	271	m^3	2883	1687	0.006	0.003	26904	-186427
Core insulation	Mineral wool (15mm)	1425	m^2	154	149	0.000	0.000	1866	
Fireboard core	Gypsum	1425	m^2	875	854	0.002	0.002	12770	
Basement floors	Reinforced concrete	1966	m^3	49390	44069	0.101	0.090	689582	
Basement walls	Reinforced concrete	252	m^3	6327	5645	0.013	0.011	88337	
Basement core	Reinforced concrete	28	m^3	715	638	0.001	0.001	9979	
Foundation piles	Reinforced concrete	340	m^3	8548	7627	0.017	0.016	119351	
			Σ	**127365**	**101974**	**0.259**	**0.208**	**1603429**	**-2549101**

Table D.13: Material quantities and shadow price concrete benchmark

				Shadow price				Embodied carbon	Carbon seq.
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**	**Kg CO_2 eq.**	**Kg CO_2 eq.**
Floors	CLT (hybrid)	7862	m^2	66496	59291	0.135	0.121	934647	
Walls	CLT	1071	m^3	23492	20961	0.048	0.043	327997	
Wall insulation	Mineral wool (15mm)	6678	m^2						
Fireboard walls	Gypsum	6678	m^2						
Core	CLT	271	m^3	5011	4471	0.010	0.009	69965	
Core insulation	Mineral wool (15mm)	1425	m^2						
Fireboard core	Gypsum	1425	m^2						
Basement floors	Reinforced concrete	1966	m^3	49390	44069	0.101	0.090	689582	
Basement walls	Reinforced concrete	252	m^3	6327	5645	0.013	0.011	88337	
Basement core	Reinforced concrete	28	m^3	715	638	0.001	0.001	9979	
Foundation piles	Reinforced concrete	340	m^3	16282	14528	0.033	0.030	227335	
			Σ	**167714**	**149604**	**0.341**	**0.304**	**2347841**	**0**

Table D.14: Material quantities and shadow price (timber from NMD) timber alternative, encapsulated walls and exposed ceiling

				Shadow price			
Element type	**Material type**	**Quantity**	**Unit**	**Total [€]**	**Total + D [€]**	**Total [€/m^2/year]**	**Total + D [€/m^2/year]**
Floors	CLT (hybrid)	7862	m^2	66360	54048	0.135	0.110
Walls	CLT	1071	m^3	22372	17636	0.046	0.036
Wall insulation	Mineral wool (15mm)	6678	m^2	720	699	0.001	0.001
Fireboard walls	Gypsum	6678	m^2	4103	4004	0.008	0.008
Core	CLT	271	m^3	5652	4455	0.012	0.009
Core insulation	Mineral wool (15mm)	1425	m^2	154	149	0.000	0.000
Fireboard core	Gypsum	1425	m^2	875	854	0.002	0.002
Basement floors	Reinforced concrete	1966	m^3	49390	44069	0.101	0.090
Basement walls	Reinforced concrete	252	m^3	6327	5645	0.013	0.011
Basement core	Reinforced concrete	28	m^3	715	638	0.001	0.001
Foundation piles	Reinforced concrete	340	m^3	8548	7627	0.017	0.016
			Σ	**165215**	**139824**	**0.336**	**0.285**