Timber as a competitive structural building material in the Netherlands

Qualification and quantification of the conditions under which structural timber is competitive with concrete

by
Emily van Helmond

Delft University of Technology | Building Engineering | April 2022

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Preface

This thesis presents the last part of my master Building Engineering at the Faculty of Civil Engineering from Delft University of Technology. The specialisation in structural design fits my interest in the interaction between architecture and building structures.

With this research my aim is to make a small contribution to the worldwide problem of climate change. However, there are multiple ways in which the construction industry can contribute and there are countless solutions to be investigated. My interest in the sustainable building material timber has led me to many interesting conversations before I decided on the main research topic. I appreciate everyone who took the time to speak with me and because of those conversations this thesis now focusses on the feasibility of timber building structures.

I want to thank my committee members, Geert Ravenshorst, Henk Jonkers, Roy Crielaard, and Rob Verhaegh for their help, their patience, all the feedback, and their guidance in performing this research. They helped me in finding a focus and made me set priorities. Also, I want to thank everyone at Arup for providing insights in the industry practice and keeping me motivated. Special thanks to Djordy van Laar who helped me with his expertise in building costs, which was essential for this research.

To my fellow students in both my bachelor and in the master, thank you for all the collaborations and for the great time. I want to thank my roommates both in Delft and in Rotterdam, for reading over parts of my thesis, listening to my thoughts and for providing distractions when needed. To my friends, parents, brother, and Seerp thank you for taking the time to discuss this research, for the help with visualising my ideas, putting things in perspective, and most important for always being confident in my capabilities.

To everyone reading this thesis, enjoy and please feel free to contact me for questions or discussions!

Emily van Helmond

April 2022

Summary

To mitigate climate change and to reach Dutch targets to reduce greenhouse gas emissions with 49% by 2030, emissions by the construction industry must be lowered. Developments regarding mass timber construction have increased the potential to do so. This thesis addresses the problem that the opportunity of reducing CO_2 emissions by constructing in timber is not utilised to its full potential. Timber can contribute because the production of structural timber elements is less carbon intensive compared to concrete, the most used structural building material in the Netherlands. Additionally, timber has the capacity to capture and store carbon. From a literature study it is concluded that one of the main reasons for the reluctance towards timber structures is the perception of higher cost.

The goal of this thesis is to qualify and quantify the conditions under which timber structures can be competitive with concrete structures in the Netherlands. For two designs to compete at the same level they must have the same potential profit and serve the same function. Nine interdependent variables are investigated in this research: |1| building use, |2| vertical bearing system, |3| stability system, |4| structural floor system, |5| floor span, |6| building height, |7| CO_2 emission costs, |8| additional revenue for timber structures, and |9| the calculation method regarding biogenic carbon.

The potential profit is defined in this thesis as project revenue minus total building cost minus imposed carbon emissions cost. This definition allows possible additional revenue for timber structures, as well as the impact of carbon emission costs as a policy tool to be investigated. The carbon emission costs are determined by multiplying the total CO_2 emissions with a CO_2 price. The total CO_2 emmisions are determined using the life cycle assesement (LCA) method to allow a specific focus and for the carbon storage in timber to be included. Only the impact category global warming potential (GWP) of the product stage (A1-3) are included. Three options are considered regarding biogenic carbon: no inclusion as per current regulations, 50% inclusion, and 100% inclusion where all stored carbon is substracted from the emitted carbon.

|1| To investigate the effect of building use on competitiveness, research is done into the average CO_2 emissions per function. No building type was identified with higher emissions than other types and the variation in emissions between buildings with the same function was found to be large. However, research into the Dutch market shows that there is a high demand for multi-storey residential buildings and that ground-level homes can already be competitive in a light timber frame structure. Therefore, multi-storey residential buildings are identified to currently have the largest potential impact on reducing the CO_2 emissions of the building industry.

|2| Secondly, research is done into the characteristics of structural timber products. It is concluded
|3| that glued laminated timber (Glulam), cross laminated timber (CLT), and laminated veneer
|4| lumber (LVL) are suitable to use for the vertical and stability system of multi-storey residential
buildings. For timber floor systems CLT, timber concrete composite (TCC), and a timber hollow
core floor are suitable.

|2| In an analysis of 34 constructed timber multi-storey residential buildings CLT seems most
|3| competitive since it is most frequently used for the stability (53%), vertical (74%), and floor
|4| system (73%). For the stability system CLT walls are used up to 13 storeys, taller buildings
|5| require a concrete core or a timber stability frame structure. Besides CLT for the vertical system,
|6|

timber columns (15%) and steel or concrete columns (9% and 3%) are used. For the floor system CLT is used up to 18 storeys, higher buildings often use a TCC floor. In the nine analysed projects in the Netherlands CLT is used for the stability system up to four storeys, a hybrid structure with a concrete core is used up to 21 storeys. The floor spans of these buildings vary between 3.6 and 6 meters. For the floor system TCC and CLT floors are both used in 38% of the analysed buildings in the Netherlands.

|2| The method of potential profit is applied to a case study of a sixteen-storey residential building,
|4| planned to be constructed in Rotterdam named: *De Scharnier*, for which a concrete, a hybrid and
|7| a timber design were developed serving the same function. In the scenario with equal revenue
|8| and no carbon emission costs, the estimated potential profits per square meter gross floor area
|9| (GFA) are €2247, €2097, and €2065 for these variants respectively. Timber is found to be competitive if the CO_2 price is €0.81 per kg CO_2, or if the additional revenue is 4% and the CO_2 price is €0.48 per kg CO_2. Both scenarios assume all stored carbon is subtracted from the emitted carbon. In comparison, the CO_2 taxes for industries in 2022 are €0.04 per kg CO_2 and on the European Emission trading market in March 2022 the CO_2 price was €0.08 per kg CO_2.

|3| Finally, a parameter study is performed to investigate the competitiveness a timber multi-storey
|5| residential building. Four floor spans and four building heights are analysed, resulting in sixteen
|6| design variants. For each variant a feasible design was made using a timber structure with CLT
|7| floors and CLT walls, which is compared with a concrete design with prefabricated concrete
|8| structural walls and floors. All finishings required for the same functional unit are considered.
|9| The potential profit is determined for three scenarios regarding additional revenue for timber structures, 0%, 2%, and 4%, and three scenarios for biogenic carbon, 0%, 50%, and 100% inclusion.

The revenue, building costs, and carbon emission costs influence the potential profit. The revenue for the 50% sold on the free housing market is based on data of the 20 largest municipalities of the Netherlands, the other 50% is assumed to be dedicated to social housing. The revenue is influenced by the ratio between the gross and the net floor area and the maximum difference in estimated revenue between concrete and timber is 2%. Secondly, the costs are based on information provided by a cost consultant and includes differences for finishings, foundations, construction interest and execution costs. The assumed price for CLT is €1200/m^3, while the concrete wall elements are estimated to cost €880/m^3. For all variants the costs for a concrete structure are lower than for timber with a difference between 2% and 27%. Furthermore, the difference in costs increases if the floor span is enlarged. Finally, the estimation of the carbon emissions uses direct EPD impact data. For all variants the carbon emissions for the concrete variant are higher than for timber. The difference in emissions lays between 37% and 61% if the biogenic carbon is excluded. If the stored carbon is subtracted the difference increases to 191% maximum.

For each investigated design variant, the required CO_2 price for which the potential profit of the timber and concrete structure is equal is determined and presented in Table 1. For example, the variant with 5 storeys and a span of 4.8 meters is competitive if the additional revenue is 2% and the CO_2 price is €0.31 per kg CO_2 and the stored carbon is 100% subtracted from the emitted carbon. All CO_2 prices below €0.08 can be considered realistic since this was the CO_2 price on the European emission trading market on March 2022. Variant 5 is competitive in timber as per current regulations, without imposed emission costs and additional revenue.

Table 1: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.70	€1.06	€2.18	€0.90	€1.41	€3.33	€1.05	€1.69	€4.39	€1.24	€2.06	€6.15
	2%	€0.77	€1.17	€2.41	€0.97	€1.53	€3.60	€1.11	€1.80	€4.68	€1.30	€2.17	€6.48
	0%	€0.85	€1.28	€2.64	€1.04	€1.64	€3.88	€1.18	€1.91	€4.97	€1.37	€2.28	€6.81
9 storeys	4%	**€0.05**	**€0.07**	€0.13	€0.42	€0.65	€1.36	€0.56	€0.87	€1.97	€0.78	€1.26	€3.23
	2%	€0.12	€0.17	€0.31	€0.49	€0.75	€1.58	€0.62	€0.97	€2.21	€0.85	€1.36	€3.50
	0%	€0.19	€0.27	€0.49	€0.56	€0.85	€1.80	€0.69	€1.08	€2.45	€0.91	€1.47	€3.76
5 storeys	4%	€-0.13	€-0.18	€-0.32	€0.24	€0.36	€0.71	€0.44	€0.68	€1.47	€0.62	€0.97	€2.30
	2%	€-0.06	€-0.09	€-0.16	€0.31	€0.46	€0.90	€0.51	€0.78	€1.68	€0.68	€1.07	€2.53
	0%	€0.00	€0.00	€0.00	€0.37	€0.55	€1.10	€0.57	€0.88	€1.89	€0.74	€1.16	€2.76
3 storeys	4%	€-0.09	€-0.12	€-0.21	€0.24	€0.35	€0.68	€0.40	€0.61	€1.29	€0.63	€0.99	€2.33
	2%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.87	€0.47	€0.71	€1.49	€0.69	€1.08	€2.54
	0%	**€0.04**	**€0.05**	€0.09	€0.36	€0.54	€1.05	€0.53	€0.80	€1.69	€0.75	€1.17	€2.76

It is concluded that for all design variants in the parameter study the competitiveness of timber increases if the floor span is smaller, as this reduces the required material and the costs. Additionally, the difference in carbon emissions between the concrete and the timber variants increases if the span decreases. This reduces the required CO_2 price for an equal potential profit. However, it is important to note that functionality limits the minimum acceptable floor span. Secondly, the competitiveness of timber structures increases if the building height decreases. The amount of CLT required for the walls decreases if the height decreases, which decreases the material costs. An exception is found for the variants with a 3.6-meter span, where the competitiveness increases from 3 to 5 storeys and then decreases up to 20 storeys. This is due to the minimum floor and wall thicknesses applied in the design. Thirdly, the competitiveness of timber increases if carbon emissions costs are imposed and if a larger percentage stored carbon is included. Finally, additional revenue for timber structures increases the competitiveness.

In additional research an extension of the parameter study is advised with variations in materials for the structural floor, wall, and stability system and more variations in building height and floor span. This will increase the knowledge on how these conditions influence the competitiveness of timber. Additionally, it is advised to verify if all barriers are removed for the designs that are competitive in this study. It is found that considering both the costs and the (non-financial and financial) benefits is important when choosing a structural building material. The competitiveness of timber structures increases if CLT is efficiently used with a limited building height and reduced floor span. Imposing a CO_2 tax will give the industry an incentive to reduce CO_2 emissions and therefore use timber more frequently, which is essential to mitigate climate change.

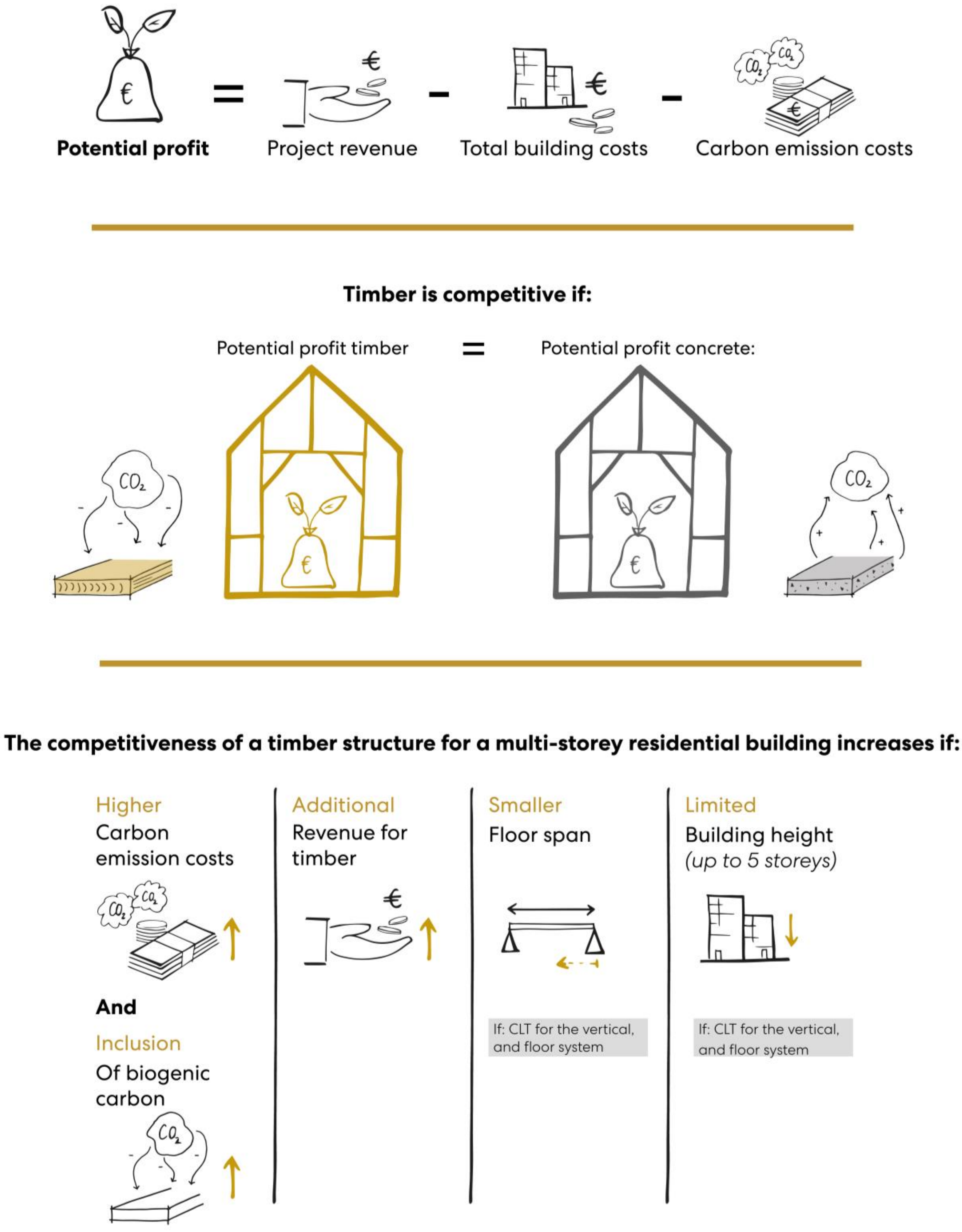


Figure 1: Overview of the competitiveness of timber structures

Contents

Key terminology

Term	Abbreviation	Description
Biogenic carbon		The carbon stored in timber and biobased products.
Building structure		All main load bearing elements of a building.
Carbon dioxide equivalent emissions	CO_2eq	Represents the CO_2 and other greenhouse gas emissions.
Carbon sink		Anything that absorbs more carbon from the atmosphere than it releases.
Carbon source		Anything that absorbs less carbon from the atmosphere than it releases, or only emits carbon.
Embodied carbon		The carbon that is emitted by the production of the building materials plus the energy required for transport of these materials to the building site.
Engineered wood product	EWP	Timber products typically manufactured by adhesively laminating together smaller softwood sections or laminates (glulam and CLT) or veneers or strands of timber (LVL).
Environmental product declaration	EPD	An independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products in a credible way.
Functional unit	FU	Quantified performance of a product system for use as a reference unit.
Green House gasses	GHG	Gasses that have the property of absorbing infrared radiation (net heat energy) emitted from Earth's surface and reradiating it back to Earth's surface, thus contributing to the greenhouse effect.
Gross floor area	GFA	The total floor area contained within the building measured to the external face of the external walls.
Net floor area	NFA	The gross floor area minus the area taken up by the walls and the vertical circulation routes.
Global warming potential	GWP	Global Warming Potential (GWP) is a metric to compare (relative to another gas) the ability of each greenhouse gas to trap heat in the atmosphere.
Life cycle assessment	LCA	A methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.
Operational carbon		The emissions associated with the heating, cooling, and energy use of the building.
Potential profit		Metric to measure the competitiveness of a building structure. Chapter 4.1 explains the method used to determine the potential profit
Serviceability limit state	SLS	The state of design beyond which a structural system loses operationally its serviceability for the actual service load that the structure is subjected to. This refers to the conditions under which a building is still considered useful.

Substructure		The structural part of the building that is built below the ground level
Superstructure		The structural part of the building that is constructed above the ground level.
Ultimate limit state	ULS	The design state to cover the governing load case scenario, a design state prior to ultimate collapse, to assure structural stability. This refers to a condition of a structure beyond which it no longer fulfils the relevant design criteria.

1 Introduction

Using timber building structures more frequently in the Netherlands can help in mitigating climate change. The production of structural timber elements is less carbon intensive than the production of concrete, additionally timber has the capacity to capture and store carbon. However, timber structures are still uncommon in the Netherlands. One of the main reasons for the reluctance towards timber structures is the (perception of) higher cost. This thesis aims to qualify and quantify the conditions under which timber structures can be competitive with concrete structures in the Netherlands.

1.1 Motive

At the 9th of august 2021 the intergovernmental panel on climate change (IPCC) published a press release stating the following:

"Scientists are observing changes in the Earth's climate in every region and across the whole climate system. ... Many of the changes observed in the climate are unprecedented in thousands, if not hundreds of thousands of years, and some of the changes already set in motion—such as continued sea level rise—are irreversible over hundreds to thousands of years." (IPCC secretariat, 2021, p. 1).

This is an important confirmation that the climate on earth is changing and that this will be irreversible if no action is taken. However, the IPCC also argues that: *"strong and sustained reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases would limit climate change"* (IPCC secretariat, 2021, p. 1).

The importance of the reduction of greenhouse gas emissions was already argued before 2021 by the IPCC in earlier reports. Therefore in 2015 the Paris Agreement was formulated and is now signed by 191 parties (UNTC, 2021) that aim to limit global warming to 2 degrees Celsius (Unfccc, 2015). The Dutch national government determined that their contribution is to reduce greenhouse gas emissions by 49% by 2030 (Rijksoverheid, 2019).

In 2019 the CO_2 emissions of the building sector accounted for 38% of the total global energy related CO_2 emissions (United Nation Environment Programme, 2020). And 10% of all global emissions were devoted to the manufacturing of building construction materials (United Nation Environment Programme, 2020).

This indicates that reducing the emissions of CO_2 in the construction industry, and specifically reducing the emissions for construction materials, will have a significant influence on mitigating climate change. To reach the 49% reduction by 2030, the emissions by the construction industry must be lowered. Constructing in timber can be part of the solution to reduce the CO_2 emissions (Keijzer et al., 2021), as is further explained in this thesis.

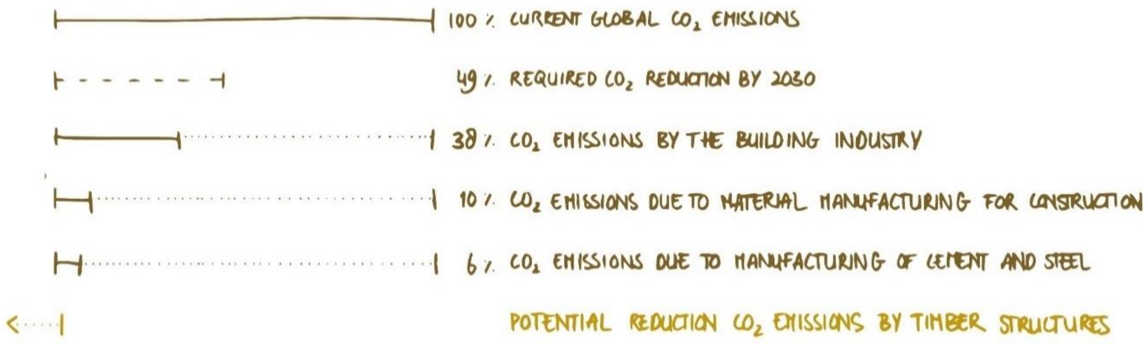


Figure 2: Global emissions and contribution building industry

1.2 State of the art

Concrete

Concrete is the most commonly used construction material in the Netherlands, with 46% of the total volume of all construction materials (van der Velde & van leeuwen, 2019). There are multiple reasons for the popularity of concrete for building structures. The main explanation is the tradition of building in concrete in the Netherlands, which started during the post-war reconstruction (van der Velde & van leeuwen, 2019). Other factors are discussed in chapter 3.2.

Recently the disadvantages of concrete have become more apparent, these will be discussed in chapter 3.3. The main issue with concrete is that the production of concrete is carbon intensive. Especially during the production of cement, which is an essential element of concrete, large amounts of CO_2 are emitted (van Oss, 2020). In 2019, 45% of the CO_2 emissions due to material manufacturing for construction were attributed to reinforced concrete (van der Velde & van leeuwen, 2019).

Timber

Using (engineered) timber instead of concrete can reduce the CO_2 emissions by the building sector significantly (Keijzer et al., 2021, Sathre & Gustavsson, 2009). Chapter 3.4 discusses the advantages of timber structures in detail. It is important to note that this research assumes the timber to be sustainable sourced and replaced after lodging. Currently 98% of the used timber in the Netherlands is sustainably sourced (Luijks et al., 2021). When a tree grows CO_2 is taken from the atmosphere and stored in the biomass (Sandhaas & Blaß, 2017). To produce timber that is ready for construction, only low amounts of CO_2 are emitted. Will Hawkins (2021, p. 20) even concludes that *"it is hypothetically possible for timber to have a negative cumulative embodied carbon, in the long term, when it is both sustainably sourced and end-of-life emissions are avoided"*. Second, timber is a renewable resource, because timber can be grown on a human timescale (Sandhaas & Blaß, 2017). This is an advantage because timber will be infinitely available when the forests are well-managed. Additionally, timber is light weight, which requires less material for the foundation structure (Luijks et al., 2021). Finally, the construction time can be reduced if timber is used (Jones et al., 2016).

At the moment timber is not frequently used as a structural building material in the Netherlands (van der Velde & van leeuwen, 2019). Multiple explanations for the reluctance to use timber can be found in literature, this is further discussed in chapter 3.5. Giesekam et al. (2016) argue that the greatest barrier is in the (assumed to be) higher building cost of timber. Ahmed & Arocho (2021, p. 6) argue that for a 18 storey residential building *"the construction cost of timber project was found 6.43% higher than the concrete construction option"*. While Luijks et al. (2021) and Jones et al. (2016) argue that the actual costs are similar if all cost factors are considered in the cost calculation. However, a study in Australia by Kremer & Symmons (2018) approximates mass timber construction to be between 6% and 12% more economical compared to concrete. Both the perception of higher costs and actual higher costs cause a reluctant approach towards timber as a structural material. Additionally, the advantages of timber structures regarding the reduction of CO_2 emissions is not taken into account sufficiently when selecting the structural material (Studio Marco Vermeulen, 2020). The restrictions to the maximum CO_2 emissions are limited and the CO_2 storage in timber is not included in the calculation (Keijzer et al., 2021).

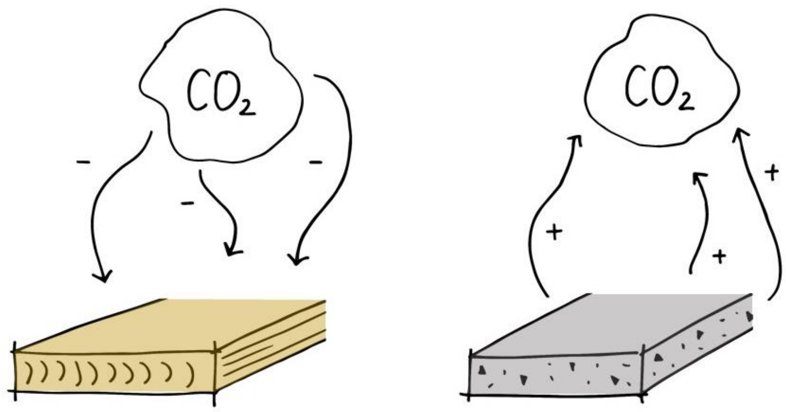


Figure 3: Illustration CO_2 storage in timber and CO_2 emissions due to the production of concrete

1.3 Problem description

Although timber has the potential to reduce the CO_2 emissions of the construction industry, it is not commonly used in the Netherlands as a structural building material (van der Velde & van leeuwen, 2019). The problem that is addressed in this thesis is that the opportunity of reducing CO_2 emissions by constructing in timber is not utilised to its full potential.

A strong reduction of carbon emissions is required to reach the goal of 49% reduction by 2030 (Rijksoverheid, 2019). To reach this target the emissions by the building industry must decrease from 24.4 bn CO_2 equivalents in 2018 to 15.3 bn CO_2 equivalents in 2030 (CBS, 2019). The Dutch Green Building Council has translated this to a maximum CO_2 emission value (carbon footprint) per square meter that can be emitted to construct the building. For multi-family residential buildings, the maximum carbon footprint is 220 kg-CO_2eq/m^2 in 2021 (Spitsbaard & van leeuwen, 2021). According to Luijks et al. (2021) a concrete apartment building has a carbon footprint of 447 kg-CO_2eq/m^2, which is more than twice the maximum value. This indicates that the targets cannot be reached unless changes are made.

There are projects that successfully implemented timber in the final structural design and used timber during construction. This was the case for the 73-meter-tall residential building *Haut* and *hotel Jakarta* a hotel constructed with modular timber units, both built in Amsterdam (Dijksterhuis, 2021). In other cases, timber may be considered in the design stage, but ultimately the decision was made to construct in concrete. This was the case for example for *Jonas* at IJburg in Amsterdam (K. Haarhuis, personal communication, February 18, 2021) and for the structural system of *De Scharnier* in Rotterdam (M. van Capelleveen, personal communication, November 23, 2021). From literature it can be concluded that high building cost of timber structures are the greatest barrier to adapting timber structures more frequently. A study by Arup and the WBCSD (2012, p. 6) concluded that *"a large number of factors influence material choice in construction, with on balance, cost remaining the overarching priority"*

The cost barrier can be removed if timber structures are competitive with concrete structures. This will motivate the building industry to use timber more frequently, which will reduce the CO_2 emissions. If only the monetary costs of the material are included there is a high probability that timber will not seem competitive with concrete. Therefore, it is important to determine the competitiveness based on all costs and benefits related to the project. This also includes the costs for emitting CO_2 by monetising the positive or negative effects on the environment (Studio Marco Vermeulen, 2020). There is the lack of knowledge on the conditions that make timber structures competitive with concrete structures in the Netherlands. This causes the opportunity for the construction industry to reduce the CO_2 emissions by using timber to not be utilised to its full potential.

Problem statement: Timber as a structural building material is not yet competitive, or not yet perceived to be competitive, with concrete. Therefore, the opportunity of reducing CO_2 emissions by constructing in timber is not utilised to its full potential.

Hypothesis: There is incomplete knowledge regarding the conditions under which structural timber is competitive with concrete. This causes a reluctant approach to timber structures in the Netherlands and the opportunity to reduce carbon emissions not being fully utilised.

2 Research approach

This section explains the approach that is used for this research.

2.1 Research goals

The aim of this research is to contribute to solving the problem that is stated before. To investigate this problem and to give guidance to this thesis a research goal is formulated.

To qualify and quantify the conditions under which structural timber is competitive with concrete as a structural building material in the Netherlands

This research aims to formulate a set of guidelines regarding where and how to apply timber, which can be used by designers and engineers in an early design phase. The focus is on the conditions that are influenced by the structural engineer and can impact the competitiveness.

Conditions

In total nine possible condition variables that can make timber competitive are investigated in this thesis. Six conditions that can be influenced by the design and three external conditions. The methods for the investigation of these conditions are discussed in chapter 2.3.

Conditions influenced by design choices:

1. Building use
2. Vertical bearing system
3. Stability system
4. Structural floor system
5. Floor span
6. Building height

External conditions:

7. CO_2 emission costs
8. Additional revenue timber structures
9. Calculation method biogenic carbon

Competitiveness

Throughout this thesis the definition that is used for the term competitive is: *"to be able to compete at the same level"* (Cambridge English Dictionary, 2021). The competitiveness is dependent on both the costs and the revenue. This can be translated to an equal potential profit. Meaning that the potential profit of a building with a timber structure should be the same as the potential profit of a building with a concrete structure. If the developer can make an equal profit, a large barrier causing the reluctance to construct in timber can be removed and the potential to reduce carbon emissions can be used. The determination method for the potential profit is explained in chapter 4.

2.2 Research questions

The thesis goal is translated to a main research question and sub research questions. The subsequent section formulates these research questions.

Main research question

The following main research question is formulated for this thesis:

Under which conditions is structural timber competitive with concrete as a structural building material in the Netherlands?

Sub research questions

To guide this thesis and to answer the main research question seven sub research questions are formulated. The combination of the answers to these sub research questions will provide a conclusion of the influence of the nine conditions that are to be investigated and answer the main research question. An overview is given of the sub research questions and which conditions are investigated in each question. Some conditions are investigated in multiple sub questions. This increases the reliability of the outcomes since the results can be compared and combined.

Table 2: Sub research questions and investigated conditions

Sub question	Investigated condition or conditions
1. What is the contribution of the buildings super and substructure to the global carbon emissions and what are the main advantages and disadvantages of concrete and timber structures?	|0| Problem context
2. How can the competitiveness of timber building structures be compared to concrete building structures?	|0| Calculation methods
3. For which building function would reducing the CO_2 emissions have the largest impact on the reduction of emissions of the whole building industry?	|1| Building use
4. What are the properties of the most common structural timber elements and which applications are suitable for multi storey residential buildings?	|2| Vertical bearing system |3| Stability system |4| Structural floor system
5. Which previous projects were built in timber and which design decisions were made?	|2| Vertical bearing system |3| Stability system |4| Structural floor system |5| Floor span |6| Building height

6. What is the potential profit of a concrete, hybrid, and a timber design variant of the project De Scharnier and under which conditions is the timber variant competitive?	|2| Vertical bearing system |4| Structural floor system |7| CO_2 emission costs |8| Additional revenue timber structures |9|Calculation method biogenic carbon
7. What is the influence of the building height, floor span, CO_2 emission costs, assumed additional revenue and calculation method regarding biogenic carbon on the potential profit of a timber multi-storey residential building? And under which conditions is the designed timber structure competitive with a concrete structure?	|3| Stability system |5| Floor span |6| Building height |7| CO_2 emission costs |8| Additional revenue timber structures |9|Calculation method biogenic carbon

2.3 Research methods

Throughout this thesis multiple methods are used to answer the main research question and the sub research questions. This variation in methods can increase the reliability of the outcomes if the same conclusions follow from two separate studies.

Sub questions 1, 2, 3, and 4 are answered using a literature study. Sub question 5 is answered by studying collected data on constructed timber residential multi-storey buildings. The method for sub question 6 is a case study. Finally sub question 7 is answered by first making a research design and subsequently performing a parameter study on this design.

Conversations with building industry experts have found place during the research process to verify the results that were found.

2.4 Research scope

To keep focused and to generate valuable results, a research scope has been defined. The specific part of the problem that is addressed in this thesis is described in this chapter.

This thesis aims to draw conclusions that are valid for the Netherlands. The motivations and barriers to applying timber can differ between countries, therefore the conclusions on the conditions that make timber competitive can differ as well. For example, in the Netherlands there is a tradition of constructing in concrete, while other countries will have other traditions. In the literature research information from other countries is used. If this is the case, the applicability for the Netherlands is critically considered. All conclusions are drawn for the Netherlands specifically.

Throughout this thesis the potential profit of a timber structure is compared to a concrete variant only. Other structural systems could be compared to timber but are outside the scope of this thesis. In the Netherlands structural steel accounts for only 0.4% of the material volume, and brick and limestone for only 5% combined (van der Velde & van leeuwen, 2019). With reinforced concrete responsible for almost half the construction material volume and almost half the CO_2 emissions, the decision was made to focus on concrete only.

The research focus is on the structural part of buildings. Structural components can be responsible for up to 50% of a buildings total carbon footprint (LETI, 2020). Because the research focusses on the structural part the scope includes the construction phase only when costs and embodied carbon are estimated. The operational phase remains outside of the scope for this research. This is further explained in chapter 3.1 and 4.4.

The research focusses on timber as a main load bearing material. Possible other applications of timber in buildings, such as for non-load bearing walls, are outside the scope. Hybrid structures are structures that combine multiple materials to optimize the benefits of each individual material (Li et al., 2019). These are considered in this thesis since research outcomes indicate this can be a viable solution. Also, non-structural additional measures required for timber buildings to comply with regulations regarding fire resistance, vibrations and acoustics are included.

Finally, the focus of this thesis is on multi-storey residential buildings. Only buildings with two storeys or more are considered. This focus is determined by the research discussed in chapter 5. Single level buildings are not investigated because it is expected that different conditions will be found. Also, it can be argued that single storey timber buildings are already competitive (Kremer & Symmons, 2018).

2.5 Research outline

To structure the research this report has been divided in three parts. Each part is subdivided in chapters which all answer one sub research question. After part 1 and after part 2 a recap is given.

In the first part the problem context is investigated, and the calculation methods are determined. This knowledge is used in the other two parts, which investigates the possible conditions under which timber structures can be competitive.

Part two aims to qualify the conditions which make timber competitive, by performing four studies. The first two studies use literature to investigate the conditions regarding the building use and to study the properties of timber. The second study uses collected data of constructed buildings to investigate the designs of these buildings. The fourth study contains an analysis of three variants of a structural building design for a case study.

The knowledge that is gained from the first two parts is used in the parameter study of part three. A research design is made based on the conditions that can make timber competitive derived from the first two parts. Subsequently the impact of the building height, floor span, CO_2 emission costs, additional revenue for timber structures and the calculation method regarding biogenic carbon is quantified. Figure 4 shows an overview of the research outline.

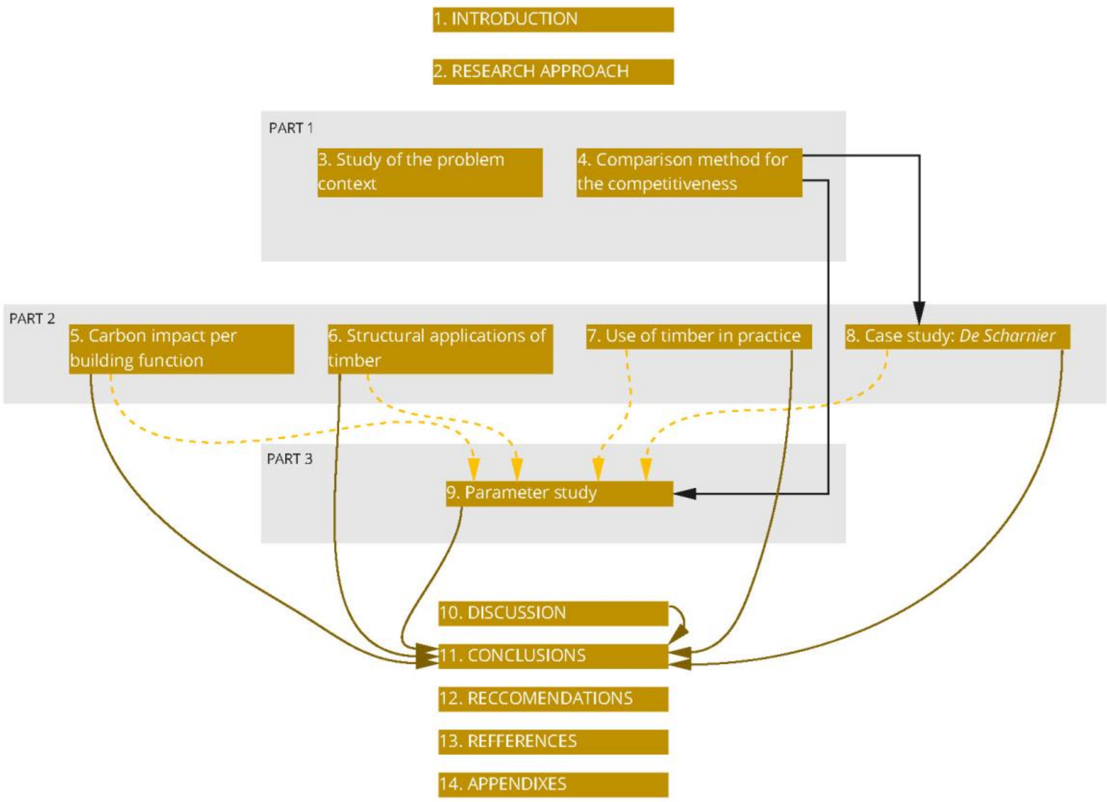


Figure 4: Overview research outline

Part 1: Definition phase

In this section the problem context is further explored and the method that is used to estimate the competitiveness of a building structure is explained. Chapter 3 goes into the contribution of a building structure to the total carbon emissions. Also, the advantages and disadvantages of concrete and the motivations and barriers of using timber are discussed in this chapter. Chapter 4 explains the method that is used to compare the competitiveness of a timber structure. This includes an explanation on the potential profit, the revenue, the total building costs, and the carbon emission costs.

3 Study of the problem context

What is the contribution of buildings super and substructure to the global carbon emissions and what are the main advantages and disadvantages of concrete and timber structures?

The goal of this thesis, to qualify and quantify the conditions under which structural timber can be competitive with concrete as a structural building material, is primarily motivated by the need to reduce the CO_2 emissions. Chapter 3.1 investigates climate change and the influence of building structures on the total CO_2 emissions. Chapter 3.2 and 3.3 go into the advantages and disadvantages of constructing in concrete. Finally, chapter 3.4 and 3.5 explain the benefits and issues of using timber as a structural building material.

3.1 Climate change and the building industry

This section discusses the contribution of the building industry on climate change.

The influence of building structures on climate change

In the recently published report by the intergovernmental panel on climate change (IPCC) the conclusions were very clear. The climate is changing and only a strong reduction of CO_2 and other greenhouse gas (GHG) emissions can mitigate this climate change. The observed temperature increase on earth is unprecedented in 2000 years, this is illustrated in Figure 5 (IPCC, 2021).

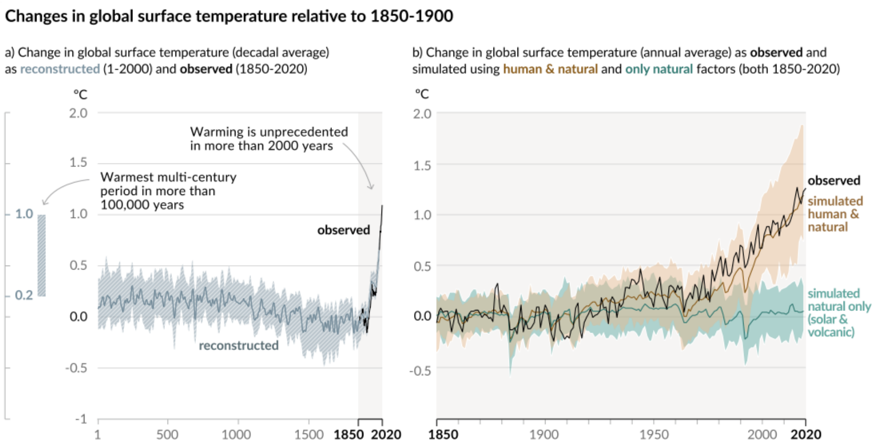


Figure 5: Changes in global surface temperature, from "Climate change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" by V. Masson-Delmotte, P. Zhai, A. Pirani et al., 2021, Cambridge University Press.

Already, climate change is affecting almost all regions across the globe. In the report by the IPCC (2021) it is illustrated that in 41 of the 45 defined regions an increase in hot extremes was observed. And in 19 of the 45 regions there was an increase in heavy precipitation. For Western and Central Europe (WCE), which includes the Netherlands, both hot extremes and heavy precipitation increased since the 1950's (IPCC, 2021).

Over the past years multiple agreements have been made on both national and international level to reduce the emission of greenhouse gasses and to limit climate change. One of the most important agreements is the Paris Agreement, which states that global warming should be limited to 2 and preferably 1.5 degrees Celsius (Unfccc, 2015). The Dutch national climate agreement (Rijksoverheid, 2019, p.5) states that the "*The government's central goal … is to reduce greenhouse gas emissions in the Netherlands by 49% compared to 1990 levels.*" The goal is to achieve this reduction by the year 2030. Research by the Dutch central bureau for statistics (CBS, 2019) shows that greenhouse gas emissions in the Netherlands are decreasing, as is visible in Figure 6. However, the required reductions to be made between 2018 and 2030 are greater than the previously achieved reductions between 2004 and 2018 for all sectors. To reach the 49% reduction target within the coming ten years direct actions should be taken.

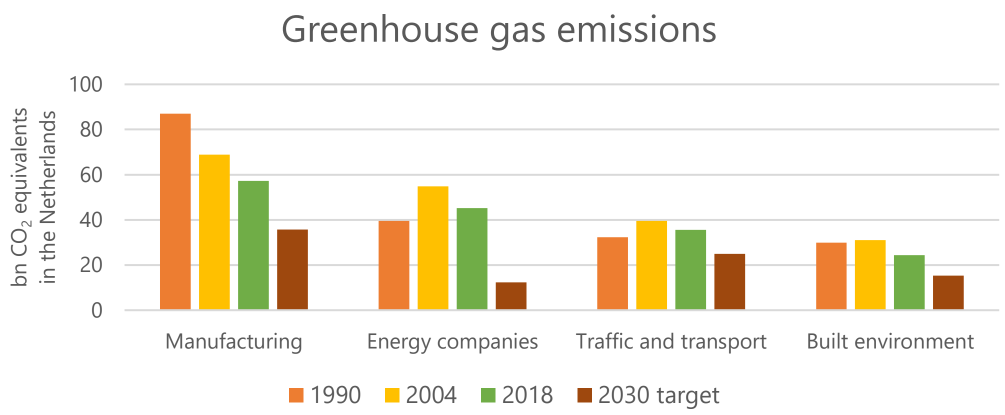


Figure 6: Greenhouse gas emissions. Adapted from: "Greenhouse gas emissions down", by CBS, 2019.

CO_2 emissions by the building sector

Research into the energy related CO_2 emissions shows that in 2019 the global share of building construction and operations was 38%. Also, it was estimated that 10% of all global emissions resulted from building construction and (building) material manufacturing. This number indicates that reducing these emissions will have a meaningful impact on the total reduction of greenhouse gas emissions. If the emissions related to material manufacturing are further analysed, it can be concluded that 6% of all global emissions are emitted by cement- and steel-manufacturing for construction (United Nation Environment Programme, 2020).

A distinction is made between operational carbon and embodied carbon. Operational carbon includes all CO_2 emissions that are emitted during the operation or use phase of the building, most of these emissions are caused by the energy required for heating and cooling. The embodied carbon is the carbon that is emitted by the production of the building materials plus the energy required for transport of these materials to the building site (Koezjakov et al., 2018). Often the term carbon footprint is used instead of embodied carbon.

The operational carbon emissions of buildings are decreasing due to better insulation and new building standards. While this is happening, the share of the embodied carbon is increasing from 12% up to 24% (Koezjakov et al., 2018). The expectation is that the relative share of the cement- and steel-related emissions will increase, despite gains in material efficiency (IEA, 2021). This has to do with the fact that the reduction in energy related emissions will be larger than the reduction of cement and steel manufacturing related emissions. Research shows that the carbon footprint contributes for over 40% to the environmental impact of (nearly) zero-energy buildings (Prinssen, 2020) if measured over the whole life cycle.

The carbon footprint is calculated by summing the CO_2 emissions during the production of all the materials that are used in a building. A division can be made to identify which parts contribute the most. While the exact numbers will differ per building type and even per unique building, an estimated embodied breakdown was presented by LETI (2020). The findings are summarized in Figure 7. From this figure the conclusion can be drawn that the structure of the building has the largest contribution to the embodied carbon, 48% - 67% in total. This can be explained by the fact that the structure often requires the largest amount of steel and/or concrete, which are carbon intensive to produce (United Nation Environment Programme, 2020). This shows that investigating the possible reduction of CO_2 emissions that are emitted during the building construction phase for the superstructure and the substructure is relevant and will have a significant impact.

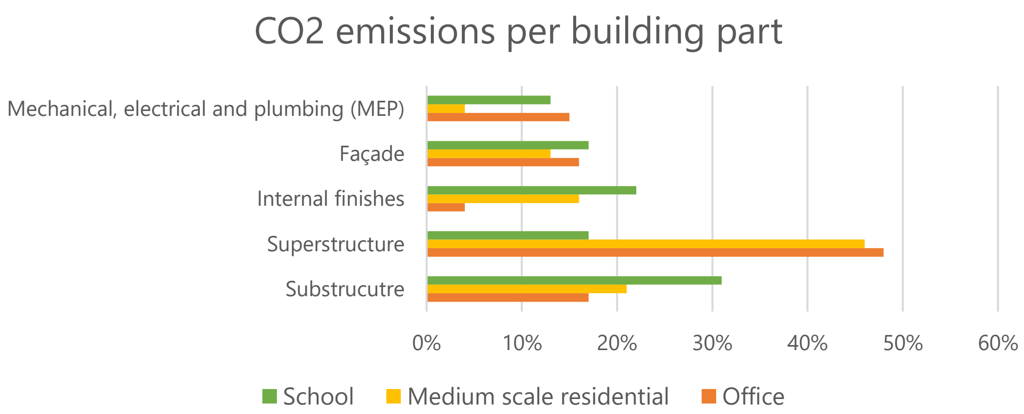


Figure 7: Embodied carbon per building part. Adapted from "Embodied carbon primer" by LETI, 2020

Mitigation strategies

Fortunately, awareness on the need for sustainable development was already present in 1987. The Bruntland definition states that sustainable development is "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). This is a broad definition, but it covers the whole meaning and has a clear goal. However, it does not give guidance on how to ensure this sustainable development.

There are various strategies that can be applied to reduce the embodied carbon of a building structure. The Dutch government has started a program called 'Nederland Circulair 2050' (Rijksoverheid, 2016). This document provides, among other things, guidance on how to realise a 50% reduction of the use of primary resources by 2030. The approach of Nederland Circulair is to transition from a linear economy to a circular economy. This is done by setting the following three goals; The first goal is to use the resources in existing chains to a high standard. Secondly, if new materials are needed fossil and unsustainable materials will be replaced by sustainably produced, renewable and widely available materials. Renewable materials are materials that can be used repeatedly and do not run out because they can be naturally replaced (Sandhaas & Blaß, 2017). Finally, new production methods should be developed, new products are to be designed and areas are to be reorganised. This is done to simulate new ways of consuming (Rijksoverheid, 2016).

Besides this general document on circular economy, the Dutch government has published an additional report called 'Transitieagenda Circulaire Bouweconomie' (Nelissen et al., 2018) which focuses on circularity in the construction sector specifically. This report describes three focus points. First, optimally use the material for all phases of the building cycle. Second, use inexhaustible resources as much as possible and reuse materials to maintain a high value. Finally, use finite resources as efficiently as possible. These three focus points can lead to various design strategies depending on the specific building, the location and on other circumstances.

Both the mentioned reports illustrate the importance of using renewable materials instead of fossil and finite resources when transforming from a linear to a circular economy. As explained by Kaufmann et al. (2018, p.24) "*The amount of CO_2 in the atmosphere can be reduced in two ways: either by reducing CO_2 emissions or by extracting CO_2 from the atmosphere and storing the carbon. Wood has the unique ability to contribute to both possible reduction methods.*" Therefore, this report focusses on the possibilities of using timber as a structural building material as a strategy to mitigate climate change.

3.2 Advantages of constructing in concrete

Concrete made up almost half of the volume of building materials used in 2019 in the Netherlands (van der Velde & van leeuwen, 2019). In this chapter, four explanations are discussed.

Tradition and experience in concrete

In 1847 a prison with was built in Amsterdam with concrete floors and in 1856 concrete was used for a bridge crossing the Ijssel. These projects mark the start of the use of structural concrete in the Netherlands, the period between 1890 and 1910 is marked as the introduction period of reinforced concrete in the Netherlands (Schippers, 1995). Van der Velde & van Leeuwen (2019) state that the tradition of building in concrete in the Netherlands started during the post war reconstruction. This tradition has made that there is a lot of experience with concrete in the Netherlands, which has multiple advantages. First of all, a multitude of references is concrete is available, known solutions can be adapted in new designs (Studio Marco Vermeulen, 2020). Second, there is knowledge on the behaviour of the material on the long term because it has been in use for a long time. Finally, the experience has made designs more efficient and more economical. The tradition in concrete makes that it is frequently used as a structural building material in the Netherlands.

Locally available materials

The raw materials required to produce concrete are widely available in the Netherlands. This decreases the transport distances (Scholtes & van leeuwen, 2018). However, it is important to mention that the raw materials needed to produce concrete are only finitely available (Studio Marco Vermeulen, 2020).

Low costs

Relatively low material costs are an important motivation to use structural concrete. This is partly because the materials required for the production are inexpensive (Giesekam et al., 2016). On the other hand, the experience and efficiency with concrete reduce the costs as well. There is a lot of knowledge on how to build with concrete, this reduces the error margin and the costs related to this.

Acoustic insulation capacity and fire resistance

The high mass of concrete increases the acoustic insulation capacity of the structural elements (Gosselin et al., 2017). Therefore, almost no additional measures are needed to comply with the acoustic regulations. Concrete also has a high fire resistance, which decreases the additional measures to ensure fire safety.

Structural properties

The compressive strength of concrete is high (NEN-EN1992-1-1), by adding reinforcement the tensile stresses can be transferred as well. This is beneficial when the concrete is used for building structures.

3.3 Disadvantages of constructing in concrete

This section discusses the disadvantages of constructing in concrete.

CO_2 emissions

The main disadvantage of concrete is the carbon intensive production process. In 2019, 45% of the emissions by production of building materials were attributed to reinforced concrete (van der Velde & van leeuwen, 2019). Especially during the production of cement large amounts of CO_2 are emitted, due to the chemical process and the high required temperatures. The production of one tonne cement emits approximately 0.8 tonne CO_2 (van Oss, 2020). To mitigate climate change and to reach 49% reduction by 2030, it is essential to reduce these emissions.

Finite resource

The resources required to produce concrete are only finitely available and will ultimately be depleted. Finite resources are resources that cannot be naturally replaced on a human timescale (European Committee for Standardization, 2011). The scarcity of the resources for concrete will ultimately increase the costs (Studio Marco Vermeulen, 2020).

Heavy foundations required

Due to the high mass of a concrete superstructure a heavy substructure will be needed (Luijks et al., 2021). This increases the amount of material needed for the foundation, which increases the costs and the CO_2 emissions.

Heavy transport required

The high mass of concrete increases the transportation costs and the transportation emissions (Luijks et al., 2021)

Long building time

To gain structural capacity, concrete needs to harden which takes time. Therefore, the construction time of concrete buildings can be long, unless prefabricated elements are used (Jones et al., 2016).

3.4 Motivations for constructing in timber

In the previous chapter the urgence for a strong reduction of CO_2 and other greenhouse gas emissions was discussed. While this can be achieved in multiple ways, the focus of this thesis is on the reduction of greenhouse gas emissions by using timber as structural building material. First an overview of the developments regarding timber is given. Secondly, the contribution of timber to the reduction of CO_2 emissions is discussed. Thereafter, the main advantages of constructing in timber are explained. Appendix A discusses more possible advantages of timber.

Timber developments

After being used for temporary structures in prehistoric times, timber was used in the Neolithic and early Bronze Age for residential buildings, the romans used wood to construct bridges and in the Middle Ages timber was used for urban buildings. Wood was popular in the machine age as well, but around the sixteenth century timber became less available and by the 18^{th} century iron and steel replaced timber in structural applications (Hough, 2019). Hough (2019) also describes that around 1920 concrete took over a large part of the market, timber buildings were unsafe in case of fire and durability issues also decreased the popularity of timber.

While engineered wood products (EWPs) have been in existence for almost 50 years more recent development in the range of engineered wood products for structural applications has made them more widely available. *"EWPs are typically manufactured by adhesively laminating together smaller softwood sections or laminates (e.g. glulam and CLT) or veneers or strands of timber (e.g. LVL, LSL and PSL)"* (Structural Timber Association, 2014, p.1).

In 2000 a building in cross laminated timber (CLT) was first constructed in the UK (Zumbrunnen, 2013). The development of engineered timber products has increased the popularity of timber as a structural building material. In the Netherlands large projects using CLT were first built five to ten years ago (Luijks et al., 2021). Technological developments of engineered timber have also increased the potential of timber for high rise buildings. This was mainly because engineered timber products can have a larger fire resistance if designed and used well (Green & Eric, 2012). Additionally, the structural potential increased, by gluing the parts together larger spans could be reached and creating equal strength properties in all directions became possible. Green and Eric (2012) even mention the race that has been triggered by these developments to create taller wood buildings.

Reduction of carbon emissions

Carbon storage

An important quality of timber is its ability to capture CO_2. Carbon dioxide is extracted from the air via photosynthesis when the biomass is formed. The "*carbon (C) is incorporated in the wood and the oxygen (O) is released into the air*" (Sandhaas & Blaß, 2017, p. 11). In this manner a growing forest can act as a carbon sink if more trees are grown than burned or decayed, since more carbon will be taken up from the atmosphere than is released back into it. If timber is used for a building structure the carbon can be stored in the building. The value of carbon storage in timber buildings is heavily influenced by the lifespan of the building and the end-of-life scenario of the structure. It is important to note that the CO_2 capturing is only temporary since the same amount of carbon will be released back into the air when the biomass breaks down. Hawkins (2021) mentions four benefits of delaying carbon emissions to be the reduction of cumulative climatic energy input, more time for system adaptation, a reduced chance of reaching a possible climate 'tipping point' and increase in the potential for future permanent CO_2 storage.

Low emissions

Sandhaas and Blaß (2017) and Sathre & Gustavsson (2009) argue that wood requires far less primary energy than other materials when being processed into construction products. This indicates that even if the carbon storage is not included the CO_2 emissions of a timber building are be lower than those of a concrete building. According to the currently required calculation method the carbon that is captured in timber cannot be subtracted from the carbon that is emitted during the other processes (Keijzer et al., 2021). Multiple studies have been performed to compare the carbon footprint of concrete building structures with timber building structures. A study by Liang et al. (2020) shows that the global warming potential of a 12-storey apartment building in the stages A1-3 of a mass timber building is 20% lower (181 kg CO_2eq/m^2) than that of the concrete building (228 kg CO_2eq/m^2). In Appendix B four studies comparing the carbon emissions of concrete and timber buildings, without subtracting the stored CO_2, can be found.

Renewable material

A key advantage of wood compared to alternative construction materials is the fact that it is a renewable resource (Sandhaas & Blaß, 2017). In NEN-EN 15978 article 3.27 renewable resource is defined as *"resource that is grown, naturally replenished or naturally cleansed, on a human time scale"* (European Committee for Standardization, 2011, p.11). This means that we can assume this resource will be infinitely available if it is well managed. Unlike finite resources such as coal, petroleum and natural gas which are also produced naturally but in thousands of years. This makes that they will be depleted before they can be renewed.

A key aspect when using wood as a natural resource is sustainable forest management. This means that the ecological impact of the timber harvest is minimised as much as possible. Also, social and economic aspects must be taken into account (Sandhaas & Blaß, 2017). As is the case with any natural resource, annually no more should be taken than can be regrown that year. At the moment in Europe more trees are grown (720.6 m^3) than harvested (522.3 m^3) each year, which means the forests acts as a carbon sink (Luijks et al., 2021).

Throughout this thesis an essential assumption is that all timber comes from sustainably managed forests. Fortunately, the timber that is used in the Netherlands can be proven to be sustainably sourced in 98% of the cases for timber sheets and in 99% of the cases for softwood (Luijks et al., 2021). Additionally, allocating value to trees and forests can prevent deforestation. If one can earn money when selling the timber, it would be wasteful to burn down forests to make place for farmland or other uses and an incentive is given to plant even more trees.

Light weight foundations required

Timber is known as a light building material, for the same capacity and structural volume the weight of timber represents only 20% of the weight of concrete (Gosselin et al., 2017; Waugh Thistleton Architects, 2018). This can reduce the required amount of material needed for the foundation or can enable the possible reuse of an existing foundation (Luijks et al., 2021). The reduced foundation capacity will impact both the GHG emissions and the building costs since less material will be needed.

Reduced construction time

Numerous publications mention a reduced building time as one of the key advantages of timber as a structural building material (Bronsvoort et al., 2020; Cover, 2020; Franzini et al., 2018; Gosselin et al., 2017; Hough, 2019; Jones et al., 2016; Luijks et al., 2021; Waugh Thistleton Architects, 2018; Zeitler-fletcher et al., 2018; Zumbrunnen, 2013). Since the timber parts can be partly assembled inside a factory before they are transported to the building site the construction time on site can be reduced. This has the additional advantage that the quality of the products can be controlled inside the factories (Luijks et al., 2021). Hough (2019) explains that timbers construction speed is a result of its light weight, dry jointing, fewer joints and precise packing and delivery of components to meet the erection programme. Cover (2020) argues that using timber can result in schedule savings up to 25%. Waugh Thistleton Architects (2018, p.36) argue that "*the overall construction of a CLT scheme will be 20% faster than an equivalent scheme for reinforced concrete*". The main advantage of these schedule savings is that this reduces the construction costs and the costs for financing (Hough, 2019). These benefits apply to all prefabricated construction parts, however due to the low weight of timber the products can be transported more easily, and prefabrication becomes more attractive.

3.5 Current barriers for constructing in timber

Despite the potential of timber to reduce the CO_2 emissions, timber is not frequently used as a structural building material in the Netherlands (van der Velde & van leeuwen, 2019). Four explanations for the reluctance to use timber are discussed in this section.

Limited experience

In 2019 the share of timber used in the Netherlands was only 7% of the total volume of building materials (van der Velde & van leeuwen, 2019). This shows the limited experience with timber as a structural building material. There is a conservative culture in the industry, a lack of knowledge sharing and example projects are missing (Franzini et al., 2018, Gosselin et al., 2017, Jones et al., 2016, Kremer & Symmons, 2018). This lack of reference buildings can increase the design time and possibly also the project costs. The limited experience with timber in the Netherlands increases reluctance to use timber (Studio Marco Vermeulen, 2020)

(Assumed) high building costs

Secondly, the building costs of timber buildings are assumed to be higher. Luijks et al. (2021) expect a CLT apartment building to costs 14% more than a benchmark building. A study by Ahmed & Arocho (2021) shows that the construction costs of a 18-storey residential timber building are 6.43% higher than the modelled concrete building. According to Giesekam et al. (2016) this is the greatest barrier for low carbon materials. The actual project costs are dependent on many factors, however if a timber structure is assumed to always be more costly than a concrete structure there will be a reluctance to use timber.

A study in Australia by Kremer & Symmons (2018) argues that the costs can be reduced if the on-site costs and time savings are considered. Cover (2020) even suggests 0.5% cost savings over the full price of the project. This thesis aims to identify the conditions under which structural timber does not have higher costs and can therefore be competitive with concrete. However, both the perception of higher costs and actual higher costs can explain the reluctance to use timber.

Design considerations

Fire resistance, vibrations, acoustic insulation, and material durability generally need additional attention when designing in timber.

Fire safety

In the Netherlands the fire regulations prescribe a minimum amount of time the structure should be able to resist fire. The exact time is dependent on the building type, building height and the considered structural element (BRIS, 2011). For most timber buildings additional measures are needed to comply with these regulations. The most common measures include the application of plaster boards, over dimensioning the timber or using sprinkler installations (Luijks et al., 2021). Even though non-timber buildings also need to comply with fire regulations, measures for timber structures are often more severe (Gosselin et al., 2017, Hough, 2019, Kremer & Symmons, 2018, Luijks et al., 2021). The additional measures that need to be taken compared to concrete or steel structures will need additional construction time, design time and materials which increases the costs and the embodied carbon of the structure.

Vibrations
The low weight of timber introduces difficulties when it comes to vibrations. This requires additional calculations and often additional design measures. The vibrations can be reduced by adding mass to the structural timber floors or by increasing the strength of timber (Gustafsson et al., 2019).

Acoustic insulation
Like for fire resistance, all buildings need to comply with the regulations regarding acoustics. These regulations include soundproofing for noise from outside the building, for reverb, and for noise between rooms (BRIS, 2011). For concrete structures the mass of the structure is often sufficient to provide the sound insulation (Luijks et al., 2021). Because timber structures are very lightweight, additional measures are needed to comply with the regulations. Measures can include adding mass to the floors or mass spring systems. These measures require additional design and construction time and additional costs (Gosselin et al., 2017, Hough, 2019, Luijks et al., 2021)

Material durability
A lack of durability of timber is often perceived as a barrier when using it for building structures (Gosselin et al., 2017, Hough, 2019, Kremer & Symmons, 2018, Luijks et al., 2021). Sandhaas & Blaß (2017, p. 75) argue that: *"Durability in the sense of resistance to destructive organisms and thus the ability to guarantee load-bearing capacity and usability throughout the service life of an object is imperative for wood as an organic material*". It is important to design timber structures in such a way that moisture cannot enter the structural parts (Luijks et al., 2021), since fungi cannot grow in the wood is the moisture content is sufficiently low (Sandhaas & Blaß, 2017). However, most interior structures are designed in such a way that moisture entering the structure is prevented. This means that there are no additional measures needed for timber structures. However, the consequences can be large and therefore additional attention should be given to material durability when designing in timber. If the design is made properly structural timber elements can last as long as their concrete or steel counterparts (Hough, 2019).

Structural properties
Solid timber has a relatively high tensile strength, however the compressive strength is lower than for concrete (Sandhaas & Blaß, 2017). The structural properties of engineered timber are more favourable but not yet equal to withstand the same loads as a concrete structure with the same dimensions. This imposes challenges when designing with timber.

Carbon reduction not monetised
When selecting the structural material the advantages of timber structures regarding the reduction of CO_2 emissions are not taken into account sufficiently (Studio Marco Vermeulen, 2020). The regulations regarding the maximum amount of CO_2 that can be emitted during the construction of a building are mild (Rijksdienst voor Ondernemend Nederland, 2021). Keijzer et al. (2021) argue that the biogenic carbon storage in timber is undervalued in the current carbon estimation standard. The lack of monetisation for the possible carbon reduction makes that the construction industry is not motivated to use timber more frequently.

3.6 Conclusions

It has been discussed that the climate is changing and a strong reduction in the emission of CO_2 and other greenhouse gasses is needed to mitigate this climate change (IPCC, 2021). In the Netherlands the goal is to reduce the CO_2 emissions by 49% by 2030 (Rijksoverheid, 2019). Since the construction sector contributes around 38% of the total global emissions (United Nation Environment Programme, 2020), it is essential that this sector decreases its emissions to reach the national goal of a 49% reduction.

At the moment in the building industry 74% of the emissions are caused by the operational energy use (United Nation Environment Programme, 2020). However, this distribution of emissions is changing (LETI, 2020). With measures taken to reduce the operational energy, the embodied carbon becomes more significant to minimize as well. For (nearly) zero-energy buildings research shows that the embodied carbon contributes for over 40% to the environmental impact (Prinssen, 2020). When the individual building parts are considered research shows that the super- and sub- structure are responsible for the largest part (48% - 67%) of a buildings total embodied carbon (LETI, 2020).

While CO_2 reduction can be achieved using various strategies both the program called 'Nederland Circulair 2050' (Rijksoverheid, 2016) and the 'Transitieagenda Circulaire Bouweconomie' (Nelissen et al., 2018), illustrate the importance on using renewable materials. This thesis focusses on reducing carbon emissions by using structural timber, which is a renewable and biobased material.

The advantages and disadvantages of concrete and timber are compared. In the Netherlands there is a tradition of constructing in concrete, therefore there is more experience with this material than with timber. Technological developments have increased the potential applications of timber, with engineered timber larger elements can be fabricated, these elements can have increased strength and increased fire resistance. This made timber applicable for more building types and structures, however the strength of timber is still lower than the strength of concrete. Timber has the capacity to take up CO_2 from the atmosphere and temporary store it (Sandhaas & Blaß, 2017). Also, without taking this CO_2 storage in account timber structures are less carbon intensive than concrete alternatives. The fact that wood is a renewable resource which is infinitely available if the forests are sustainably managed, make it favourable over concrete which depends on finite resources to be produced. The construction time of a timber structure will be shorter than for an in-situ concrete structure which needs time to harden. Because timber is a lightweight building material, less heavy foundation structures are needed than for concrete buildings. However, this low mass of timber also causes additional measures to be required for acoustics and vibrations. Fire safety and material durability of timber are also important to consider. The building costs of timber structures are assumed to be higher than for concrete structures. Finally, the lower CO_2 emissions are not monetised which increases the barrier to use timber.

The advantages and disadvantages of timber and concrete are summarised in Table 3.

Table 3: Advantages and disadvantages of concrete and timber

Advantages of constructing in concrete	Disadvantages of constructing in concrete	Motivations for constructing in timber	Current barriers for constructing in timber
A tradition of constructing in concrete	Large amounts of CO_2 are emitted	Reduction of CO_2 emissions	Limited experience with constructing in timber
A lot of experience with constructing in concrete	Resource is only finitely available	Renewable material	Carbon reduction is not monetised
High strength and acoustic insulation capacity and fire resistance	Heavy foundations are needed	Lighter foundations needed	Medium strength and additional measures needed regarding fire resistance, acoustics, vibrations, and material durability
Low construction costs	The required hardening time increases the building time	Reduced construction time	(Assumed) high construction costs

4 Competitiveness comparison method

How can the competitiveness of timber building structures be compared to concrete building structures?

To identify the conditions under which structural timber is competitive with concrete, first the method to determine the competitiveness must be defined.

The definition that is used for the term competitive is: *"to be able to compete at the same level"* (Cambridge English Dictionary, 2021). For two structural design to compete at the same level they must serve the same function and have the same balance between costs and revenue. Therefore, the competitiveness is not based on the project costs but on the potential profit. Sathre and Gustavsson (2009) explain that competitiveness is a complex issue depending on consumer preferences, industry traditions, and material functionality. They also argue that the relative cost of a product is an important factor affecting the competitiveness.

This chapter explains the methods that are used throughout this thesis to determine the competitiveness.

4.1 Potential profit determination method

Since the competitiveness is based on the project potential profit, a method must be defined to determine this potential profit. In this research the potential profit is determined using the following formula:

$$Potential\ profit = Project\ revenue - Total\ building\ costs - Carbon\ emission\ costs$$

It is important to note that the potential profit of two designs can only be compared if they fulfil the same function. This function is described in a functional unit which contains the building function, design decisions such as building height and floor span, imposed loads, fire resistance, acoustic insulation, and vibration requirements. The potential profit is normalised by dividing the outcome over the gross floor area (GFA) of the building. Therefore, the potential profit is expressed in the unit €/m^2. Also, it should be noted that fictive carbon emissions costs are included in this research although these costs are not present in current practice.

The subsequent sections explain the methods used to determine the project revenue, the total building costs and the carbon emission costs

4.2 Project revenue

The method that is used to determine the project revenue is explained in this section.

Building revenue

The project revenue can be determined by multiplying the revenue per square meter with the total sellable floor area of the building. It is important to note that the total sellable floor area does not include floor area dedicated to circulation in the building. The revenue per square meter mainly depends on the location, the building function and on the economic situation on the building market. A distinction is made between the revenue for owner occupied homes which are sold on the free housing market and the revenue of social rental residences.

To determine the revenue for the case study of *De Scharnier* (chapter 8) information was provided by Heijmans. Approximately half of the sellable floor area of this project contains owner-occupied apartments the other half contains social rental homes and non-residential areas. The revenue was compared to the current average revenue per square meter for the neighbourhood of the project (Funda, 2021b), which showed similar revenues.

To determine the revenue of the parameter study (chapter 9) the average revenue per square meter of the 20 largest municipalities in the Netherlands was used. First data from the CBS (2021a) was gathered to determine the 20 largest municipalities. The urbanisation trends are the greatest in large cities (Faber et al., 2020). Since this causes high demands for multi-storey residential buildings, the revenue in urban areas was used. Almost 30% of all Dutch citizens live in one of these 20 cities, which makes it a representative sample. Subsequently information provided by Funda on the average revenue in September 2021 per square meter for these 20 municipalities was collected (2021a). The average revenue of these municipalities is used as the revenue for the design discussed in chapter 9.

For the social rental homes the revenue is based on the maximum rent for a social renal home (Rijksoverheid, 2022) and the gross initial yield. The assumption is made that the floor area of a social rental home is 60 m^2 on average. By dividing the total rent for one year per square meter over the gross initial yield the value per square meter can be found. With a rent of €12.72 per month per square meter and a gross initial yield of 5.2% (Troostwijk, 2020) the value is €2936.42 per square meter. This value is rounded to €2900, - per square meter. The assumption is made that 50% of the sellable floor area of this design in the parameter study is sold on the free housing market and the remaining 50% is dedicated to social rental homes

Revenue free market sector	**Revenue social rental homes**
De Scharnier (chapter 8) €5200, - /m^2 NFA	*De Scharnier* (chapter 8) €4100, - /m^2 NFA
Parameter study (chapter 9) €3400, - /m^2 NFA	Parameter study (chapter 9) €2900, - /m^2 NFA

Additional revenue timber buildings

There are multiple studies which show that sustainable real estate has more value (Koppels & de Jong, 2019). A research by Eichholtz, Kok & Quigley (2010, p. 2492) suggest that "*selling prices of green buildings are higher by about 16 percent*". A higher revenue for timber buildings can have a significant influence on the competitiveness. The experience in the Netherlands with multi-storey timber buildings is limited. Therefore, no specific information regarding the revenue of timber buildings was found.

Talvitie et al. (2021) performed a research into the economic feasibility of wood-based structures in Finland, where timber is a more common structural material. Through hedonic regression analysis the effect of wood on the dwelling prices in Finland was estimated. This study showed that the effect in the city of Helsinki was statistically significant, and a wood-based building structure increased the dwelling prices with 8,85%. However, in the cities Espoo and Vantaa no significant effect on the dwelling prices was found. Talvitie et al. (2021) mention that no previous studies on the effect of wooden structures on dwelling prices were found. Also, the study does not specifically explain the reason for the positive effect on the revenue in Helsinki and the insignificant results in Espoo and Vantaa.

There is a chance that timber buildings are higher valued by residents because of the aesthetic and sustainability quality. Therefore, despite the lack of information on the additional value of timber buildings in the Netherlands, the impact of potential additional value is investigated in this research. The study by Talvitie et al. (2021) has shown that there is a potential increased revenue for timber in urban areas. From conversations with industry expert Djordy van Laar (personal communication, January 11, 2022) it was concluded that an additional revenue of 8% is not realistic in the Netherlands. Therefore, the possible effects on the competitiveness of timber structures are investigated by including a 0%, 2% and 4% additional revenue in the analysis in chapter 8 and 9. This additional revenue is only be applied to owner-occupied apartments that are solid in the free market. For the social rental residences, the revenue for timber and concrete is assumed to be the same.

4.3 Total building costs

To determine the potential profit of timber and concrete structures a method to determine the total building costs must be defined. This section describes the method that is used to determine the total building costs.

Cost classification

The total costs of a project consist of the direct and the indirect costs. Where the direct costs are the costs related to the physical parts of the building, including the costs for labour, material and equipment, the indirect building costs consist of the costs for the contractor regarding the building site, execution and operations (Koppels & de Jong, 2019).

The total costs for a building project consist of many different aspects, the terminology and classification that is described in NEN 2699 (Koninklijk Nederlands Normalisatie Instituut, 2017) is used throughout this thesis. At level 1 this building code identifies nine rubrics:

- [A] land costs
- [B] construction costs
- [C] furnishing costs
- [D] additional costs
- [E] unforeseen
- [F] taxes
- [G] financing
- [X] operating costs
- [Z] revenue

Each rubric can be subdivided in clusters (level 2) which are divided in element clusters (level 3). Element clusters can be subdivided in elements (level 4) and finally the elements are divided in technical solutions in level 5. This can be summarised in a tree diagram of which an example is shown in Appendix C. It is possible to make cost estimations on each of these levels depending on the level of detail of the analysis and the availability of information regarding the design.

Level of detail

The classification of NEN 2699 (Koninklijk Nederlands Normalisatie Instituut, 2017) can also be used to explain the level of detail at which the costs are estimated. In the technical design phase, the exact elements that will be used are known, therefore it is possible to estimate the costs on the element level. However, in an early design stage not all exact elements might be known, in that case the cost estimate can be made on cluster level or even rubric level and will therefore be less precise. The level of detail at which the costs are estimated throughout this research is on the level of element clusters (level 3). This level is assumed to provide sufficient detail for a fair comparison but not zoom in too much on specifics.

Cost actor

During the cost estimation it is important to consider both the costs and the revenue for the same actor. In NEN 2699 (Koninklijk Nederlands Normalisatie Instituut, 2017) three main actors are described, the developer of the building, the owner of the building and the user or tenant of the building. This is important since the costs for the building owner will be the revenue of the developer and the costs for the user will be the revenue of the owner. In this research the costs and revenue for the developer of the building are estimated.

Information sources

There are multiple sources that can be used to find key figures for building costs. There are organisations like 'BouwkostenKompas.nl' that publish books with key figures of different building types (BouwkostenKompas, n.d.). Suppliers also provide cost information regarding their specific products and there are online databases that combine the cost information of multiple suppliers like Bouwkosten-online and bouwkosten.nl (Koppels & de Jong, 2019). For this thesis *IGG Bouweconomie* acts as an advisor regarding the cost estimates that are to be made.

Cost influencers

For all cost estimations and cost calculations it is important to consider the moment at which the costs are made and at which moment the revenue is collected. This has to do with the fact that 1 euro today is less valuable than 1 euro in ten years, the value will decrease due to inflation (Binnekamp et al., 2018). Because the building costs of the variants are assessed as if they were to be built at the same time, the inflation will be the same and can therefore be neglected in the comparison.

Currently timber is not commonly used as a construction material in the Netherlands, this increases the uncertainty of the building costs of timber buildings. There are only a few reference projects built that can be used as a reference for cost estimation. Also, the available material stock in Europe is smaller since timber is used less frequently. As for all products, the costs of timber products are influenced by demand and supply on the market. An increase in the demand for timber products in 2020 and 2021 made the prices go up (NOS, 2021). However, at the moment of writing this research the price of timber is stabilising again (de Waard, 2021). The future developments of the timber prices remain uncertain. Figure 8 shows the development of the price of one cubic meter of lumber since February 2019.

Figure 8: Price lumber assuming that 1 board feet is 2.35 cubic meter, and 1 dollar is 0.90 euro. Adapted from: Lumber Price: Latest Futures Prices, Charts & Market News, by Nasdaq, 2022 (https://www.nasdaq.com/market-activity/commodities/lbs)

The price for other construction materials changes over time as well. Figure 9 shows the material costs index of concrete, steel, timber and isolation materials between January 2021 and February 2022. This shows that the price of steel has increased more than the price of timber during this time. The competitiveness of timber structures is dependent on the price of wood and on the price of competing materials such as steel and concrete.

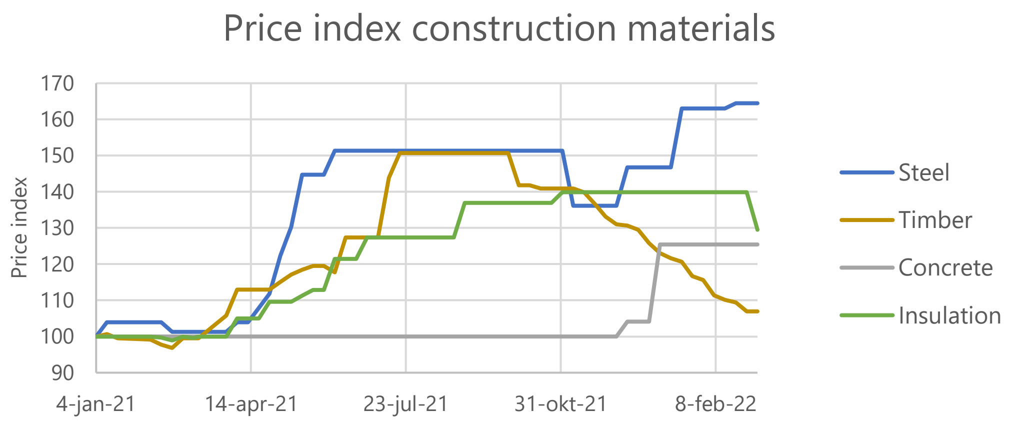


Figure 9: Price index construction materials. Adapted from Materialen Index, by bouwkostenindex, 2022 (https://www.bouwkostenindex.nl/nl/materialenindex)

Cost estimations

Not all elements that are described in NEN 2699 are influenced by the structural material, however the total building costs must be estimated to determine the potential profit. If there are large cost contributors excluded from the calculation the potential profit will seem much higher than it is. A distinction is made between costs that are included and influenced by the structural material, costs that are included and independent of the structural material, and costs that are outside of the scope of this research. In Figure 10 an overview is given of the cost that are dependent on the structural material in green, the costs that are included but are independent of the structural material in yellow and the excluded costs in grey. In the remainder of this section an explanation of the cost estimation method is discussed per rubric.

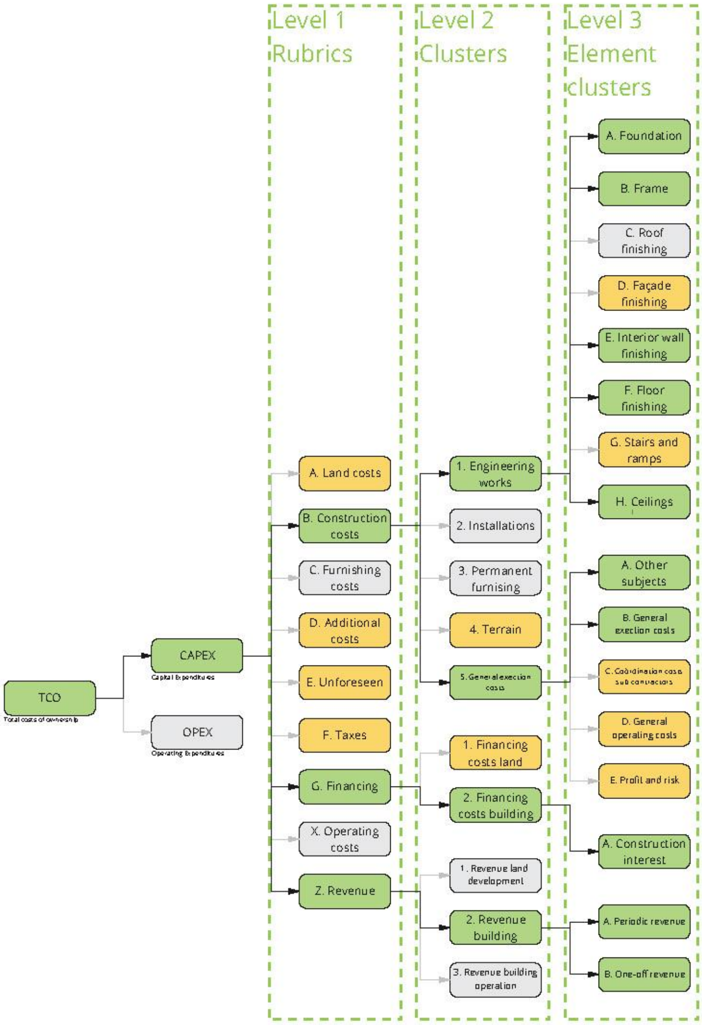


Figure 10: Overview of the included element clusters in the cost estimations. Adapted from "NEN 2699" by Koninklijk Nederlands Normalisatie Instituut, 2017.

A. Land costs

The land costs are not directly influenced by the structural building material. However, it is important to note that there is a relation between the land costs and the building costs. In the Netherlands the land costs are determined by calculating the residual value of the land. The residual value is the sales value of the building subtracted by the building costs and additional costs (IGG Bouweconomie, 2021).

The land costs are included as a percentage of the total construction and general execution costs. Three percentages, provided by *IGG Bouweconomie*, are used dependent on the project specifications (D. D. D. van Laar, personal communication, November 9, 2021). These percentages also include the financing costs for the land (G.1) and the engineering works for the terrain (B.4). For the cost estimation of *De Scharnier* (chapter 8) the high percentage is used since the project is in the city centre of Rotterdam. For the parameter study (chapter 9) the mean value is used.

Table 4: Land costs as a percentage over the total construction costs and general execution cost. Based on percentages provided by IGG Bouweconomie

Land costs		
% Over total construction costs and general execution costs		
Low	Mean	High
6.0%	7.5%	9.0%

B. Construction costs

The construction costs relate to the physical realisation of the building. These building costs can be subdivided in five clusters. The cost of the engineering works (B.1) and general execution costs (B.5) will be dependent on the structural material and are therefore based on the cost of the elements that are used. The costs of the engineering works of the terrain are included in the land costs (A). The costs for the installations and the permanent finishing are outside of the scope of this research and are therefore not included.

The engineering works consist of eight element clusters, the cost estimation method for each element cluster is shortly discussed.

- A. Foundation: The amount of material and therefore the costs of the foundation are influenced by the weight of the superstructure. The expectation is that the weight of a timber structure will be only 20% of the weight of concrete (Gosselin et al., 2017), which would mean that the foundation costs are significantly lower for a timber building. Therefore, the foundation costs are varied depending on the weight of the superstructure. The elements included in the foundation are ground provisions, floors on base level, foundation structures and pile foundations.
- B. Frame: The frame includes the vertical and horizontal load bearing components. Since the structural material of these components will vary between the different options in the comparison the costs related to the frame must certainly be included. Elements that are included in the frame are structural walls, floors, roofs, and main load bearing structural elements such as beams and columns.
- C. Roof finishing: The costs for the roof finishings are dependent on the floor type. Therefore, the costs will vary depending on the structural material.
- D. Façade finishing: The costs related to the finishing of the façade are strongly dependent on the specific type of façade and less on the structural material. Therefore, the assumption is made that the costs for the façade are €550 per m^2 façade area for all design variants (D. D. D. van Laar, personal communication, January 11, 2022).
- E. Interior wall finishing: The costs of the interior wall finishing are included based on the specific design. The insulation, acoustics, fire protection and sound insulation quality are dependent on the finishing of the interior walls. The assumption is that additional measures are needed for timber building structures to receive the same comfort levels as for concrete structures (Luijks et al., 2021) and to comply with the building regulations. To keep the functional unit of the different options the same, the interior wall finishing will vary between the different designs.
- F. Floor finishing: As for the interior wall finishing the cost for the floor finishing are dependent on the structural material and must therefore be included based on the specific design.

- G. Stairs and ramps: The decision is made to use the same the structural material of the stairs and ramps of all design variants. Since the contribution to the total costs is minimal and independent of the structural material this element cluster is neglected in the comparison.
- H. Ceiling finishing: The materials required for finishing the ceiling are dependent on the structural material for the floors. Therefore, the costs related to this element cluster will be included in the cost estimation, dependent on the structural material. If the timber on the underside of a timber floor element can be left exposed the ceiling finishing costs can be reduced.

The cluster of the general execution costs consist of five element clusters. The element clusters other subjects (5.A) and general execution costs (5.B) are included in the comparison. These costs are relevant since they can be reduced if the construction time is reduced. Various sources mention the reduction of building time as one of the main characteristics of constructing in timber (Bronsvoort et al., 2020; Cover, 2020; Franzini et al., 2018; Gosselin et al., 2017; Hough, 2019; Luijks et al., 2021; Zeitler-fletcher et al., 2018; Zumbrunnen, 2013). The coordination costs for the sub-contractors (5.C), General operating costs (5.D) and profit and risk (5.E) are included as a percentage of the total construction and execution costs. The combined costs of these three element clusters are referred to as developer costs and the percentages can be found in Table 5 (D. D. D. van Laar, personal communication, November 9, 2021). For the cost estimation of *De Scharnier* (chapter 8) and for the parameter study (chapter 9) the mean value is used.

Table 5: Developer costs as a percentage over the total construction costs and general execution cost. Based on percentages provided by IGG Bouweconomie

Developer costs		
% Over total construction costs and general execution costs		
Low	Mean	High
3.5%	7.3%	18.5%

C. Furnishing costs

The furnishing costs are excluded from the analysis since it relates to the use phase of the building. All aspects related to this phase are outside of the scope of this research. Additionally, the furnishing costs are independent of the structural material.

D. Additional costs

In the total building costs determined in this research the additional costs are included as a percentage of the total construction and execution costs. The additional costs are related to professional fees, connection fees and selling fees. The percentages that are used are provided by *IGG Bouweconomie* and can be found in Table 6(D. D. D. van Laar, personal communication, November 9, 2021). For the cost estimation of *De Scharnier* (chapter 8) and for the parameter study (chapter 9) the mean value is used.

Table 6: Professional fees, connection fees and selling fees as a percentage over the total construction costs and general execution cost. Based on percentages provided by IGG Bouweconomie

Professional fees		
% Over total construction costs and general execution costs		
Low	Mean	High
6.7%	9.8%	17.3%

Connection fees		
% Over total construction costs and general execution costs		
Low	Mean	High
2.1%	3.3%	5.0%

Selling fees		
% Over total construction costs and general execution costs		
Low	Mean	High
1.2%	1.2%	2.7%

E. Unforeseen

The unforeseen costs are the costs related to the risks that could not be predicted in advance. These costs are not directly related to the structural material but are included to cover the additional costs of possible unforeseeable future scenarios. In the analysis of this research the unforeseen costs are included as a percentage of the total construction and general execution costs. The percentages that are used are provided by *IGG Bouweconomie* and can be found in Table 7 (D. D. D. van Laar, personal communication, November 9, 2021). For the cost estimation of *De Scharnier* (chapter 8) and for the parameter study (chapter 9) the mean value is used.

Table 7: Unforeseen costs as a percentage over the total construction costs and general execution cost. Based on percentages provided by IGG Bouweconomie

Unforeseen costs		
% Over total construction costs and general execution costs		
Low	Mean	High
3.0%	4.0%	5.0%

F. Taxes

In most cases the taxes are related to the building costs and are therefore only indirectly dependent on the structural material choice. Therefore, in the analysis the taxes will be included as a percentage of the total building and execution costs. The percentages that are used are provided by *IGG Bouweconomie* and can be found in Table 8 (D. D. D. van Laar, personal communication, November 9, 2021). For the cost estimation of *De Scharnier* (chapter 8) and for the parameter study (chapter 9) the mean value is used. The taxes related to carbon emissions are not included in this percentage, these costs are determined in section 4.4.

Table 8: Taxes as a percentage over the total construction costs and general execution cost. Based on percentages provided by IGG Bouweconomie

Taxes		
% Over total construction costs and general execution costs		
Low	Mean	High
1.0%	2.0%	5.0%

G. Financing

The financing costs are included in the comparison because these costs are influenced by the construction time. Like is described earlier in this chapter, the construction time of a timber building is assumed to be significantly shorter than for other structural materials which reduces the financing time. A reduced financing time decreases the costs for financing. Another important factor determining the financing costs is the assumed risk by the bank and the marketability of the building. While banks might see more risks for timber buildings this assumption is changing since concrete buildings appear to have a higher risk on vacancy. The assumption for this comparison is that these risk factors are comparable for timber and concrete buildings. Therefore, the financing costs are based on an interest rate of 3% of the building and execution costs is assumed for the concrete design variants. Due to the reduced construction time for the timber variants, an interest rate that is 5% lower is used in consultation with *IGG Bouweconomie*. This results in an interest rate of 2.85% for the timber variants of *De Scharnier* (chapter 8) and the parameter study (chapter 9).

X. Operating costs

The operating costs are outside the scope of this thesis since these costs are made during the use phase of the building. It is interesting to mention that there can be advantages for buildings with a timber structure during the use phase. Luijks et al. (2021) even state that living in a timber building is healthy.

Z. Revenue

The methods used to determine the revenue are discussed in chapter 4.2.

4.4 Carbon emission costs

"The rationale of internalising the external costs of climate change is to impose a financial incentive to reduce the emission of greenhouse gases to the atmosphere" (Sathre & Gustavsson, 2009, p.251). The carbon emission costs in this thesis are determined by multiplying the total CO_2 emissions of a building strucutre with a determined price per kg CO_2. To make a fair comparison between concrete and timber it is important to include the carbon emissions of all elements that are required to comply with the defined functional unit. It is important to note that the emission costs are ficitve costs added as a potential policy measure to investigate the influence on the potential profit. It is possible that the emission costs are to be paid in the future in the form of a CO_2 tax.

In this chapter first the current parctice in the Netherlands is discussed. Second, the method that is used to determine the CO_2 emissions is explained. Finally, the method to determine the price per kg CO_2 is illustrated.

Current practice

Currently it is not required to estimate the carbon footprint for new building designs in the Netherlands, and there are no carbon emissions cost. However, it is required to perform an environmental performance calculation (MPG in Dutch) for all houses, office buildings and civil engineering constructions with a total user surface larger than 100 m^2. This score is an indicator of the environmental profile of a building that results from a life cycle assessment (LCA) and is simplified to one value (Prinssen, 2020). This value is expressed in euros per square meter per year. The MPG can be determined by dividing the environmental cost indicator (MKI in Dutch) over the gross floor area and the intended lifespan of the building (Prinssen, 2020). The MKI contains environmental costs related to 19 impact categories. These impact categories contain 'climate change' (expressed as GWP) and other environmental impacts such as 'depletion of raw materials' and 'water use' (National Environmental Database Foundation, 2020). The category 'climate change' is divided into four separate impact categories, this makes the carbon stored in biobased materials explicitly visible in the product data. However, it is still not allowed to include the biogenic carbon when determining the MKI and MPG; this would require a change in the 'Bepalingsmethode Milieuprestatie Bouwwerken' (Keijzer et al., 2021).

All impact categories have an individual weighting factor which is used to translate the environmental impacts to costs per square meter per year. As of the first of July 2021 the MPG score must be under €0.80/ m^2/ year (Rijksdienst voor Ondernemend Nederland, 2021). The MPG score will be graduality lowered to €0.50/ m^2/ year in 2030. Even though the MPG score is expressed in euro's, the corresponding price is only fictive and does not have to be paid.

The research in this thesis focusses specifically on reducing carbon emissions. Because 15 of the 19 impact categories included in the MPG score are not related to CO_2 emissions, the MPG score is not suited to determine the carbon emission costs. Also, there are three other issues regarding the MPG score that make it less appropriate to use in this research. First, the MPG score is calculated per year. If the compared building designs have the same functional unit, the design lifespan will be the same. Therefore, this will not change the relative outcome and only impose extra issues. Additionally, to reduce the emissions by 2030, the impact that is made the coming years is more relevant than the impact over the full building lifespan. Second, the exclusion of the impact of carbon storage in biobased materials neglects an important benefit of constructing in timber (Studio Marco Vermeulen, 2020). A research by TNO (Keijzer et al., 2021) has investigated the potential of CO_2 storage in timber buildings. This research shows that if the carbon storage is included in the calculation over a period of 100 years, the net contribution to climate change is half the contribution of a scenario without the inclusion of carbon storage. Which would mean that the current method, without carbon sequestration, the CO_2 footprint of timber seems higher than it is in realty. This is illustrated in the next section of this chapter. Finally, the MPG score is not translated to actual costs therefore there is no incentive to minimise carbon emissions as much as possible.

Comparison carbon emissions of timber and concrete

Figure 11 illustrates the carbon emissions of a timber and a concrete example building structure over time. In this example, the average carbon emissions of the parameter study are used. The emission of the concrete and timber variant are 285 and 141 kg CO_2/ m^2 respectively. However, in the timber building structure 324 kg CO_2/m^2 is stored, this storage is indicated with a negative number. The wood that is used to construct the timber building started growing 50 years before the construction started, in which the 324 kg CO_2/m^2 was captured from the atmosphere. At the time of construction, the carbon emissions caused by the production of the structural materials, transport and manufacturing are made. Adding 141 kg CO_2/m^2 emitted carbon to the -324 kg CO_2/m^2 stored carbon results in -183 kg CO_2/m^2 carbon for the timber structure. New trees can be planted which will again capture carbon from the atmosphere.

At the end of the buildings first functional lifespan multiple options are considered. The currently used MPG calculation assumes that all the stored carbon in timber products is released back into the atmosphere at the end of the building's functional lifespan. Which neglects the stored carbon and would bring the total emissions to 141 kg CO_2/m^2 in this example. However, new trees can be plated which can again capture and store carbon. This can be included in the analysis by again subtracting the 324 kg CO_2/m^2 stored carbon from the total emissions at the end of life. If the timber can be reused and trees are replanted the total emissions reach a total of -496 kg CO_2/m^2. If all timber would be burned but trees are replanted the total emissions are -183 kg CO_2/m^2.

This shows that the currently used calculation method is only correct in the scenario that no trees are replanted, and all used timber is burned at the end of the building's lifespan. This is unlikely since sustainable forest management ensures no more trees are harvested than grown.

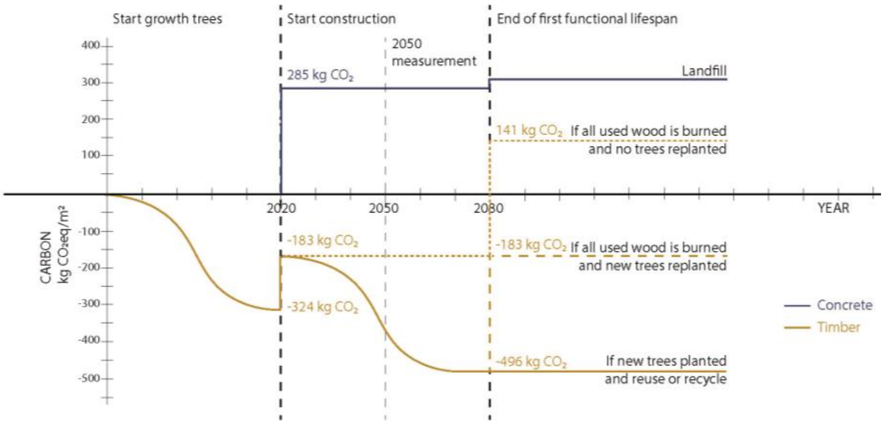


Figure 11: Example of the carbon emissions of a timber and concrete building structure

Carbon emission estimation method

This section explains the method that is used in this research to determine the carbon emissions.

The LCA method is used to estimate the carbon footprint of the analysed timber and concrete structures in this research. The "*LCA provides a holistic approach for quantifying the environmental impacts*" (Akbarnezhad & Xiao, 2017, p. 9), an additional reason is that this approach is used in the building regulations (NEN-EN 15804, ISO 14025 and NEN-EN 15978. Finally, it provides the option to determine a scope that is appropriate for the application of the analysis. An overview of the four steps of the LCA method is given in Figure 12, in Appendix D the four steps of the LCA method are explained in detail. This section explains the goal and the scope of the LCA that is made for the design variants of *De Scharnier* (chapter8) and the parameter study (chapter 9).

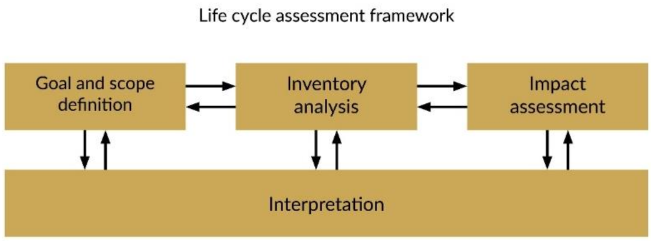


Figure 12: Life cycle assessment framework. From ISO 14040 (Technical Committee ISO/TC 207, 2006)

Goal

The intended application of the life cycle assessment is to determine the carbon emission costs based on the total carbon emissions. Information regarding environmental 'hot-spots' is useful but the main objective is to compare multiple structural designs. The main purpose of the LCA is to contribute to research and education. The audience of this study will vary from industry experts to interested readers without any knowledge on life cycle assessments.

Scope – functional unit

Since the main goal of the LCA is to compare multiple systems, a clear definition of the functional unit is important. For this thesis the functional unit consists of a load bearing structural system that complies with all building regulations for strength, stiffness, fire resistance, acoustics, and vibrations. This means that all materials needed to comply with the regulations are included in the analysis. For example, the required floor finishing that might be needed to achieve the fire performance requirements are included in the analysis. In Table 9 the performance criteria are summarized. The results of the analysis in this research are normalized by dividing the total carbon emissions over the gross floor area.

Table 9: Summary of performance criteria

Performance criteria residential buildings	Value	Unit
Live load (BRIS, 2011)	1.75	kN/m^2
Minimum fire resistance for buildings with the highest floor below 7 meters (BRIS, 2011)	60	min
Minimum fire resistance for buildings with the highest floor between 7 and 13 meters (BRIS, 2011)	90	min
Minimum fire resistance for buildings with the highest floor above 13 metres (BRIS, 2011)	120	min

Acoustic insulation (airborne) D>	57	dB
Acoustic insulation (impact) L<	49	dB
Minimal F1 (vibrations)	8	Hz

Scope – system boundaries
The second element of the scope definition is the establishment of the system boundaries (Jonkers & Ottelé, 2020). These are the boundaries regarding the analysed life cycle stages that are included in the analysis, Figure 13 provides an overview of the life cycle stages.

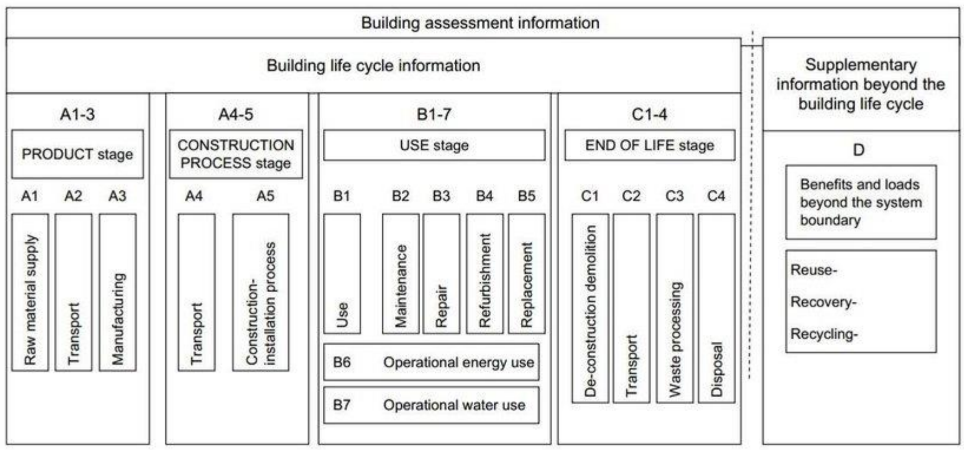


Figure 13: Life cycle stages. From EN 15978:2011 (E) figure 6

The first stage is the product stage (A1-3), this stage contains the emissions related to the material supply, transport and manufacturing of the products that are used in the building. LETI (2020) researched example data, for typical office, medium scale residential and school developments over 60 years. This shows that especially for ultra-low energy buildings, which will become more common in the future, the impact of the stages A1-3 is very large. Additionally, D'Amico & Pomponi (2020, p. 1) state *"the most energy-demanding and GHG-intensive activities are those associated with the so called cradle-to-gate stage"* which refers to stage A1-3. Because this stage contains the emissions due to the production of concrete and timber structural elements it is included in the analysis.

The emissions in stages A4-5 make up the construction process stage. The emissions of this stage contribute maximum 2% to the total emissions (LETI, 2020). The emissions in stages A4-5 are assumed to be neglectablestages and therefore not included.

The use stage includes both the operational energy and the emissions due to maintenance and replacements. The assumption is made that the structural building material does not influence the required operational energy. Also, the difference in emissions due to maintenance and replacements is assumed to be similar for the various structural designs. Timber will be applied indoors and therefore the assumption is that no more maintenance than for a concrete structure will be needed. Although the emissions in stage B can contribute between 43% and 81% to the total emissions (LETI, 2020) this stage is outside of the scope of the analysis.

For the end-of-life stage (C1-4) the emissions are dependent on the assumed end of life scenario. This stage includes emissions related to the processes required at the end of the building's lifespan for example for reuse, remanufacturing or for disposal. According to the research by LETI (2020) the emissions in this stage are maximum 2% of the total emissions. Therefore, the emissions in this stage are neglected.

Stage D contains the benefits and loads dependent on the end-of-life scenario. For the analysis in this thesis two different end of life scenarios are investigated. In the first scenario the assumption is made that all materials will be reused at the end of the building's lifespan. This will influence the results of the analysis since there will be no carbon emissions caused by burring the used timber. Therefore, the biogenic carbon that is stored in timber products can be subtracted from the emitted carbon. The second scenario assumes that the carbon captured in timber will be released back in the atmosphere at the end of the building's lifespan. Therefore, this scenario will not include the carbon storage in timber. For the parameter study a third scenario where 50% of the biogenic carbon is subtracted from the emitted carbon is included. By investigating multiple scenario's, the influence of including the carbon storage in timber products can be determined. It is important to note that the assumptions regarding the end of life are uncertain.

The system boundaries of the LCA performed in this thesis include life cycle stages A1-3 and assume reuse of all materials at the end of life.

Scope – LCA methodology

The LCA in this thesis only includes the impact categories influencing the global warming potential (GWP) which was called 'climate change' in the environmental impact category units used before the 1st of January 2021. After the 1st of January 2021 this category was divided over four separate impact categories regarding climate change: total, fossil, biogenic and land use. The unit in which this category is measured is CO_2 equivalents. This LCA method which only focusses on the GWP can also be called the carbon footprint method (Jonkers & Ottelé, 2020). The alteration of dividing the category 'climate change' into four separate impact categories has made the carbon stored in timber explicitly visible in the product data.

Scope – sources for inventory data

The reliability of the sources for inventory data heavily influences the reliability of the results. In the Netherlands the 'Nationale Millieudatabase' is an important source of information since it is a central database that provides information on varying products (Nationale Milieudatabase, n.d.). This database includes information on the lifespan and functional unit of the product as well as providing environmental information (Nationale Milieudatabase, n.d.). This information can be accessed by anyone, and different products can easily be compared. However, the underlying assumptions made when calculating the environmental impact are not visible and there is a lack of (recent) information for some materials.

The life-cycle environmental impact of a material or product can be registered in verified document called an environmental product declaration (EPD). The website of One Click LCA (One Click LCA, 2021d) has a database that includes both data directly from EPDs and data generated by One Click LCA. The calculation method is transparent and the EPDs can be downloaded and directly used, which are important advantages over the 'Nationale Millieudatabase'.

If possible, the data that is used for the calculations in this thesis will come from EPDs directly. This ensures that the reasonings behind the numbers that are used is transparent. For materials of which there is no EPD available, the data provided by one click LCA is used.

Because this research aims to draw conclusions that are applicable to the Dutch construction industry in general, it is not desirable to use inventory data of only one specific material. EPD's are collected from as many sources as possible, if needed information from one click LCA is included. From the composed database for each material an EPD that is representative is chosen, together with an EPD that has a higher impact than average and an EPD with a lower impact than average. This gives insights on the possible range of environmental impacts for a specific product.

When selecting the EPDs for the timber products an important factor was if the biogenic carbon was made explicitly visible in the calculation. This enables the comparison between a calculation with and one without the inclusion of the carbon stored in timber. Also, the location where the timber is produced and processed was considered. The environmental impact of concrete products is highly dependent on the mixture and the cement that is used. In the Netherlands it is common to use CEM III as a binder in the concrete mixture (Bijleveld & Beeftink, 2020). This binder is a waste product from steel production and therefore has a lower environmental impact. The required concrete strength determines the amount of cement that is needed and therefore influences the environmental impact. Therefore, various concrete strength classes are considered separately. Steel production can be done using the blast or electric arc furnace process (Jing et al., 2014) which method is chosen, influences the environmental impact of the product. Combined with the differences per production location this makes for a high variance between the low and the high impact values. For the non-structural materials the goal was to represent the products required to comply with the stated functional unit.

The study into the various product declarations and the consideration of a range of impacts results in a more reliable and accurate estimation of the environmental performance of the studied structural systems. In Table 10 below the mean representative impacts of the considered materials are given, Appendix E holds a summary of all the considered data.

Table 10: Mean global warming potential for considered materials

		A1-3 [kg-CO2eq/ kg]			
	Material	**GWP**	**BIO GWP**	**TOT GWP**	**Source**
Timber					
	CLT	0.272	-1.615	-1.343	(W. u. J. Derix GmbH & Co, 2020)
	Glulam	0.308	-1.602	-1.294	(Institut Bauen und Umwelt e.V., 2021)
	Softwood	0.232	-1.610	-1.379	(Wood Solutions, 2017b)
	Hardwood	0.284	-1.497	-1.208	(Wood Solutions, 2017a)
	LVL	0.306	-1.576	-1.271	(Stora Enso, 2019)
Concrete		**GWP**	**BIO GWP**	**TOT GWP**	**Source**
	Hollow core slab	0.136	0	0.136	(Strängbetong AB, 2019)
	Precast plank floor	0.175	0	0.175	(Con-Form AS, 2016)
	Precast concrete	0.189	0	0.189	(UPB AS, 2016)

		GWP	BIO GWP	TOT GWP	Source
	In situ concrete C25/30	0.070	0	0.070	(One Click LCA, 2021i)
	In situ concrete C30/37	0.081	0	0.081	(One Click LCA, 2021j)
	In situ concrete C35/45	0.082	0	0.082	(One Click LCA, 2021k)
	In situ concrete C40/50	0.144	0	0.144	(Thomas Betong, 2020)
	In situ concrete C50/60	0.131	0	0.131	(Transgulf Readymix Concrete Co. LLC, 2019)
Steel		**GWP**	**BIO GWP**	**TOT GWP**	**Source**
	Beams	0.908	0	0.908	(Bouwen met Staal, 2013)
	Reinforcement	1.025	0	1.025	(VWN - Vereniging Wapeningsstaal Nederland, 2021)
Non-structural materials		**GWP**	**BIO GWP**	**TOT GWP**	**Source**
	Mineral wool	1.244	0	1.244	(Knauf insulation, 2016)
	Gypsum board fire resistant	0.194	0	0.194	(Saint-Gobain Construction Products Hungary, 2018)
	Glass wool	1.855	0	1.855	(Saint-Gobain ISOVER G+H AG, 2016)
	Metal framing	1.700	0	1.700	(Saint-Gobain construction Products, 2015)
	MDF	1.029	-1.480	-0.451	(Thinkstep Pty Ktd & Stephen Mitchell Associates, 2020)
	Washed gravel	0.004	0	0.004	(One Click LCA, 2021c)
	PIR insulation	3.990	0	3.990	(Peverelli & Bealu, 2018a)
	Cementitious screed	0.156	0	0.156	(Institut Bauen und Umwelt e.V., 2016)

Scope – level of quality of the data and reflection

As for the level of quality of the data used it is assumed that the data will be reliable since multiple sources are gathered and compared. The fact that not just one source is used gives a less specific but more reliable outcome. A quality review of the analysis is useful since small errors can easily influence the results, also there might be biases. Optionally a sensitivity analysis can be performed after the calculations are made.

Benchmarking results

To benchmark the results the outcomes of the study are be compared to the carbon footprint of earlier analysis found in literature. Additionally the SCORS rating (Arnold et al., 2020) scheme can be used to determine how the analysed structural designs perform compared to the industry standards. Also, the outcomes will be compared to the required limit values to the embodied carbon per m^2 to reach the targets from the Paris agreement (Spitsbaard & van leeuwen, 2021). Finally, a comparison will be made to the research by Liang et al. (2020).

Emission costs

To determine the total carbon emission costs a price must be determined per kg emitted CO_2. This section discusses how this price can be determined.

CO_2 taxes

Currently there are regulations in the Netherlands that impose a maximum amount of CO_2 emissions for industries and demand a higher tax for the CO_2 that is emitted above the limit. In 2022, the tax for one tonne of CO_2 is €41.75, which is equal to €0.04 per kg of CO_2 that is emitted. This CO_2 price will increase yearly and in 2030 the price for one kg of CO_2 will be €0.127 (Nederlandse Emissieautoriteit, 2020).

CO_2 prices on the European market

The price for CO_2 emissions on the emission trading market is not predefined. In Figure 14, the development of the CO_2 price in the European emission trading can be found. In March 2022, the price for 1 kg of CO_2 was around €0.08/ kg-CO_2eq (Beunderman, 2021). This price gives an indication of possibly realistic emission prices in the future.

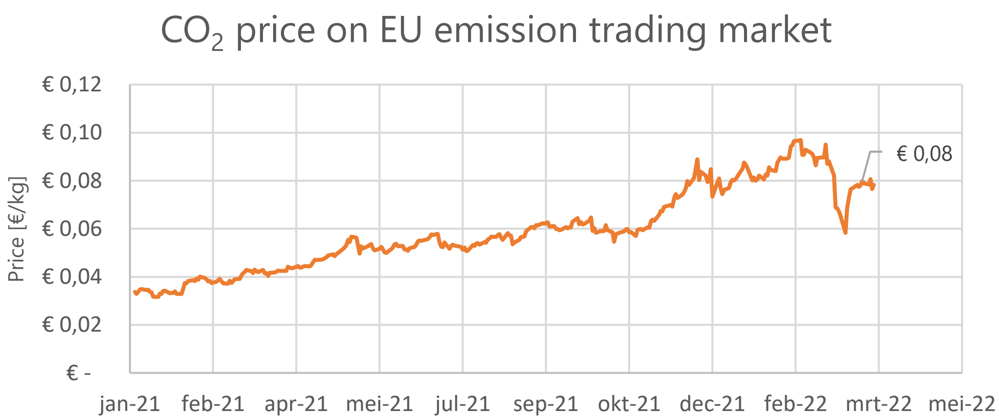


Figure 14: CO_2 prices on the European trading market. Adapted from Carbon price viewer, by Ember (https://ember-climate.org/data/carbon-price-viewer/)

CO_2 prices in this research

The CO_2 emission price is one of the conditions that can make timber competitive with concrete. Therefore, this research will study the influence of various CO_2 prices. For the analysis in the case study and in the parameter study the CO_2 price for which the potential profit of the concrete and timbe variant is equal is determined. This gives an indication of the competitiveness of timber. These prices will be compared to the current CO_2 taxes and the CO_2 price on the European emission trading market.

4.5 Conclusions

The competitiveness of the structural designs in this thesis is determined by comparing the potential profit. The potential profit is determined by subtracting the total building costs and the carbon emission costs from the project revenue.

Revenue

For the project revenue a distinction is made between the revenue of owner-occupied homes and social rental homes. The assumed revenue for *De Scharnier* is based on information provided by Heijmans. For the parameter study the revenue for the free-market sector is based on the average revenue of the 20 largest municipalities of the Netherlands. The revenue of the social rental homes is based on the maximum rent of a social renal house and the gross initial yield. Because there are studies showing that sustainable real estate has more value, the potential effect of 0%, 2% and 4% additional revenue for buildings with a timber structure is investigated.

Total building costs

The method that is used to estimate the total building costs follows the classification from NEN 2699 (Koninklijk Nederlands Normalisatie Instituut, 2017). The cost estimation of this thesis is made on the level of the element clusters and the developer of the building is assumed to be the cost actor. For each rubric it was decided if the costs are influenced by the structural material directly, if costs should be included but are independent of the structural material, or it the costs are outside of the scope of this research. Figure 10 provides an overview. The costs in the element cluster that are directly dependent on the structural material are estimated based on the design of the elements. The costs that are independent of the structural material are included as a percentage of the total construction and general execution costs. The cost outside of the scope are excluded from the calculation. For this research *IGG Bouweconomie* acts as an advisor to help determine the costs for the elements.

Carbon emission costs

The carbon emission costs are calculated by multiplying the total CO_2 emissions of a building strucutre with the costs per kg CO_2. The total CO_2 emissions are determined using the LCA method. For this thesis this goal is to determine the CO_2 emissions of a specific structural building design to determine the emission costs. For the functional unit requirements regarding variable loads, fire resistance, acoustic performance and vibrations are established. The system boundaries are life cycle stages A1-3 for this thesis. The LCA methodology that is used only includes the categories regarding climate change since this the focus of this thesis. The results express the global warming potential (GWP) of the buildings structure in kg-CO_2eq/m^2, the stored carbon in timber elements will be made explicitly visible. The inventory data that is used comes from environmental product declarations directly or from the data provided by one click LCA. For each product the most likely value is determined but also a lower and an upper bound value are considered.

The price per kg CO_2 not fixed but used as a variable in the calculation of the potential profit. Because the CO_2 emission price is one of the conditions that can make timber competitive with concrete this research will study the influence of various CO_2 prices. These prices are compared to the current CO_2 taxes and the CO_2 price on the European emission trading market.

Recap part 1

In part one of this research the problem context is explored and the method which is used to determine the competitiveness of a building structure is explained.

To mitigate the current climate change a strong reduction of CO_2 emissions is needed (IPCC, 2021). The construction sector contributes around 38% of the total global emissions (United Nation Environment Programme, 2020). Within the building sector the operational energy causes the largest part of the CO_2 emissions. However, the contribution of the embodied energy (which can also be named the carbon footprint) is gaining significance because the operational energy is being reduced. When the individual building parts are considered research shows that the super- and sub- structure are responsible for the largest part (48% - 67%) of a buildings total embodied carbon (LETI, 2020). This thesis focusses on reducing these carbon emissions by using structural timber as a mitigation strategy.

Currently concrete is responsible for almost half the construction material volume that is produced. The popularity of concrete can be explained by the tradition and experience in concrete, the local availability of the materials, the relatively low costs and the acoustic insulation capacity and fire resistance. However, the large amount of CO_2 emissions during the production of concrete is a large disadvantage. Other disadvantages are that the resources will only be finitely available, the heavy foundations that are required, the heavy transport and the relatively long construction time. The possibility to reduce carbon emissions is an important motivation for constructing in timber. Multiple studies show that the carbon footprint of buildings with a timber structure is significantly lower than for concrete structures. Also, timber is a renewable material, it required lightweight foundations and the construction time can be reduced. Current issues with timber are the limited experience, the (assumed) high building costs, the need for additional measures to comply with the regulations regarding acoustics, fire, and vibrations. Also, the carbon storage capacity of timber is currently undervalued.

The competitiveness of two structural building designs can be compared by estimating the difference in potential profit. The potential profit is determined by subtracting the total building costs and the carbon emission costs from the project revenue.

The project revenue is estimated using input from industry experts and analysing the average revenues in the Netherlands. Additionally, the influence of an additional revenue of 0%, 2% and 4% for timber structures is investigated. The total building costs are estimated using the classification of NEN2699 and advise from *IGG Bouweconomie*. For each rubric it was decided if the costs are influenced by the structural material directly, if costs should be included but are independent of the structural material, or it the costs are outside of the scope of this research. The carbon emission costs are determined by multiplying the total CO_2 emissions with a price per kg CO_2 that is emitted. The CO_2 emissions are determined using the LCA method. The stages A1-3 are considered, the stored carbon in timber is made explicitly visible, only the impact category global warming potential is considered, and the impact data comes from EPDs directly and includes a low, mean, and high impact value. The price per kg CO_2 not fixed but used as a variable in the calculation of the potential profit.

Part 2: Qualification phase

The qualification phase aims to qualify the conditions under which timber as a structural building material can be competitive with concrete in the Netherlands. The aim is to give an overview of the possibilities regarding timber structures and to identify which applications of timber have the potential to be used more often. First the building types of which reducing the CO_2 emissions will have a large influence on the total CO_2 emissions are identified Thereafter, an overview of possible applications of structural timber is given. Thirdly, research into constructed timber buildings is performed. Finally, a case study is described in which a timber, a hybrid, and a concrete design variant are compared.

5 Carbon impact per building function

For which building function would reducing the CO_2 emissions have the largest impact on the reduction of emissions of the whole building industry?

To define which building functions are most relevant to investigate, two main aspects are considered. First the average emissions of various building uses are analysed to identify where a decrease of carbon emissions would be most effective. Thereafter, an investigation is done into demands on the Dutch building market. Finally, additional arguments for the research focus are discussed.

5.1 Carbon emissions per building function

To determine which building types would benefit most from reducing the embodied carbon, research was done into the average embodied carbon for the most common building functions. There are multiple studies performed into this subject, the most relevant studies are discussed. In Appendix F more studies regarding the carbon emissions per building function can be found.

A database of embodied quantity outputs (DEQO) was developed by C. de Wolf with the goal to benchmark the embodied carbon of building structures. This database contains data from recently published LCA's, collected structural material quantities from globally leading structural design firms, and has an interactive online interface to enable users to input their projects into the growing database (De Wolf et al., 2020). The interactive interface also allows the user to sort the data by various categories, and thus compare the average embodied carbon of multiple building functions. Figure 15 shows the range of collected embodied carbon (GWP) for various functions measured in kg-CO_2eq/m^2. Some program categories contain only a few cases which makes it difficult to identify the accuracy of these results. Besides that, there is a large difference between the minimum and maximum within each building function.

In Table 11 a list of the medians of the GWP of is shown (de Wolf et al., 2021). This list shows that the medians of most residential building types are smaller than those of other building programs.

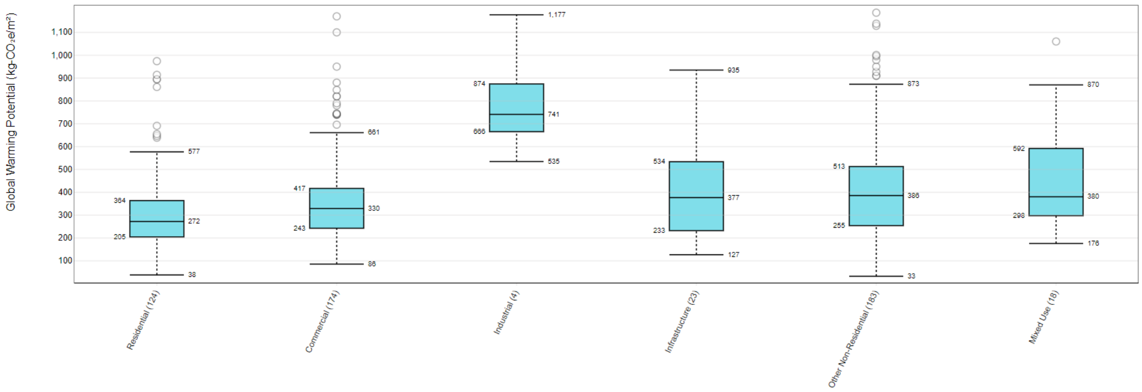


Figure 15: Embodied carbon per program category. Adapted from "Database of Embodied Quantity Outputs: Lowering Material Impacts Through Engineering," by de Wolf et al., 2020, Journal of Architectural Engineering, 26(3), (10.1061/(asce)ae.1943-5568.0000408)

Table 11: Median GWP per building program. Adapted from deQo database of embodied Quantity outputs, by de Wolf et al., 2021 (https://www.carbondeqo.com/database/graph)

Building program	**Median GWP [kg-CO$_2$eq/m^2]**
Multifamily low rise < 5 storeys (9)	159
Multifamily mid rise 6 - 15 storeys (23)	168
Civic building (11)	240
Multifamily high rise > 15 storeys (13)	257
Single family (77)	277
Office (169)	329
Hotel (6)	356
Sports (23)	377
Healthcare (52)	378
Residential/ Office/ Retail (18)	380
Educational (87)	389
Cultural (18)	418

A study performed by Simonen et al. (2017) aimed to benchmark the embodied carbon of buildings. This research focussed on the embodied carbon of life cycle stage A. This study compiled private LCA datasets, publicly accessible datasets and published embodied carbon reports. The results of this study are presented in Figure 16. The results are similar to those of de Wolf et al. (2021) but the figure gives additional information regarding the number of storeys.

A comparison of the medians of the study by Simonen et al. (2017) in Table 12 shows again only small differences between the different building functions. However, the difference between the medians of single-family and multi-family uses is quite large (245 kg-CO$_2$eq/m^2). What also stands out is that in the research by de Wolf et al. (2021) median for the embodied carbon for single-family uses was higher than for multi-family uses while the research by Simonen et al. (2017) shows the opposite.

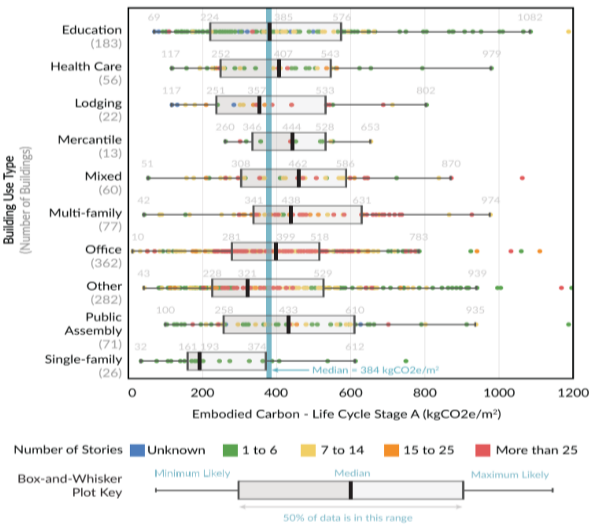


Figure 16: Embodied carbon per building use type. From "Benchmarking the Embodied Carbon of Buildings," by K. Simonen et al., 2017, Technology Architecture and design, 1(2), p.212 (10.1080/24751448.2017.1354623).

Table 12: Median embodied carbon per building use type. Adapted from "Benchmarking the Embodied Carbon of Buildings," by K. Simonen et al., 2017, Technology Architecture and design, 1(2), p.212 (10.1080/24751448.2017.1354623).

Building use type	Median embodied carbon stage A [kg-CO_2eq/m^2]
Single-family (26)	193
Other (282)	321
Lodging (22)	357
Education (183)	385
Office (362)	399
Healthcare (56)	407
Public assembly (71)	433
Multi-family (77)	438
Mercantile (13)	444
Mixed (60)	462

A research by Luijks et al. (2021) investigated the difference in CO_2 equivalent emissions between a timber frame structure and a concrete or limestone structure for four types of residential buildings in a study of 69 000 residences in the Netherlands. As is visible in Table 13 the emissions for apartments are higher than for the other types of residential buildings, for both timber frame structures as for concrete and limestone structures. This is in accordance with the research of Simonen et al. (2017).

Table 13: Average CO_2 emissions for residential buildings not including CO_2 storage. Adapted from "Rapportage woningbouw in hout" by T. Luijks et al., 2021, Centrum hout, p. 23.

	Timber frame structure [kg-CO_2eq/m^2]	Concrete or limestone structure [kg-CO_2eq/m^2]	Gross floor area [m^2]
Rowhouses	307	396	146
Semi-detached houses	311	438	180
Detached houses	306	404	264
Apartments	336	447	77

Apart from the higher emissions for industrial buildings, no single building use with significantly higher emissions per square meter than others are found in the analysis of greenhouse gas emissions per building function. The data from different sources is somewhat contradicting and the variation between the minimum and maximum results is large. This indicates that the embodied carbon of a building structure is highly dependent on the specific project and the design decisions.

5.2 Current demands for buildings in the Netherlands

This section goes into the current building stock of the Netherlands, the functions of newly constructed buildings and other trends on the Dutch building market.

Current building stock

When considering the current building stock in the Netherlands the preliminary figures of the CBS (2021) show that in July 2021 87.3% of all buildings were residential buildings. The non-residential buildings made up the remaining 12.7% and included the following building functions: meeting, detention, healthcare, industry, office, lodging, education, sports, shopping, other uses, and mixed use. A research by PICO, a cooperation of six consortium partners (2006) found that 85% of the buildings registered in the municipalities base administration (BAG) were residential buildings, which is similar to the numbers of the CBS. From these residential buildings in the Netherlands, in 2015 15% consisted of apartments, 42.5% of rowhouses, 19.6% of semi-detached houses and 23% of detached houses (CBS, 2016). This indicates that 85% of the residential buildings are ground-level homes which is 74% of the total building stock, while the remaining 15% are multistorey buildings which is 13% of the total building stock. This is almost equal to all remaining non-residential buildings which make up 12.7% of the total building stock.

Newly constructed buildings

In Figure 17 the newly constructed buildings between 2012 and 2020 are shown (CBS, 2021b). Although the percentage of non-residential buildings is increasing between 2017 and 2020, in absolute values many more residential buildings are constructed than non-residential buildings. This development over the past years indicates that it can be expected that in the coming years most of the newly constructed buildings will have a residential function.

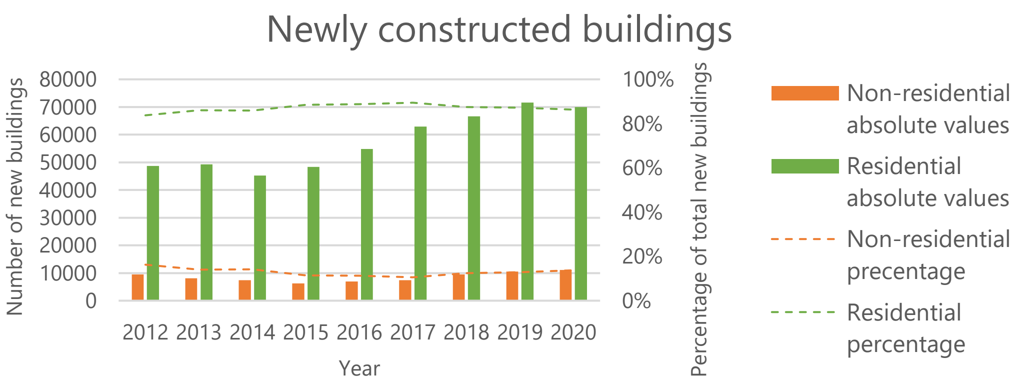


Figure 17: Newly constructed buildings. Adapted from "Voorraad woningen en niet-woningen; mutaties, gebruiksfunctie, regio" by CBS, 2021(https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81955NED/table?fromstatweb).

When the newly constructed non-residential buildings between 2012 and 2020 are further investigated, an increase in industry buildings is clearly visible (CBS, 2021b). Figure 18 also shows that there are no other building functions that are constructed in large quantities.

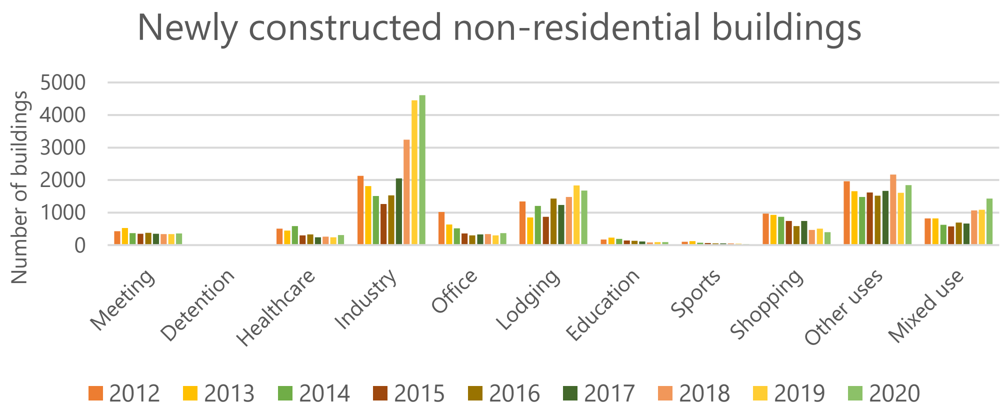


Figure 18: Newly constructed non-residential buildings. Adapted from "Voorraad woningen en niet-woningen; mutaties, gebruiksfunctie, regio" by CBS, 2021(https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81955NED/table?fromstatweb).

Research by the economical bureau of the Dutch bank ING expects an increase in the production of the building industry of 2.0% in 2022. In Figure 19 the volume developments of the building sector in percentages year to year are given. The expectation is that in 2022 there will be a 3% increase in the production of residential and commercial buildings (van Sante, 2021).

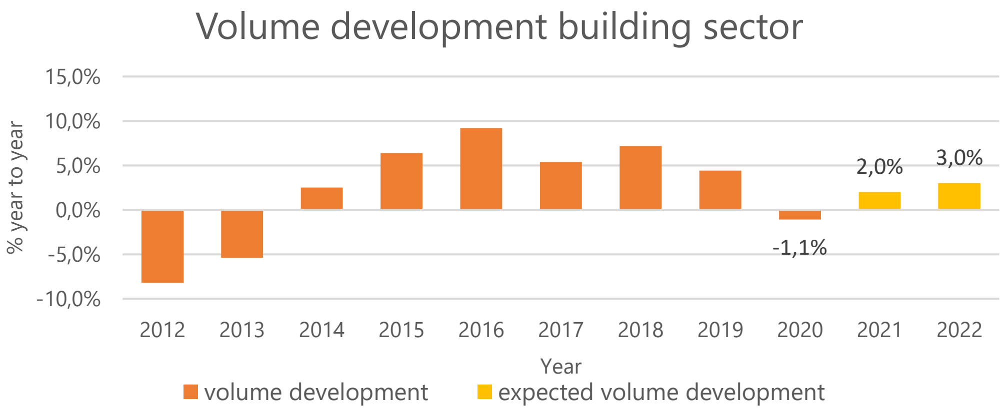


Figure 19: Volume development building sector. Adapted from In 2020 groeit de bouwproductie weer na twee jaar van licht krimp, by M. van Sante, 2021 (https://www.ing.nl/zakelijk/kennis-over-de-economie/uw-sector/outlook/bouw.html)

Koenraadt et al. (2021) argue that the production growth in the buildings sector before 2020 was mainly due to the production growth of residential and utility buildings. In the utility building sector, there was an increase in the demand for distribution centres. However, the construction of new offices did not grow as much, only at larger cities there was a demand for offices. The current housing shortage in the Netherlands is at 315000 houses, this indicates a large demand for residential buildings. Therefore, the production of residential buildings must increase, preferably to 100000 houses per year. In another article Koenraadt & Smit (2021) argue that building biobased will be the future of the building industry, which implies the expectation of more timber structures in the future.

Urbanisation trends

While most of the residential buildings are ground-level homes, this might change in the future if the urbanisation trends continue. As illustrated in Figure 20, the percentage of the total Dutch population the lived in urban area's has grown from 87% to 92% between 2010 and 2020 (O'Neill, 2021), this growth is expected to continue.

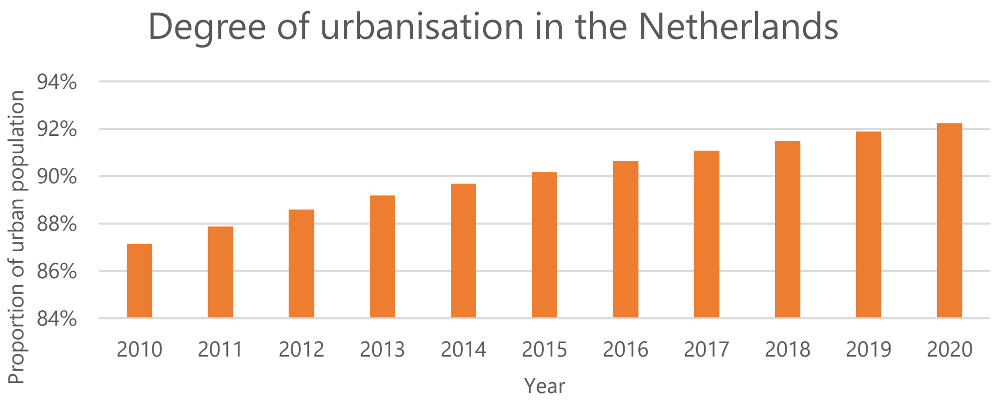


Figure 20: Degree of urbanisation in the Netherlands. Adapted from: Urbanization in the Netherlands 2020, by A. O'Neill, 2021 (https://www.statista.com/statistics/276724/urbanization-in-the-netherlands/)

This urbanisation trend most likely is the cause for the increase of constructed and planned high rise buildings (Faber et al., 2020). Additionally, the governmental advisor for the physical living environment (Dutch: Rijksadviseur voor de fysieke leefomgeving), Daan Zandbelt, argues that there is a lot of potential for mid-rise to reach the climate goals and the goals for the urban living environment (Janse, 2019). Both these developments show that research into the possibilities of constructing multi-storey residential buildings in timber is relevant.

From the research into the current building stock and recently constructed buildings, it is concluded that most of the newly constructed buildings will be residential buildings. The urbanization trends will most likely cause an increase in the demands for high-rise and mid-rise buildings. Because of the large demand for these typologies, reducing the carbon emissions of these building typologies will have a large impact on the total carbon emissions of the construction industry.

5.3 Additional arguments

For ground-level homes it can be argued that using a timber frame structure is already competitive. Many homes in America use this construction type. Also, in the Netherlands timber frame structures are in use for some ground-level residential buildings and it could be competitive to use this more often (Lubbers, n.d.). Various examples can be found of constructed timber frame residential buildings in the Netherlands with a viable business case, like Fumerus in Sneek (Lustenhouwer & Georgius, 2019).

> *"I think that people recognise that for single-storey, one-to-two storey family homes that a timber frame building is ultra-competitive and works extremely well" Supplier" (Kremer & Symmons, 2018, p. 3)*

Investigating the competitiveness of timber structures for multi-storey buildings is more relevant because high-rise and mid-rise buildings in timber are currently increasing in popularity (Hough, 2019). Also, engineered wood products (EWP's) are upcoming and have the potential to be used more frequently. These EWP's have higher strength and stiffness properties than solid timber and can be manufactured into large dimensions. This creates the potential for EWP's to be used for multi-storey buildings, which is especially relevant with the urbanisation trend and housing shortage.

5.4 Conclusions

When the embodied carbon of various building functions is analysed, the findings are that the variation between the minimum and maximum embodied carbon for the same building use can be very large. This indicates that the embodied carbon of a building structure is highly dependent on the specific project and the design decisions. Also, no single building function with significantly higher carbon emissions than other functions is found.

The research into the Dutch building market shows that most of the current building stock consists of residential buildings (87.3%). From these residential buildings in the Netherlands in 2015, 15% consisted of apartments (multi-storey), and the remaining 85% were ground-level homes. When the newly constructed buildings between 2012 and 2020 are considered, again most of the buildings are used for residential purposes. Because of the current housing shortage of 315000 houses and the urbanisation trends, the expectation is that the demands for multi-storey residential buildings will increase.

Additionally, it is argued that ground-level homes in timber can already be competitive if a timber frame structure with solid timber is used. On the other side, EWPs are upcoming and can be used for multi-storey buildings because they have various advantages over solid timber.

It is concluded that reducing the CO_2 emissions for multi-storey residential buildings has the largest impact on the reduction of emissions of the whole building industry. Therefore, the research focus of this thesis is on multi-storey residential buildings in the Netherlands.

6 Structural applications of timber

What are the properties of the most common structural timber elements and which applications are suitable for multi storey residential buildings?

To identify how and where timber can be competitive with common construction materials, it is important to investigate its structural possibilities and limitations. In chapter 3.4, the general benefits of using timber are described. This chapter focusses on the structural aspects of timber and various engineered timber materials and timber floor systems. In Appendix G an overview of the structural properties is given.

6.1 Structural timber elements

Unlike steel and concrete, timber is anisotropic, which means that its properties are different when stress is applied in different directions. Wood is an organic material and the orientation of the cell walls and the elongated structure of the cells influences the behaviour of the material (Sandhaas & Blaß, 2017). When using structural timber, the assumption is made that wood is orthotropic and has directional properties in three perpendicular axes. These directions are aligned with the grain (L), radial (R) and tangential (T), as is shown in Figure 21. When defining the properties of timber, the strength and stiffness in radial (R) and tangential (T) direction are assumed to be similar and are therefore both described as perpendicular to the grain. The properties in the longitudinal direction (L) are referred to as parallel to the grain (Porteous & Kermani, 2007).

Figure 21: Longitudinal, tangential, and radial direction of timber

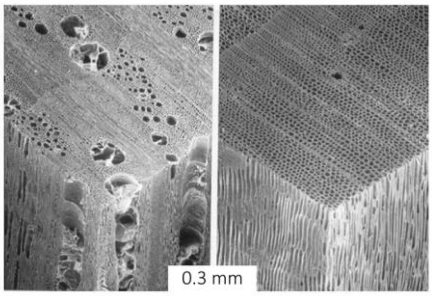


Figure 22:Microscopic structure of hardwood (right) and softwood (left). Adapted from Timber engineering, principles for design (p. 22) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

Wood species are generally divided in two main groups: hardwoods and softwoods. This division is made based on the cell structure. Hardwood has both large water-conducting cells and smaller tracheids, softwood only has only the tracheids which act as reinforcement and are used for water transport (Sandhaas & Blaß, 2017), see Figure 22. Even though hardwood often has a higher strength than softwood, softwood is more commonly used for engineered timber products. Softwood is more widely available, and the higher density of hardwood makes the bonding of the glue used for engineered timber products more complicated. For solid timber both softwood and hardwood are considered, for engineered timber products the hardwood variants are outside of the scope of this research because they are uncommon.

Because wood grows natural it’s characteristics can be diverse. This results in differences between trees but also between timber logs cut from the same stem. The slope of the grain and the presence or absence of knots influence the strength of the timber. To fully exploit the potential of timber, visual or mechanical strength grading is done (Sandhaas & Blaß, 2017). To reduce the variance in material properties of timber, different timber products can be manufactured. Additional advantages of using engineered wood products are the possibilities to create longer elements by finger-jointing timber, to take out imperfections and to produce a more homogeneous material. An overview of these products is given in Table 14, the variance declines for each row in the table. Cross laminated timber (CLT) is a variation of glued laminated timber in this table. The wood products that are named in Table 14 can be used for different structural applications.

Table 14: Wood construction products and components. Adapted from Timber engineering, principles for design (p. 99) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

Wood product	Components
Logs	Stems
Sawn timber	Squared timber, planks, boards, and battens
Glued laminated timber	Boards
Laminated veneer lumber	Veneers
Plywood	Veneers or sawn timber
Parallel strand lumber	Veneer strands
Particleboards	Particles (chips)
Fibreboards	Fibres

The analysis of constructed timber buildings, discussed in chapter 7, shows that most of the multi-storey residential buildings use solid timber, glued laminated timber (glulam), cross laminated timber (CLT) and laminated veneer lumber (LVL) or a combination of these. This chapter discusses the possible applications, strengths, and limitations of these four timber elements. Chapter 6.2 describes multiple timber floor systems.

Figure 23: from left to right, solid timber, glued laminated timber, cross laminated timber, and laminated veneer lumber

Solid timber

Solid timber is produced by sawing longitudinal logs form a tree stem after which it is kiln-dried or naturally dried. After the drying process the timber is visually, or machine graded and assigned a strength class (Sandhaas & Blaß, 2017). The strength and stiffness properties of solid timber are dependent on the type of timber, softwood, or hardwood, and on the class that it was graded in. The material properties for both softwood and hardwood can be found in Appendix G.

The dimensions of solid timber elements are dependent on the dimensions of the tree of which the elements are sawn. Therefore, there are limits to the width, thickness, and length. The width varies between 60 and 305 mm, the thickness between 12 and 145 mm and the maximum length is 5 meters (Hasslacher group, 2020). If larger elements are created the conversion and seasoning defects would increase (Porteous & Kermani, 2007). However, it is possible to finger joint solid wood to create longer elements, up to a length of sixteen meters.

Solid timber is most often used for timber frame structures, or for beams and columns with a short span or height. The application of solid timber in multi-story residential buildings is less common due to the low strength and stiffness of solid timber elements. Also, the safety factors for solid timber are high because wood is a natural material with uncertain properties. This reduces the design strength and stiffness even further. Therefore, it is concluded that solid timber is only suitable to use for buildings up to 4 storeys. The carbon emissions of softwood and hardwood solid timber can be found in Table 10 and Figure 28.

Glued laminated timber

Glued laminated timber (glulam) is produced by bonding sections of timber boards with adhesives, all components are arranged parallel to the grain. This lamination of timber has multiple advantages compared to solid timber. Longer spans are possible, larger structural heights can be reached and it allows for homogenisation of wood as a construction material. Weak parts of the timber, like knots, can be removed and the remaining parts can be finger jointed (Sandhaas & Blaß, 2017). The material properties of glulam elements differ per strength class, these properties can be found in Appendix G.

Glulam elements are typically used as structural beams and columns. The linear alignment of the grain makes that the strength in the direction of the grain is significantly higher than the strength perpendicular to the grain. Ceiling plates of glulam are also available but less common (Schneider-holz, 2021)

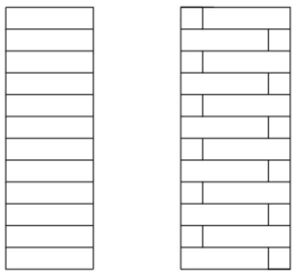


Figure 24: Section of glulam (left) and block glued glulam (right). From Timber engineering, principles for design (p.103) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

The dimensions of glulam elements can be significantly larger than those of solid timber because multiple solid timber beams are bonded together. The width varies between 60 and 300 mm, the height between 100 mm and 1 meter and the length can vary between 2.5 and 24 meters (DERIX, 2019). Even larger cross sections are possible by using block-glulam, with this technique multiple narrow glued laminated timber elements are bonded to form a single wider element (Sandhaas & Blaß, 2017), this is illustrated in Figure 24. Glulam ceiling elements have a default width of 600, 1000 or 1200 mm and a thickness between 60 and 280 mm. The length of these elements varies between 6 and 18 meters. It is also possible to manufacture curved beams, sloped beams, trusses, or free shapes using glulam, this enables longer possible spans. The lamination makes that the material is more homogeneous and the safety factors that are used are a bit lower than for solid timber. This makes glulam suitable to use in multi-storey buildings. The environmental impact of glulam can be found in Table 10 and Figure 28.

Cross laminated timber

Cross laminated timber (CLT) is produced by laminating timber boards, in contrast to glulam the planks are arranged cross wise, see Figure 25. This creates a more homogeneous material that is suitable for structural purposes. The cross wise arrangement of the timber in CLT plates enables load transfers in two directions, also this arrangement reduces the swelling and shrinkage behaviour. An advantage of CLT is the possibility to create large slab elements. The material properties of CLT depend on the grade and sort of timber that was used and the number of layers that are laminated, these properties can be found in Appendix G.

The maximum dimensions of CLT plates differ per producer, Gustafsson et al. (2019) describe the available thickness to be between 60 and 500 mm, the maximum available width to be 4.5 metres and the maximum length to be 25 meters. When CLT is used to produce prefabricated elements, the transportation often limits the element sizes. Because CLT elements can transfer loads in two directions and because it is possible to produce large slabs, CLT is most often used for structural floors and load bearing walls. The advised maximum span of CLT floor elements is 6 meter but 5.4 meter is more economical (Vos et al., 2021). In Table 10 and Figure 28 the environmental impact of CLT panels is given. The cost for delivery and montage of CLT products is around €1200, -/m^3 (D. D. D. van Laar, personal communication, October 13, 2021).

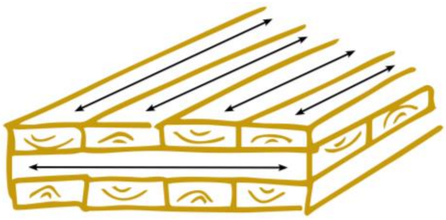


Figure 25: Grain direction CLT element, own image

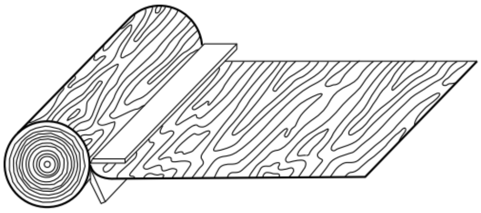


Figure 26: Schematic illustration of rotary peeling. From Timber engineering, principles for design (p.123) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

Laminated veneer lumber

Laminated veneer lumber (LVL) is produced by gluing together rotary cut veneers of approximately 3 mm thick. A schematic illustration of rotary peeling can be found in Figure 26. The fibre direction of the veneers is most often parallel to the longitudinal direction of the grain (Sandhaas & Blaß, 2017). This resembles glued laminated timber, however for LVL the layers of wood are a lot thinner, which creates a more homogeneous material. Some LVL products have crossband veneers to create a higher strength perpendicular to the grains. The material properties of LVL can be found in Appendix G.

The available material dimensions according to Metsä wood (2021) for LVL are a thickness between 21 and 75 mm, a width between 0.04 and 2.5 meters and a maximum length of 25 meters. The high strength and stiffness in longitudinal direction makes that LVL elements are suitable to be used as beams and columns of multi-storey buildings. However, if crossband veneers are used the strength in the direction perpendicular to the grain is significantly increased which makes using LVL for plate elements interesting as well. The environmental impacts of LVL can be found in Table 10 and Figure 28. The delivery and montage cost of LVL products is around €1350, -/m^3 (D. D. D. van Laar, personal communication, October 13, 2021), which is a bit higher than for CLT.

6.2 Timber floor systems

When using structural timber, there are multiple floor systems that can be used. To comply with the building regulations timber floors often need additional materials in the floor build-up. The four most common timber floor systems are described, both the benefits and the limitations are discussed.

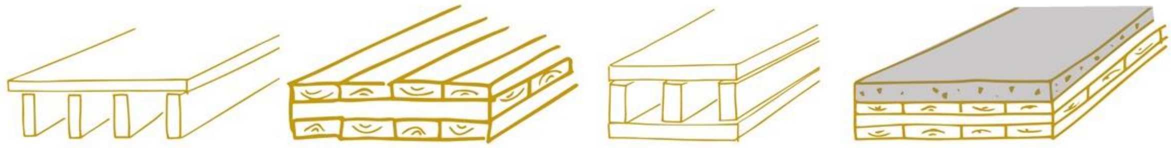


Figure 27: From left to right wooden beam layer, CLT floor, hollow core timber floor, and TCC floor

Wooden beam layer floor

A floor system with a wooden beam layer consists of timber beams which are placed with a centre-to-centre distance between 45 and 75 cm. On top of this a timber decking floor is placed and if desired a ceiling is placed underneath the beams (van Rijk, 2021). This type of flooring is common for row houses that were built around 1900 in the Netherlands, with floor spans around 4.5 meter. The structural capacity, sound insulation and fire proofing of these floors is low. Therefore, wooden beam layer floors are not commonly used for new residential buildings and are assumed to be unsuitable for multi-storey buildings.

CLT floor

As discussed before, cross laminated timber (CLT) elements are suitable to use as structural floor elements for multi-storey buildings, there are three main reasons for this. First, large dimensions can be produced which makes spanning larger distances possible and the large width of the elements increases the installation speed. Second, the floor can be designed to transfer lateral forces. Finally, loads can be transferred in two directions this makes it easier to make small openings in the floor panels without additional structural measures. However, it is not common to design CLT floors spanning the same distance in two directions. The asymmetric build-up of a CLT panel with three planks in one direction and two planks in the direction perpendicular to this, makes that one direction will always be stronger than the other direction. Therefore, it a two-way spanning slab will require larger thicknesses (Structurlam, 2016).

To comply with the regulations additional materials must be placed on top of the CLT floor because the acoustic performance of CLT only is insufficient. This acoustic insulation of can be provided by adding mass or by using an insulating material that has still air inside it, like mineral wool. Often a combination of these two insulation methods is used to ensure sound insulation for both high and low frequencies. The need for additional layers makes that that the total thickness of the floor build-up can become large, which is a disadvantage for this floor system especially if it is to be used in multi-storey buildings. The maximum floor span of CLT floors is dependent on the loading and application of the material a design guide by Structurlam (2016) suggest maximum roof spans of 12 meter and maximum spans for residential buildings to be 8 meters. Vos et al. (2021) argue that CLT floors should preferably span 5.4 metres, which reduces the design freedom of the architect is this floor system is chosen. The two main advantages of this system are the demountability and the fast build-up time.

Cassette and hollow core timber floor system

A cassette or hollow core timber floor system is build-up out of ribs with a top and a bottom plate. This leaves hollow cores within the floor that can be filled with a material that provides additional mass, with insulation materials or with cables and ducts (Gustafsson et al., 2019). This floor system can be executed in Glulam, CLT, LVL or a combination of these.

The main advantage of this floor system is the possibility to have large floor spans, up to 20 meters. However, this also results in a larger height of the structural system which is not beneficial. The structural height of the timber floor would be 200 mm for a span of 7.65 meters and 600 mm if the total span was 16.05 meters (Bogaerts, 2015). A disadvantage is that the sound insulating capacity of the cassette floor itself is insufficient and would require additional layers, which make the floor even thicker. The thickness of the total floor build-up can be reduced if some of the insulation material is placed inside the ducts. However, van Wijnen (2020) argues that the floor packet of an LVL hollow box floor is thicker compared to CLT floors. Despite the large total floor height, this floor system is suitable for multi-storey buildings.

Timber concrete composite floor systems

A timber concrete composite (TCC) floor system is a hybrid system where timber and concrete are combined. In most cases the floor consists of a CLT slab on the underside with a precast or in situ concrete slab on top. To increase the stiffness of the floor shear connections are made between the concrete and the timber (Gustafsson et al., 2019). This way both materials are optimally used, and relatively large spans can be created with a relatively thin floor. Also, horizontal loads can spread evenly across the floor and can be transferred creating diaphragm action. The maximum economical span that can be reached with a TCC floor system is 9 meter (KLH massivholz GmbH, 2019).

Like for the previous floor systems additional materials are needed to sufficient sound insulation. However, the mass of the concrete already provides some insulation which makes the build-up less thick. Therefore, TCC floors are suitable for multi-storey buildings. Unfortunately, the used concrete also increases the carbon footprint of this system, and it increases the building time required if the concrete layer is poured on site.

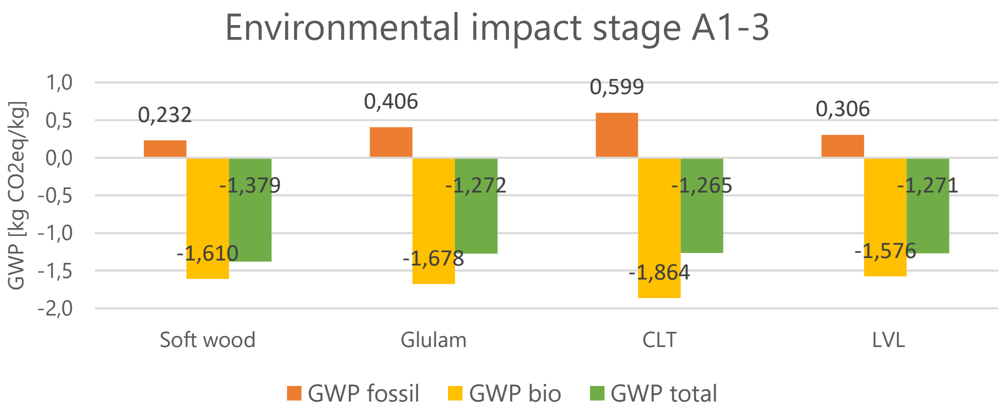


Figure 28: Environmental impacts of solid timber, glued laminated timber, cross laminated timber, and laminated veneer lumber, combined from Table 10. GWP fossil represents the emitted carbon, GWP bio represents the stored carbon, and GWP total combines these numbers including 100% carbon storage.

Table 15: Summary of the properties of solid timber, Glulam, CLT, and LVL

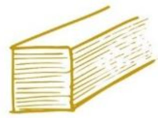
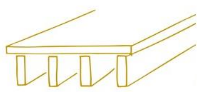
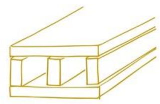
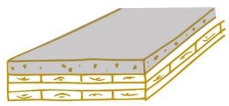
	Solid timber	**Glulam**	**CLT**	**LVL**
Production	Cutting logs from a tree stem	Gluing planks in longitudinal direction	Gluing planks in crosswise direction	Gluing veneers in longitudinal or crosswise direction
Application	Low-rise timber frame structures and short span beams	Beams and columns	Structural floor, wall, and roof plates	Beams and columns or less often structural floor, wall, and roof plates
Width	60 – 300 mm	60 – 300 mm	Max 4.5 m	0.04 – 2.5 m
Thickness	12 – 145 mm	0.1 – 1 m	60 – 500 mm	21 – 75 mm
Length	Max 5 m Max 16 m with finger jointing	Max 24 m	Max 25 m	Max 25 m
				

Table 16: Summary of the performance of wooden beam layer, CLT, cassette and TCC floors

Performance criteria	**Wooden beam layer**	**CLT floor**	**Cassette floor**	**TCC floor**
Fire resistance	- -	o	o	+
Sound insulation	- -	- -	-	o
Maximum spans	Up to 4.5 m	Up to 8 m	Up to 20 m	Up to 9 m
Floor thickness	-	-	- -	+
Installation speed	o	+ +	+	o
2-way span	no	Yes, but limited	no	Yes, but limited
Resistance of lateral forces	- -	+ +	o	+ +
Demountability	+	+ +	+ +	-
Sustainability	+ +	+ +	+ +	o
				

6.3 Conclusions

Timber is a natural and anisotropic material, which makes that the strength and stiffness are dependent on the direction of loading but also on the specific tree that is used. Engineered wood products have an increased homogeneity and a reduced variance compared to solid timber products. This makes engineered wood products suitable for the construction of multi-storey buildings. The possible applications, strengths, and limitations of four timber element types and four timber floor systems are discussed.

Solid timber elements are produced by sawing logs from a tree stem. The limitation to the sizes and the low strength of solid timber make that it is not suitable for the construction of multi-storey buildings. Solid timber elements are only suitable for beams and columns that transfer small loads. Glued laminated timber (glulam) is produced by bonding timber boards in longitudinal direction. With glulam large cross-sections can be manufactured and spans up to 18 meter can be reached. With these properties, glulam is suitable to use for beams and columns of multi-storey buildings. Cross laminated timber (CLT) has laminated planks orientated in crosswise direction, this creates a more homogeneous material that has a similar strength and stiffness in two directions. CLT slabs are suitable to use for structural walls, floors, and ceilings of multi-storey buildings. Finally, laminated veneer lumber (LVL) is produced by laminating thin veneers of approximately 3mm thick. LVL elements can have a length up to 25 meters and are most often used for beams and columns. If crossband veneers are applied LVL can be used for wall and floor elements as well. The environmental impact of these four types of timber is comparable and can be found in Table 10 and Figure 28, a summary of the four types of timber is given in Table 15.

Wooden beam layer floors are common for single storey older residential buildings. The low strength, low fire resistance and the low acoustic insulation capacity make this system not suitable for multi-storey residential buildings. CLT floors require a large build-up to ensure sufficient acoustic insulation but can be installed quick, transfer lateral loads, made demountable and the materials can be reused. This makes CLT floors suited for multi-storey buildings. Hollow core timber floors are constructed out of timber ribs with a top and bottom plate. Large spans can be reached with this system, but the system has a large height which makes it less suitable for multi-storey buildings. TCC floors structurally combine CLT with concrete, which creates a relatively thin floor that is suitable for multi-storey buildings with a better sound insulating capacity than the other three floor systems. However, the use of concrete increases the environmental impact and the building time required. A summary of the performance of these four floor types is given in Table 16, the scores presented in this table are based on the literature discussed in chapter 6.2.

7 Use of timber in practice

Which previous projects were built in timber and which design decisions were made?

In this chapter an analysis of constructed multi-storey residential timber buildings is performed. The assumption is made that the fact that the observed projects were realised, indicates that the choice for timber resulted in a building that was competitive. The analysis focusses on the aspects that can be influenced by the engineer with the goal to gain insights in common design decisions. Five possible conditions which are investigated in this chapter: the building height, the material for the vertical system, the material of the stability system, the material of the floor system and the floor span. Also, other observations are discussed and the relation between the conditions is investigated. The outcomes for these aspects are discussed in chapter 7.2, in chapter 7.3 specific cases are analysed in detail. First chapter 7.1 provides an overview of the collected information.

7.1 Constructed multi-storey timber residential buildings

A database of currently constructed timber buildings was set up by combining information from various sources (Bronsvoort et al., 2020, CTBUH Journal, 2017, Houtwereld, 2021, Kaufmann et al., 2018, Waugh Thistleton Architects, 2018). Because the amount constructed timber buildings in Europe is limited, projects outside of Europe are investigated as well. This resulted in a list of 115 buildings which used structural timber. After excluding the projects with non-residential functions and two floors or less, 77 buildings remained. This selection was narrowed down further by removing the projects with insufficient information available and the projects that did not yet started construction, which resulted in a list of 34 buildings to be analysed. The information that is used in the analysis is processed by hand and therefore prone to human errors. Also, the use of the book '100 projects CLT UK' (Waugh Thistleton Architects, 2018) as a source to find timber residential buildings might have increased the percentage of projects located in the UK and the projects constructed with CLT.

In Appendix H an overview of the gathered information of all projects can be found, a list of these 34 buildings with the most important characteristics can be found below in Table 17.

Table 17: List of gathered multi-storey residential timber buildings

	Building name	City	Country	Floors	Additional function
1	Forte Tower	Melbourne	Australia	10	Retail
2	HoHo	Vienna	Austria	24	Commercial
3	Origine	Quebec	Canada	13	Residential only
4	Arbora	Montreal	Canada	8	Residential only
5	Brock Commons	Vancouver	Canada	18	Residential only
6	C 13 Berlin	Berlin	Germany	7	Office
7	E3 Berlin	Berlin	Germany	7	Residential only
8	Velve-lindenhof	Enschede	Netherlands	3	Residential only
9	Plant-je-vlag	Nijmegen	Netherlands	3	Residential only
10	NEZZT	Purmerend	Netherlands	3	Residential only
11	Iewan	Nijmegen	Netherlands	4	Residential only

12	Patch 22	Amsterdam	Netherlands	6	Office
13	Buiksloterham Stories	Amsterdam	Netherlands	8	Office
14	Doorman	Rotterdam	Netherlands	20	Residential only
15	Haut	Amsterdam	Netherlands	21	Residential only
16	Houtbaar	-	Netherlands	3	Residential only
17	The Treet	Bergen	Norway	14	Residential only
18	Mjøstårnet	Brumunddal	Norway	18	Office + Hotel
19	Sunken Hous/ Ed's Shed	London	United Kingdom	3	Residential only
20	Cavendish Avenue	Cambridge	United Kingdom	3	Residential only
21	Woodblock House	London	United Kingdom	3	Residential only
22	Mazarin House	London	United Kingdom	4	Residential only
23	Russel street	Cambridge	United Kingdom	4	Residential only
24	Fairmule House	London	United Kingdom	5	Residential only
25	Bacton low rise	London	United Kingdom	5	Residential only
26	Barretts Grove	London	United Kingdom	5	Residential only
27	UEA Blackdale	Norfolk	United Kingdom	5	Residential only
28	Cobalt Palace	London	United Kingdom	6	Residential only
29	Whitmore Road	London	United Kingdom	7	Residential only
30	Kingsgate House	Chelsea	United Kingdom	7	Residential only
31	Stadthaus	London	United Kingdom	9	Residential only
32	The Cube Building	London	United Kingdom	10	Commercial
33	Dalston Works	London	United Kingdom	10	Commercial
34	Trafalgar Palace	London	United Kingdom	10	Residential only

7.2 Analysis all timber buildings

The analysis of currently constructed timber buildings focusses on the building height, the material for the stability, vertical and floor system, and the floor span. First all five conditions are discussed individually, thereafter the relation between the conditions is investigated and other observations are discussed. The 34 analysed projects are located all over the globe, for some aspects a specific analysis for the projects located in the Netherlands is made.

Results per condition

First the results of the investigated conditions are discussed separately.

Building height

In Figure 29 the number of storeys of all buildings in the analysis are visualised, the orange bars represent the buildings located in the Netherlands. This figure shows that only eight of the analysed projects have more than ten storeys. The remaining 27 projects all have between three and 10 levels, which shows that timber structures are more often used for mid-rise than for high rise buildings. The highest residential timber building in the Netherlands is *Haut* with 21 storeys. *HoHo* in Vienna has 24 storeys, which makes it the highest analysed building.

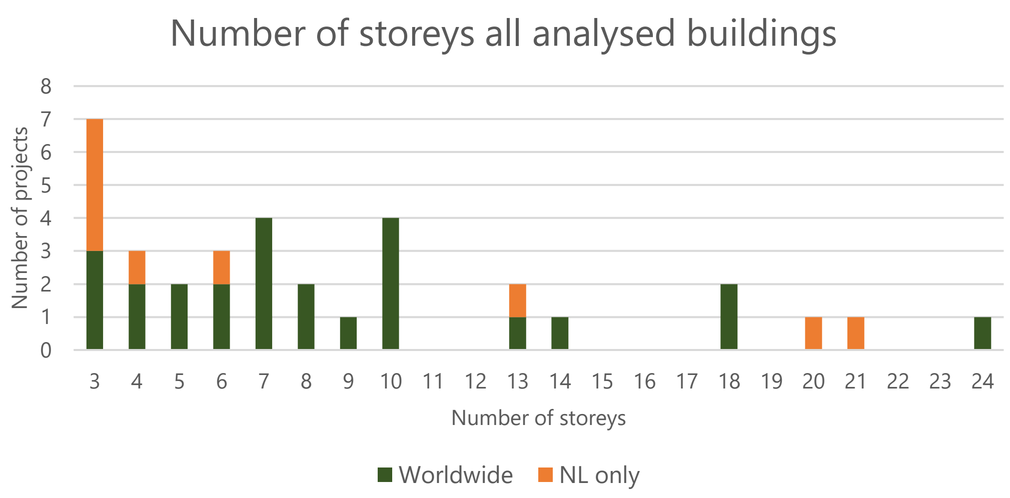


Figure 29: Number of storeys of all analysed buildings

Structural material

In Figure 30 the structural material of the projects in the analysis is categorised. From the 34 projects in the comparison 23 have a structure completely made of timber. The remaining eleven projects either combine the timber with steel, with concrete or with both steel and concrete. This figure shows that if only the projects located in the Netherlands are analysed, mare than half of the projects uses a hybrid structural system. The next sub sections discuss the structural material for the stability, vertical and floor system.

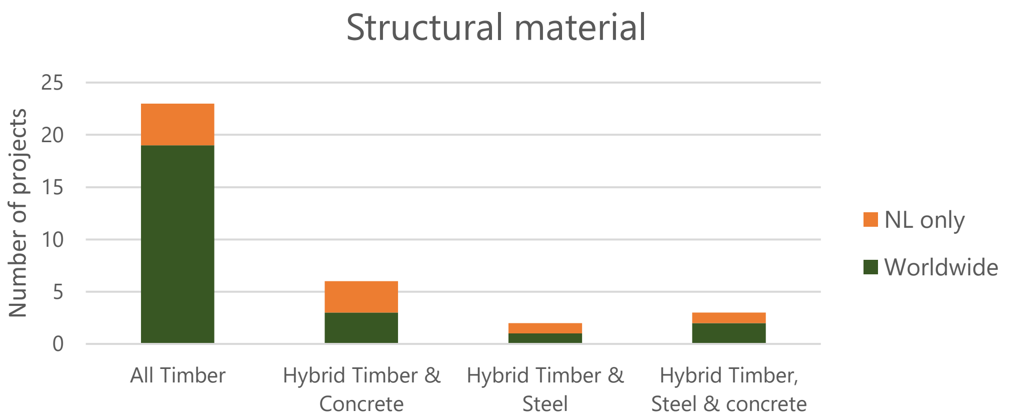


Figure 30: Structural material of all analysed buildings

Material stability system

In Figure 31 the material of the stability system of all analysed projects is presented. This shows that most of the buildings uses CLT walls to ensure stability. This figure also shows that half of the projects in the Netherlands use a concrete core.

Material vertical system

As is indicated in Figure 32, in most of the projects timber walls are used for the vertical bearing system. This also applies to the projects in the Netherlands.

Material floor system

The material of the floor system of the analysed projects is presented in Figure 33. This shows that most projects have CLT floors. However, in the Netherlands CLT and TCC both occur in 38% of the analysed projects.

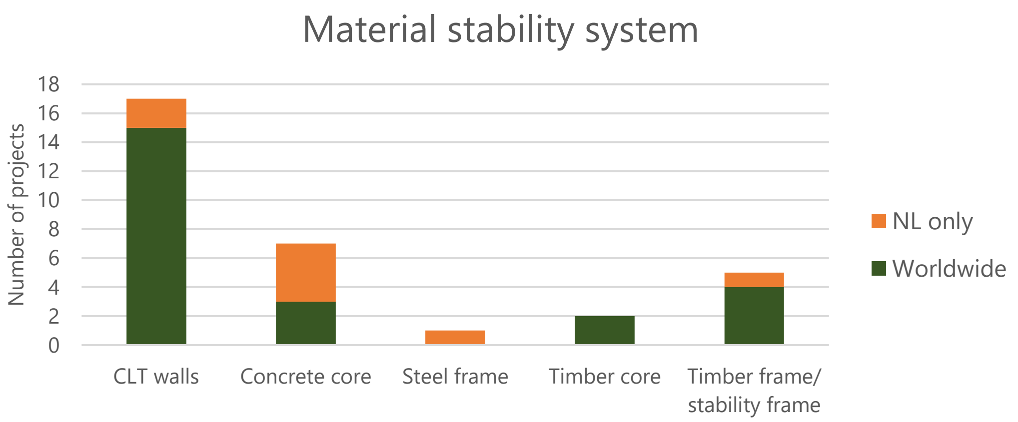


Figure 31: Material of the stability system of all analysed buildings

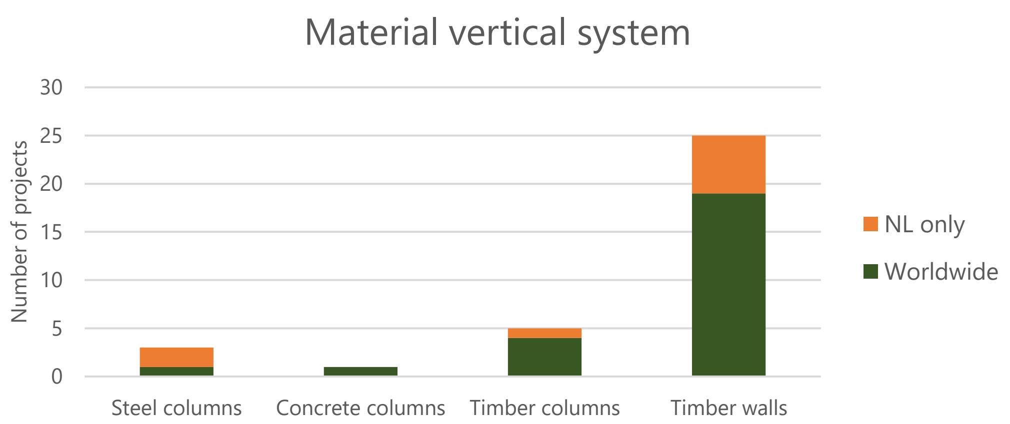


Figure 32: Material of the vertical system of all analysed buildings

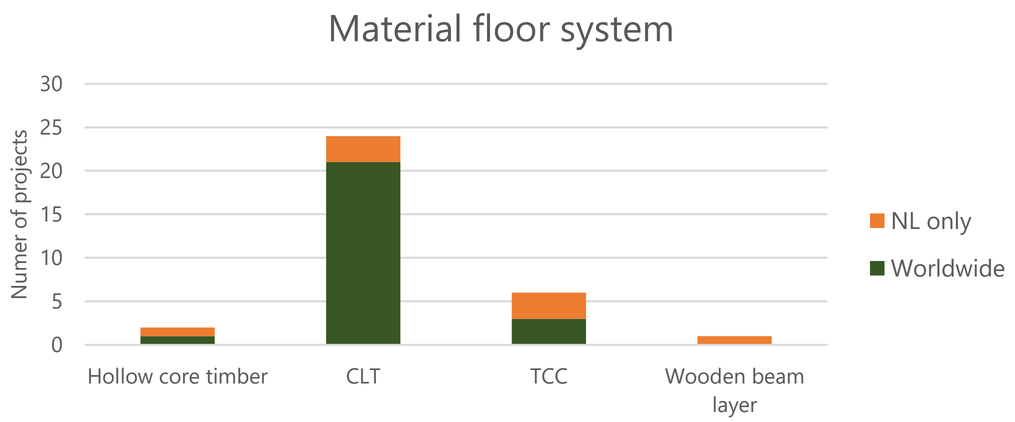


Figure 33: Material of the floor system of all analysed buildings

Floor span

Of only 15 of the 34 projects the floor span was found, these floor spans can be found in Figure 34. The floor spans of the projects in the Netherlands are presented by the orange bars. This sample shows that spans of timber floors are generally between 3 and 7 meters, with most floor spans around 5 meters. For the Netherlands the maximum span is 6 meters, which is used in *Haut*.

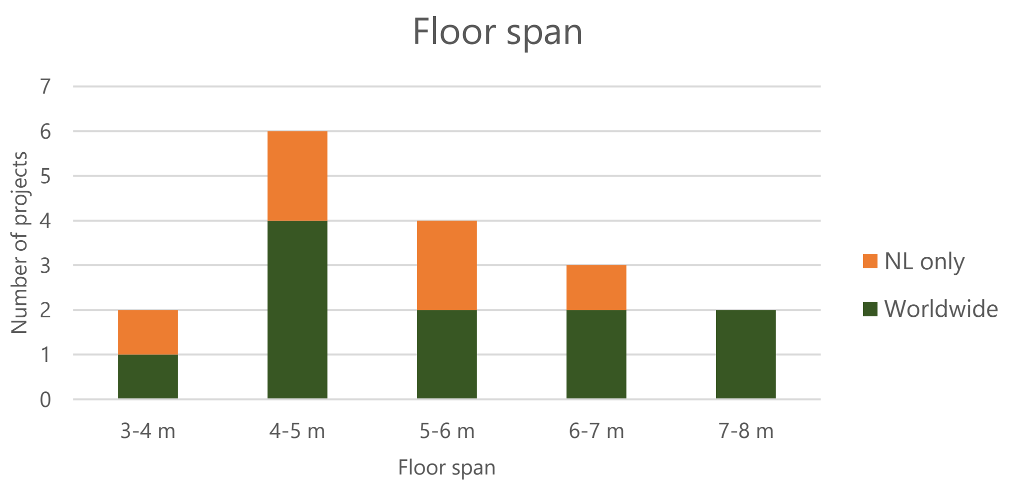


Figure 34: Floor spans in meters of all analysed buildings, projects in the Netherlands are represented by the orange bars

Relation building height and remaining conditions

In this section the relation between the building height and the remaining 4 conditions is investigated.

The structural material

Figure 35 shows that the hybrid structures are often used for the projects with a large height. The three buildings with more than ten storeys in all timber are Origine, The Treet and Mjøstårnet which are unique high-profile projects. However, it is important to note that the highest of these three buildings, Mjøstårnet, has concrete floors on the upper seven levels to help with the dynamic behaviour and the acoustics (de Groot, 2018).

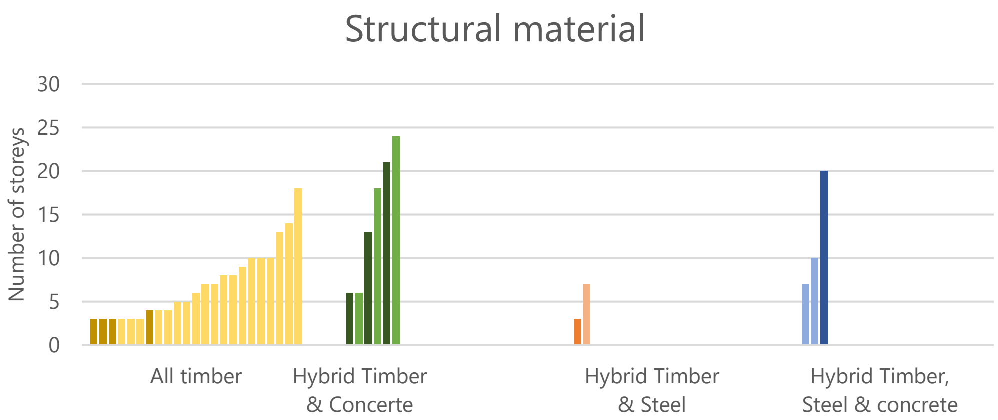


Figure 35: Number of storeys per structural materialisation, the darker colours represent the projects in NL

The darker colours in Figure 35 represent the projects located in the Netherlands. This shows that in the Netherlands the projects in all timber have a maximum height of 4 storeys. If more storeys are added a hybrid structure is used. A possible explanation for the limited height of all timber buildings can be that the rules regarding fire resistance are more strict for buildings with the top floor higher than 13 meters above ground-level (BRIS, 2011). With a floor-to-floor height of 3.5 meter, the highest floor is above 13 meter if you build five storeys or more. The strict fire safety demands can make the building industry hesitant to use timber for projects with more than four storeys. Another explanation might be the lack of experience with all timber structures in the Netherlands, the limited strength of timber or increased costs. The structural material for the stability, vertical and floor system is discussed in the next sub sections.

The chosen stability system

Figure 36 shows the stability structures of the analysed projects in relation to the number of storeys. The results correspond to the analysis of the structural material, if the building gets higher a hybrid structure with a concrete core is used more frequently. Alternative to a concrete core a timber stability frame structure can be used to transfer the wind loads for higher timber buildings. This system is used by the two highest all timber buildings currently built the Treet and Mjøstårnet. The highest building with CLT walls for stability is Origine. The darker colours represent the projects in the Netherlands. This shows that a concrete core is used if the height exceeds five storeys.

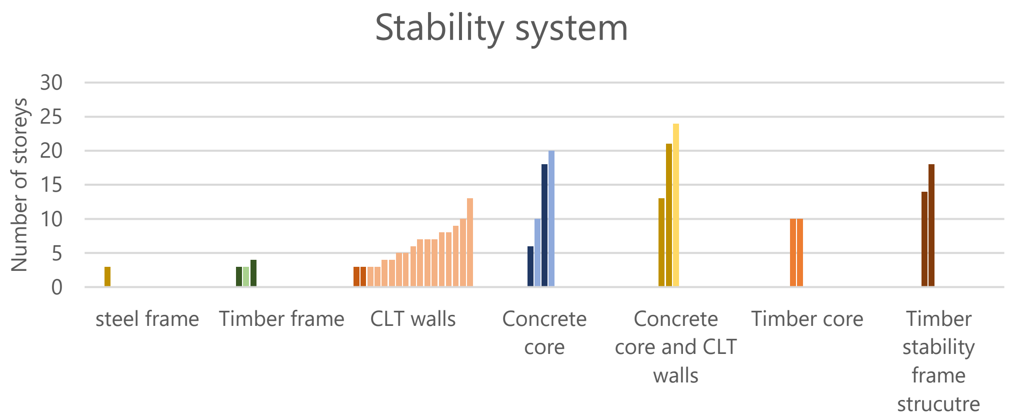


Figure 36: Number of storeys per stability system, the darker colours represent the projects in NL

The vertical load bearing system

Research into the projects vertical bearing system shows that timber walls are used for all building heights. Figure 37 shows that timber or steel columns can be used for higher buildings as well. If the building projects in the Netherlands are analysed there seems to be a preference for timber walls.

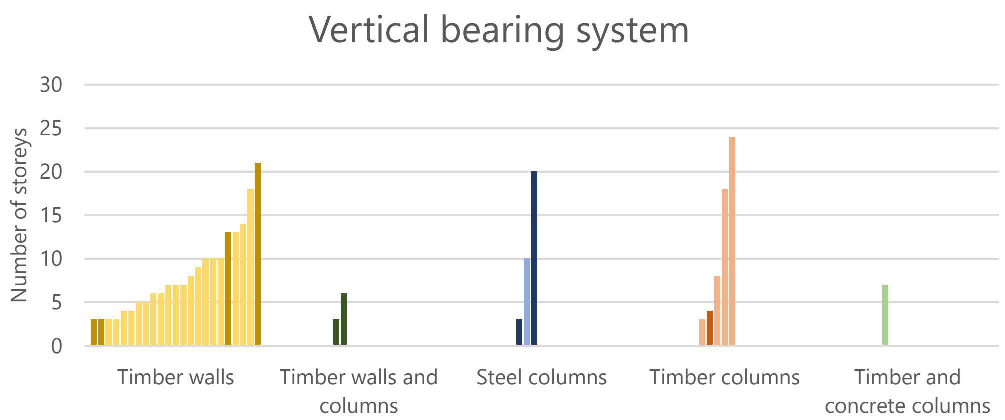


Figure 37: Vertical bearing system, the darker colours represent the projects in NL

The used floor system

The research into the floor systems of timber buildings shows that CLT floors are used up to 18 storeys. TCC floors are used for timber buildings with various heights, but this system is favourable for heights above 18 storeys. Wooden beam layer floors are only used once in the analysis for a building with 4 storeys.

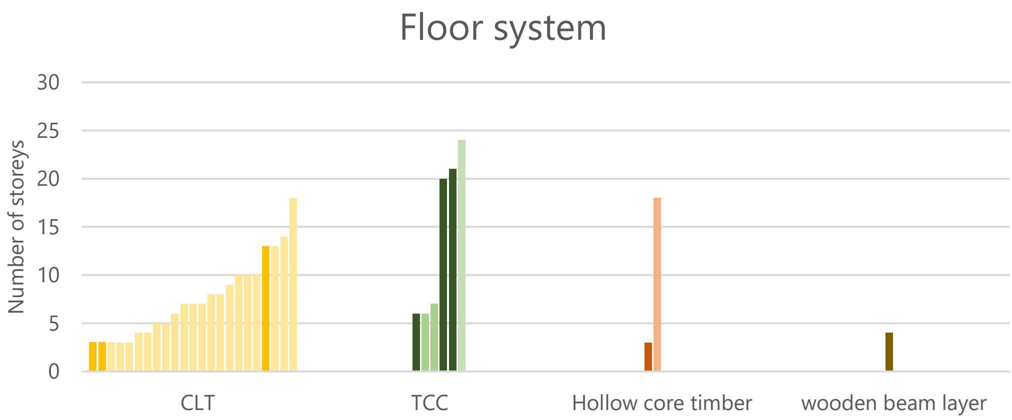


Figure 38: Floor system, the darker colours represent the projects in NL

Floor spans

In Figure 39 the height per floor span is shown, no relation between these conditions was found. It is notable that the highest two floor spans correspond to the largest building heights. HoHo has a floor span of 7 metres and a height of 84 metres and Mjøstårnet has a height of 85.4 metres and a floor span of 7.5 metres.

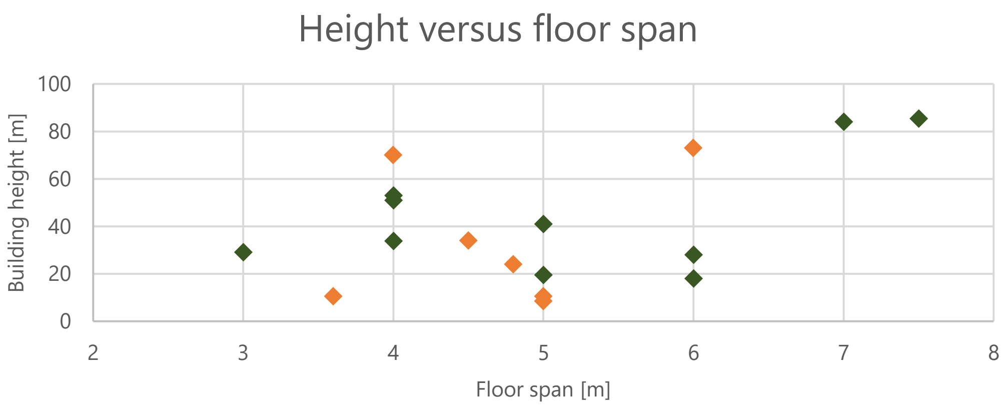


Figure 39: Relation height and floor span, the orange dots represent the projects in NL

The relation between material for the floor system and the floor span

In Figure 40 the applied floor spans of three different floor systems can be found, the darker colours represent the buildings located in the Netherlands. From the research into timber floor systems it was expected that the floor spans for TCC and casette floors would be larger than the spans of CLT floors. The CLT floors have a maximum span of 6 meters, the TCC and casette floors have a maximum span of 7 meters. However, the analysis of the constructed timber projects does not show a clear relation between the floor span and the used floor system since TCC and casette floors are also used for floors with a smaller span.

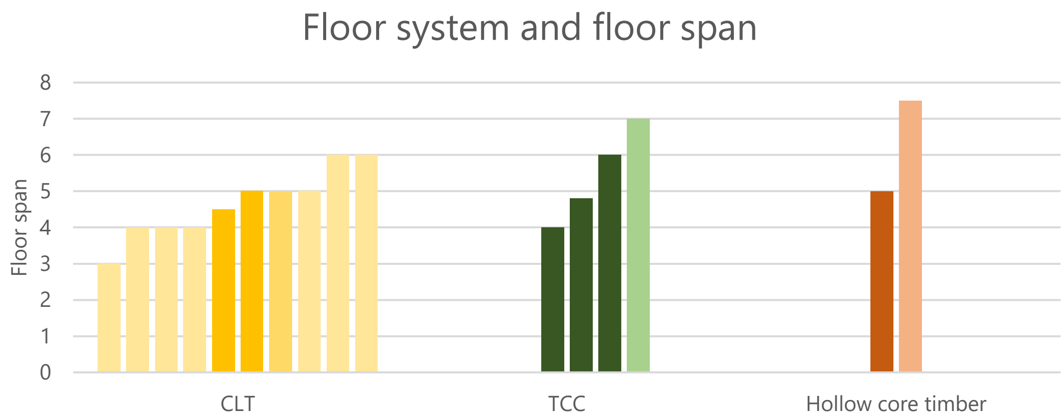


Figure 40: Floor system and floor span for all projects, the darker colours represent the projects in NL

The relation between material floor system and the vertical bearing system

Figure 41 shows that the floor span does not have a large influence on the chosen vertical bearing system. The darker colours represent the projects located in the Netherlands and the lighter colours represent the projects outside of the Netherlands. Timber walls are used for projects with spans up to 7,5 meters but there is also a project that used timber columns in combination with a 7-meter span. This shows there is a high chance that other factors have more influence on the chosen floor span than the vertical bearing system.

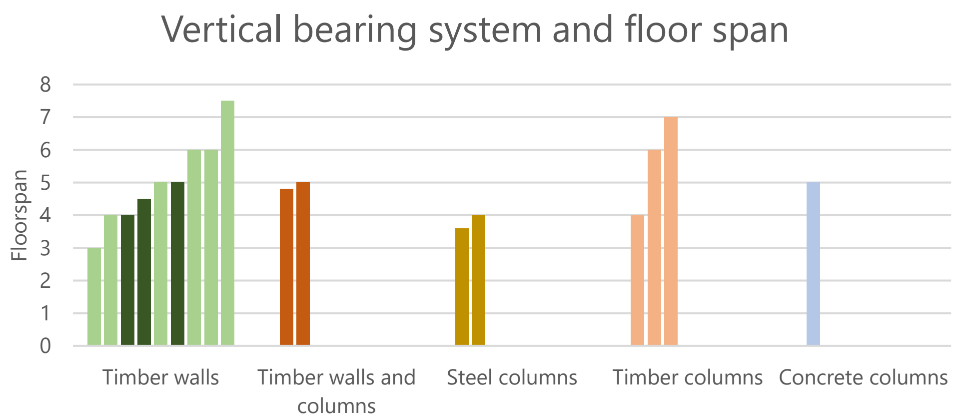


Figure 41: Vertical bearing system and floor span of all projects, the darker colours represent the projects in NL

The relation between vertical and stability system

In Figure 42 the relation between the chosen system for the vertical loads and for the stability is visualised. This indicates that the combination with CLT walls for both the vertical and stability system occurs sixteen times. While the other combinations occur in two different projects maximum. An explanation for this can be that it is efficient to use timber walls for the vertical system if they are already in place for the stability system. Timber and steel columns on the other hand can only transfer vertical loads, therefore additional measures must be taken to ensure stability.

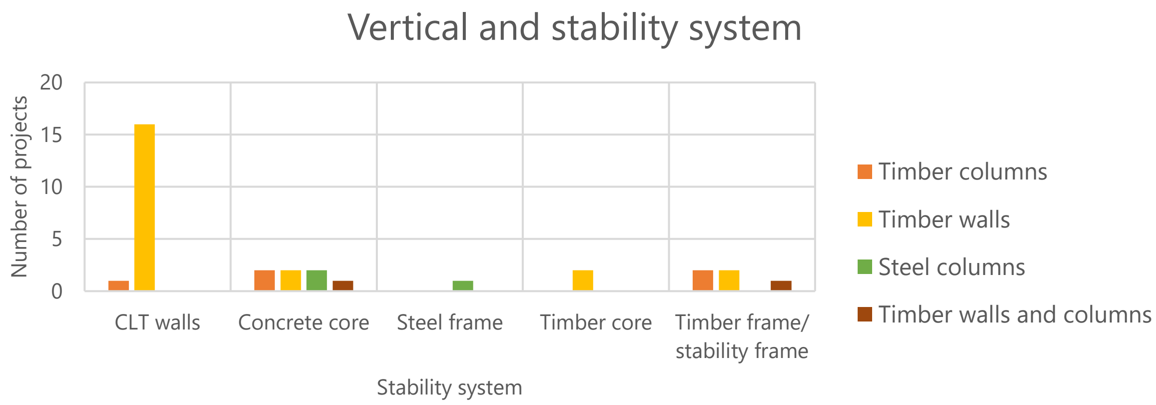


Figure 42: Relation vertical system and stability system

The relation between building height and width

As a final part of the analysis the relation between the building height and the building width is summarised in a slenderness factor. This factor is determined by dividing the building height over the building width. In this case the smallest length measured at the footprint of the building is used for the width. The relation between this slenderness and the stability system of the analysed projects is illustrated in Figure 43. This shows that projects with a core are used for more slender buildings. If the slenderness of the analysed projects becomes larger than 2.1 the CLT walls are not sufficient and a stability structure using a core or braced frame is chosen. This was expected since CLT walls need a certain width per building height to ensure sufficient stability.

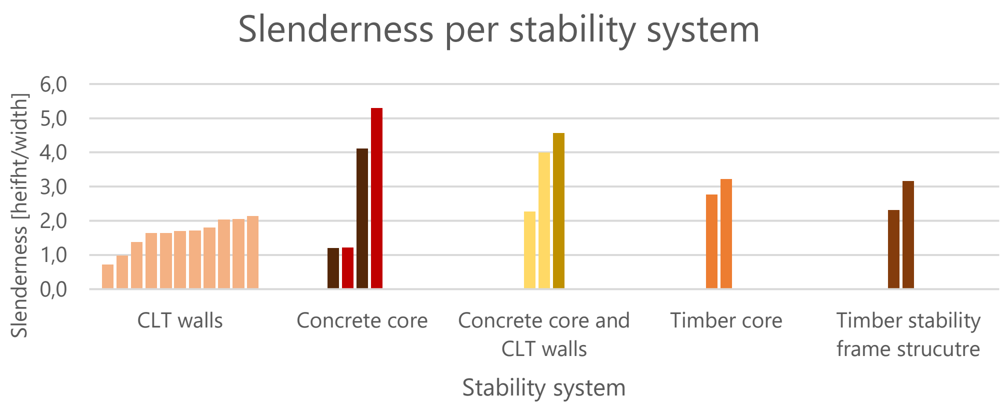


Figure 43: Slenderness per used stability system, all projects

Other observations

Besides the previously discussed analysis of the timber residential buildings, some other observations were made. The first thing that stood out is that 60% of the analysed timber buildings have a concrete plinth. In some cases, the ground floor also has a different function, like a commercial or other public function. A concrete plinth makes it possible to create larger free spans which is favourable for these functions. Also, a concrete plinth is chosen more frequently for higher buildings. Secondly it was observed that only 15% of the analysed buildings used a modular structural system. While there are various advantages to prefabricating elements, it appears that modular systems are not yet used on a large scale for residential buildings. However, prefabrication of timber floor and wall elements was used for almost all projects that were analysed. Finally, it is important to note that while all projects are assumed to be competitive because they were built, some projects were extremely costly. The fact that there are two realised buildings with 14 levels or more that use a timber stability frame structure, does not indicate that this is less costly than any other stability structures. However, since both projects are high-end and unique it might have been more profitable than using a concrete structure. Unfortunately, only very limited information regarding the costs and revenues was found, therefore the costs are not included in this analysis.

7.3 Analysis specific cases

For an in-depth analysis, the two projects *Haut* and *Buiksloterham Stories* were selected from the database. These projects are selected because they are both located in the Netherlands and present different choices in structural material, height, and floor span. The characteristics and the design decisions of the projects are discussed in this section.

Figure 44: Impression Haut. From Haut, by Team V Architectuur, 2021 (https://teamv.nl/projecten/haut/).

Figure 45: Impression Buiksloterham stories. From BSH20A 'Stories', by Olaf Gipser Architects, 2021 (https://olafgipser.com/projects/residential-building-bsh/#1).

Haut

Haut is located next to the Amstel in Amsterdam and will be the highest residential timber building in the Netherlands once finished. The tower has 21 storeys, is 73 meters tall and contains 14500 m^2 of residential area. The main reason for using mass timber was the high sustainability ambition of the project. According to Verhaegh et al. (2020) the design decisions were influenced by the height of the building, its residential function and the conscious decision to use mass timber as much as possible.

The stability of the building is ensured by a concrete core and two CLT walls, which help in resisting torsional forces. The concrete core provides sufficient strength in the ultimate limit state, therefore the CLT walls are only relied on in the serviceability limit state. This stability system was chosen because it leaves the façades unobstructed and because the mass of the core reduces the wind induced vibrations. An alternative stability system using a steel braced frame and timber wall was explored as well. Ultimately the design with a concrete core was more sustainable and more feasible (Verhaegh et al., 2020). The location of the core and the CLT walls is illustrated in Figure 46 and Figure 47.

The vertical system uses concrete for the first two levels to provide a plinth. From the first floor up, load bearing timber walls transfer the vertical forces. These CLT walls also function as separation walls between residences, which is an advantage over a column structure. Additionally, the timber walls can be used for both the vertical and the stability system in this design. Steel brackets are used to attach the balconies to the façade and for the cantilevering floors in the 'wedge-shaped' north part of the building (Verhaegh et al., 2020). Figure 48 provides an overview of the structural materials that are used in the building.

The floors are timber concrete composite (TCC) floors, which consist of 160 mm CLT with a concrete top layer of 80 mm thick on top of it. The main advantage of this floor system is the added mass, which reduces the vibrations. Also, the exposed timber ceiling incorporates the aesthetic qualities of timber in the architecture (Verhaegh et al., 2020). The floors span a maximum of six meters. In Figure 49 a typical cross section of the TCC floors can be found

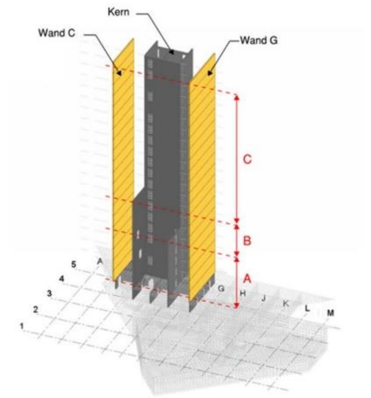


Figure 46: Stability system Haut. From "Haut - A 21-storey Tall Timber Residential Building", by R. Verhaegh et al., 2020, International Journal of High-Rise Buildings, 9(3), p. 216.

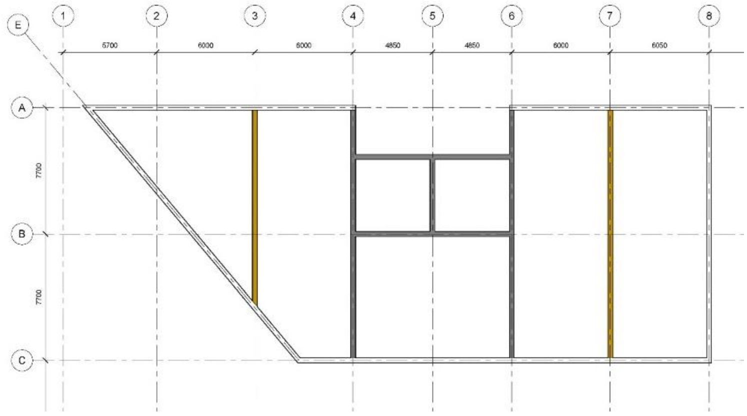


Figure 47: Typical floorplan. Adapted from "Haut - A 21-storey Tall Timber Residential Building", by R. Verhaegh et al., 2020, International Journal of High-Rise Buildings, 9(3), p. 216.

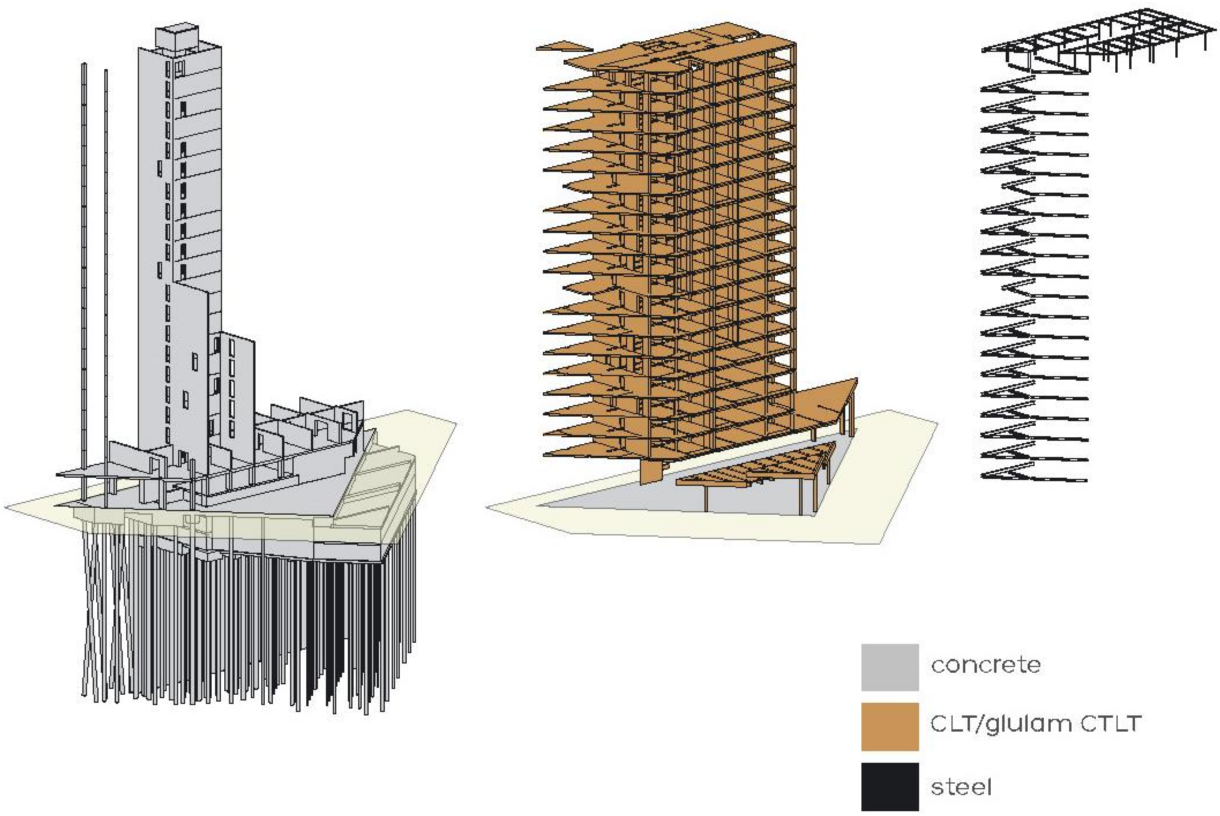


Figure 48: Structural materials used in Haut. From Haut, by Team V Architectuur, 2021 (https://teamv.nl/projecten/haut/).

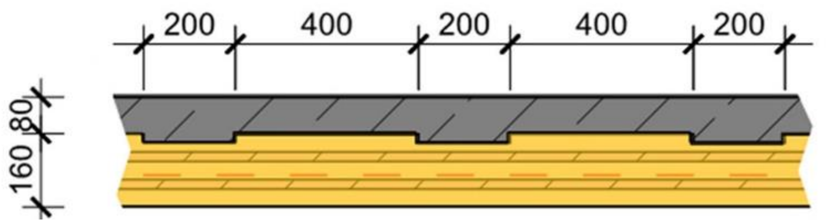


Figure 49: TCC floor build-up. From "Haut - A 21-storey Tall Timber Residential Building", by R. Verhaegh et al., 2020, International Journal of High-Rise Buildings, 9(3), p. 217.

Buiksloterham stories

In a former industrial harbour area in the north of Amsterdam, the neighbourhood buiksloterham is located. The building *Stories* was realised in 2021 using a housing cooperative concept. In the project circularity and sustainability were key concepts. This motivated the decision to use timber as a structural building material. Besides an on-ground parking area the 5500 m^2 floor area is dedicated to 35 residential and commercial units. The building has 13 storeys and is 34 meters tall, which makes it a mid-rise residential building. The costs of this project were €2075,- per square meter (Schouten, 2021).

The stability of the structure is ensured by a concrete core that holds the stairwells and an elevator (Olaf Gipser Architects, 2021). This core is located in the central part of the building, as is illustrated in Figure 51 and Figure 52.

The first two floors have a vertical bearing system made of concrete. This provides a concrete plinth, which also contains the parking area. The remaining floors utilise CLT walls to transfer the vertical loads to the foundation. These walls can be used as separation walls between residences. However, large openings in these walls allow for a flexible floorplan. The facades on the long edge of the building are not load bearing and could therefore be constructed using a timber frame structure. The steel frame surrounding the façade is constructed as a separate structure and does not contribute to the load bearing structure of the building (Olaf Gipser Architects, 2021, Schouten, 2021).

The floors are made of CLT panels with a thickness of 160 mm, on a few places the thickness is increased to 180 mm. A layer of non-structural foamed concrete is added on top of the CLT to ensure sufficient acoustic insulation capacity. No finishing layer is added at the bottom of the floors to keep the timber exposed. The CLT floors are spanning 4.5 meters (Schouten, 2021). An image of the floor detail and the connection to the steel frame surrounding the building can be found in Figure 54. Generally, the CLT walls have a thickness of 160 mm (S. van Herk, personal communication, March 22, 2022).

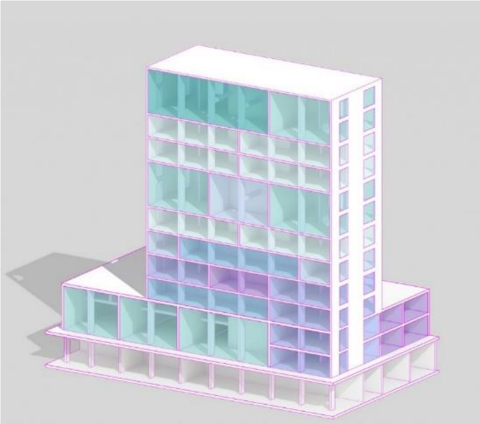


Figure 50: 3D view. From BSH20A 'Stories', by Olaf Gipser Architects, 2021 (https://olafgipser.com/projects/residential-building-bsh/#1).

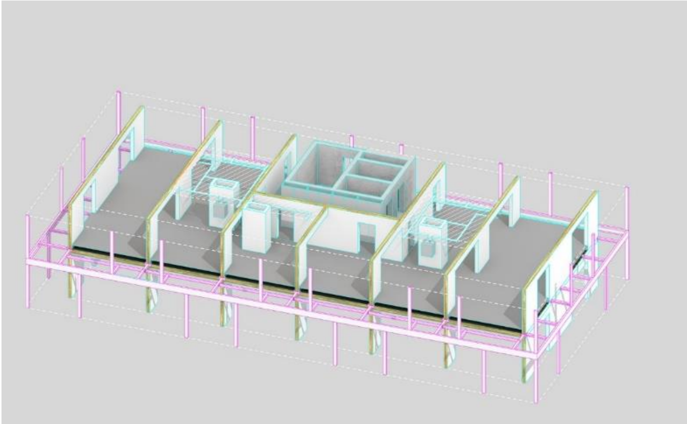


Figure 51: 3D section. From BSH20A 'Stories', by Olaf Gipser Architects, 2021 (https://olafgipser.com/projects/residential-building-bsh/#1).

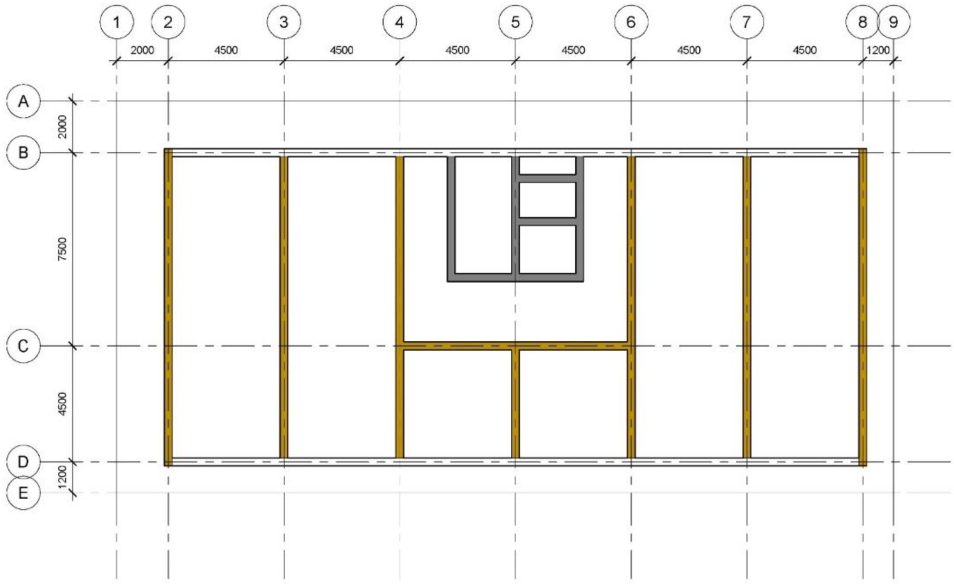


Figure 52: Floorplan buiksloterham stories. Adapted from "Stories", by Heutink, 2021. Actual sizes might differ from the image

Figure 53: Impression buiksloterham stories. From BSH20A 'Stories', by Olaf Gipser Architects, 2021 (https://olafgipser.com/projects/residential-building-bsh/#1).

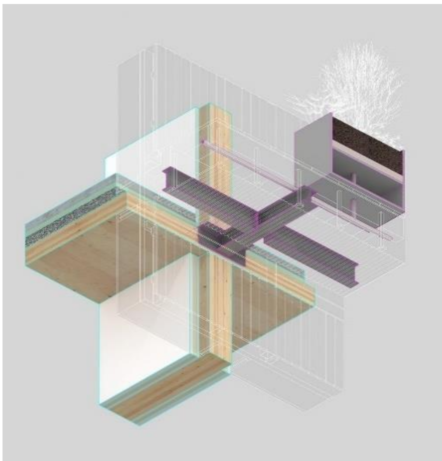


Figure 54: 3D Detail stories. From BSH20A 'Stories', by Olaf Gipser Architects, 2021 (https://olafgipser.com/projects/residential-building-bsh/#1).

7.4 Conclusions

An analysis of currently constructed timber buildings was made to gain insights in the design decisions that were made for previously constructed residential buildings. The fact that the projects are realised implicates that timber was competitive. Although the results are prone to human error conclusions can be drawn from the analysis.

The height of the analysed projects varied between 3 and 24 storeys. Timber structures are not frequently used for high rise buildings but more often for mid-rise buildings. Only 15% percent of the analysed projects has 18 storeys or more. From the analysed projects 68% has an all-timber structural system. CLT walls are most frequently used for the stability system (53%) and occur most frequent for the vertical bearing system (68%). Floors constructed out of CLT occur in 73% of the analysed projects. It is important to note that the frequent use of CLT in the analysed projects can be influenced by the use of the book '100 projects CLT UK' (Waugh Thistleton Architects, 2018) as a source. The floor spans vary between 2.8 and 7.5 metres.

In the Netherlands specifically the highest timber residential building has 21 storeys. All timber buildings occur less frequently in the Netherlands than in the rest of the countries only 44% is constructed in timber only. While CLT is still used most frequent for the stability (25%), vertical (44%), and floor system (38%) the difference with other structural systems is smaller than for the whole dataset. The floor spans in the Netherlands varies between 3.6 and 6 metres.

The analysis of the relation between the building height and the structural material shows that the highest all timber building has 18 storeys, above this height a hybrid structure was used. An investigation of the relation between the stability system and the building height shows that CLT walls are used for buildings up to 13 storeys, taller buildings used either a concrete core or a timber stability frame structure. In the Netherlands specifically the highest all timber building has only 4 storeys, this can be due to a lack of experience, possible increased costs or by the increased fire resistance that is required above 13 meters. A concrete core is used for the stability system of structures above 4 storeys. No strong relation between the vertical bearing system and the building height was found. The relation between the floor system and the building height shows that CLT and hollow core timber floors are used for projects up to 18 storeys, for taller buildings a TCC floor system is used. No relation between the building height and the floor span was found. It appears that CLT walls for the vertical system are used for all most all projects that use a stability system of CLT walls (94%).

One of the other observations that was made is that concrete plinths are frequently used for timber structures, namely in 60% of the cases. Modular structures are less common, only 15% of the projects have a modular structure. A final remark is that high-end projects with a large budget might distort the outcomes of the analysis. A building can be competitive without having the lowest building costs if the revenue is high or the sustainability ambition is governing.

The analysis of the projects *Haut* and *Stories*, both located in Amsterdam, gives insights in the reasoning behind some design decisions. In *Haut* a concrete core and TCC floors are used to minimise the issues with vibrations. For S*tories* the vertical system using CLT walls provides a flexible floorplan. Both projects have a concrete plinth on the lower two levels and expose the timber in the ceilings. The ambition to realise a circular and sustainable project was the main drive to use a timber structure for both cases.

8 Case study: *De Scharnier*

What is the potential profit of a concrete, hybrid, and a timber design variant of the project De Scharnier and under which conditions is the timber variant competitive?

The method on potential profit is applied on a case study of the sixteen -storey residential building planned to be constructed in Rotterdam named: *De Scharnier*. This project is a collaboration between Heijmans, Kraaijvanger and New Industry. Arup has advised on the technical feasibility of a concrete, a hybrid, and a timber design option. *IGG Bouweconomie* has advised on the construction costs of these three variants.

A concrete, a hybrid, and a steel design option for *De Scharnier* were explored in an early design stage. After which a decision was made to continue the project with the concrete design variant (M. van Capelleveen, personal communication, November 23, 2021). The main reasons for this decision were the higher building costs and the lack of a supplier for the prefabricated timber concrete composite (TCC) floors. This case study aims to determine the conditions under which the hybrid or the timber variant of this project would have been competitive.

First, the project outlines and the design options are described. Thereafter, the revenue, total building cost and carbon emission costs are estimated for the three design variants. Finally, the potential profit of the variants is compared, and conclusions are drawn.

8.1 Introduction *De Scharnier*

The three design variants of *De Scharnier* are shortly explained in this chapter.

Building specifics

De Scharnier is located in Katendrecht, which is a neighbourhood in the city Rotterdam. The building will be built close to the water at a nod of the quay. Therefore, the building shape is not rectangular but adapted to the location, as is illustrated in Figure 55. *De Scharnier* has sixteen floors of 3.2 meters high, which brings the total height to 60 meters. The footprint of the building is about 53 by 43 meters, the gross floor area (GFA) is 16983 m².

The ground floor and first floor contain a school, a day-care, a commercial program, and space for parking of both bicycles and cars. The second till the sixteenth floor consist of homes of which half will be sold in the fee market sector, these houses will have use areas between 55 and 200 m². The other half will consist of social rental houses with use areas between 50 and 85 m². This makes for a total area of 6005 m² of owner-occupied homes, 3163 m² of social rental houses and 3539 m² of public functions.

Figure 55: Floorplan ground floor De Scharnier. From personal communication R. Crielaard, September 9, 2021.

Design variants

For the comparison in this research, three design variants for *De Scharnier* are considered. The main differences between the variants are in the use of concrete walls versus timber columns and the use of concrete floors versus timber concrete composite (TCC) floors. The characteristics of all three variants are described below.

Design principles for concrete variant

The design of the concrete variant of *De Scharnier* has a concrete foundation and plinth above which concrete load bearing walls with a centre to centre (c.t.c) distance of 6.6 meters are placed. The building has a concrete core which will continue uninterrupted until the foundation. At the location of the end-walls, the construction will consist of concrete beams and columns. To transition from the 6.6-meter spans to larger spans on the ground floor, wall beams can be cast in place. However, due to the design uncertainty this transition structure is excluded from the analysis. From the third floor up all floors will be reinforced precast concrete plank floors.

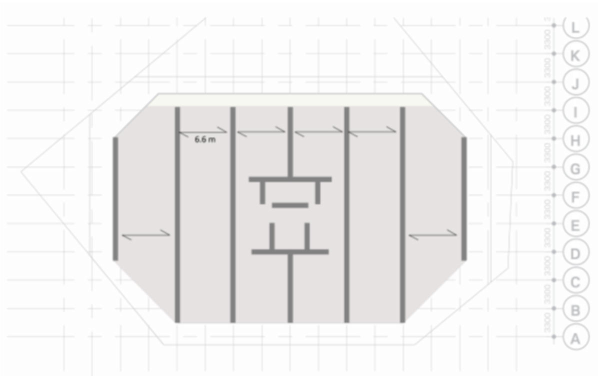


Figure 56: Floorplan concrete design variant. Adapted from personal communication R. Crielaard, September 9, 2021.

Design principles for hybrid variant

The design of the hybrid variant of *De Scharnier* is identical to the concrete variant with an exception for the floors. From the third floor up all floors will be timber concrete composite (TCC) floors. These TCC floors will span 6.6 metres. Only the floors in the core of the building will be made of concrete.

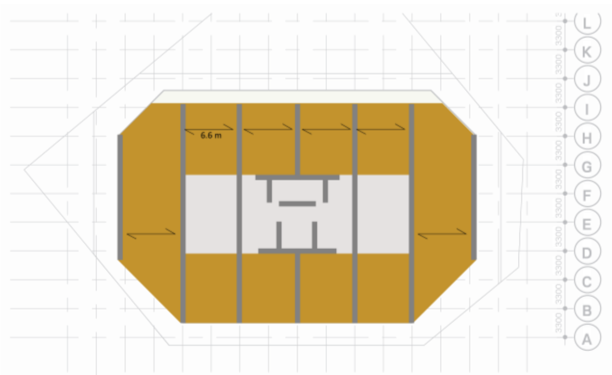


Figure 57: Floorplan hybrid design variant. Adapted from personal communication R. Crielaard, September 9, 2021.

Design principles for timber variant

As for the concrete and hybrid variants the foundation and plinth of the timber variant will be constructed in concrete. From the third floor up timber columns with a c.t.c distance of 3.3 meter and a concrete core will form the main vertical load bearing structure. At the location of the end walls, timber beams and columns will be used. To transition to larger free spans at the ground floor level an additional transition structure will be needed, this can be made of timber, steel, or concrete. Because of the design uncertainty this transition structure is excluded from the analysis. As for the hybrid variant, from the third floor up all floors will be hybrid timber floors spanning 6.6 metres. In the central part of the building concrete floors will be used. Because the floors in the timber variants are supported by columns instead of walls, the TCC floors will need to be thicker than for the hybrid variant.

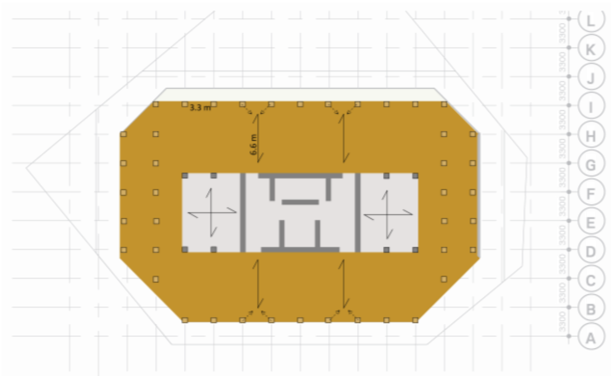


Figure 58: Floorplan timber design variant. Adapted from personal communication R. Crielaard, September 9, 2021.

Design principles for all variants

The three designs are designed for the same purpose, withstand the same loads, and follow the same regulations. Therefore, it is assumed that the functional unit of the three variants is identical and that a fair comparison of the potential profit can be made. For all variants the same principles apply for required fire resistance and acoustic insulation. The following design rules apply to the structural components and are implemented in the design:

- Minimum fire resistance of load bearing structure: 120 minutes
- Minimum fire resistance of floors: 90 minutes
- A sprinkler installation will be used in parts with timber load bearing elements

To ensure sufficient noise resistance the following requirements regarding sound insulation are followed:

- Airborne sound insulation $D_{nTak} \geq 53$ dB
- Contact borne sound insulation $L_{nTa} \leq 49\text{-}54$ dB
- Consider a wider frequency area than described in the building codes (also the low frequency sound insulation (50-100 Hz)
- The hybrid timber floor system will have a floor build up with an additional layer to ensure sufficient mass in the structure, a sound insulation layer and finally a floating floor layer.
- In the case that timber columns are used the partition walls must include additional plasterboard sheeting to ensure sufficient sound insulation.

The assumed floor and wall build up is based on the feasibility study by Arup and conversations with the design leader for this project at Heijmans (M. van Capelleveen, personal communication, November 23, 2021). Figure 59, Table 18, Figure 60, Table 19, Figure 61, Table 20, Figure 62, and Table 21 give the floor and wall build-up of the concrete floors, TCC floors, concrete walls, and timber walls.

It is interesting to note that the CLT layer in the TCC floor for *De Scharnier* (240 mm) is significantly thicker than the TCC floor which is applied in *Haut* (160 mm) (Verhaegh et al., 2020) and *HoHo* (180 mm) (Woschitz & Zotter, 2017). The floor span for *Haut* (6m) is a bit smaller than for *De Scharnier* (6.6m) However, the main difference is that the floors in *Haut* are supported by walls and the floors of *De Scharnier* are supported by timer columns. *HoHo* on the other hand has a similar floor span (7m) and floors supported by timber columns as well. However, the concrete layer on top of the CLT for *Hoho* (120 mm) is thicker than for *De Scharnier* (80 mm).

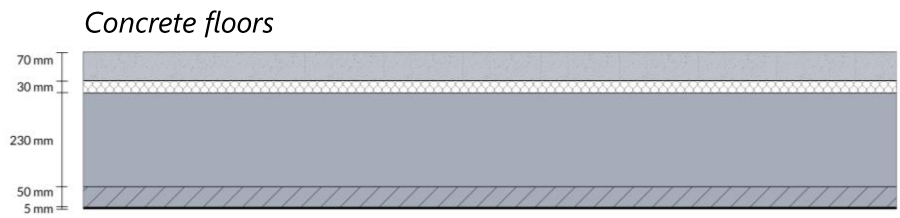


Figure 59: Floor section concrete design variant

Table 18: Concrete floor build-up and mass, De Scharnier

Material	Mass	Unit	Thickness	Unit	Load	Unit
Finishing flooring						
Concrete screed	24	kN/m^3	70	mm	1.68	kN/m^2
Insulation	0.334	kN/m^3	30	mm	0.01	kN/m^2
In situ concrete (100 kg/m^3 reinforcement)	24	kN/m^3	230	mm	5.52	kN/m^2
Precast plank floor	24	kN/m^3	50	mm	1.20	kN/m^2
Plaster finishing	9.68	kN/m^3	5	mm	0.05	kN/m^2
Total			385	mm	8.46	kN/m^2

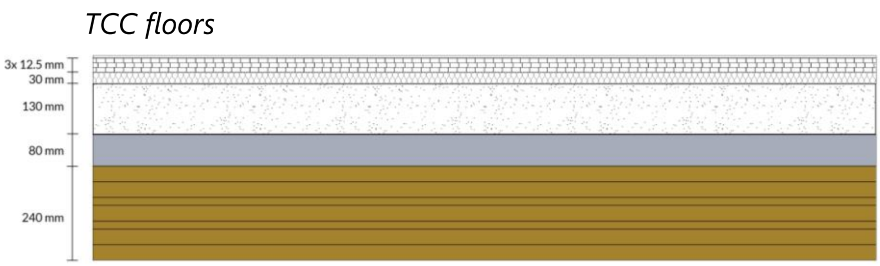


Figure 60: Floor section hybrid and timber design variant

Table 19: TCC floor build-up and mass, De Scharnier

Material	Mass	Unit	Thickness	Unit	Load	Unit
Finishing flooring						
Gypsum floorplate	9.68	kN/m^3	37.5	mm	0.36	kN/m^2
Insulation	0.33	kN/m^3	30	mm	0.01	kN/m^2
Mass layer	20	kN/m^3	130	mm	2.60	kN/m^2

Concrete decking	24	kN/m³	80	mm	1.92	kN/m²
CLT slab	4.7	kN/m³	240	mm	1.23	kN/m²
Total			517.5	mm	6.0	kN/m²

Concrete walls

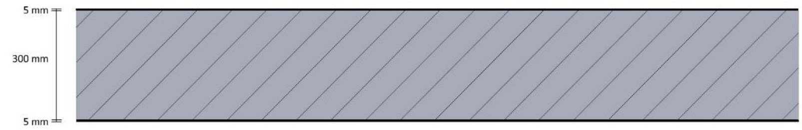


Figure 61: Wall section concrete and hybrid design variant

Table 20: Concrete wall build-up and mass, De Scharnier

Material	Mass	Unit	Thickness	Unit	Load	Unit
Plaster finishing	9.68	kN/m³	5	mm	0.05	kN/m²
Precast concrete wall	24	kN/m³	300	mm	7.2	kN/m²
Plaster finishing	9.68	kN/m³	5	mm	0.05	kN/m²
Total			310	mm	7.3	kN/m²

Timber walls

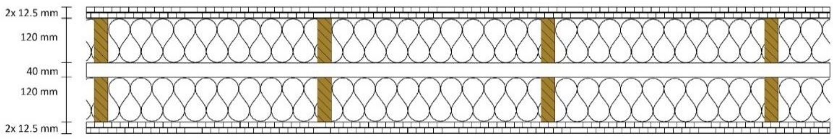


Figure 62: Wall section timber design variant

Table 21: Timber wall build-up and mass, De Scharnier

Material	Mass	Unit	Thickness	Unit	Load	Unit
Gypsum board	9.68	kN/m³	25	mm	0.24	kN/m²
Timber framing with glass wool	53.58	kN/m³	120	mm	6.43	kN/m²
cavity	0	kN/m³	40	mm	0	kN/m²
Timber framing with glass wool	53.58	kN/m³	120	mm	6.43	kN/m²
Gypsum board	9.68	kN/m³	25	mm	0.24	kN/m²
Total			330	mm	13.35	kN/m²

8.2 Potential profit comparison

This chapter discusses the potential profit of the three design variants of *De Scharnier*. First the revenue, total building costs, and carbon emission costs are discussed. Thereafter the potential profit is analysed and compared. The methods that are discussed in chapter 4.3 are used.

Revenue

The revenue in this calculation assumes that the building will be sold as a whole, therefore there will be no periodic profits only one-off profits. For the calculation of the revenue an average of €5200, - per square meter for the owner-occupied apartments and of €4100, - per square meter for the rental homes and the remaining non-residential areas is assumed. This is based on information provided by Heijmans (M. van Capelleveen, personal communication, November 23, 2021). This revenue corresponds to the current average price per square meter in Katendrecht of €4415,- per square meter found on Funda (2021). The assumption is made that the gross and net floor area are equal for the three variants.

For the hybrid variant an additional revenue of 1% and 2% is considered. For the timber variant an additional revenue of 2% and 4% is considered. This additional revenue is calculated over the houses sold on the free market sector. Figure 63 shows the revenue of the three variants per m² gross floor area (GFA).

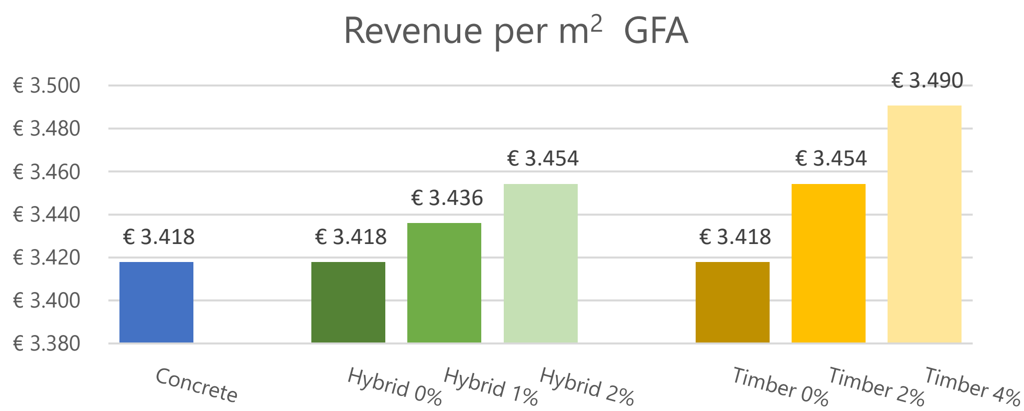


Figure 63: Revenue, all variants De Scharnier

Total building costs

As described in chapter 4.3, the building cost estimation uses the categorisation of costs as described in NEN2699. Appendix I provides a detailed overview of the cost for all categories. This section analyses the total building costs for the three variants of *De Scharnier*. Figure 64 shows the total building costs per m² GFA for all three design variants of *De Scharnier.* This shows that the costs for the concrete variant are the lowest, followed by the costs for the hybrid variant. The costs of the timber variant are found to be the highest.

The total building costs are divided into seven categories of which the costs are shown in Figure 65. This figure shows that for all variants the costs of the frame have the largest contribution to the total costs, followed by the additional, the finishing and the execution costs. This section shortly discusses the assumptions and the influences on the costs for each category.

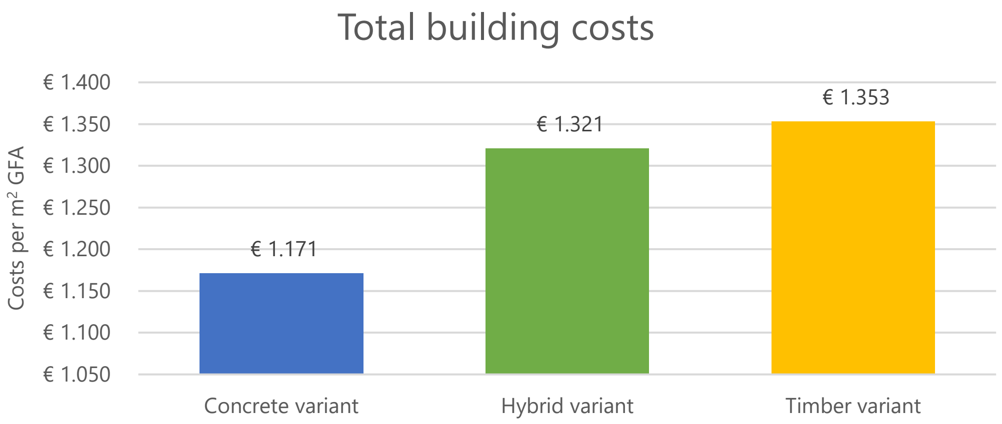


Figure 64: Total building costs, De Scharnier

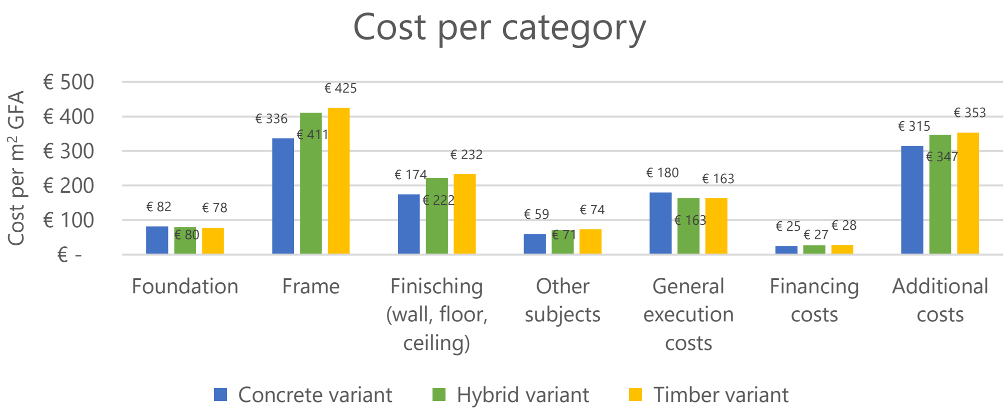


Figure 65: Costs per category, De Scharnier

Foundation

The of the foundation are based on a cost estimation made by *IGG Bouweconomie*. For this calculation, the assumption is made that the costs for the foundation are reduced if the weight of the superstructure is reduced, since less material and labour will be needed for the foundation. In consultation with *IGG Bouweconomie* this is translated to a cost reduction of 2% and 5% percent for the piles and foundation structure of the hybrid and timber variant respectively.

Frame

The costs of the structural frame are also based on a cost estimation made by *IGG bouweconomie* and contains the costs for the interior walls, floors, roofs, and other main structural elements like beams and columns. The variance in costs between the three options is mainly caused by the difference in material costs that are used for the floors and walls. The higher price of timber products and the very low price for the reinforced concrete slab floors makes that the differences between the variants are large. The material costs for the variants that include timber are higher than for the concrete variant, which was expected.

If the costs for the structural frame are further divided over the different elements, it is found that the floors and beams have the largest contribution to the total costs. The costs for the floors of the timber variant are the highest. On the other hand, the costs for structural walls and columns are the lowest for the timber variant. The timber variant uses columns only where the concrete and hybrid variant use walls.

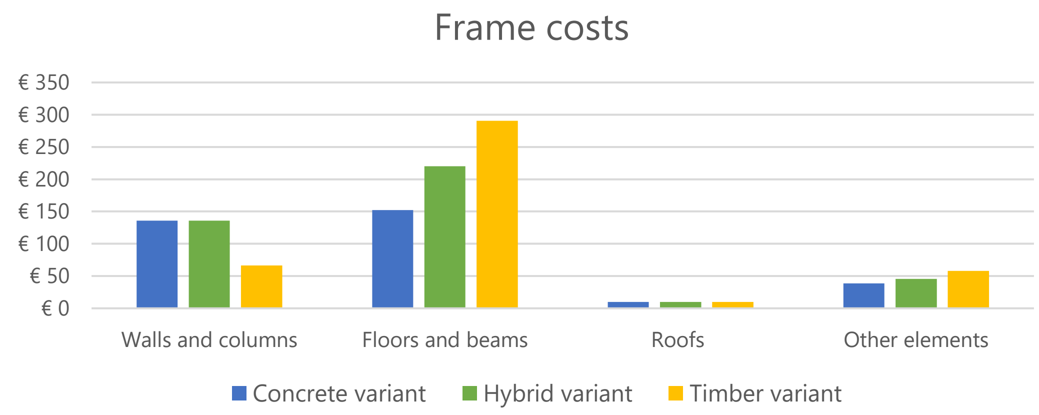


Figure 66: Subdivision frame costs, all variants De Scharnier

Interior wall finishing, floor finishing and ceiling finishing

The costs for the interior wall, floor and ceiling finishing of the concrete variant are based on standard values provided by *IGG Bouweconomie*. The wall finishing costs are higher for the variant with timber columns because additional measures are needed to ensure sound insulation and fire resistance of the walls. The floor finishing costs are lower for the concrete variant because less additional build up materials are needed for the concrete floor than for the hybrid floors. For both the hybrid and the timber variant the costs for a sprinkler system are included in the floor finishing costs. Since the underside of the TCC floors can remain in sight the ceiling finishing costs are lower for the hybrid and the timber variant.

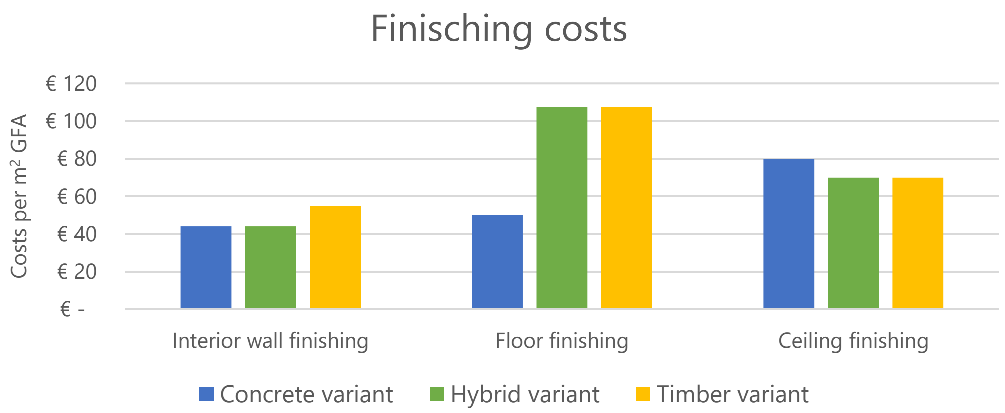


Figure 67: Finishing cost, all variants De Scharnier

Cost related to other subjects

The costs related to other subjects is calculated to be 10% of the building costs in correspondence with *IGG Bouweconomie*. This percentage will decrease if a more detailed design is made, and ultimately go to zero. These costs are included in the calculation but are influenced by the building costs and therefore only indirectly by the structural material.

General execution costs

The costs for the execution of the building are based on standard values provided by *IGG Bouweconomie*. The assumption is made that the execution time for TCC floors is shorter than for the concrete floors. Also, the execution time for the timber columns is assumed to be shorter than for the concrete walls (Hough, 2019). However, considering the time required to install the non-load bearing walls the difference between the concrete walls and timber columns is assumed to be neglectable. This makes that the execution costs of the timber and hybrid variant are assumed to be 10% lower than for the concrete variant.

Financing costs (interest)

The financing costs are determined by taking a percentage of the building costs and execution costs. An interest rate of 3% of the building and execution costs is assumed for the concrete design variant. Due to the reduced construction time for the timber and hybrid variant, an interest rate that is 5% lower is used in consultation with *IGG Bouweconomie*. This results in an interest rate of 2,85% for the timber and hybrid design variant. An alternative assumption is that the interest rate for a timber building is higher than for a concrete building because the bank might consider timber projects to be riskier. This higher perceived risk is because the precedence of building structures made from engineered timber is limited. Therefore, the bank can ask for a higher interest rate. For this thesis the assumption is made that timber and hybrid projects can be proven to not have a higher risk and therefore the scenario with the lower interest rate will be used.

Additional costs

The costs that are not directly dependent on the building material decision are included as a percentage of the total building and execution costs. These percentages were provided by *IGG Bouweconomie* (D. D. D. van Laar, personal communication, November 9, 2021). An overview of these additional cost categories with a low, middle, and high percentage in relation to the building costs is given in chapter 4.3 and Table 22.

Table 22: Percentages for additional costs

Cost category	low	mid	high
Land costs	6.0%	7.5%	9.0%
Unforeseen	3.0%	4.0%	5.0%
Professional fees	6.7%	9.8%	17.3%
Connection fees	2.1%	3.3%	5.0%
Taxes	1.0%	2.0%	5.0%
Developer fees	3.5%	7.3%	18.5%
Selling fees	1.2%	1.2%	2.7%

For all categories and variants, the middle percentage was used, with an exception for the land costs. These costs are assumed to be independent of the building and execution costs should be identical for all three variants. Also, the land costs are assumed to be higher than average since the building site is in the city centre of Rotterdam. With these two assumptions the land costs for all three variants are calculated by using the high percentage for the total building and execution costs of the hybrid variant.

Carbon emission costs

To determine the carbon emission costs, the total carbon emissions are estimated for the three variants. This estimation is made using the four steps of the LCA framework, which is described in chapter 4.4. In Appendix I an overview of the carbon calculations of *De Scharnier* can be found. The CO_2 price is a variable in this case study, the required CO_2 price for which the timber variant is competitive is determined in the next section.

Input for calculation/ goal and scope definition
The goal of this analysis is to compare the embodied carbon of the concrete, hybrid, and timber design variant for *De Scharnier*. Therefore, this analysis includes all materials required to comply with the functional unit. This includes the foundation, the frame structure and the floor, wall, and ceiling finishing. The method and assumptions that are used for the estimation of carbon emissions is described in chapter 4.4. The results are expressed per square metre gross floor area (GFA) (kg-CO_2eq/m^2).

Inventory analysis
The second step of the LCA is to gather information regarding the materials that are used, their quantities for each design variant and their environmental impacts. The inventory data for the environmental impacts is based in direct EPD's and includes a high, a low, and a mean value, these values can be found in Appendix E. The information regarding the materials used and their quantities was found using the cost calculation made by *IGG Bouweconomie*, which included the amounts of most of the materials that are used for each variant. Some assumptions have been made; these are discussed below.

Foundation
The structure of the foundation consists of a hollow core slab, an in-situ concrete foundation structure and concrete piles. The hollow core slab has a thickness of 260 mm for all variants. The in-situ concrete foundation has a strength class C30/37 and is 300 mm thick for all variants. The assumption is made that all variants will have 210 foundation piles with a length of 26 meter and a strength class C35/45. For the concrete variant the diameter is 580 mm, and the reinforcement consists of 6 bars wit 25 mm diameter for the first 6.5 m of all piles and 6 bars with a diameter of 16 mm for the remaining 19,5 m of the piles (M. van Capelleveen, personal communication, December 13, 2021).

The load in the foundation piles differs between the tree variants, therefore the thickness of the concrete piles and the reinforcement is reduced based on the load difference. This reduction is equal to the difference in load on the foundation piles between the variants. The load on the foundation of the hybrid variant is 99.7% of the load on the foundation of the concrete variant. The load on the foundation of the timber variant is 87.8% of the load on the foundation of the concrete variant. Therefore, the foundation piles and reinforcement bars of the hybrid and timber variant have an area equal to 99.7% and 8.7.8% of the concrete variant respectively.

Frame
The concrete used in the frame is mostly precast concrete for all design variants. If concrete is poured on site is assumed to have a strength class C30/37. If the reinforcement ratio of a concrete element was unknown 100 kg/m^3 is assumed. The timber columns in the timber variant are assumed to be constructed out of CLT, this corresponds to the assumptions made in the cost estimate made by *IGG bouwecomomie*. Since the costs for the transition structure are not included in the cost comparison, the carbon emissions of this transition structure are neglected.

Finishing materials
The finishing materials are used for the walls and floors are described in chapter 8.1. The wall and floor area are based on the areas of the structural floors and the structural walls.

Impact assessment

Table 23 and Figure 68 give an overview of the total embodied carbon for each variant. This shows that in all scenarios the emissions for the concrete variant are the highest, followed by the hybrid variant. The emissions of the timber design variant are the lowest. This meets the expectations as literature stated that timber buildings have lower CO_2 emissions (Hart et al., 2021; Kaufmann et al., 2018; Keijzer et al., 2021). Table 23 also shows that the variance between the high the mean and the low impacts is large for all design options. The SCORS ratings (Arnold et al., 2020) are within the expected margins. The mean impact values without the subtraction of biogenic carbon are similar to the study by Liang et al. (2020) of 181 kg CO_2eq/m^2 and 228 kg CO_2eq/m^2 for timber and concrete respectively.

Table 23: Overview global warming potential for all three design variants De Scharnier

	Total emissions	**GWP (excl. biogenic carbon)**		**TOT GWP (incl. biogenic carbon)**		**Unit**
Low impact	Concrete variant	154	B	154	B	kg-CO_2eq/m^2
	Hybrid variant	111	A	5	A++	kg-CO_2eq/m^2
	Timber variant	96	A+	-70	A+++	kg-CO_2eq/m^2
Mean impact	Concrete variant	235	C	235	C	kg-CO_2eq/m^2
	Hybrid variant	208	C	103	A	kg-CO_2eq/m^2
	Timber variant	176	B	12	A++	kg-CO_2eq/m^2
High impact	Concrete variant	355	F	355	F	kg-CO_2eq/m^2
	Hybrid variant	337	E	218	C	kg-CO_2eq/m^2
	Timber variant	300	E	113	A	kg-CO_2eq/m^2

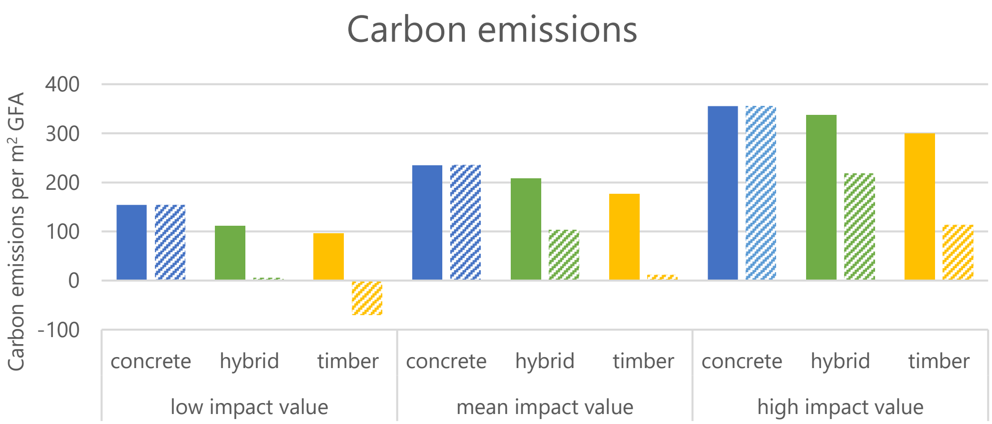


Figure 68: Total global warming potential per m^2 including biogenic carbon for all variants De Scharnier, the hatched bars represent the values with 100% subtraction of stored carbon, the solid bars assume 0% subtraction

The mean value is used in the calculation of the potential profit because this represents the most likely value. In Figure 69, the impact per part of the building structure is shown. The structural walls and columns and the structural floors and beams have the largest contribution to the total embodied carbon for all variants if the biogenic carbon is not included in the calculation. The walls and columns and the foundation have the second largest impact. This corresponds to the results of the research by van Wijnen (Van Wijnen, 2020). However, if the biogenic carbon is included in the calculation the impact of the floors and beams is negative for the hybrid and timber variant.

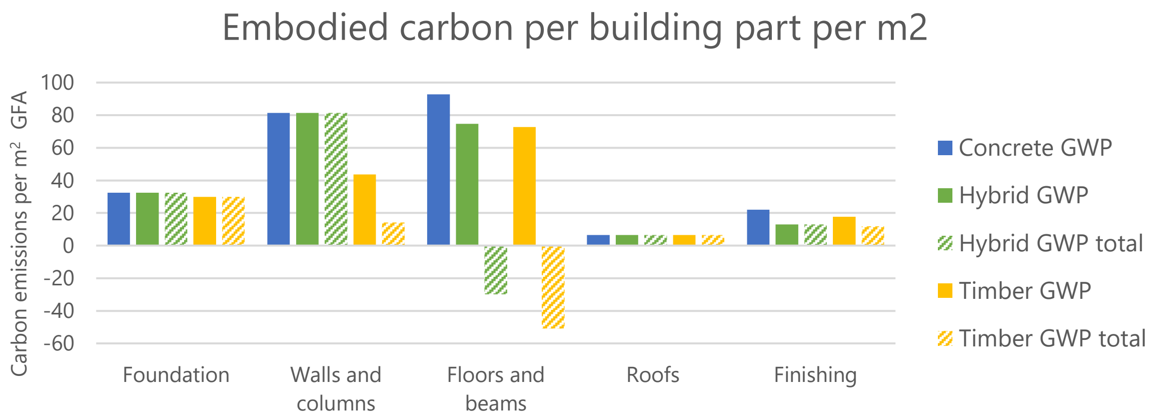


Figure 69: Embodied carbon per building part, the total values include the biogenic carbon with 100%

Interpretation and conclusions

From the embodied carbon calculation, it is concluded that the emissions of the concrete variant are the highest followed by the hybrid and timber variant. Including the biogenic carbon in the calculation increases the difference between the variants. The variation between the results for the high, mean, and low impact values for the materials is large for all variants. However, the difference between the variants remains comparable. The structural frame has the largest contribution to the total emissions it the biogenic carbon is not included in the calculation.

Potential profit

The results from the estimation of the revenue, total building cost, and carbon emission costs are combined to determine and compare the potential profit for the three variants. The CO_2 price is included as a variable in the comparison. Table 24 shows the potential profit in the scenario that the carbon costs are zero and there is no additional revenue for the hybrid and timber variant. This shows that the concrete variant is most competitive in this scenario.

Table 24: Potential profit per m² without carbon costs, De Scharnier

Variant	Revenue	Total building costs	Carbon costs	Potential profit	Difference with concrete variant
Concrete	€ 3 418	€ 1 171	€ -	€ 2 247	€ -
Hybrid	€ 3 418	€ 1 321	€ -	€ 2 097	€ 150
Timber	€ 3 418	€ 1 352	€ -	€ 2 065	€ 182

Table 25: Required CO_2 price for the potential profit of a timber and a concrete structure to be equal

Variant	Carbon storage			Carbon storage			Carbon storage		
	0%	**50%**	**100%**	**0%**	**50%**	**100%**	**0%**	**50%**	**100%**
	if 0% additional revenue			if 1% additional revenue			if 2% additional revenue		
Hybrid	€5.48	€1.88	€1.14	€4.81	€1.65	€1.00	€4.15	€1.43	€0.86
	if 0% additional revenue			if 2% additional revenue			if 4% additional revenue		
Timber	€3.09	€1.29	€0.81	€2.47	€1.03	€0.65	€1.85	€0.77	€0.49

In Table 25 the required CO_2 prices for which the potential profit of the hybrid and the timber variant are equal to the potential profit of the concrete variant are given. This shows that the required CO_2 prices are lower for the timber variant than for the hybrid variant. However, if no additional revenue is assumed the potential profit of the hybrid variant is higher up until a CO_2 price of €0.35 per kg of CO_2. It can be expected that the timber variant is more competitive than the hybrid variant because the execution of the hybrid variant is very complicated (M. van Capelleveen, personal communication, January 10, 2022). Finally, it is concluded that the prices decrease if a larger percentage of the stored carbon is included and if more additional revenue is assumed.

Compared to the CO_2 tax in the Netherlands of €0.04 per kg of CO_2 and the price on the European emission trading market of €0.08 per kg of CO_2 the required CO_2 prices are high. This shows that there is a large difference in potential profit between the variants and that the current emissions prices are not sufficient to increase the competitiveness of timber structures.

8.3 Conclusions

The revenue, total building costs and carbon emissions costs of three design variants the project *De Scharnier* are estimated and compared. All design variants have the same functional unit, but there are differences for the structural material that was used for the floors and the vertical system. The concrete variant has concrete plank floors and concrete walls, the hybrid variant has hybrid timber concrete composite floors and concrete walls, and finally the timber variant has timber concrete composite floors that are supported by timber columns.

The assumed revenue is equal for the three variants. However, the influence of assuming additional revenue for the hybrid and the timber variant is investigated. This is done by adding 0%, 1%, 2%, or 4% to the revenue for the houses sold in the free market sector.

The cost comparison shows that the concrete variant has the lowest costs followed by the hybrid variant. The timber variant has the highest costs. For all variants the costs of the frame have the largest contribution to the total costs, followed by the additional, the finishing and the execution costs.

The comparison of greenhouse gas emissions shows that in al scenario's the carbon emissions are the highest for the concrete variant followed by the hybrid and the timber variant, as can be seen in Table 23 and Figure 68. Deducting the stored carbon in timber products from the emitted carbon increases the difference between the variants. The difference between the results for the high, the mean and the low impact value is large for all three variants. The structural wall-and-column and the structural floor-and-beam elements have the largest impact for all variants if the biogenic carbon is not included. The CO_2 price is a variable in this study.

The comparison of the potential profit shows that the required CO_2 price for which the timber variant is competitive with the concrete variant is lower than for the hybrid variant. The required CO_2 prices decreases if a larger percentage of the stored carbon is included and if more additional revenue is assumed. The calculated required carbon prices show that the current emissions prices are not sufficient to increase the competitiveness of timber structures.

Recap part 2

In the second part of this research the conditions under which timber can be competitive with concrete are qualified. This is done using four separate studies which investigate one or multiple conditions.

The first study investigates for which building function a decrease of carbon emissions has the largest impact on the total emissions of the construction industry. The research into the average carbon emissions per building function shows no single building use which has higher emissions than the other uses. Also, the variation of emission for the same building use is very large. Therefore, it is concluded that the carbon emissions of a building structure are more dependent on the specific project and the design decisions than on the building function. Research into the Dutch market shows that there is a high demand for multi-storey residential buildings and that ground-level homes can already be competitive in light timber frame. Therefore, it is concluded that reducing the CO_2 emissions for multi-storey residential buildings has the largest impact.

Secondly, the possibilities and limitations of four structural timber elements and four structural timber floors are investigated. From the research into the possible applications of timber it is concluded that glued laminated timber (glulam), cross laminated timber (CLT) and laminated veneer lumber (LVL) are suitable to use for the vertical and stability system of multi-storey residential buildings. Solid timber appears to be suitable for residential buildings with a height up to 4 storeys. For timber floor systems CLT, timber concrete composite (TCC) and a timber hollow core floor are suitable for multi-storey residential buildings. A wooden beam layer floor system is only suitable for buildings up to four storeys.

Thereafter, the study into 34 constructed timber residential buildings is presented. It is concluded that CLT walls are most frequently used for the stability system (53%) and occur most frequent for the vertical bearing system (68%). Floors constructed out of CLT occur in 73% of the analysed projects. For the stability system CLT walls are used up to 13 storeys, taller buildings require a concrete core or a timber stability frame structure. In the Netherlands specifically the highest residential timber building has 21 building storeys and the highest building which uses CLT walls for the stability has only 4 storeys. Floor spans of timber buildings in the Netherlands vary between 3.6 and 6.0 meters. Finally, it is concluded that for *Haut* and *Stories* the ambition to realise a circular and sustainable project was the main drive to use a timber structure.

The fourth study is a case study of a concrete, a hybrid and a timber design variant for the sixteen-storey residential building planned to be constructed in Rotterdam named: *De Scharnier*. From the comparison it is concluded that both the potential profit and the carbon emissions of the concrete variant are the highest, followed by the hybrid and the timber variant. In the scenario that the biogenic carbon is included in the calculation and there is no additional revenue assumed the required CO_2 price for the timber variant to be competitive with the concrete variant is €0.81 per kg of CO_2. For the hybrid variant this price is higher, €1.41 per kg of CO_2. The required CO_2 prices decreases if a larger percentage of the stored carbon is included and if more additional revenue is assumed.

Part 3: Quantification phase

The quantification phase aims to quantify the conditions under which timber building structures are competitive. The specific conditions that are researched in this phase are the building height, the floor span, the CO_2 emission cost, the additional revenue for timber structures and the calculation method regarding biogenic carbon. The potential profit of sixteen structural timber building designs is determined and compared to concrete design variants. First, the research from the quantification phase is translated into a base scenario design and design variants that are to be studied. Subsequently the element sizes of the floors and walls are determined. Third, the potential profit of these variants is determined. Finally, the conditions under which timber can be competitive are determined and conclusions are drawn.

9 Parameter study

What is the influence of the building height, floor span, CO_2 emission costs, assumed additional revenue and calculation method regarding biogenic carbon on the potential profit of a timber multi-storey residential building? And under which conditions is the designed timber structure competitive with a concrete structure?

In this chapter the difference in potential profit between a concrete and a timber structure is determined for sixteen design variants for a multi-storey residential building. The studies that are performed in the qualification phase are used to determine which designs are investigated. In chapter 9.1 the sixteen design variants are explained. In chapter 9.2 the method that is used to determine the element sizes of the timber floors and walls is discussed. In chapter 9.3 the potential profit of the various designs is presented. Finally, conclusions are drawn in chapter 0.

9.1 Design decisions and variants

This section discusses the designs that are investigated in the parameter study and explains the reasoning behind the design decisions.

Design decisions based on the quantification phase

The design variants are made with the goal to find a design for a timber building structure that is competitive with a concrete structure. The outcomes of the qualification phase are used to determine the design variants for the parameter study. In this section the design decisions that are based on the qualification phase are discussed.

Building function

From the research presented in chapter 5 it is concluded that reducing the CO_2 emissions for multi-storey residential buildings has the largest impact on the reduction of emissions of the whole building industry. Therefore, the decision is made to focus on multi-storey residential buildings in this thesis. All design variants in the parameter study will have a residential function and all variants will have three storeys or more.

Properties structural timber

From the investigation into the properties of structural timber elements it was concluded that Glulam, CLT and LVL are suitable to use for multi-storey residential buildings. For timber floor elements CLT, TCC and a timber hollow core floor are all suitable for multi-storey residential buildings. Therefore, only these elements are considered in the parameter study.

Analysis constructed timber buildings

The analysis of constructed timber buildings shows important trends in which structural materials are used most frequently. For the stability system it is concluded that in the Netherlands all residential buildings with 6 storeys or more use a concrete core. Therefore, a concrete core will be used for the variants with 6 storeys or more in the parameter study. The stability system of the design variants with less than 6 storeys will consist of timber walls because this was found to be common. Since the timber walls are needed for the stability system, they will be used for the vertical bearing system of all timber variants. In the analysed projects in the Netherlands CLT and TCC floors occurred equally often. In all timber design variants CLT floors are used because in chapter 6 it is found that the carbon emissions of CLT floors are lower than for TCC floors.

The highest residential timber building in the Netherlands has 21 storeys. The aim of the research design is to find a competitive structural design in timber. The assumption is made that pushing the boundaries of what is currently possible does not increase the competitiveness. Therefore, the maximum height of the research design will be 20 storeys. The floor spans of the analysed cases in the Netherlands vary between 3.6 and 6 meters. Therefore, the analysed floor spans in the parameter study will vary between 3.6 and 6 meters as well.

Case study De Scharnier

It was calculated that the timber variant for the project *De Scharnier* is competitive with the concrete design variant if the stored carbon is subtracted from the emitted carbon and the CO_2 price is €0.81 per kg emitted CO_2. If an additional revenue of 4% for the timber variant is added the required CO_2 price for equal profit decreases to €0.49 per kg emitted CO_2. This gives an estimate of the range in which the CO_2 price could vary.

Also, the significant influence of additional revenue for timber structures shows that this variable should be included in the analysis. Therefore, the influence of 0%, 2% and 4% additional revenue for timber structures will be investigated in the parameter study. Finally, the case study of *De Scharnier* shows that including or excluding the stored carbon in timber from the total carbon emissions has a large influence on the required CO_2 price for which a timber structure is competitive. Therefore, the influence of the calculation method for the estimation carbon emission is investigated in the parameter study.

Table 26: Summary design decisions based on the qualification phase

Building function	**Properties structural timber**	**Analysis constructed timber buildings**	**Case study *De Scharnier***
- Residential buildings - Multi-storey (3 levels or more)	- Solid timber and wooden beam layer floors are no longer considered - CLT floors have lower emissions than TCC floors	- CLT walls for vertical system - CLT floors - Stability below 5 storeys with timber walls, above this a concrete core - Maximum 21 storeys in NL - Maximum 6 m and minimum 3.6m floor span in NL	- CO_2 price expected between €0 to €0.90 per kg - Additional revenue of timber of 0%, 2% and 4% is investigated - Investigate the influence of subtracting 0%, 50% and 100% of the stored carbon from the emitted carbon

Research design

The combination of the conclusions of the qualification phase has led to a research design. The research design that is used for the parameter study consists of sixteen variants with differences in floor span and building height. These two design variables are chosen because the research performed in the qualification phase did not conclude on the impact on the competitiveness of these two conditions. Oher designs variants with different structural systems would be interesting to investigate, however these are outside the scope of this parameter study. The research performed in the qualification phase did not analyse the buildings layout in detail. The floorplan and further layout of the research design is based on *Stories*, of which the design is discussed in chapter 7.3. Other designs might be competitive or interesting to investigate. Due to the limited scope these are not considered in this research.

General design

The design consists of 7 bays with one apartment per bay, the middle bay is dedicated to vertical circulation. The bays and therefore the apartments have a width that is determined by the floor span. Seven times the floor span determines the building width, which results in a wider building if the span is enlarged. The building depth is 12 m for all variants. Access to the residences is provided via a gallery on every level and the elevator and stairwell in the central bay of the building. This gallery is 2 metres wide which leaves a depth of 10 m for each apartment. The height of one storey is assumed to be 3.2 m, which is the same as the height of one storey of *De Scharnier* (personal communication R. Crielaard, September 9, 2021). This height can be multiplied by the number of storeys to determine the total building height. For the variants 5 storeys or less CLT walls will ensure the stability of the building. For variants with more than 5 storeys, a concrete core is added to resist the wind forces. This concrete core is placed around the elevator and stairwell. Also, additional concrete stability walls are added at the end walls for the variants which required additional stability measures. In Figure 70 and Figure 71 a floorplan and a section of the research design can be found. In Appendix K enlarged versions of the floorplan and section can be found for all design variants.

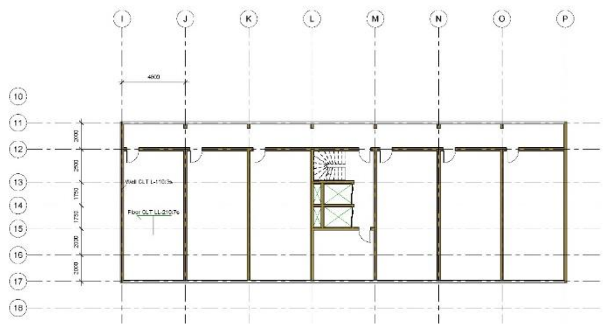


Figure 70: Floorplan research design

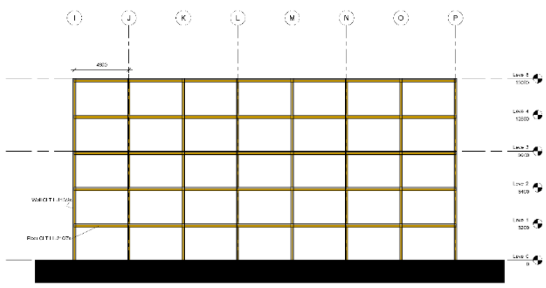


Figure 71: Section research design

Design variations

In total four different floor spans are included in the analysis. The smallest span and largest span are based on the minimum and maximum span found in the analysis of timber buildings in the Netherlands, which are 3.6 and 6.0 meters. A span of 4.8 meters appeared to be most common for timber floors in the Netherlands, therefore a variant with this span is also included. Finally, a span between 4.8 and 6 meters was found to provide a more detailed overview. Therefore, the fourth span that is considered is 5.4 meters.

The building heights that are to be investigated are determined in a similar manner. The minimum height that is considered is a project with three storeys. A design with less storeys is no longer considered a multi-storey building. The second variant has a height of 5 storeys, this is the maximum building height that will not use a concrete core to ensure the stability. The maximum height that is considered is a building with 20 storeys. Finally, a building with 9 storeys is investigated, this results in a building with the highest floor on 25.6 meters. From research performed by Qvist (2022) and the fire safety measures described by Hagen & Witloks (2018) it was concluded that sprinkler installations must be applied for timber buildings with the highest floor above 28 meters. The variant with 9 storeys is just below this height, which makes it an interesting variant to investigate.

Each of the four floor spans is combined with each of the four building heights, this results in sixteen variants to be studied. For all variants a design with a timber structure and a design with a concrete structure is made and compared. An overview of the numbering is given in Table 28.

Table 27: Numbering of design variants

	3.6 m span	**4.8 m span**	**5.4 m span**	**6.0 m span**
20 storeys	13	14	15	16
9 storeys	9	10	11	12
5 storeys	5	6	7	8
3 storeys	1	2	3	4

Floor build-up

To ensure sufficient sound insultation, additional layers are added on top of the structural CLT floors. The ceiling will remain unfinished so the timber will be visible, this contributes to the indoor climate and increases the aesthetic value. This build-up is chosen to comply with the demands of the functional unit described in chapter 4.4, the specifics can be found in Figure 72 and Table 28. The impact sound insulation level (L) is 44 dB and the airborne sound insulation level (D) is 63 dB (Gustafsson et al., 2019). This build-up is used for the floors of all timber variants.

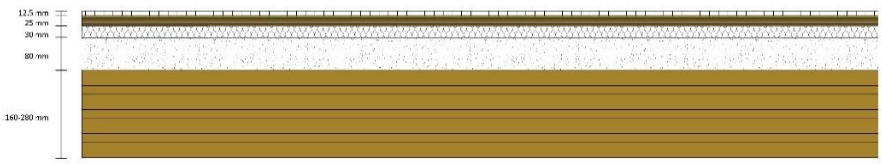


Figure 72: Timber floor build-up

Table 28: Timber floor build-up and mass

Material	**Mass**	**Unit**	**Thickness**	**Unit**	**Load**	**Unit**
Finishing flooring						
Gypsum plasterboard	9.68	kN/m³	12.5	mm	0.121	kN/m²
Fibre board (MDF)	7	kN/m³	25	mm	0.175	kN/m²
Impact insulation (PIR)	0.33	kN/m³	30	mm	0.01	kN/m²
Washed gravel 8-10 mm	20	kN/m³	80	mm	1.6	kN/m²
Timber floor element	4.5	kN/m³	160-280	mm		
Total non-structural			147.5	mm	1.91	kN/m²

For the concrete design variants, the floor build-up is based on the build-up that was used in the case study of *De Scharnier*. These build-ups are commonly used and comply with the functional unit described in chapter 4.4.

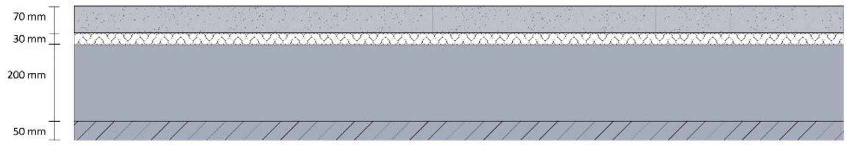


Figure 73: Concrete floor build-up

Table 29: Concrete floor build-up and mass

Material	Mass	Unit	Thickness	Unit	Load	Unit
Finishing flooring						
Cementous screed	15	kN/m^3	70	mm	1.05	kN/m^2
Impact insulation (PIR)	0.33	kN/m^3	30	mm	0.01	kN/m^2
In situ concrete floor C30/37 (100 kg/m^3 reinforcement)	24	kN/m^3	200	mm	4.8	kN/m^2
Precast plank floor	24	kN/m^3	50	mm	1.2	kN/m^2
Total non-structural			100	mm	1.06	kN/m^2

Wall build-up

The CLT walls also need additional layers to ensure sufficient sound and fire resistance. This build-up is chosen to comply with the demands of the functional unit, the specifics can be found in Figure 74 and Table 28. The airborne sound insulation level (D) is 62 dB (Calculatis by Stora Enso, 2021). This build-up is used for the walls of all timber variants.

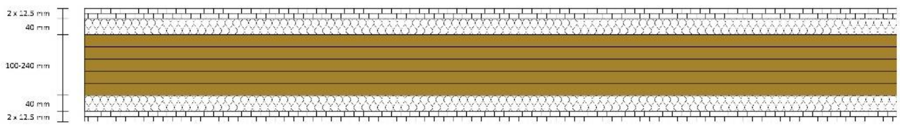


Figure 74: Timber wall build-up

Table 30: Timber wall build-up and mass

Material	Mass	Unit	Thickness	Unit	Load	Unit
Gypsum plasterboard	9.68	kN/m^3	25	mm	0.24	kN/m^2
Mineral wool	1.35	kN/m^3	40	mm	0.05	kN/m^2
CLT	4.5	kN/m^3	100-240	mm		kN/m^2
Mineral wool	1.35	kN/m^3	40	mm	0.05	kN/m^2
Gypsum plasterboard	9.68	kN/m^3	25	mm	0.293	kN/m^2
Total non-structural			130	mm	0.59	kN/m^2

The wall build-up for the concrete design variants is based on the build-up that was used for *De Scharnier* and is kept simple. An overview is given below.

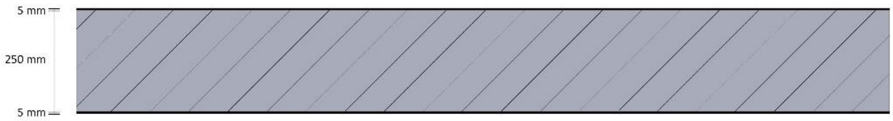


Figure 75: Concrete wall build-up

Table 31: Concrete wall build-up and mass

Material	Mass	Unit	Thickness	Unit	Load	Unit
Plaster	9.68	kN/m^3	5	mm	0.05	kN/m^2
Prefab concrete wall	24	kN/m^3	250	mm	6	kN/m^2
Plaster	9.68	kN/m^3	5	mm	0.05	kN/m^2
Total non-structural			10	mm	0.10	kN/m^2

9.2 Calculation method to determine element sizes

To study the influence of the floor span and building height on the potential profit, the required floor and wall thicknesses for the studied variants must be determined. This section explains the assumptions and methods that are used for the determination of the element sizes. Thereafter, an overview of the elements sizes of each variant is given. Appendix J provides a full calculation of the floor and wall elements of variant 6, which has 5 storeys and a 4.8-meter span.

Design assumptions timber variants

This section provides an overview of the assumptions made for the calculation of the structural elements of the timber design variants. This will include CLT floor elements, CLT wall elements and concrete stability walls.

Floor design assumptions

- All timber floors are protected from weather and wetting and therefore fall under use class 1 and service class 1.
- The loads are transferred from the floors to the walls using steel angle profiles. A hinged connection is assumed between the floors and the walls. This gives the mechanical scheme of a simply supported beam.
- The angle brackets attaching the floors to the walls are 150x150mm for all variants.
- The calculations are done assuming a reference slab with a width of 1 meter.
- The assumed width of one floor panel is 2.25 meter, all panels are assumed to be connected to ensure diaphragm action and can transfer the lateral loads to the stability walls.
- The build-up of the floor can be found in Figure 72. This shows that the timber is exposed on the underside of the floor, therefore calculations assuming a reduced floor thickness in the case of fire are performed.
- The assumed damping is 2.5% (Gustafsson et al., 2019).

Wall design assumptions

- All timber walls are protected from weather and wetting and therefore fall under use class 1 and service class 1.
- In the scenarios with 3 and 5 storeys the walls will transfer both the horizontal and the vertical loads.
- In the variants with more than 5 storeys the CLT walls will only transfer the vertical loads and the concrete stability walls will transfer the horizontal loads. This must be ensured in the specific detailing
- The walls are assumed to be rigidly connected to the foundation. This results in the mechanical scheme of a clamped beam.
- To account for deformations in the foundation the deflections of the walls due to bending, shear and slip in the connections are limited to the building height divided by 1000.
- The walls are designed so that there are no tension forces in the foundation.
- The height of the wall elements is assumed to be equal to the height of one building storey. The wall elements are connected using screws.
- Due to the required wall openings at the side of the building with the circulation routes the structural depth of the walls is assumed to be 2 meters less than the building depth.

- To reduce the risks in the case of fire, both sides of the walls are covered with fireproof gypsum boards, therefore no calculation with a reduced element thickness is made for the walls.
- The wall build-up can be found in Figure 74.
- The calculations are performed for both the end wall (axis A) and the second wall (axis B).
- The façade loads (1.5 kN/m^2 façade area) are taken by the walls as a normal force distributed over the full length of the wall.
- All variants are assumed to be in wind area II on rural terrain. $q_p(z_e)$ is determined using linear interpolation between the given values in NEN 1991, table NB-5.
- The wind loads are based on the total building height, assuming no reduced loads if the height of the building is larger than the building width.

Fire design assumptions

Since the underside of the timber floors is exposed the structural capacity in the case of fire must be checked. For the variants with 3 storeys the minimum fire resistance must be 60 minutes since the highest floor is below 7 meters. For the variants with 5 storeys the minimum fire resistance must be 90 minutes since the highest floor is between 7 and 13 meters. The variants with 9 and 20 storeys require a fire resistance of 120 minutes. Sprinklers are applied for the variant with 20 storeys. The assumption is made that the CLT uses fire resistant adhesives so no fall-off of the panels will occur. The assumed charring rate is 0.65 mm/min. The gypsum boards on both sides of the timber walls are assumed to provide sufficient protection for the walls in the case of fire.

Concrete stability element design assumptions

Concrete stability elements are added to the variants with 9 and 20 storeys to transfer the lateral loads. To determine the required element sizes for the concrete stability elements rules of thumb were used. This states that the depth of a concrete core should be approximately 1/6th of the building height. All concrete stability elements are assumed to be cast in-situ and have a concrete strength class C30/37 and 200 kg reinforcement per m^3.

For the design variants with 9 storeys the rule of thumb states that a concrete core should be approximately 4.8 meters in depth. To match the design, a concrete core was used with a variable width equal to the floor span and a depth of 6 meters in the central bay of the building. Based on estimation of the deflections of the core due to the wind load the concrete wall thickness of 280mm for all variants with 9 storeys.

For the design variants with 20 storeys a core with the width of one bay appeared to be insufficient since the rule of thumb states a core wall width of approximately 10.6 meters. For these variants a concrete core with the width equal to the floor span and a depth of 10 meters is placed at the central bay of the building. Additionally, the end walls are constructed out of reinforced concrete and contribute to the stability. All reinforced concrete stability elements for the variants with 20 storeys have a thickness of 300 mm.

Foundation design assumptions

To assess the embodied carbon of the full structure, assumptions are made regarding the amount of foundation piles required and the dimensions of these piles. For all concrete variants piles with a 300mm diameter and a length of 26 meter are used, these piles are assumed to have a capacity of 1300 kN. The required number of piles is determined by summing the total weight and the imposed variable and wind loads of the concrete design and dividing this by the pile capacity. The lower limit is set to minimum 3 piles under each load bearing wall, which results in a total of at least 24 piles.

Since the weight of a timber structure is lower than the weight of a concrete structure, the dimensions of the foundation of a timber structure can be smaller. This is done by reducing the pile area for the timber design variants with a percentage of half the difference in design load on the piles. The pile area for the timber variants is determined using the following formula:

$$Area\ timber\ piles = \pi \cdot (0.5 * 300)^2 \cdot (\%\ load\ difference \cdot 0.5)$$

For example, for the variant with 5 storeys and a 5.4m span the design load of the concrete and timber variant are 46450kN and 22660kN respectively. The load of the timber variant is 51.2% less than of the concrete variant. Both the concrete and the timber variant have 46450/ 1300 = 36 foundation piles. The pile area and the reinforcement area of the timber variant are reduced by 25.6%. Half the difference in load is used instead of the full difference to keep a conservative approach and ensure a realistic foundation design.

Connection design assumptions

The carbon emissions and cost for connections of the structural elements are outside the scope of this study.

Cost determination assumptions

The assumptions made in the cost estimations are discussed in chapter 4.3. The following specific assumptions are made for the parameter study:

- The costs for a sprinkler installation are assumed to be €37.50 per m² GFA.
- The costs for the CLT walls and floors are assumed to be €1200, -per m³ CLT.
- The costs for the façade are assumed to be €550, - per m² façade area, these costs are equal for the timber and concrete variant.
- For the foundations the costs for the timber variants are reduced with the same percentage as the area of the piles. This percentage is half the percentual difference in load on the piles. It is ensured that the minimum price per square meter GFA is not below €60, - for the foundation structure.
- Since the floor and wall finishing for the timber variant is different than for the concrete variant the costs are adapted according to this.
- The assumed wall finishing costs are €145, - and €180, - per square meter GFA for the concrete and the timber variant respectively.
- The floor finishing costs are €50, - and €70, - per square meter GFA for the concrete and the timber variant respectively.
- The assumed costs for the ceiling finishing are lower for the timber variant since the CLT can be left exposed. The ceiling finishing cost are €80, - and €70, - per square meter GFA for the concrete and the timber variant respectively.
- The assumed general execution costs are €180, - and €163, - per square meter GFA for the concrete and the timber variant respectively.

Required element sizes timber variants

This section provides an overview of the required element sizes for all variants. The element sizes are determined following the calculations as described in Appendix J. For all variants the performed checks are described in Table 32 and Table 33. In Appendix K the unity checks of the performed calculations can be found for all variants. Although accelerations can be governing for the variants with 9 and 20 storeys this check is not performed due to the limited time for this research. It is recommended to investigate the influence of accelerations in further research.

Table 32: Floor checks

Floor ULS	**Floor SLS**
Bending stresses	Deformation Quasi-permanent design situation
Shear stresses	Deformation Characteristic design situation initial deformation
Rolling shear stresses	Deformation Characteristic design situation final deformation
Reaction force at supports	Frequency criterion
Fire and bending stresses	Stiffness criterion
Fire and shear stresses	Limit acceleration
Fire and rolling shear stresses	
Fire and reaction force at supports	

Table 33: Wall checks

Wall ULS	**Wall SLS**
Bending and compression check in plane	Total deflections
Check tension in the foundation	
Shear force check	
Bending and compression check out of plane	

Floor elements

The required thickness of the CLT floor elements is given in Table 31 below and plotted in the graph in Figure 76.

Table 34: Concrete wall build-up and mass

Variant	Span	Floor thickness	Unit	Type	Governing criterion	Utilisation
1, 5, 9, 13	3.6 m	160	mm	Derix L-160/5s	SLS - frequency criterion	61%
2, 6, 10, 14	4.8 m	210	mm	Derix LL-210/7s	SLS - limit acceleration	87%
3, 7, 11, 15	5.4 m	240	mm	Derix LL-240/7s	SLS - limit acceleration	87%
4, 8, 12, 16	6.0 m	280	mm	Derix LL-280/7s	SLS - limit acceleration	86%

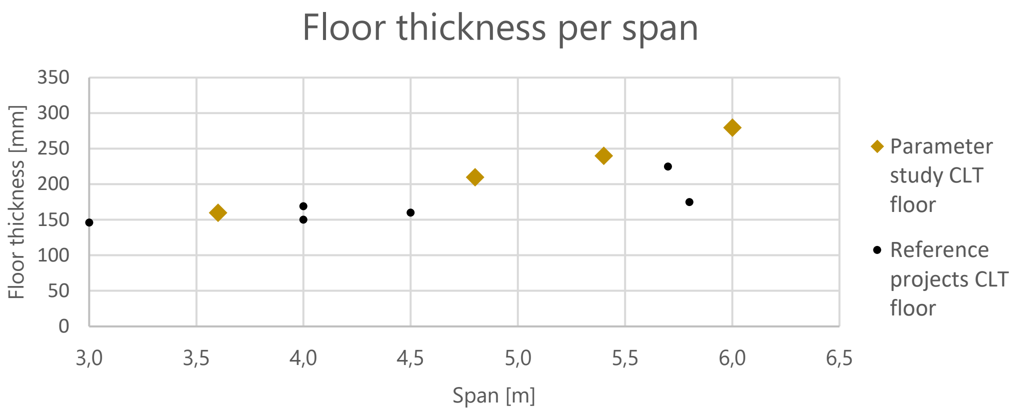


Figure 76: Floor thickness per floor span

The calculated floor thicknesses can be compared to floor thicknesses of CLT floors found in the analysis of constructed timber buildings. Table 35 provides an overview. This shows that the floor thickness for the parameter study is conservative but within the expected range.

Table 35: Floor thickness constructed timber buildings and case studies

Project	Floor span	Floor thickness
Stadthaus	3 m	146 mm
Dalston works (average)	4 m	150 mm
Buiksloterham stories	4.5 m	160 mm
Brock Commons	4 m	169 mm
Arbora (has 50 mm concrete)	5.8 m	175 mm
Case study van Rhijn (van Rhijn, 2020)	5.7 m	225 mm
Case study van Wijnen (Van Wijnen, 2020)	7.8 m	300 mm

Wall elements

In Table 36 an overview of the timber wall thicknesses for each variant is given, the results are plotted in Figure 77.

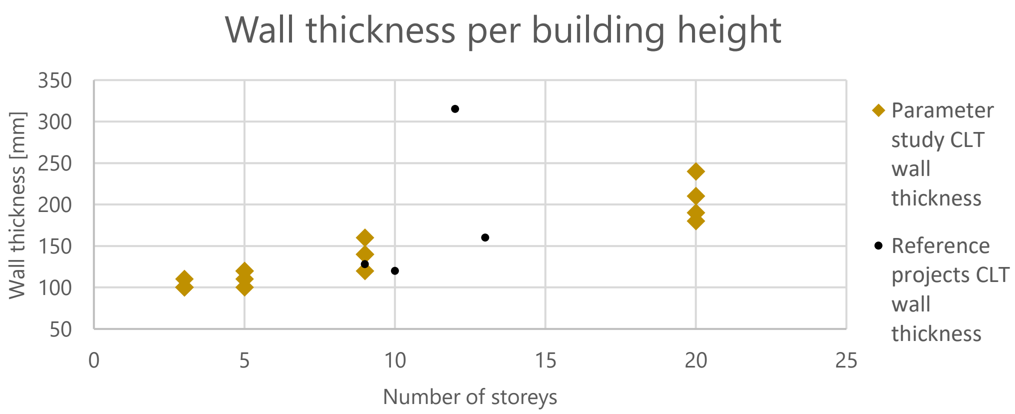


Figure 77: Timber wall thickness per building height

Table 36: Wall thickness CLT walls

Variant	Span	Number of storeys	Wall thickn ess	Unit	Type	Governing criterion	Utilisation
1	3.6 m	3	100	mm	Derix L-100/3s	ULS – out of plane check	48%
2	4.8 m	3	100	mm	Derix L-100/3s	ULS – out of plane check	64%
3	5.4 m	3	100	mm	Derix L-100/3s	ULS – out of plane check	72%
4	6.0 m	3	110	mm	Derix L-110/3s	ULS – out of plane check	59%
5	3.6 m	5	100	mm	Derix L-100/3s	ULS – out of plane check	80%
6	4.8 m	5	110	mm	Derix L-110/3s	ULS – out of plane check	58%
7	5.4 m	5	120	mm	Derix L-120/3s	ULS – out of plane check	70%
8	6.0 m	5	120	mm	Derix L-120/3s	ULS – out of plane check	79%
9	3.6 m	9	120	mm	Derix L-120/3s	ULS – out of plane check	84%
10	4.8 m	9	140	mm	Derix L-140/5s	ULS – out of plane check	77%
11	5.4 m	9	140	mm	Derix L-140/5s	ULS – out of plane check	86%
12	6.0 m	9	160	mm	Derix L-160/5s	ULS – out of plane check	72%
13	3.6 m	20	180	mm	Derix L-180/5s	ULS – out of plane check	82%
14	4.8 m	20	190	mm	Derix LL-190/7s	ULS – out of plane check	85%
15	5.4 m	20	210	mm	Derix LL-210/7s	ULS – out of plane check	90%
16	6.0 m	20	240	mm	Derix LL-240/7s	ULS – out of plane check	75%

The calculated wall thicknesses can be compared to the wall thicknesses found in the analysis of constructed timber buildings. An overview is provided in Table 37. This comparison shows that the calculated wall thicknesses can be realistic.

Table 37: Wall thickness constructed timber buildings and case studies

Project	Floor span	Number of storeys	Wall thickness
Stadthaus	3 m	9	128 mm
Dalston works (average)	4 m	10	120 mm
Case study van Wijnen (Van Wijnen, 2020)	7.8 m	12	315 mm
Buiksloterham stories	4.5 m	13	160 mm

Concrete stability elements

As mentioned previously in this chapter the thickness of the concrete stability elements varies depending on the building height. An overview is given in Table 38.

Table 38: Wall thickness concrete stability walls

Variant	Span	Number of storeys	Wall thickness	Unit
9	3.6 m	9	280	mm
10	4.8 m	9	280	mm
11	5.4 m	9	280	mm
12	6.0 m	9	280	mm
13	3.6 m	20	300	mm
14	4.8 m	20	300	mm
15	5.4 m	20	300	mm
16	6.0 m	20	300	mm

Design assumptions concrete variants

The potential profit of the timber variants is compared to a variant where the structural timber wall elements are replaced by prefab concrete walls and the CLT floors are replaced by concrete precast plank floors. This section provides an overview of the assumptions made for the element thicknesses for the concrete design variants. This will include concrete floor elements, concrete wall elements and concrete stability walls.

Floor design assumptions

The thickness of concrete floors in the parameter study is governed by the acoustic requirements. From conversations with a contractor, the required floor thickness is determined to be 250 mm for spans up to 6.6 meters (M. van Cappelleveen, personal communication, November 23, 2021). Since all spans in the parameter study are under 6.6 meters this floor thickness is used for all variants. Although structurally the concrete floors can be thinner the absence of additional measures for acoustics is assumed to increase the competitiveness of the concrete variants. The floor build-up ca be found in Figure 73 and Table 31.

Wall design assumptions

Like for the floors, the wall thickness is governed by the acoustic requirements. A wall thickness of 250 mm is assumed to be sufficient for all variants (M. van Cappelleveen, personal communication, November 23, 2021). The wall build-up can be found in Figure 75 and Table 31.

Fire design assumptions

The fire resistance of the concrete walls and floors is assumed to provide sufficient safety in the case of fire. Therefore, no additional measures are needed.

Concrete stability element design assumptions

For the stability of the variants with 3 and 5 storeys is ensured by the load bearing walls and floors. For the variants with 9 and 20 storeys additional reinforced concrete core walls are used, these walls have the same thickness and dimensions as in the corresponding timber variant. All concrete stability elements are cast in-situ since this is most common in the Netherlands (*Concrete Building Structures*, 2016). The concrete strength class is C30/37 and 200 kg reinforcement per m^3 is assumed.

Foundation design assumptions
The foundation design assumptions for the concrete design variants are explained in the section regarding the foundation of the timber design variants.

Connection design assumptions
The carbon emissions and cost for connections of the structural elements are outside the scope of this study.

Cost determination assumptions
The assumptions made in the cost estimations are discussed in chapter 4.3. The specific assumptions for the parameter study are discussed in the section regarding the timber design assumptions. The cost calculation of variant 6 can be found in Appendix M.

Required element sizes concrete variants
In Table 39 an overview is given of the element thicknesses for the concrete design variants.

Table 39: Wall thickness concrete walls

Variant	Span	Number of storeys	Floor thickness	Wall thickness	Stability wall thickness	Unit
1	3.6 m	3	250	250	0	mm
2	4.8 m	3	250	250	0	mm
3	5.4 m	3	250	250	0	mm
4	6.0 m	3	250	250	0	mm
5	3.6 m	5	250	250	0	mm
6	4.8 m	5	250	250	0	mm
7	5.4 m	5	250	250	0	mm
8	6.0 m	5	250	250	0	mm
9	3.6 m	9	250	250	280	mm
10	4.8 m	9	250	250	280	mm
11	5.4 m	9	250	250	280	mm
12	6.0 m	9	250	250	280	mm
13	3.6 m	20	250	250	300	mm
14	4.8 m	20	250	250	300	mm
15	5.4 m	20	250	250	300	mm
16	6.0 m	20	250	250	300	mm

9.3 Potential profit comparison

This section discusses the potential profit of the concrete and timber design variants. It is important to note that all results are dependent on the design choices and the assumptions that have been made. However, the goal of the parameter study can be reached by analysing and comparing the outcomes of the variants within the study. In this chapter first the revenue, total building costs and carbon emissions costs are discussed. Thereafter, these aspects are combined to compare the potential profit of the sixteen design variants. Finally, the results' sensitivity to important assumptions is evaluated and conclusions are drawn

Revenue

As discussed in chapter 4.2 the revenue for the homes sold on the free-market sector is assumed to be €3400, - /m^2 and the revenue for social rental homes is €2900, - /m^2 for all variants. Half of the sellable floor area is dedicated to social rental homes and the remaining 50% is sold on the free housing market. Additional revenue for the timber designs of 0%, 2% and 4% is considered.

The revenue is determined based on the net floor area (NFA), subsequently is it divided over the gross floor area (GFA) to compare the results of the studied variants. Because of differences in the ratio between gross and net floor area of the variants, there are slight differences in the revenue per m^2. Although the gross floor area is the same for the timber and concrete option for each variant, the net floor area differs due to the different wall thicknesses.

A larger floor span, thin walls and less space dedicated to vertical circulation are aspects that increase the percentage net floor area. Therefore, these aspects increase the revenue per m^2. The results show that, if no additional revenue is assumed, the maximum difference between the concrete and the timber variant is 2%. An overview of the results is given in Table 40.

Table 40: Revenue per m^2 for all variants

		Additional revenue	3.6 m span	4.8 m span	5.4 m span	6.0 m span
20 storeys	Concrete	-	€2662	€2745	€2790	€2826
	Timber	0%	€2618	€2706	€2743	€2768
	Timber	2%	€2647	€2735	€2773	€2798
	Timber	4%	€2675	€2764	€2803	€2828
9 storeys	Concrete	-	€2766	€2839	€2873	€2901
	Timber	0%	€2775	€2832	€2868	€2885
	Timber	2%	€2805	€2863	€2898	€2916
	Timber	4%	€2835	€2893	€2929	€2948
5 storeys	Concrete	-	€2766	€2839	€2873	€2901
	Timber	0%	€2793	€2852	€2879	€2906
	Timber	2%	€2823	€2883	€2910	€2938
	Timber	4%	€2853	€2913	€2941	€2969
3 storeys	Concrete	-	€2818	€2886	€2915	€2939
	Timber	0%	€2845	€2905	€2933	€2949
	Timber	2%	€2875	€2937	€2964	€2981
	Timber	4%	€2906	€2968	€2996	€3013

Total building costs

The method that is used to determine the total building costs for each variant is described in chapter 4.3. The assumptions regarding the costs for the parameter study are discussed in chapter 9.2. As an example, the cost calculation of variant 6 can be found in Appendix M.

The total building cost of all analysed variants are presented in Table 41. It is found that for all variants the costs for a timber structure are higher than for a concrete structure. For small spans the costs for the concrete variants are relatively high compared to the timber variants. The cost difference varies between 2% for variant 5 and 27% for variant 16. The average cost difference between concrete and timber is 13%. This cost difference is higher than the difference found by Ahmed & Arocho (2021) of 6%, but similar is to the expected increase in cost of Luijks et al. of 14% (2021) The cost difference between the timber and concrete variant of *De Scharnier* is estimated to be 15%, this corresponds to the parameter study.

Table 41: Costs per m² for all variants

		3.6 m span	**4.8 m span**	**5.4 m span**	**6.0 m span**
20 storeys	Concrete	€2502	€2249	€2174	€2097
	Timber	€2783	€2626	€2630	€2661
	Difference	€281	€377	€456	€564
9 storeys	Concrete	€2516	€2265	€2181	€2114
	Timber	€2606	€2508	€2491	€2543
	Difference	€89	€244	€310	€429
5 storeys	Concrete	€2529	€2278	€2194	€2127
	Timber	€2555	€2466	€2480	€2512
	Difference	€27	€189	€286	€385
3 storeys	Concrete	€2573	€2322	€2238	€2171
	Timber	€2618	€2522	€2525	€2589
	Difference	€45	€200	€287	€418

In Figure 78 and Figure 79 the relation between the costs and the floor span is shown. The costs decrease for the timber variant if the span increases from 3.6 to 4.8 m. However, the costs increase between the variants with a 4.8 m span and a 6m span. For the variants with a concrete structure the costs per m² decrease if the floor span increases. Figure 79 shows that that for all building heights the difference in costs increases if the span is enlarged.

In Figure 80 and Figure 81 the relation between the building height and the costs can be found. For the timber variants the costs decrease if the height increases from 3 to 5 storeys, the costs increase between 5 and 20 storeys. The costs of the concrete variants decrease slightly if the height increases. This results in a decreased difference in costs between 3 and 5 storeys and an increased difference in costs between 5 and 20 storeys.

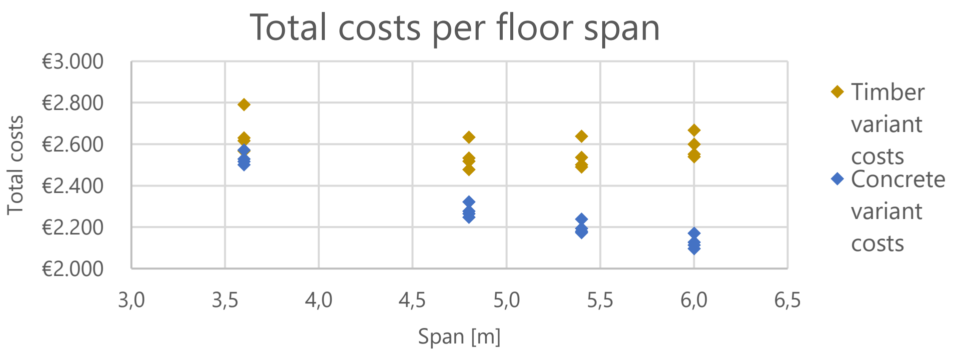


Figure 78: Total cost per span

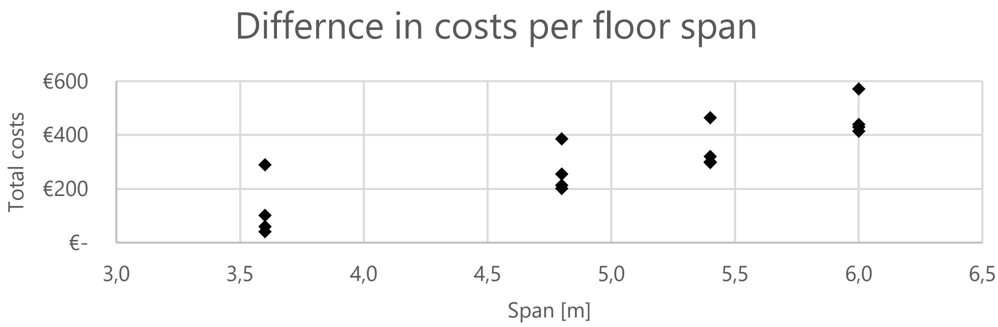


Figure 79: Difference in costs per span

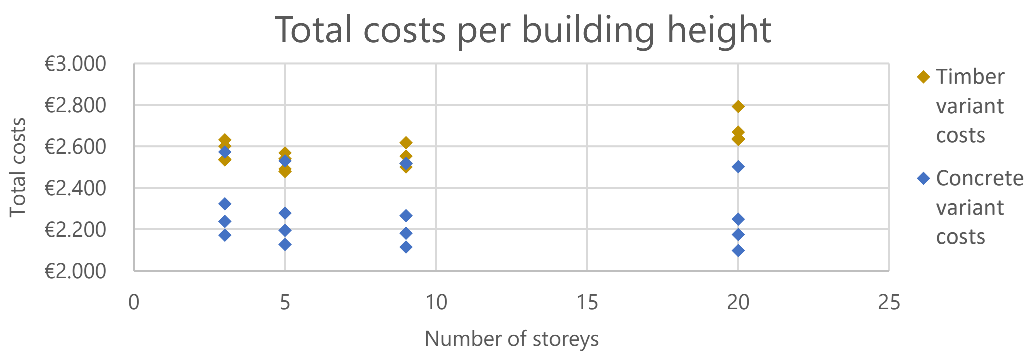


Figure 80: Costs per building height

Figure 81: Difference in costs per building height

Carbon emission costs

To determine the carbon emission costs, the total carbon emissions and the CO_2 price must be determined. The CO_2 price is a variable in the parameter study. The carbon emissions are based on the materials that are required for the structure of the design and the materials required for the finishes. Emissions due to the materials required for connections, installations and the facade are neglected. These emissions are assumed to be identical for the concrete and the timber variant and are therefore irrelevant. The method that is used to determine the carbon emissions is discussed in chapter 4.4. Three scenarios are included regarding the biogenic carbon, which is stored in timber products: a scenario with 100% of the stored carbon subtracted from the emitted carbon, one with 50% subtracted and one with 0% subtracted. All presented results use the selected mean value of the global warming potential for each material, Appendix E provides an overview of these values.

Table 52 shows the carbon emissions for each variant for each of the three scenarios regarding biogenic carbon. For all variants including the biogenic carbon storage has a large effect on the total emissions. It can be concluded that the emissions are lower for the timber variants in all scenarios. The difference in emissions lays between 37% and 61% if the biogenic carbon is excluded. The average results for all timber variants (141 kg CO_2eq/m^2) and all concrete variants (285 kg CO_2eq/m^2) can be compared with the study by Liang et al. (2020) of 181 kg CO_2eq/m^2 and 228 kg CO_2eq/m^2 for timber and concrete respectively. This shows that the difference between concrete and timber is larger in the parameter study than in the study by Liang et al. (2020). The percentual difference in emissions is close to the 45% found in the study of Sathre and Gustavsson (2009). The SCORS ratings indicate that the carbon emissions of the studied design are within the expected limits.

Table 42: Carbon emissions per m^2 for all variants

		Carbon storage	3.6 m span		4.8 m span		5.4 m span		6.0 m span	
20 storeys	Concrete	-	291	D	262	D	255	D	247	C
	Timber	0%	168	B	154	B	154	B	155	B
	Timber	50%`	37	A++	9	A++	-8	A+++	-26	A+++
	Timber	100%	-93	A+++	-137	A+++	-169	A+++	-207	A+++
9 storeys	Concrete	-	299	D	271	D	262	D	256	D
	Timber	0%	134	A	132	A	133	A	138	A
	Timber	50%	-1	A+++	-22	A+++	-31	A+++	-47	A+++
	Timber	100%	-136	A+++	-176	A+++	-194	A+++	-233	A+++
5 storeys	Concrete	-	313	E	285	D	276	D	271	D
	Timber	0%	124	A	125	A	128	A	133	A
	Timber	50%	-14	A+++	-31	A+++	-43	A+++	-56	A+++
	Timber	100%	-152	A+++	-188	A+++	-214	A+++	-244	A+++
3 storeys	Concrete	-	348	E	315	E	304	E	298	D
	Timber	0%	147	A	143	A	145	A	151	B
	Timber	50%	1	A++	-20	A+++	-31	A+++	-49	A+++
	Timber	100%	-145	A+++	-183	A+++	-207	A+++	-248	A+++

Spitsbaard & van Leeuwen (2021) state that the carbon emissions of multi-family homes should be maximum 220 kg CO_2-eq /m^2 in 2021 to reach the climate goals of the Paris agreement. All timber variants meet this requirement. However, the emissions of the concrete variants are all higher than 220 kg CO_2-eq /m^2. In 2030 the emissions of multi-family homes should be maximum 139 kg CO_2-eq /m^2. This requirement is met for the timber variants with 5 of 9 building storeys.

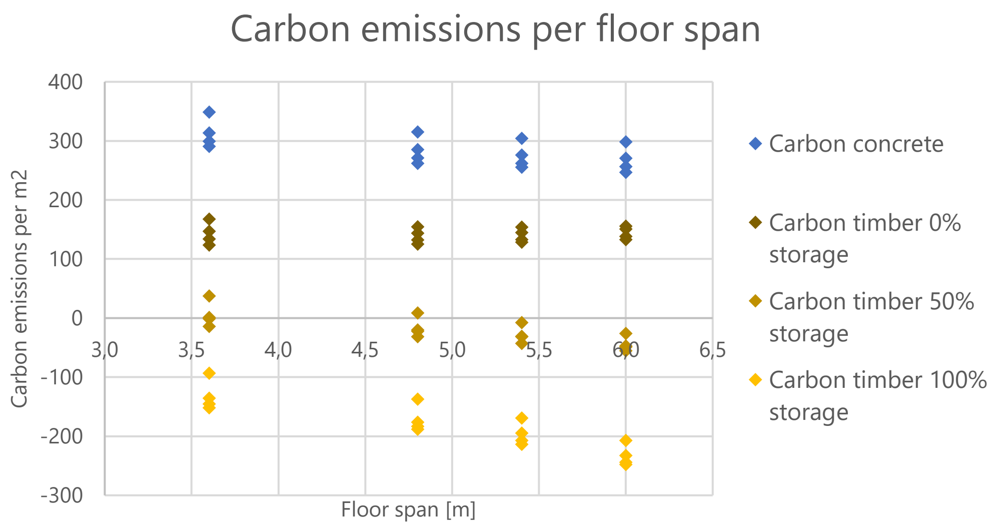


Figure 82: Carbon emissions per floor span

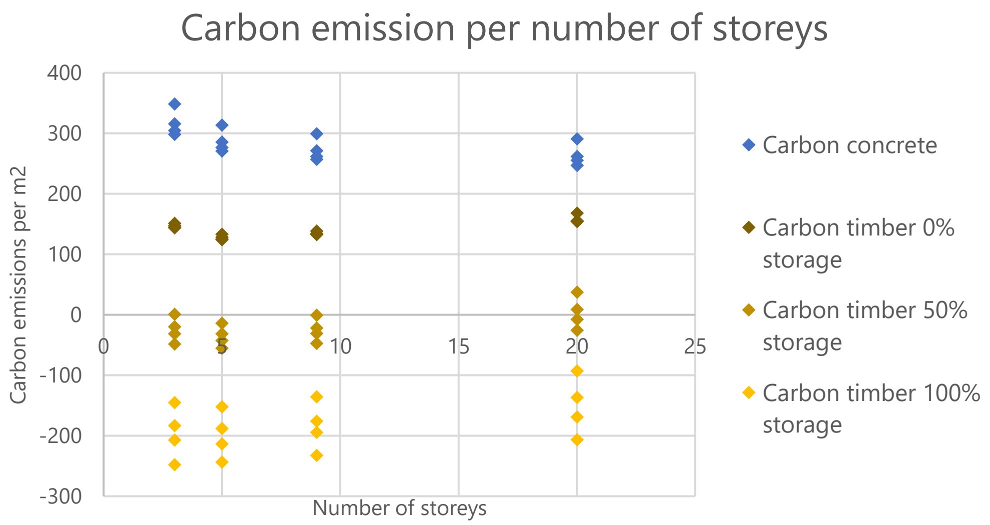


Figure 83: Carbon emissions per number of building storeys

In Figure 82 and Figure 83 the influence of the building height and floor span on the total carbon emissions can be found. As is visible in Figure 82 for the concrete variants the carbon emissions per m^2 decrease if the floor span increases. The same holds for the timber variants if 50% or 100% carbon storage is included. However, if the carbon storage is not included in the calculation this trend is not followed. Figure 83 shows that for the concrete variants the carbon emissions decrease if more building storeys are added. For the timber variants the emissions increase between 5 and 20 storeys for all scenario's regarding the biogenic carbon. For all variants the difference in emissions between a concrete and a timber structure decreases if the number of building storeys increases. The difference in emissions also decreases if the floor span increases and the carbon storage is not included.

Potential profit

The potential profit is determined by subtracting the total building costs and the carbon cost from the revenue. Since multiple scenarios are considered for each variant regarding the CO_2 price, carbon storage and additional revenue, multiple outcomes for the potential profit of each variant are found. A parallel coordinated plot has been made using Arup parameter space to visualise all the results. The results can be assessed using this link: http://parameterspace-legacy.arup.com/?ID=BL_3NABJ0E.

An overview of the potential profit of all variants in the case that the carbon emission costs are zero is given in Table 43. This shows that in this scenario the potential profit is higher for the designs with a concrete structure for all the investigated variants. This was expected since the cost for the concrete variants are lower, the difference in revenue is small and the carbon emission costs are set to zero. Also, it can be concluded that a timber structure for the variant with 20 storeys and a 3.6 m span is not favourable since it has a negative potential profit, which indicates that the estimated costs are greater than the estimated revenue.

Table 43: Potential profit per m² without carbon costs

		Additional revenue	**3.6 m span**	**4.8 m span**	**5.4 m span**	**6.0 m span**
20 storeys	Concrete	-	€160	€496	€616	€729
	Timber	0%	€-164	€80	€113	€107
	Timber	2%	€-136	€109	€143	€137
	Timber	4%	€-108	€138	€172	€167
9 storeys	Concrete	-	€250	€574	€692	€787
	Timber	0%	€169	€324	€377	€342
	Timber	2%	€199	€354	€407	€373
	Timber	4%	€229	€385	€438	€404
5 storeys	Concrete	-	€237	€561	€679	€774
	Timber	0%	€237	€385	€400	€394
	Timber	2%	€267	€416	€431	€425
	Timber	4%	€297	€447	€462	€457
3 storeys	Concrete	-	€245	€564	€677	€767
	Timber	0%	€227	€384	€407	€360
	Timber	2%	€258	€415	€439	€392
	Timber	4%	€288	€447	€470	€424

For each variant it is determined which CO_2 price would result in an equal potential profit for a timber and a concrete building structure. The CO_2 prices are determined for the scenarios with 0%, 2% and 4% additional revenue for a timber structure and for 0%, 50% and 100% subtraction of the stored carbon from the emitted carbon. The required CO_2 price is determined by setting the potential profit of the concrete variant equal to the potential profit of the timber variant. An algebraic description leads to a formula with the CO_2 price as the output variable.

$$Potential\ profit_{concrete} = Potential\ profit_{timber}$$

$$Revenue_{concrete} - Build.costs_{concrete} - Carbon\ emissions_{concrete} \cdot CO2\ price = Revenue_{timber} - Build.costs_{timber} - Carbon\ emissions_{timber} \cdot CO2\ price$$

$$CO2\ price = \frac{Revenue_{concrete} - Revenue_{timber} - Build.costs_{concrete} + Build.costs_{timber}}{Carbon\ emissions_{concrete} - Carbon\ emissions_{timber}}$$

Table 44: Required CO_2 price for the potential profit of a timber and a concrete structure to be equal

	Additional revenue	3.6 m span			4.8 m span			5.4 m span			6.0 m span		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.70	€1.06	€2.18	€0.90	€1.41	€3.33	€1.05	€1.69	€4.39	€1.24	€2.06	€6.15
	2%	€0.77	€1.17	€2.41	€0.97	€1.53	€3.60	€1.11	€1.80	€4.68	€1.30	€2.17	€6.48
	0%	€0.85	€1.28	€2.64	€1.04	€1.64	€3.88	€1.18	€1.91	€4.97	€1.37	€2.28	€6.81
9 storeys	4%	**€0.05**	**€0.07**	€0.13	€0.42	€0.65	€1.36	€0.56	€0.87	€1.97	€0.78	€1.26	€3.23
	2%	€0.12	€0.17	€0.31	€0.49	€0.75	€1.58	€0.62	€0.97	€2.21	€0.85	€1.36	€3.50
	0%	€0.19	€0.27	€0.49	€0.56	€0.85	€1.80	€0.69	€1.08	€2.45	€0.91	€1.47	€3.76
5 storeys	4%	€-0.13	€-0.18	€-0.32	€0.24	€0.36	€0.71	€0.44	€0.68	€1.47	€0.62	€0.97	€2.30
	2%	€-0.06	€-0.09	€-0.16	€0.31	€0.46	€0.90	€0.51	€0.78	€1.68	€0.68	€1.07	€2.53
	0%	€0.00	€0.00	€0.00	€0.37	€0.55	€1.10	€0.57	€0.88	€1.89	€0.74	€1.16	€2.76
3 storeys	4%	€-0.09	€-0.12	€-0.21	€0.24	€0.35	€0.68	€0.40	€0.61	€1.29	€0.63	€0.99	€2.33
	2%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.87	€0.47	€0.71	€1.49	€0.69	€1.08	€2.54
	0%	**€0.04**	**€0.05**	€0.09	€0.36	€0.54	€1.05	€0.53	€0.80	€1.69	€0.75	€1.17	€2.76

In Table 44 the required CO_2 prices for the potential profit of a timber and a concrete structure to be equal are given. This table shows zero or negative CO_2 prices in 15 scenarios, which indicates that the timber variant is competitive without additional cost for CO_2 emissions. This shows for example that the variant with 5 storeys and a 3.6 m span can be competitive without carbon storage and without additional revenue. The variant with 3 storeys and a 3.6 m span is competitive if 2% additional revenue is assumed. If the CO_2 price on the European trading market of March 2022 of €0.08/ kg-CO_2eq (Beunderman, 2021) would be applied the variant with 9 storeys and a 3.6 m span can be competitive if there would be 4% additional revenue and 50% carbon storage included.

Table 44 also shows that the required CO_2 prices decrease if more additional revenue is assumed or if a larger percentage of the biogenic carbon is subtracted of the emitted carbon. For all investigated building heights, the required CO_2 price increases if the floor span increases. This indicates that a smaller span increases the competitiveness of a timber building structure. For almost all variants the required CO_2 price increases if the number of storeys increases. There is an exception for the variant with a 3.6m span, for this variant the required CO_2 price decreases between 3 and 5 storeys and then increases between 5 and 20 storeys.

Finally, Table 44 shows a high required CO_2 price for many variants. For example, a CO_2 price of €1.10 for variant 6 would result in additional costs of €313, - per square meter GFA for the concrete variant. This is an indication that the cost difference between a concrete and a timber building structure is high.

Sensitivity study

To investigate the influence of the key assumptions on the results a sensitivity study is performed. The investigated aspects are shortly discussed in this section, Appendix N provides an overview of the results with alternative assumptions. An overview of the average required CO_2 price is given in Table 46.

First the influence of the assumption regarding the price for 1 cubic meter of CLT is investigated. An increase of 10% for the CLT price results in an increase in building costs between 2.2% and 3.6% for the timber variants. This also influences the required CO_2 prices for which the timber variants would be competitive. In Table 45 the required CO_2 prices are shown if the CLT price would be €1320, - per cubic meter. The average required CO_2 price of all investigated variants (€1.53) is 27% higher than for the base scenario with a CLT price of €1200, - per cubic meter (€1.21). Table 45 also shows there are no longer negative CO_2 prices, which means that there is no scenario under which a timber structure would be competitive if the CO_2 price is zero. However, if the CLT price would decrease with 10%, variants 1 and 5 are competitive without emission costs. Also, variant 9 would be competitive if 2% additional revenue is assumed or if the CO_2 price would be €0.04/ kg-CO_2eq or more.

Table 45: Required CO_2 price for the potential profit of a timber and a concrete structure to be equal with a 10% higher CLT price

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.85	€1.29	€2.67	€1.07	€1.68	€3.96	€1.22	€1.98	€5.13	€1.42	€2.37	€7.08
	2%	€0.93	€1.41	€2.90	€1.14	€1.80	€4.23	€1.29	€2.09	€5.43	€1.49	€2.48	€7.41
	0%	€1.00	€1.52	€3.13	€1.21	€1.91	€4.50	€1.36	€2.20	€5.72	€1.56	€2.59	€7.74
9 storeys	4%	€0.19	€0.28	€0.50	€0.58	€0.89	€1.88	€0.72	€1.13	€2.56	€0.96	€1.55	€3.97
	2%	€0.26	€0.38	€0.69	€0.65	€1.00	€2.10	€0.79	€1.23	€2.80	€1.02	€1.65	€4.23
	0%	€0.33	€0.48	€0.87	€0.72	€1.10	€2.32	€0.86	€1.34	€3.04	€1.09	€1.75	€4.49
5 storeys	4%	€0.01	€0.01	€0.02	€0.40	€0.59	€1.17	€0.61	€0.93	€2.02	€0.79	€1.24	€2.94
	2%	€0.07	€0.10	€0.18	€0.46	€0.69	€1.36	€0.67	€1.03	€2.23	€0.85	€1.34	€3.17
	0%	€0.14	€0.20	€0.34	€0.53	€0.79	€1.55	€0.74	€1.13	€2.44	€0.91	€1.44	€3.40
3 storeys	4%	€0.05	€0.07	€0.13	€0.39	€0.58	€1.13	€0.57	€0.86	€1.81	€0.80	€1.26	€2.97
	2%	€0.11	€0.16	€0.28	€0.45	€0.67	€1.31	€0.63	€0.96	€2.01	€0.86	€1.35	€3.18
	0%	€0.18	€0.25	€0.43	€0.51	€0.77	€1.49	€0.69	€1.05	€2.21	€0.92	€1.45	€3.40

Secondly, the influence of increased costs for the finishing of the walls and floors of the timber variants is studied. A 10% increase of these finishing costs increases the building costs of the timber variants with 2.0% to 2.9%. The average required CO_2 prices of all variants with higher finishing costs (€1.47) are 22% higher than in the base scenario (€1.21).

Decreasing the thickness of the concrete floors by 10% to 225 mm, decreases the carbon emissions of the concrete variants by 2.8% to 3.5%. The costs of the floors are assumed to remain unchanged. Decreasing the concrete floor thickness has a limited influence on the required CO_2 price, the average increase is 6%.

Decreasing the thickness of the concrete walls with 10% reduces the carbon emissions of the concrete variants with 2.6% to 4.8%. This shows a larger influence on the emissions than reducing the floor thickness. However, the influence on the required CO_2 price for the timber variants to be competitive is similar, a 6% increase.

The design of the core is the same for the concrete and the timber variant. Therefore, the assumption of the amount of reinforcement in the concrete core does not influence the required CO_2 prices for which a timber structure is competitive. The influence on the total carbon emissions compared to the concrete base variant is limited between 0.6% for variant 12 and 2.2% for variant 13.

The assumed reinforcement in the concrete precast plank floors does influence the required CO_2 prices. The total carbon emissions of the concrete variants increase with 0.9% to 1.2% if the reinforcement ratio is increased by 10%. The required CO_2 prices decrease with 2% on average.

The chosen concrete strength class has a large influence on the carbon emissions of the concrete variants. If the concrete class increases from C30/37 to C40/50 the carbon emissions increase with 15% (variant 5) to 21% (variant 14). This increases the difference in carbon emissions between the concrete and the timber variant. Therefore, the influence on the required CO_2 prices for an equal potential profit is large. These prices are reduced by 17% on average.

The influence of the assumptions regarding the foundation structure are investigated by changing the costs and amount of material reduction for the timber variant. Instead of reducing the foundation of the timber variant with half the difference in load on the foundation, the full load difference is considered. This results in a cost reduction of 0.3% to 1.2% for the timber variants, and a carbon reduction of 1.0% to 5.6%. The required CO_2 prices for the timber variant to be competitive are 8% lower on average in this scenario.

The sensitivity of the results on the assumption that the core is constructed out of in situ concrete core is tested. Changing the core to a prefabricated concrete core increases the carbon emissions of the variants with 9 or 20 storeys for both the timber and the concrete option. The percentual difference in emissions for the concrete variants is between 0.9% and 3.1%. Since the core design is the same for the concrete and the timber variant the required CO_2 prices are not affected.

Finally, the effect of the chosen EPD input values for the carbon emissions is investigated. The average CO_2 prices increase with 56% if the low impact values are used instead of the mean impact values. However, the variants that would be competitive without emission costs are the same as for the base scenario. The same holds for the scenario in which the high EPD input values are used.

The results are sensitive to the assumptions since the required CO_2 prices can change significantly. However, in all investigated scenario's the variant with lowest required CO_2 price is variant 5. Also, the effect of enlarging the floor span or increasing the number of storeys on the required CO_2 price, is the same for all scenarios in the sensitivity study.

Table 46: Summary sensitivity of the average required CO_2 price

Scenario	Average required CO_2 price	% Difference with base scenario
Base scenario	€ 1.21	0%
CLT price + 10%	€ 1.53	27%
CLT price – 10%	€ 0.88	-27%
Floor and wall finishing costs timber + 10%	€ 1.47	22%
Thickness concrete floors - 10%	€ 1.28	6%
Thickness concrete walls - 10%	€ 1.28	6%
Decreases core reinforcement -10%	€ 1.21	0%
Decreases concrete slab floors reinforcement -10%	€ 1.19	-2%
Concrete strength class C40.50 instead of C30/37	€ 1.00	-17%
Reduce foundation timber variant with 100% of the load difference	€ 1.11	-8%
Prefab core instead of in situ core	€ 1.21	0%
All EPD's low value	€ 1.88	56%
All EPD's high value	€ 0.89	-27%

9.4 Conclusions

To investigate the influence of the building height, floor span, CO_2 emission costs, assumed additional revenue and calculation method regarding biogenic carbon on the competitiveness of timber building structures, a parameter study is performed. The outcomes of the qualification phase are used as design input for the variants of the parameter study. The research design that is used for the parameter study consists of sixteen variants. Four different floor spans of 3.6, 4.8, 5.4 and 6 meters are included and four different building heights of 3, 5, 9 and 20 building storeys are considered.

For each variant the potential profit is determined by subtracting the total building costs and the carbon cost from the revenue. The revenue is influenced by the ratio between the gross and the net floor area. Therefore, thin walls, a larger floor span and less space dedicated to circulation routes can increase the revenue per m^2. The costs depend mostly on the amount of used material. For all variants the costs for a concrete structure are lower than for a timber structure with an average cost difference of 13%. The difference in costs between the concrete and the timber variant increases if the floor span increases. For all variants the carbon emissions for a timber structure are lower than for a concrete structure. The CO_2 emissions per m^2 of the concrete variants decrease if the building height or the floor span increases. The carbon emissions for the timber variants decrease if the floor span increases and 50% or 100% carbon storage is included. However, if the carbon storage is not included in the calculation this trend is not followed.

To compare the competitiveness of the sixteen design variants, the required CO_2 price for which the potential profit of a timber structure is equal to the potential profit of a concrete structure is determined. Additionally, this required CO_2 price is used to investigate the influence of assumed additional revenue for timber structures and of the inclusion of biogenic carbon in the calculation, on the competitiveness of timber structures. It is concluded that without additional CO_2 emission costs and without additional revenue for timber structures variant 5 the required CO_2 price is zero, which indicates a timber structure is competitive in this scenario. Variant 1 can be competitive if the additional revenue is 2% is applied. In general, the required CO_2 price is lower if the carbon storage is included 100% or if more additional revenue for timber structures is assumed. Also, it can be concluded that smaller spans result in lower required CO_2 prices and therefore a more competitive building design. The amount of CLT required for the floors decreases if the span decreases, which decreases the material costs. The competitiveness of timber structures increases if the building height decreases. However, there is an exception for the variants with a 3.6-meter span. In this case the competitiveness increases if the building height increases from 3 to 5 storeys and subsequently decreases between 5 and 20 storeys. The assumption that the floor and wall thickness are the same for variant 1 and 5 can be an explanation for this.

Part 4: Discussion, conclusion, and recommendations

In this section the final parts of this thesis are presented. First, the results of the research are discussed. Thereafter, conclusions are drawn for both the sub research questions and the main research question. Finally, recommendations for further research and for practice are made.

10 Discussion

Although using timber as a structural building material can help reducing the carbon emissions by the building industry, it is not commonly used in the Netherlands. Therefore, the opportunity of reducing CO_2 emissions by constructing in timber is not utilised to its full potential. One of the main reasons for the reluctance towards timber structures is the (perception of) higher cost. This thesis aims to identify under which conditions structural timber is competitive with concrete as a structural building material in the Netherlands. The competitiveness of timber is determined by comparing the potential profit of concrete and timber building structures. The potential profit is defined as the project revenue minus the total building costs minus the carbon emission costs.

First the validity and limitations of the research are discussed per sub research question. Thereafter the results and method regarding the main research question are discussed.

10.1 Discussion per sub question

This section discusses the results of the seven sub research questions of this thesis.

Study into the problem context

The research into the contribution of the buildings super and substructure to the global carbon emissions uses information from multiple sources. This makes the results reliable since the numbers from these various sources are consistent. However, it is practically impossible to precisely measure the global carbon emissions. The results show an accurate estimation, but the actual emissions in the Netherlands can vary from the presented results. However, the results are suitable to determine if reducing the emissions of building structures is relevant.

The performed research into the advantages and disadvantages of concrete and timber, as structural building materials, gives insights in the current situation in the Netherlands. This research is based on Dutch and international literature on the subject. The outcomes of this research could be strengthened by more research into the Dutch industry specifically and by adding interviews with industry experts. This would also strengthen the conclusion on which barrier currently has the largest influence.

Competitiveness comparison method

The method to estimate the competitiveness of timber structures by calculating the potential profit is chosen because it provides the possibility to not only compare the total cost but to include the revenue and environmental costs. This is beneficial since regulations regarding the environmental impact of buildings and the willingness of users to pay a higher cost for a more sustainable building has a large influence on the competitiveness of timber. More complex issues such as consumer preferences and industry traditions are not included in the comparison. However, it is important to recognise their influence. Project specific conditions which might influence the competitiveness of a timber structure are excluded in this method as well.

Other methods to compare the competitiveness are not investigated in this research. Including interviews, with industry experts to assess the competitiveness of timber structures, could be an interesting addition to this research.

The outcomes of this research are strongly influenced by the assumptions that are made while determining the potential profit. The revenue of a project is strongly dependent on the location of the building, the building function and on the economic situation on the building market. The total building cost are variable depending on the market situation as well. The assumption is made that all these external factors are equal for the two variants which are compared. Therefore, the difference between the two variants is assumed to be independent of these uncertainties and thus have no effect on the competitiveness of timber compared to concrete.

The calculated carbon emissions, and therefore the imposed emission costs, are strongly dependent on the selected EPD input data. This influence is minimised by comparing EPD data from various sources and selecting a representative mean, low and high source for each material. However, case study and the parameter study show a large variance in the results for the mean, the low and the high input data. This shows that the specific material selection can have a large influence on the total carbon emissions. Including more impact categories, more life cycle stages and a more detailed inventory of the required materials for the building structure would make the results more precise. However, the chosen system boundaries and methodology result in representative outcomes for the comparison.

Carbon impact per building function

The results of the average carbon emissions per building function are based on multiple sources, this increases the reliability of the results. However, the combination of multiple databases can increase the spread of the found carbon emissions per building function. The research into the demands on the Dutch building market is mostly based on the previously constructed building types. The assumption is made that these trends will continue the coming years, however the precise future remains uncertain.

There might be other building functions of which reducing the carbon emissions would have a large effect on the total carbon emission of the construction industry. However, these uses are outside of the scope of this research. Further research is needed to determine if outcomes of this research regarding the conditions under which timber is competitive are true for other building functions.

Structural applications of timber

The results regarding which timber elements are suitable for multi-storey residential buildings are based on the general properties of the elements and on literature. The outcomes provide an estimate of the suitability of the four investigated structural elements for the vertical and stability system and the four investigated floor system. However, additional research is needed to investigate the suitability of less common structural timber applications.

Use of timber in practice

The research into the currently constructed timber buildings assumes that the fact that the analysed projects are realised, indicates that a timber building structure was competitive in these cases. This does not consider the scenario in which a timber structure is chosen to meet the sustainability ambitions although it was less profitable than a concrete structure. Therefore, the realised buildings might not always be competitive with concrete.

Additionally, only the projects with sufficient information available are selected, this might bias the results. The largest amount of information is available on outstanding or record-breaking projects. Therefore, it can be assumed that the most extreme projects are included in the analysis. Additional research into the motivations for constructing timer and into the motivations for selecting a specific system can provide more insights into the conditions under which timber buildings are competitive.

Case study: De Scharnier

The analysed concrete, hybrid and timber variant of *De Scharnier* were developed serving the same function. The assumed total building costs are based on an estimation by the cost advisor *IGG Bouweconomie,* the assumed revenue is also based on the estimation by a professional. Therefore, the results regarding these two aspects are assumed to be trustworthy. The found carbon emissions determined using the LCA method as described and discussed previously in this research. By comparing the outcomes of the case study to the carbon emissions found in literature it can be assumed that the outcomes are reliable. The required CO_2 price for the timber variant to be competitive should be similar to the required CO_2 price for similar building designs. To verify this, more case studies should be performed.

Parameter study

The results from the parameter study are influenced by the assumptions regarding the revenue, total building costs and carbon emissions. Because these assumptions are the same for the 16 analysed variants the influence of the building height, floor span, CO_2 emission costs, assumed additional revenue and calculation method regarding biogenic carbon can still be investigated. Since the parameter study only investigates sixteen variants the results are not sufficient to find an optimal building design. More variations in building height and floor span would increase the reliability of the results.

The results of the parameter study are also dependent on the design decisions regarding the buildings floorplan and structural system. Therefore, the outcomes of this study can only be applied on projects with similar characteristics. Further research is needed to determine if the outcomes are applicable for other structural systems as well. However, the results regarding the effect of including or excluding the biogenic carbon from the calculation are very clear and can therefore be assumed to apply to other projects as well. The same holds for the effects of assuming additional revenue for timber structures.

The decision to assume a thickness of 250 mm for all walls and floors of all concrete variants results in an over dimensioned design in some cases. This can have a negative impact on the results of the concrete variants. However, due to the acoustic and fire safety requirements it is likely that the structural concrete elements would be over dimensioned in practice. The reason for this is that over dimensioning the concrete is less costly than adding layers to the structure to ensure sufficient acoustic insulation. Additionally, it is important to note that the utilisation of the timber floor and wall elements is not equal for all variants which influences the results. For all variants the utilisation is aimed to be close to 80%. There are no checks performed regarding accelerations, these could be governing for the he variants with 20 storeys. Adding these checks could indicate that the floor and wall thickness of these variants needs to be increased or that additional mass should be added to the building. Both these adaptions would decrease the competitiveness of these variants since the costs, or the carbon emissions would increase.

The results from the parameter study can be compared to the results of the case study. Since the structural design of *De Scharnier* uses different systems for the floors and the vertical loads, a comparison of the required CO_2 prices could be used to identify which structural timber system is more competitive. However, the parameter study does not include a variant with similar properties as *De Scharnier* in terms of building height and floor span. Which makes it difficult to draw general conclusions regarding the influence of the structural system on the competitiveness.

10.2 Discussion main research question

To qualify and quantify the conditions under which structural timber is competitive with concrete as a structural building material seven sub research questions are answered using seven studies. The research is structured in three parts.

In the first part the problem context is analysed, and it is determined which calculation methods are to be used. The results of this part are important to understand the research outcomes, and to understand why timber is not yet competitive. Also, this part explains the assumption that the assumed higher building costs are the main barrier for timber structures in the Netherlands. However, for timber to be used more frequently all barriers must be kept in mind when determining the potential profit. There might be other significant barriers which are missed. Conducting interviews with industry experts to gain more in-depth insights into the current barriers could strengthen the conclusions of this research.

The second part aims to qualify which conditions can make timber competitive. The results of this part are useful to determine which variables are to be studied in the parameter study and which design decisions are likely to result in a competitive design. However, these results only give an indication of which conditions could result in a competitive design. There are numerous factors influencing which structural material is chosen and there are various factors determining the competitiveness of a building. The studies in this phase do not isolate one condition to investigate the influence on the competitiveness. Therefore, the conclusions regarding the competitiveness of the conditions researched in this phase are only applicable to situations with a similar context and further research is needed to strengthen the results.

In the parameter study performed in the third phase the influence of the building height and floor span on the competitiveness can be determined for the chosen structural system. The parameter study is also suitable to study the influence of the CO_2 emission costs, possible additional revenue for timber structures, and the calculation method biogenic carbon on the competitiveness. The lack of variations in building use, vertical bearing system, stability system, and structural floor system makes that the influence of these conditions is not quantified. Because number of analysed building heights and floor spans is limited an optimal design cannot be defined. While this study focusses on the Netherlands the results might be applicable for other countries as well.

Finally, it is important to note that not all possible conditions that can make a timber building structure competitive are investigated in this research. For example, it would be interesting to investigate the influence of the building layout and architectural design on the competitiveness. However, the selected conditions are investigated while keeping the other factors as constant as possible. Therefore, the results regarding the influence of these nine conditions on the competitiveness of timber building structures are useful to design more competitive buildings using timber in the future.

11 Conclusions

The goal of this thesis is to quantify and qualify the conditions under which a timber building structure is competitive with a concrete building structure in the Netherlands. In this chapter first the conclusions to the sub research questions are summarised. Thereafter, the conclusions for the main research question are formulated.

11.1 Conclusions sub research questions

In this chapter the conclusions of each sub research question are discussed.

Study into the problem context

The estimated impact of the buildings super- and sub- structures is 7-10% of the total global CO_2 emissions. Therefore, it can be concluded that reducing the emissions of buildings structures makes a significant contribution to mitigating climate change.

This research has focussed on reducing the CO_2 emissions by using timber structures instead of concrete structures. While concrete is inexpensive and most frequently used in the Netherlands, the high CO_2 emissions of this material impose a disadvantage. Additionally, the production of concrete is dependent on finite resources. Timber on the other hand is infinitely available if the forests are well managed. The production of structural timber elements is less carbon intensive and CO_2 is captured when trees are grown. However, the current barriers of implementing timber make that it is not commonly used in the Netherlands. While limited experience and additional measures regarding acoustics and fire safety impose issues, the (perception of) higher cost is found to be the main barrier for timber structures.

Competitiveness comparison method

The competitiveness of timber structures in relation to concrete is determined by comparing the potential profit. It can be concluded that this method is suitable for including the total building costs, the revenue, and the carbon emissions in the comparison. Also, the additional measures that are needed to ensure the same functional unit are included and an option to monetise carbon reduction is provided. However, not all possible barriers can be included, for example barrier of limited experience in timber is not investigated in this method.

Carbon impact per building function

The variation between the minimum and maximum embodied carbon emissions for the same building use is very large. This indicates that the carbon emissions of a building structure are highly dependent on the specific project and design decisions. An investigation into the demands on the Dutch market shows that there is a high demand for multi-storey residential buildings. Additionally, ground-level homes in timber can already be competitive in a light timber frame structure. Therefore, it is concluded that reducing the CO_2 emissions for multi-storey residential buildings has the largest impact on the reduction of emissions of the whole building industry.

Structural applications of timber

From the research into the properties of structural timber elements it is concluded that glued laminated timber (Glulam), cross laminated timber (CLT), and laminated veneer lumber (LVL) are suitable to use for the vertical and stability system of multi-storey residential buildings. Due to the limited strength and dimensions solid timber appears to be suitable for residential buildings with a height up to 4 storeys. For timber floor systems CLT, timber concrete composite (TCC), and a timber hollow core floor are suitable for multi-storey residential buildings. Because of the low possible spans and low acoustic performance, a wooden beam layer floor system is only suitable for buildings up to four storeys.

Use of timber in practice
From the analysis of 34 multi-storey residential buildings, it can be concluded that timber structures are not frequently used for high rise buildings but more often for mid-rise buildings. Only 15% percent of the analysed projects has 18 storeys or more. Also, lower spans are more common in timber buildings. Since the highest analysed building has 24 building storeys it is concluded that buildings above this hight are not yet feasible. Hybrid structures are used for the analysed buildings with more than 18 storeys. The limited strength of timber elements can be an explanation for this.

For the vertical, stability and floor system, CLT seems most competitive since it is most frequently used. CLT walls for the stability system are only used up to 13 storeys, taller buildings require a concrete core or a timber stability frame structure. For the vertical system CLT walls are used up to 21 storeys. For the floor system CLT is used up to 18 storeys, higher buildings often use a TCC floor. A TCC floor is beneficial if additional mass is required to limit the vibrations or if large spans must be made.

The highest all timber building in the Netherlands has four storeys and the highest hybrid building has 21 storeys. Therefore, it can be concluded that currently hybrid structures are more competitive than all timber structures in the Netherlands for high-rise timber residential buildings. For the stability system a concrete core is used frequently and for the floor system TCC and CLT floors are both used in 38% of the analysed buildings in the Netherlands. Additionally, it can be concluded that floor spans between 3.6 and 6.0 meters are most feasible in the Netherlands.

Case study: De Scharnier
The potential profit of a concrete, hybrid, and timber design variant of the project *De Scharnier* are estimated. In the base scenario, with equal revenue and no carbon emission costs, the potential profits per square meter GFA are €2247, €2097, and €2065 for the concrete, hybrid, and timber variant respectively. From this it can be concluded that in this scenario both the timber and the hybrid variant are not competitive.

It is concluded that assuming additional revenue and adding carbon emission costs increases the competitiveness of the timber and hybrid variants. Under the conditions that the stored carbon is 100% subtracted from the emitted carbon and the CO_2 price would be €0.81 per kg CO_2, the timber variant would be competitive. For the hybrid variant the required CO_2 price in this scenario is €1.29. Assuming an additional profit of 2% percent reduces the required CO_2 prices to €0.65 and €0.77 for the timber and the hybrid variant respectively. It can be concluded that the hybrid variant is more competitive than the timber variant up to a CO_2 price of €0.35. A comparison with the CO_2 price on the European trading market of €0.08 in March 2022 shows that the required CO_2 prices for the timber and hybrid design variant for *De Scharnier* are high. Changing the floor span, building height, or floor system could make timber more competitive.

Parameter study

For sixteen design variants the potential profit of a concrete and a timber building structure is compared in a parameter study. Four different floor spans of 3.6, 4.8, 5.4 and 6 meters are included and four different building heights of 3, 5, 9 and 20 building storeys are considered.

The potential profit is the largest for the variants with a high revenue, low building costs and low carbon emission cost. It is found that thin walls, a larger floor span and less space dedicated to circulation routes can increase the revenue per m^2. The total building costs of the timber variants decrease if the walls and floors are thinner. The carbon emissions and therefore the emission costs are the lowest for the variants that have no concrete elements.

For each variant the required CO_2 price for which a timber building structure is competitive is determined. The results show that without additional CO_2 emission costs a timber structure would be competitive for the design variant with 5 storeys and a 3.6-meter floor span. The same holds for the variant with 3 storeys and a 3.6-meter span if the additional revenue for timber structures is 2%. From this it can be concluded that a timber building structure can already be competitive if an efficient structure is used.

The parameter study shows that the decreasing the floor span and/or the building height increases the competitiveness. Both these measures reduce the amount of timber used per square meter; this reduces the building costs. Additionally, in the scenario that the stored carbon is not subtracted from the emitted carbon the difference in carbon emissions between the concrete and the timber variant increases if the span or the height decreases. Which decreases the required CO_2 price for an equal potential profit. However, it is important to note that the functionality limits the minimum acceptable floor span and building height. Additionally, it is concluded that adding CO_2 emission costs increases the competitiveness of timber structures. If these costs are added including the biogenic carbon with a larger percentage increases the competitiveness of timber even more. Finally, it is found that, as expected, additional revenue increases the competitiveness of timber.

11.2 Conclusions main research question

The influence of each of the nine investigated conditions on the competitiveness of structural timber is discussed to answer the main research question: Under which conditions is structural timber competitive with concrete as a structural building material in the Netherlands?

Building use

Since there is a high demand for multi-storey residential buildings, this building typology is assumed to be the most competitive. This creates the potential to quickly gain experience and by applying timber more often, current barriers can be removed. Additionally, the high demand makes that reducing the CO_2 emissions for multi-storey residential buildings has the largest impact on the reduction of emissions of the whole building industry. Further research is required to determine under which conditions timber can be competitive for other building uses.

Material vertical bearing system

From the research performed in this thesis it can be concluded that both a vertical bearing system of CLT columns (*De Scharnier*) and of CLT walls (parameter study) can be competitive. CLT columns are competitive for a 16-storey residential building with TCC floors and a 6.6m span under the conditions that the stored carbon is 100% subtracted from the emitted carbon and the CO_2 price would be €0.81 per kg CO_2. A vertical bearing system of CLT walls can result in a competitive timber building for a building with 9 storeys, a 6-meter span, CLT floors, and a CO_2 price of €0.91 per kg CO_2. Although there are differences other than the vertical system, this implies that for the vertical system CLT columns can be more competitive than CLT walls. However, in the analysis of constructed timber buildings it was found that CLT walls are used more frequently. Also, it is important to realise that CLT walls can be used for both the vertical and the stability system while CLT columns can only be used for the vertical system.

Additional research is needed to increase the knowledge on the influence of the material for the vertical system on the competitiveness and to study more possible vertical bearing systems. Is advised to make a comparison between CLT walls and columns with the same floor system, stability system, floor span and building height.

Material stability system

The research shows that both a stability structure of CLT walls (parameter study) and of a concrete core (case study and parameter study) can result in a competitive design for timber buildings. Due to the limited strength and stiffness of CLT and due to the limited experience with timber multi storey buildings, a concrete core is more competitive for buildings with more than 9 storeys in the Netherlands. The parameter study shows that for a building with 5 storeys a CLT stability system can be competitive without carbon emission costs. Additional research is needed to investigate the competitiveness of these two systems between 5 and 9 storeys. Further research is advised on how the stability system influences the competitiveness and on the competitiveness of timber stability frame structures and timber core structures.

Material structural floor system

The research in this thesis shows that timber building designs with a CLT and with a TCC floor can both be competitive with a concrete building design. Since the maximum span of CLT floor is limited to approximately 6 meters, TCC floors are favourable for larger spans. TCC floors are also favourable for high-rise timber buildings because the added mass reduces the vibrations. If carbon emission costs are included a CLT floor is favourable since this system has lower carbon emissions. Further research is needed to determine the competitiveness of hollow core timber floors and to gain more precise knowledge on the influence of the structural material for the floor system on the competitiveness.

Floor span

The parameter study has investigated the competitiveness of building designs with floor spans varying from 3.6 to 6.0 meters. In this study it was concluded that for CLT floors a smaller span results in a more competitive design for all building heights. The amount of CLT required for the floors decreases if the span decreases, which decreases the material costs and increases the competitiveness. It was found that the floor span has a large influence on the competitiveness. However, it is important to note that a small span can decrease the competitiveness if it is no longer functionality acceptable. More research is needed to determine the influence of the floor span on the competitiveness for other floor systems.

Building height

The parameter study has investigated the competitiveness of building designs of 3, 5, 9 and 20 building storeys. From this study it is concluded that, with an exception for the variant with a 3.6 m span, the competitiveness decreases if the hight increases. The amount of CLT required for the walls increases if the height increases, which increases the material costs. Further research is needed including more building heights to determine the optimal building height for a timber structure. Also, it is advised to investigate the influence of the building height on the competitiveness for other structural timber systems.

CO_2 emission costs

Because the carbon emissions are higher for a concrete building structure than for a timber building structure in al investigated scenario's it can be concluded that the competitiveness of a timber building structure increases if the CO_2 emission costs increase. Including CO_2 emission cost would have a large influence on the competitiveness of timber structures.

Additional revenue timber structures

Assuming additional revenue for timber buildings increases the potential profit. Therefore, for all investigated variants the competitiveness of a timber building structure increases if the assumed additional revenue for a timber structure increases.

Calculation method regarding biogenic carbon

Subtracting the stored carbon in timber products from the emitted carbon reduces the total emissions of the timber variants. If CO_2 emission cost are imposed the competitiveness of timber increases if a larger percentage of biogenic carbon is included. The calculation method regarding biogenic carbon has a large influence on the required CO_2 prices for the timber structure to be competitive.

Combination of conditions

Because the defined conditions are interdependent, the influence of one condition on the competitiveness should be considered in relation to the fixed conditions. The parameter study shows that the variant with 5 storeys and a 3.6-meter span would be competitive on the current market without emission costs. This study also shows that by decreasing the building height and the floor span the design can become more efficient and therefore more competitive.

However, additional revenue for timber structures, increasing the CO_2 emission costs, and including a larger percentage of the biogenic carbon can increase the competitiveness of timber buildings. Building experience in timber and considering the carbon emissions when designing a building structure is essential to make timber more competitive and to reduce the carbon emissions by the construction industry to mitigate climate change.

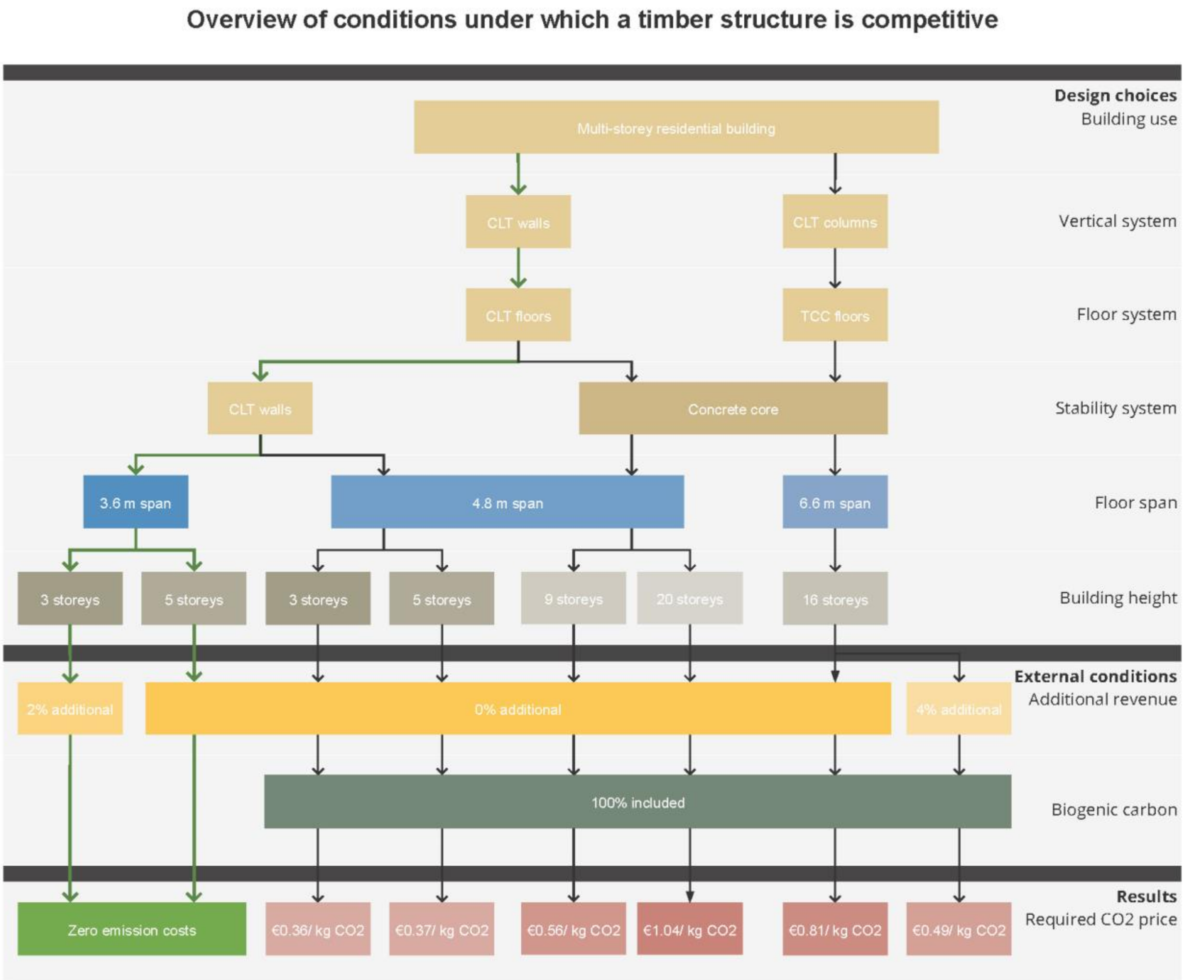


Figure 84: Overview of the combination of conditions under which a timber structure is competitive

12 Recommendations

The recommendations are subdivided in recommendations for further research and recommendations for practice.

12.1 Recommendations for further research

This chapter discusses the additional research which is recommended based on the findings in this thesis.

- This research has found that the high building costs are the main barrier for implementing timber structures more frequently. Therefore, the competitiveness of timber structures is based on the potential profit. Additional research into the current barriers in the Netherlands for implementing timber is advised to investigate if there are additional barriers which are missed in this research. It would be advised to conduct interviews with industry experts to test if the proposed timber building structures would be competitive under the stated conditions.
- The research shows that the carbon emissions are higher for concrete buildings than for timber buildings. However, this research only considers lifecycle stages A1-3. Additional research into the emissions in stage A4-5 and in the use stage of the building could increase the reliability of the results regarding the difference in carbon emissions between concrete and timber structures.
- In this research the carbon emissions are monetised by assuming a price per kg emitted CO_2. This price is based on the emissions in lifecycle stages A1-3 only. Additional research is recommended on how to include the other sustainability and circularity advantages. For example, a discount on the carbon emissions cost could be given to designs with a high recyclability or reuse potential. Including additional costs for depleting finite resources could increase the competitiveness of timber structures as well. Also, it is recommended to investigate the effect of including additional impact categories in the life cycle assessment.
- The results of the parameter study are based on sixteen investigated design variants. In further research it would be recommended to expand this study to gain more knowledge on the conditions that can make timber competitive. These following additional variants are recommended:
    - Variations in vertical bearing systems
    - Variations in stability systems
    - Variations in floor systems
    - Additional variations in floor span
    - Additional variations in building height
    - Variations in building use
    - Variations in building layout by changing the floorplan
- This research does not include a condition regarding the influence of industrialisation and mass production of prefabricated timber elements and modules. Further research is needed to investigate how these developments can increase the competitiveness of timber structures.

12.2 Recommendations for practice

For industry practice the main advice it to use timber more frequently to gain experience and reduce the carbon emissions by the building industry. This section provides an overview of all recommendations for practice.

- To create awareness of the possible impact on mitigating climate change by reducing the carbon emissions of building structures it is recommended to estimate the carbon emissions for every building design. This will increase the knowledge on which design decisions result in a building design with low carbon emissions. Also, estimating the carbon emissions in an early design stage is advised to gain knowledge on how design choices can influence the carbon emissions. With this information an informed decision can be made on how the available budget can be optimally used to decrease the carbon emissions.
- Research shows that neglecting the carbon storage capacity of timber and other biobased materials undervalues the sustainability potential of these materials. Therefore, it is advised to subtract at least 50% of the stored carbon from the emitted carbon in timber products when determining the carbon footprint or performing an MPG calculation.
- It is recommended to include taxes for CO_2 emissions or give subsidies if carbon is stored for newly constructed buildings. This will provide an incentive for the construction industry to reduce the carbon emissions and increase the use of renewable building materials. These measures will increase the chance of reaching the 49% reduction of CO_2 emissions in 2030.
- The competitiveness of timber structures is affected by not only the total building costs but also by the financial and non-financial returns. It is recommended to include the revenue and the reduced carbon emissions in the consideration when choosing a structural building material.
- The competitiveness of timber building structures will increase if there is more experience with this material. Therefore, it is recommended to apply timber more often if the project allows it. Using timber can currently increase the risks. However, if in the future concrete structures can no longer be used because the emissions are too high, the companies with experience in timber have a large advantage.

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14 Appendixes

Appendix A. Additional advantages timber structures

Besides the renewable nature, possible reduction of CO_2 emissions, CO_2 storing capacity and increasing technical possibilities, timber has numerous advantages that make it an interesting building material. The characteristics that have the most influence on the possible reduction of greenhouse gasses or the total building costs are discussed below.

Lower failing costs

Another benefit of prefabrication is the fact that this results in lower failing costs (Bronsvoort et al., 2020; Green & Eric, 2012; Luijks et al., 2021;). Since much of the work is done in the conditioned environment of the factory the processes can be controlled better and errors can be corrected without disturbing the work done on site. Like for a shorter building time these benefits apply to all prefabricated construction parts, however due to the low weight of timber the products can be transported more easily, and prefabrication becomes more attractive.

Design flexibility

With the development of engineered timber products, the design flexibility increased as well (Gosselin et al., 2017; Green & Eric, 2012; Luijks et al., 2021; Waugh Thistleton Architects, 2018). This is an important quality since this means that the architect does not have to be restricted when designing in timber. However it is important to note that when designing timber floors the most effective span for costs and carbon is smaller for timber than for concrete (van Haalen, 2018). Still, the restrictions when designing in timber are decreasing and this results in the fact that timber can be used more often, which enables the reduction of CO_2 emissions.

Aesthetic value

Cover (2020, p. 90) mentions that *"The aesthetic value of exposed mass timber provides market distinction".* Other sources also mention the fact that exposed timber interiors have an aesthetic quality and benefits the indoor climate (Cover, 2020; Franzini et al., 2018; Gosselin et al., 2017; Luijks et al., 2021; Waugh Thistleton Architects, 2018). Additionally, this can save the costs of internal finishes (Cover, 2020). If timber buildings have a higher quality the profit margins go up and the relative costs decrease.

Thermal insulation

An important quality of timber is its low heat conductivity, this means that wood has insulating capacity which makes the building more energy efficient (Archivibe, n.d., Luijks et al., 2021, Sandhaas & Blaß, 2017). The heat conductivity of wood (λ) is between 0.13 and 0.20 W/m·K, while for steel λ= 60 W/m·K (Sandhaas & Blaß, 2017). This reduces the cold bridges created by the structure and the need for additional insulation materials to manage this, this can save costs on materials and energy use in the operation phase.

Appendix B. Research comparing carbon emissions of concrete and timber

The first study is a research done in the name of the institution TNO compared the carbon footprint of houses with Timber frame, a CLT and a concrete (Keijzer et al., 2021). The carbon footprint was calculated only considereing the materials. A standard regular calculation was made and compared with a calculation including the contribution of a temporary storage of CO_2 in timber. The results are presented in Figure 85. This shows that especially timber frame strucures have a lower carbon footprint than concrete houses.

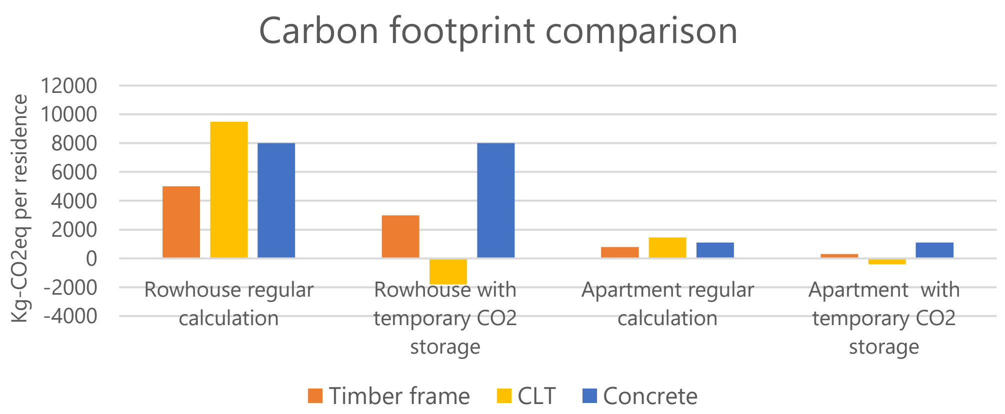


Figure 85: Carbon footprint comparison, adapted from " Een verkenning van het potentieel van CO2- opslag bij houtbouw", by E. Keijzer, S. Klerks et al., 2021

The second research, performed by Luijks et al. (2021), investigated the difference in CO_2 equivalent emissions between a timber frame structure and a concrete or limestone structure for four types of residential buildings in a study of 69000 residences in the Netherlands. As is visible in Figure 86 the emissions are significantly lower for timber frame structures even without biogenic carbon included.

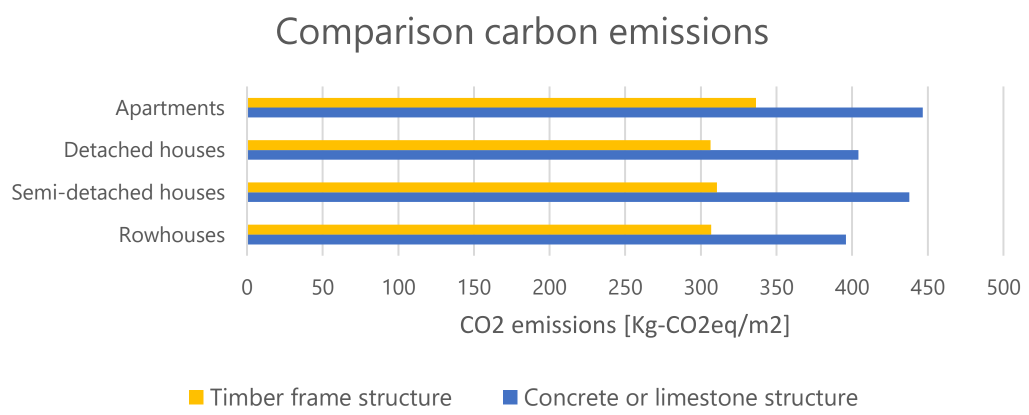


Figure 86: Average CO_2 emissions for residential buildings. Adapted from "Rapportage woningbouw in hout" by T. Luijks et al., 2021, Centrum hout, p. 29.

The third research by de Wolf and Oschsendorf (2021) gathered data on global warming potential (GWP) and structural material quantities of published life cycle assessments (LCAs), projects by leading structural design firms and manually inserted data in an interactive interface. This database can be accessed online (https://www.carbondeqo.com) and the data can be sorted on different categories. In Figure 87 shows the data is sorted per main structural material. This shows that the GWP of timber building structures is significantly smaller than the GWP of buildings where concrete was used as the main structural material.

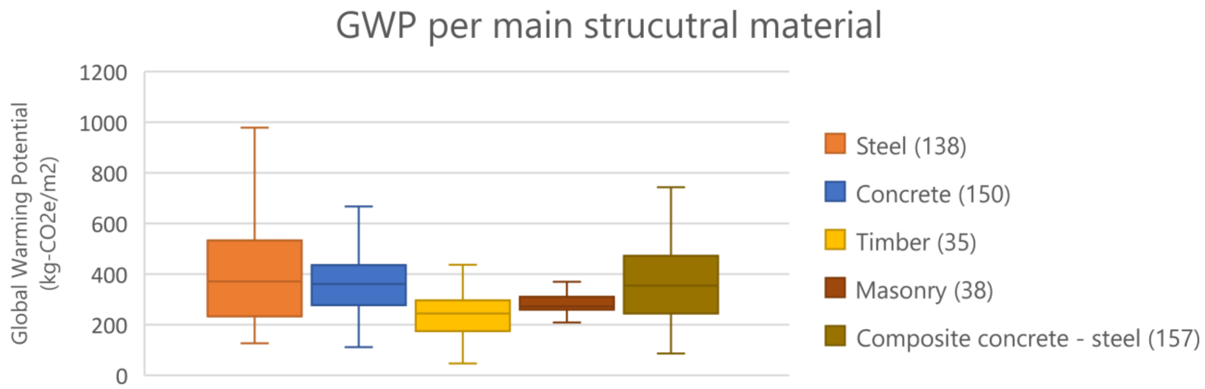


Figure 87: GWP per main structural material. Adapted from deQo database of embodied Quantity outputs, by C. de Wolf, 2021 (https://www.carbondeqo.com/database/graph).

Finally, a research by Hart et al. (2021) aimed to compare the embodied carbon building structures in steel, concrete and timber. This was done by comparing the embodied carbon coefficients for all building life cycles of 127 identical frame configurations of the three materials. All concrete frames used reinforced concrete, the steel frames had a composite floor, and the timber frames were made of glulam with steel connectors and a CLT floor deck. While temporary carbon storage of timber is not included in this analysis "*The results confirm the widely held assumption that timber structures and buildings are likely to have lower WLEC (Whole-life embodied carbon) than their steel and concrete counterparts*." (Hart et al., 2021, p. 410).

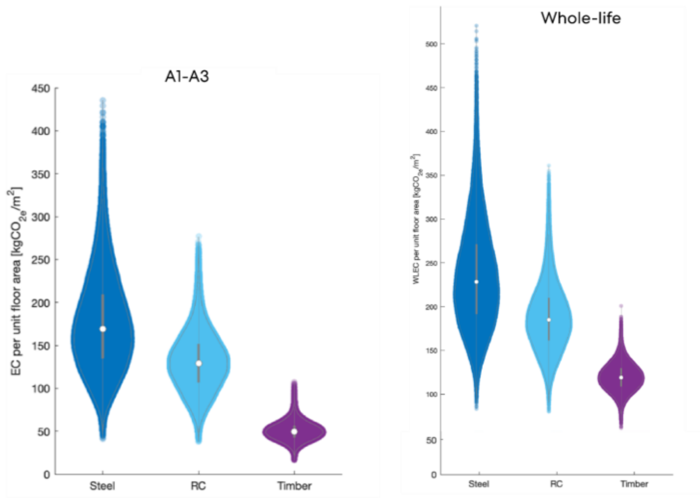


Figure 88: Embodied carbon per unit floor area [kg-CO_2eq/m^2]. From "Whole-life embodied carbon in multi-storey buildings: Steel, concrete and timber structures," by J. Hart et al., 2021, Journal of industrial ecology, 25(2), p. 412-413 (10.1111/jiec.13139)

Appendix C. Example of the classification of NEN2699

Example of the classification of NEN2699

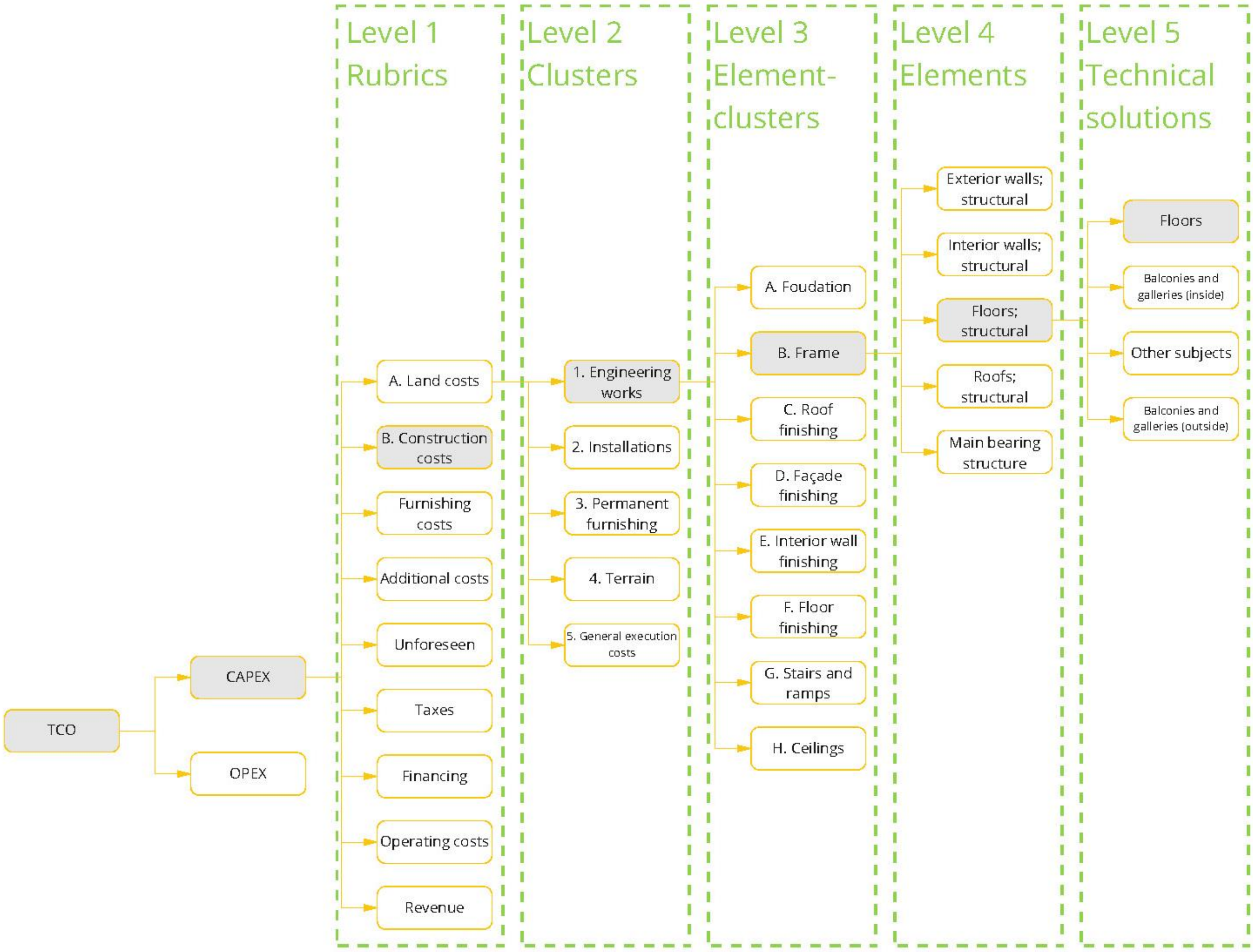


Figure 89: Tree diagram with all five levels. Adapted from: IGG Bouweconomie, 2021and NEN2699

Appendix D. Life cycle assessment method

"*Life Cycle Assessment (LCA) is a specific method that has been developed over several decades that can be used to quantify aspects of the environmental 'performance' or 'impact' of a product or process*" (Jonkers & Ottelé, 2020, p. 30). This is the method that is used to determine the MKI of a building, the specific rules of this analysis method are defined in the Eurocodes (NEN-EN 15804, ISO 14025 and NEN-EN 15978). The life cycle assessment consists of four steps. First, the goal and the scope of the analysis is determined. The next step is to make an inventory analysis, in this step al necessary data is collected regarding the quantities of materials and emissions. Third, the environmental impact is assessed by calculating the impact scores, in this step the shadow price (MKI) can be calculated. Finally, the results are interpretated, to see which materials or life cycle stages have a high impact and to identify how the environmental impact can be reduced. This framework is summarised in Figure 90. The environmental cost indication (MKI in Dutch) of products and constructions can be calculated using various (online) tools or by hand (Jonkers & Ottelé, 2020). The four steps of the life cycle assessment will be described in detail and the relevant concepts will be explained.

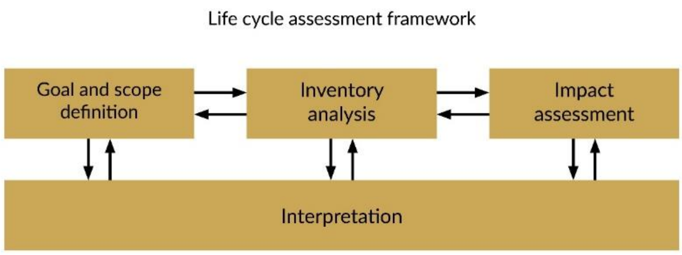


Figure 90: Life cycle assessment framework. From ISO 14040 (Technical Committee ISO/TC 207, 2006)

Step 1: Goal and scope definition

At the beginning of a life cycle assessment, it is important to determine why the analysis is performed therefore the goal of the study must be defined. Jonkers & Ottelé (2020) describe that this consist of three elements; first the intended application should be described, for example this can be a comparison of products with the same function or an identification of environmental 'hot-spots'. Second an explanation of the reason for performing the LCA should be given this can be to support business strategies, but it can also be for educational purposes. Third, the description of the audience for which the LCA is intended must be defined, which can be a governmental institution or involved stakeholders for example.

With the goal of the LCA defined the scope of the study can be defined, this is an important step since this determines what will be included in the calculation. Jonkers & Ottelé (2020) define six elements within this scope definition. The first is the determination of the functional unit of the product, this is defined in ISO 14040 as the "*quantified performance of a product system for use as a reference unit*" (Technical Committee ISO/TC 207, 2006, p. 4). Especially when comparing multiple options, it is important that the functional unit of the two objects is the same. For example, if the sustainability of two different floor systems is compared, they must serve the exact same function so they must cover the same span and withstand the same loads but also have the same intended lifespan. Second the system boundaries of the study should be established (Jonkers & Ottelé, 2020), this determines which modules of the products life cycle stages will be included. In the building's life cycle four stages are identified, the product stage (A1-3), the construction process stage (A4-5), the use stage (B1-7) and the end-of-life stage (C1-

4). These stages are indicated in Figure 91, all carbon emissions are included so both the operational and the embodied carbon.

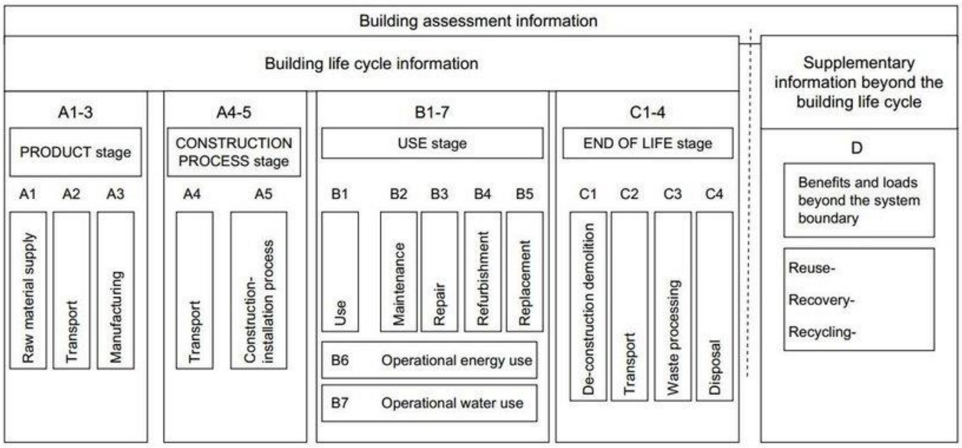


Figure 91: Life cycle stages. From EN 15978:2011 (E) figure 6

Thirdly the followed LCA methodology should be chosen (Jonkers & Ottelé, 2020), this determines which and how many environmental impact categories will be included in the study. Until recently eleven impact categories were defined in accordance with EN 15808 (European Committee for Standardization, 2019), but as of the 1st of January 2021 this has been altered to nineteen impact categories (Nationale Milieudatabase, 2020). Both the impact categories before and after this amendment can be found in Table 47. In some life cycle assessments the decision is made to include only one or two specific impact categories these are 'single-issue' methods, other cases include all categories (Jonkers & Ottelé, 2020). Another part of the LCA methodology determination is to choose the Life Cycle inventory Analysis procedure. This specifies how the impact categories are combined and are internally weighed against each other (Jonkers & Ottelé, 2020).

Table 47: Environmental impact categories before and after the 1st of January 2021. Adapted from "Guide to environmental performance calculations" by National Environmental Database Foundation 2020.

	Environmental impact category units before 1-1-2021	**Indicator**	**Equivalent**
1	Depletion of abiotic raw materials (excluding fossil energy carriers)	ADP	Sb eq
2	Depletion of fossil energy carriers	ADP	Sb eq
3	Climate change	GWP100 j.	CO_2 eq
4	Ozone layer depletion	ODP	CFK-11 eq
5	Photochemical oxidant formation	POCP	C_2H_4 eq
6	Acidification	AP	SO_2 eq
7	Eutrophication	EP	PO_4 eq
8	Human toxicity	HTP	1,4-DCB eq
9	Ecotoxicological effects, aquatic (freshwater)	FAETP	1,4-DCB eq
10	Ecotoxicological effects, aquatic (marine)	MAETP	1,4-DCB eq
11	Ecotoxicological effects, terrestrial	TETP	1,4-DCB eq

	Environmental impact category units after 1-1-2021	**Indicator**	**Unit**
1	Climate change – total	GWP-total	kg-CO_2eq
2	Climate change – fossil	GWP-fossil	kg-CO_2eq
3	Climate change – biogenic	GWP biogenic	kg-CO_2eq
4	Climate change – land use and change to land use	GWP-luluc	kg-CO_2eq
5	Ozone layer depletion	ODP	Kg-CFC_{11}eq.
6	Acidification	AP	mol H+ eq.
7	Freshwater eutrophication	EP freshwater	Kg-PO_4eq.
8	Seawater eutrophication	EP-seawater	Kg-N eq.
9	Land eutrophication	EP-land	mol N eq.
10	Photochemical ozone formation	POCP	Kg-NMVOC eq.
11	Depletion of abiotic raw materials, minerals, and metals	ADP-minerals&metals	Kg-Sb eq.
12	Depletion of abiotic raw materials Fossil fuels	ADP-fossil	MJ, net cal. val.
13	Water use	WDP	m3 world eq. deprived
14	Fine particulate emissions	Illness due to PM	Illness incidence
15	Ionizing radiation	Human exposure	kBq U235-eq.
16	Ecotoxicity (freshwater)	CTU ecosystem	CTUe
17	Human toxicity, carcinogenic	CTU human	CTUh
18	Human toxicity, non-carcinogenic	CTU human	CTUh
19	Land-use related impact /soil quality	Soil quality index	Dimensionless

Jonkers & Ottelé (2020) state that the fourth element of the scope definition is to determine the type and sources of the product life inventory data that will be used. This data can be gathered from existing databases like the 'Nationale Milieudatabase' or can come directly from the environmental product declaration (EPD) if these are available. It is important to realise that the reliability of the LCA depends on the reliability of the data that is used. The fifth and sixth element are the review of the level of quality of the data used and the possible need for a quality review of the analysis itself (Jonkers & Ottelé, 2020), both these elements reflect on the study.

Step 2: Inventory analysis

The second step of the LCA is the inventory analysis. In this step all the required information regarding the materials, processes (inputs) and their environmental impact (outputs) is gathered (Jonkers & Ottelé, 2020). If environmental product declarations (EPD's) of half products are used, it is important to study if this data covers all life cycle stages and impact categories that are included in the analysis.

Step 3: Impact assessment

In the third step of the LCA the life cycle impact assessment (LCIA) is done, in this step the output data is gathered and weighed according to the defined method (Jonkers & Ottelé, 2020).

In this step it is possible to calculate the shadow price of a specific product (MKI) or determine the embodied carbon, depending on the intention of the analysis. Also, the normalization can be done in this step, for example by dividing all environmental impacts over the analysed floor area to obtain the impacts per square meter. >

Step 4: Interpretation

In the final step the results from the analysis are interpretated (Jonkers & Ottelé, 2020), this includes a discussion on the results, completeness, sensitivity and possible limitations. This step is finalized by drawing conclusions and giving recommendations for further studies.

Appendix E. Environmental impacts per material

This appendix contains the considered environmental impacts for each material and the reasoning behind the chosen EPDs to be used in this thesis. The considerations will be discussed for each material type.

Timber

		A1-3 [kg-CO2eq/ kg]			
Material		GWP	BIO GWP	TOT GWP	Source
CLT	mean	0.272	-1.615	-1.343	(W. u. J. Derix GmbH & Co, 2020)
	high	0.599	-1.864	-1.265	(Studiengemeinschaft Holzleimbau e.V., 2019)
	low	0.116	-1.621	-1.504	(Stora Enso, 2020)
Glulam	mean	0.308	-1.602	-1.294	(Institut Bauen und Umwelt e.V., 2021)
	high	0.406	-1.678	-1.272	(Studiengemeinschaft Holzleimbau e.V, 2018)
	low	0.247	-1.760	-1.513	(FPInnovations, 2018)
Softwood	mean	0.232	-1.610	-1.379	(Wood Solutions, 2017b)
	high	0.070	-1.614	-1.545	(Institut technologique FCBA, 2020)
	low	0.332	-1.601	-1.269	(Wood Solutions, 2017b)

Concrete

		A1-3 [kg-CO2eq/ kg]			
Material		GWP	BIO GWP	TOT GWP	Source
Hollow core slab	mean	0.136	0	0.136	(Strängbetong AB, 2019)
	high	0.171	0	0.171	(DW Systembau GMBH, 2020)
	low	0.120	0	0.120	(Nordland Betongelement AS, 2013)
Precast plank floor	mean	0.175	0	0.175	(Con-Form AS, 2016)
	high	0.186	0	0.186	(thomas gruppe -Geschäftsfeld Betonbauteile, 2020b)
	low	0.164	0	0.164	(thomas gruppe -Geschäftsfeld Betonbauteile, 2020a)
Precast concrete	mean	0.189	0	0.189	(UPB AS, 2016)
(Incl. rebar)	high	0.244	0	0.244	(thomas gruppe -Geschäftsfeld Betonbauteile, 2021)
	low	0.085	0	0.085	(Syndicat National du Béton Prêt à l'Emploi, 2019)
In situ concrete C25/30	mean	0.070	0	0.070	(One Click LCA, 2021i)
	high	0.110	0	0.110	(One Click LCA, 2021f)

	low	0.031	0	0.031	(One Click LCA, 2021m)
In situ concrete C30/37	mean	0.081	0	0.081	(One Click LCA, 2021j)
	high	0.126	0	0.126	(Lujabetong, 2021)
	low	0.052	0	0.052	(One Click LCA, 2021g)
In situ concrete C35/45	mean	0.082	0	0.082	(One Click LCA, 2021k)
	high	0.146	0	0.146	(Building Research Institute, 2013)
	low	0.071	0	0.071	(One Click LCA, 2021l)
In situ concrete C40/50	mean	0.144	0	0.144	(Thomas Betong, 2020)
	high	0.162	0	0.162	(Betongindustri AB, 2021)
	low	0.096	0	0.096	(One Click LCA, 2021h)
In situ concrete C50/60	mean	0.131	0	0.131	(Transgulf Readymix Concrete Co. LLC, 2019)
	high	0.172	0	0.172	(Building Research Institute, 2013)
	low	0.093	0	0.093	(Transgulf Readymix Concrete Co. LLC, 2019)

Steel

		A1-3 [kg-CO2eq/ kg]			
Material		GWP	BIO GWP	TOT GWP	Source
Beams	mean	0.908	0	0.908	(Bouwen met Staal, 2013)
	high	2.390	0	2.390	(Tata Steel, 2017)
	low	0.701	0	0.701	(AFV Beltrame Group, 2017)
Reinforcement	mean	1.025	0	1.025	(VWN - Vereniging Wapeningsstaal Nederland, 2021)
	high	2.890	0	2.890	(One Click LCA, 2021n)
	low	0.240	0	0.240	(ift Rosenheim GmbH, 2018)

Non-structural materials

		A1-3 [kg-CO2eq/ kg]			
Material		GWP	BIO GWP	TOT GWP	Source
Mineral wool	mean	1.244	0	1.244	(Knauf insulation, 2016)
	high	1.379	0	1.379	(Knauf Insulation (Northern Europe), 2019)
	low	0.129	-0.008	0.120	(Knauf insulation, 2021)

Gypsum board	mean	0.194	0	0.194	(Saint-Gobain Construction Products Hungary, 2018)
	high	0.250	0	0.250	(Belgisch Luxemburgse Gips Vereniging, 2020)
	low	0.077	0	0.077	(Fermacell GmbH, 2016)
Glass wool	mean	1.855	0	1.855	(Saint-Gobain ISOVER G+H AG, 2016)
	high	2.565	0	2.565	(SAINT-GOBAIN ISOVER AUSTRIA GmbH, 2019)
	low	1.070	0	1.070	(One Click LCA, 2021b)
MDF	mean	1.029	-1.480	-0.451	(Thinkstep Pty Ktd & Stephen Mitchell Associates, 2020)
	high	1.205	-1.472	-0.265	(Thinkstep Pty Ktd & Stephen Mitchell Associates, 2020)
	low	0.792	-1.508	-0.715	(Thinkstep Pty Ktd & Stephen Mitchell Associates, 2020)
Washed gravel	mean	0.004	0	0.004	(One Click LCA, 2021c)
	high	0.007	0	0.007	(One Click LCA, 2021a)
	low	0.002	0	0.002	(One Click LCA, 2021e)
PIR insulation	mean	3.990	0	3.990	(Peverelli & Bealu, 2018a)
	high	4.510	0	4.510	(Peverelli & Bealu, 2018b)
	low	2.946	0	2.946	(Unilin, 2020)
Cementitious screed	mean	0.156	0	0.156	(Institut Bauen und Umwelt e.V., 2016)
	high	0.300	0	0.300	(Syndicat National des Mortiers Industriels, 2021)
	low	0.081	0	0.081	(Henry & Pele, 2021)

Material	Sub material	GHG emissions A1-3 excl. bigenic carbon GWP	only bigenic carbon BIO GWP	incl. biogenic carbon TOT GWP	Unit	Unit	Source	specific product	thichkness	unit	density	unit	link to source
Timber													
CLT	**CLT mid**	**0,272**	**-1,615**	**-1,343**	**kg CO2e/**	**kg**	**direct EPD**	**Derix, german market**			**470**	**kg/m3**	**https://www.d**
	CLT high impact	0,599	-1,864	-1,265	kg CO2e/	kg	direct EPD	Derix			470	kg/m3	https://www.de
	CLT low impact	0,116	-1,621	-1,504	kg CO2e/	kg	direct EPD	Stora Enso			470	kg/m3	https://arup.sha
	Binderholz	0,223	-1,618	-1,395	kg CO2e/	kg	direct EPD	Binderholz			470,88	kg/m3	https://arup.sha
	KLH Massivholx	0,402	-1,655	-1,253	kg CO2e/	kg	direct EPD	KLH Massivholx			480	kg/m3	https://arup.sha
	Rubner Holding AG		?	-1,440	kg CO2e/	kg	direct EPD	Rubner Holding AG			461	kg/m3	https://arup.sha
	Sodra	0,079	-1,637	-1,558	kg CO2e/	kg	direct EPD	Sodra			430	kg/m3	https://arup.sha
Low	Stora Enso	0,116	-1,621	-1,504	kg CO2e/	kg	direct EPD	Stora Enso			470	kg/m3	https://arup.sha
	Crosslam	0,258	?	0,258	kg CO2e/	kg	direct EPD	Crosslam			481	kg/m3	https://arup.sha
	wpma	0,256	-1,610	-1,356	kg CO2e/	kg	direct EPD	wpma			500	kg/m3	https://arup.sha
	Xlam	0,931	-1,542	-0,610	kg CO2e/	kg	direct EPD	Xlam			480	kg/m3	https://arup.sha
High	Derix	0,599	-1,864	-1,265	kg CO2e/	kg	direct EPD	Derix			469,94	kg/m3	https://www.de
Mean	Derix, german market	0,272	-1,615	-1,343	kg CO2e/	kg	direct EPD	Derix, german market			470	kg/m3	https://www.dr
	HASSLACHER	0,199	-1,604	-1,404	kg CO2e/	kg	direct EPD	HASSLACHER			470	kg/m3	https://www.ha
	Derix Nibe	0,324	-0,879	-0,555	kg CO2e/	kg	direct EPD	Derix Nibe			470	kg/m3	file:///C:/Users/
	Binderholz 2			0,000	kg CO2e/	kg	direct EPD	Binderholz 2			470,8	kg/m3	
	Egoin			-1,306	kg CO2e/	kg	direct EPD	Egoin			525	kg/m3	https://static1.s
	Holzbau.de	0,440	-1,70447291	-1,265	kg CO2e/	kg	direct EPD	Holzbau.de			469,94	kg/m3	https://www.br
	Rubner			-1,440	kg CO2e/	kg	direct EPD	Rubner			461	kg/m3	file:///C:/Users/
	Derix german market 2	0,147	-1,615	-1,468	kg CO2e/	kg	direct EPD	Derix german market 2			470	kg/m3	https://www.m
	Average thesis Wouter van W	0,244	-1,640	-1,380	kg CO2e/	kg							
	CLT veracity	*0,324*	*-1,614*	*-1,290*	*kg CO2e/*	*kg*	*Arup varacity*	*Derix X-LAM CLT 2019 EPD Spruce w 759kg/m. ?*					*http://veracity-*
	Istructe.org	*0,250*											
Glulam	**Glulam mid**	**0,308**	**-1,602**	**-1,294**	**kg CO2e/**	**kg**	**direct EPD**	**HASSLACHER Holding GmbH**			**470**	**kg/m3**	**https://www.h**
	Glulam high impact	0,406	-1,678	-1,272	kg CO2e/	kg	direct EPD	Holzleimbau			483	kg/m3	https://arup.sha
	Glulam low impact	0,247	-1,760	-1,513	kg CO2e/	kg	direct EPD	Nordic Lam			406	kg/m3	https://arup.sha
	wpma	0,277	-1,637	-1,360	kg CO2e/	kg	direct EPD	wpma			491	kg/m3	https://arup.sha
	American wood council and canadian wood council			-0,431	kg CO2e/	kg	direct EPD	American wood council and canadian wood cc			459,2	kg/m3	https://arup.sha
	Binderholz	0,230	-1,622	-1,392	kg CO2e/	kg	direct EPD	Binderholz			459,2	kg/m3	https://arup.sha
Low	Nordic Lam	0,247	-1,760	-1,513	kg CO2e/	kg	direct EPD	Nordic Lam			406	kg/m3	https://arup.sha
	Rubner Holding AG			-1,392	kg CO2e/	kg	direct EPD	Rubner Holding AG			464	kg/m3	https://arup.sha
	Structurlam	0,212	-1,730	-1,518	kg CO2e/	kg	direct EPD	Structurlam			544	kg/m3	https://arup.sha
High	Holzleimbau	0,406	-1,678	-1,272	kg CO2e/	kg	direct EPD	Holzleimbau			483,21	kg/m3	https://arup.sha
	Wood Solutions solfwood	0,612	-1,597	-0,986	kg CO2e/	kg	direct EPD	Wood Solutions solfwood			621	kg/m3	https://arup.sha
	Wood Solutions hardwood	0,782	-1,387	-0,605	kg CO2e/	kg	direct EPD	Wood Solutions hardwood			674	kg/m3	https://arup.sha
	Moelven Limtre AS Standard	0,224	-1,927	-1,703	kg CO2e/	kg	direct EPD	Moelven Limtre AS Standard Limtrebjelke			357	kg/m3	https://www.ep
	Moelven Glulam Beams and F	0,144	-1,670	-1,526	kg CO2e/	kg	direct EPD	Moelven Glulam Beams and Pillars			430	kg/m3	https://www.ep
	Rubner Holding AG - S.p.A. GLULAM			-1,452	kg CO2e/	kg	direct EPD	Rubner Holding AG - S.p.A. GLULAM			445	kg/m3	file:///C:/Users/
	Shiliger Holz			-1,450	kg CO2e/	kg	direct EPD	Shiliger Holz			424	kg/m3	https://www.sc
Mean	HASSLACHER Holding GmbH	0,308	-1,602	-1,293617021	kg CO2e/	kg	direct EPD	HASSLACHER Holding GmbH			470	kg/m3	https://www.ha

	Average thesis Wouter van W	0,199	-1,64	-1,44	kg CO2e/	kg							
	Glulam veracity	0,320	-1,590	-1,270	kg CO2e/	kg	Arup varacity	Studiengemeinschaft Holzleimbau EPD Glulam ?					http://veracity-
	Istructe.org	0,280											
Softwood	**Softwood mid**	**0,232**	**-1,610**	**-1,379**	**kg CO2e/**	**kg**	**direct EPD**	**Softwood timber woodsolutions sawn**			**551**	**kg/m3**	**https://arup.sh**
	Softwood high impact	0,332	-1,601	-1,269	kg CO2e/	kg	direct EPD	Softwood timber woodsolutions dressed			551	kg/m3	https://arup.sha
	Softwood low impact	0,070	-1,614	-1,545	kg CO2e/	kg	direct EPD	Finger-jointed solid wood, 443.5 kg/m3, bioge			444	kg/m3	https://oneclick
Mean	Softwood timber woodsolutio	0,232	-1,610	-1,379	kg CO2e/	kg	direct EPD	Softwood timber woodsolutions sawn			551	kg/m3	https://arup.sha
High	Softwood timber woodsolutio	0,332	-1,601	-1,269	kg CO2e/	kg	direct EPD	Softwood timber woodsolutions dressed			551	kg/m3	https://arup.sha
	Planed and strength-graded t			-1,517	kg CO2e/	kg	direct EPD	Planed and strength-graded timber, pine or sp			460	kg/m3	https://oneclick
	Sawn timber, pine or spruce,			-1,520	kg CO2e/	kg	direct EPD	Sawn timber, pine or spruce, 460 kg/m3, sawr			460	kg/m3	https://oneclick
Low	Finger-jointed solid wood, 44	0,070	-1,614	-1,545	kg CO2e/	kg	direct EPD	Finger-jointed solid wood, 443.5 kg/m3, bioge			443,5	kg/m3	https://oneclick
	Wooden stud frame, biogenic			-1,410	kg CO2e/	kg	direct EPD	Wooden stud frame, biogenic CO2 not subtra			497	kg/m3	https://oneclick
	Wooden stud wall frame, bio			-1,158	kg CO2e/	kg	direct EPD	Wooden stud wall frame, biogenic CO2 not su			15,8	kg/m2	https://oneclick
	Stora enso classic sawn	0,075	-1,593	-1,517	kg CO2e/	kg	direct EPD	Stora enso classic sawn			460	kg/m3	https://portal.e
	Swedish wood sawn dried spr	0,059	-1,581	-1,521	kg CO2e/	kg	direct EPD	Swedish wood sawn dried spruce or pine			489	kg/m3	https://portal.e
	Swedish sawn dried timber of	0,303	-1,571	-1,268	kg CO2e/	kg	direct EPD	Swedish sawn dried timber of spruce or pine f			455	kg/m3	https://portal.e
	Wood for good sawn timber	0,223	-1,710	-1,486	kg CO2e/	kg	direct EPD	Wood for good sawn timber			479	kg/m3	https://woodfo
	Average thesis Wouter van W	0,199	-1,62	-1,420	kg CO2e/	kg							
	Veracity Planed Timber EU Str	0,0872	-1,6372	-1,55	kg CO2e/	kg	Arup varacity	Stora Enso Classic Planed Timber EPD 2020					http://veracity-
Other timber	**LVL**	**0,306**	**-1,576**	**-1,271**	**kg CO2e/**	**kg**	**direct EPD**	**LVL (Laminated Veneer Lumber) by Stora Ens**			**510**	**kg/m3**	**https://www.m**
	Hardwood	0,284	-1,497	-1,208	kg CO2e/	kg	direct EPD	sawn kiln dried Wood solutions hardwood			735	kg/m3	Wood solutions
LVL	Stora enso	0,306	-1,576	-1,271	kg CO2e/	kg	direct EPD	LVL (Laminated Veneer Lumber) by Stora Ensc			510	kg/m3	https://www.m
Hardwood	Wood solutions hardwood	0,284	-1,497	-1,208	kg CO2e/	kg	direct EPD	sawn kiln dried Wood solutions hardwood			735	kg/m3	Wood solutions
	Wood solutions hardwood	0,445	-1,442	-0,995	kg CO2e/	kg	direct EPD	dressed kiln dried Wood solutions hardwood			735	kg/m3	Wood solutions
	Wood solutions hardwood	0,197	-1,302	-1,108	kg CO2e/	kg	direct EPD	sawn green Wood solutions hardwood			768	kg/m3	Wood solutions
LVL	Veracity arup	0,64	-1,93	-1,29	kg CO2e/	kg	Arup varacity	Kerto LVL EPD 2015 no biognenic					http://veracity-

Concrete

Material	Sub material	GWP (A1-3)	BIO GWP (A1-	TOT GWP (A1-3)	Unit	Unit	Source and expla	specific product	thichkness	unit	density	unit	link to source
Hollow core slab	**Hollow core slab mid**	**0,136**	**0**	**0,136**	**kg CO2e/**	**kg**	**direct EPD**	**Hollow core concrete slab,**	**200**	**mm**	**258**	**kg/m2**	**https://oneclicl**
	Hollow core slab high impact	0,171	0	0,171	kg CO2e/	kg	direct EPD	Spannbeton-Fertigteildecke	265	mm	375	kg/m2	https://oneclick
	Hollow core slab low impact	0,120	0	0,120	kg CO2e/	kg	direct EPD	Hollow core concrete slab (Norland Betongele			2400	kg/m3	https://oneclick
High	Hollow core concrete slab	0,171	0	0,171	kg CO2e/	kg	direct EPD	Spannbeton-Fertigteildecke	265	mm	374,71	kg/m2	https://oneclick
Low	Hollow core concrete slab (No	0,120	0	0,120	kg CO2e/	kg	direct EPD	Hollow core concrete slab (Norland Betongele			2400	kg/m3	https://oneclick
Mean	Hollow core concrete slab, HI	0,136	0	0,136	kg CO2e/	kg	direct EPD	Hollow core concrete slab,	200	mm	258	kg/m2	https://oneclick
	Hollow core slab veracity	0,147	0	0,147	kg CO2e/	kg	Arup varacity	VBI Consolis EPD	260	mm	1540	kg/m3	http://veracity-
Precast plank floor	**Precast plank floor mid**	**0,175**	**0**	**0,175**	**kg CO2e/**	**kg**	**direct EPD**	**Precast concrete cover slal**	**45**	**mm**	**2400**	**kg/m3**	**https://oneclicl**
	Precast plank floor high impa	0,186	0	0,186	kg CO2e/	kg	direct EPD	precast concrete decking sl	100	mm	2402	kg/m3	https://oneclick
	Precast plank floor low impac	0,164	0	0,164	kg CO2e/	kg	direct EPD	Floor plates thomas betonl	80	mm	2533	kg/m3	https://onhttps

High	precast concrete decking slab	0,186	0	0,186	kg CO2e/	kg	direct EPD	precast concrete decking sl	100	mm	2402	kg/m3	https://oneclick
Low	percast concrete floor slab	0,164	0	0,164	kg CO2e/	kg	direct EPD	Floor plates thomas betonk	80	mm	2533	kg/m3	https://onhttps
Mean	Precast concrete cover slab, E	0,175	0	0,175	kg CO2e/	kg	direct EPD	Precast concrete cover slab	45	mm	2400	kg/m3	https://oneclick
	Precast plank floor veracity	*0,192*	*0*	*0,192*	*kg CO2e/*	*kg*	*Arup varacity*	*NMD (Netherlands) - SBK44 -*			*2500*	*kg/m3*	*http://veracity-*
Precast concrete incl rebai	**Precast concrete mid**	**0,189**	**0**	**0,189**	**kg CO2e/**	**kg**	**direct EPD**	**Precast concrete wall elem**	**250**	**mm**	**2400**	**kg/m3**	**https://oneclicl**
	Precast concrete high impact	0,244	0	0,244	kg CO2e/	kg	direct EPD	Precast concrete structural elements (beams,			2420	kg/m3	https://oneclick
	Precast concrete low impact	0,085	0	0,085	kg CO2e/	kg	direct EPD	Precast concrete slabs, ep.	160	mm	385	kg/m2	https://oneclick
	Concrete balcony, C45/55 (B4	0,133	0	0,133	kg CO2e/	kg	direct EPD	Concrete balcony, C45/55 (	200	mm			https://oneclick
	Precast concrete slabs, ep. 0.:	0,103	0	0,103	kg CO2e/	kg	direct EPD	Precast concrete slabs, ep.	160	mm	369,011	kg/m2	https://oneclick
Low	Precast concrete slabs, ep. 0.:	0,085	0	0,085	kg CO2e/	kg	direct EPD	Precast concrete slabs, ep.	160	mm	384,979	kg/m2	https://oneclick
Mean	Precast concrete wall elemen	0,189	0	0,189	kg CO2e/	kg	direct EPD	Precast concrete wall elem	250	mm	2400	kg/m3	https://oneclick
	Precast concrete wall, (Egersu	0,115	0	0,115	kg CO2e/	kg	direct EPD	Precast concrete wall, 200	200	mm	500	kg/m2	https://oneclick
	Precast wall element, reinforc	0,150	0	0,150	kg CO2e/	kg	direct EPD	Precast wall element, reinf	200	mm	500	kg/m2	https://oneclick
	Uninsulated concrete wall ele	0,177	0	0,177	kg CO2e/	kg	direct EPD	Uninsulated concrete wall element, C30/37 (B			2450	kg/m2	https://oneclick
	Precast concrete wall elemen	0,180	0	0,180	kg CO2e/	kg	one click epd	Precast concrete wall elem	200	mm	2400	kg/m3	One Click LCA ge
	Concrete prefabricated eleme	0,141	0	0,141	kg CO2e/	kg	direct EPD	Concrete prefabricated elements, reinforced,			2363	kg/m3	https://oneclick
	Concrete prefabricated eleme	0,146	0	0,146	kg CO2e/	kg	direct EPD	Concrete prefabricated elements, reinforced,			2359,2	kg/m3	https://oneclick
	Concrete prefabricated eleme	0,165	0	0,165	kg CO2e/	kg	direct EPD	Concrete prefabricated elements, reinforced,			2376,3	kg/m3	https://oneclick
	Concrete prefabricated eleme	0,172	0	0,172	kg CO2e/	kg	direct EPD	Concrete prefabricated elements, reinforced,			2348,9	kg/m3	https://oneclick
High	Precast concrete structural el	0,244	0	0,244	kg CO2e/	kg	direct EPD	Precast concrete structural elements (beams,			2420	kg/m3	https://oneclick
	Precast Concrete with Rebar (	*0,149*	*0*	*0,149*	*kg CO2e/*	*kg*	*Arup varacity*	*CE Delft - "Milieu-impact van betongebruik in de Nederlandse bouw'*					*http://veracity-*
In situ concrete C25/30	**In situ concrete C25/30 mid**	**0,070**	**0**	**0,070**	**kg CO2e/**	**kg**	**one click epd**	**Ready-mix concrete, norm**	**200**	**mm**	**2400**	**kg/m3**	**https://oneclicl**
	In situ concrete C25/30 high i	0,110	0	0,110	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	In situ concrete C25/30 low ir	0,031	0	0,031	kg CO2e/	kg	one click epd	Ready-mix concrete for floo	200	mm	2310	kg/m3	https://oneclick
high	Ready-mix concrete, normal s	0,110	0	0,110	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,110	0	0,110	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,095	0	0,095	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,085	0	0,085	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,100	0	0,100	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,079	0	0,079	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
Mean	Ready-mix concrete, normal s	0,070	0	0,070	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,061	0	0,061	kg CO2e/	kg	one click epd	Ready-mix concrete, norma	200	mm	2400	kg/m3	https://oneclick
Low	Ready-mix concrete for floors	0,031	0	0,031	kg CO2e/	kg	one click epd	Ready-mix concrete for floo	200	mm	2310	kg/m3	https://oneclick
	Ready-mix concrete for walls,	0,031	0	0,031	kg CO2e/	kg	one click epd	Ready-mix concrete for wa	180	mm	2311	kg/m3	https://oneclick
	Ready-mix concrete, Rebeton	0,130	0	0,130	kg CO2e/	kg	direct EPD	Ready-mix concrete, Rebetong C25/30 (Skansl			1975,2	kg/m3	https://oneclick
	Ready-mix concrete, manufac	0,109	0	0,109	kg CO2e/	kg	direct EPD	Ready-mix concrete, manufacturer average, C			2280	kg/m3	https://oneclick
	Ready-mix concrete, C25/30 (	0,084	0	0,084	kg CO2e/	kg	direct EPD	Ready-mix concrete, C25/30 (B25 M90) (Åkra			2350	kg/m3	https://oneclick
	Ready-mix concrete, C25/30 (	0,083	0	0,083	kg CO2e/	kg	direct EPD	Ready-mix concrete, C25/30 (B25 M90) D22, p			2405,09	kg/m3	https://oneclick
	Ready-mix concrete, C25/30 (	0,085	0	0,085	kg CO2e/	kg	direct EPD	Ready-mix concrete, C25/30 (B25 M60) (BM V			2400	kg/m3	https://oneclick
	Ready-mix concrete, C25/30 S	0,417	0	0,417	kg CO2e/	kg	direct EPD	Ready-mix concrete, C25/30 S5 D32, ZL20005:			2400	kg/m3	https://oneclick
	Ready mix concrete, excluding	0,081	0	0,081	kg CO2e/	kg	direct EPD	Ready mix concrete, excluding rebar, C25/30 (			2358	kg/m3	https://oneclick

In situ concrete C30/37	**In situ concrete C30/37 mid**	**0,081**	**0,000**	**0,081**	**kg CO2e/**	**kg**	**one click epd**	**Ready-mix concrete, normal strength, generi**	**2400**	**kg/m3**	**https://oneclicl**
	In situ concrete C30/37 high i	0,126	0,000	0,126	kg CO2e/	kg	direct epd	Ready-mix concrete, C30/37 (Lujabetong)	2332,8	kg/m3	https://oneclick
	In situ concrete C30/37 low ir	0,052	0,000	0,052	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS beton (Var	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,072	0	0,072	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,081	0	0,081	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-s	0,123	0	0,123	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-s	0,113	0	0,113	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-s	0,103	0	0,103	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-s	0,093	0	0,093	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-s	0,084	0	0,084	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37 X	0,057	0	0,057	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37 XC1 S3, with 20%	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37 X	0,059	0	0,059	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37 XC1 S3, with 50%	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,072	0	0,072	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
Mean	Ready-mix concrete, normal s	0,081	0	0,081	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
Low	Ready-mix concrete, C30/37,	0,052	0	0,052	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS beton (Var	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,048	0	0,048	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,047	0	0,047	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,046	0	0,046	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,042	0	0,042	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,037	0	0,037	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,036	0	0,036	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Ready-mix concrete, C30/37,	0,035	0	0,035	kg CO2e/	kg	one click epd	Ready-mix concrete, C30/37, PLUS groen beto	2400	kg/m3	https://oneclick
	Concrete (ex rebar), C30/37 (	0,141	0	0,141	kg CO2e/	kg	direct epd	Concrete (ex rebar), C30/37 (B35 M40) (Scanb	2363	kg/m3	https://oneclick
High	Ready-mix concrete, C30/37 (	0,126	0	0,126	kg CO2e/	kg	direct epd	Ready-mix concrete, C30/37 (Lujabetong)	2332,8	kg/m3	https://oneclick
	C30/37 100% CEM1	*0,111*	*0*	*0,111*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C30/37 25% CEM1 75% CEMI	*0,057*	*0*	*0,057*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C30/37 50% CEM1 50% CEMI	*0,078*	*0*	*0,078*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C30/37 75% CEM1 25% CEMI	*0,096*	*0*	*0,096*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
In situ concrete C35/45	**In situ concrete mid C35/45**	**0,082**	**0**	**0,082**	**kg CO2e/**	**kg**	**one click epd**	**Ready-mix concrete, normal strength, generi**	**2400**	**kg/m3**	**https://oneclicl**
	In situ concrete C35/45 high i	0,146	0	0,146	kg CO2e/	kg	direct epd	Concrete (ex rebar), C35/45 (B35 M40) (Scanb	2359,2	kg/m3	https://oneclick
	In situ concrete C35/45 low ir	0,071	0	0,071	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,136	0	0,136	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,124	0	0,124	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,112	0	0,112	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,100	0	0,100	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal s	0,093	0	0,093	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
Mean	Ready-mix concrete, normal s	0,082	0	0,082	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
Low	Ready-mix concrete, normal s	0,071	0	0,071	kg CO2e/	kg	one click epd	Ready-mix concrete, normal strength, generic	2400	kg/m3	https://oneclick
High	Concrete (ex rebar), C35/45 (	0,146	0	0,146	kg CO2e/	kg	direct epd	Concrete (ex rebar), C35/45 (B35 M40) (Scanb	2359,2	kg/m3	https://oneclick
	Ready-mix concrete, group 3:	0,090	0	0,090	kg CO2e/	kg	direct epd	Ready-mix concrete, group 3: C35/45, represe	2322,5	kg/m3	https://oneclick
	Ready-mix concrete, group 5:	0,136	0	0,136	kg CO2e/	kg	direct epd	Ready-mix concrete, group 5: C35/45, represe	2285,7	kg/m3	https://oneclick
	Ready-mix concrete, group 7:	0,201	0	0,201	kg CO2e/	kg	direct epd	Ready-mix concrete, group 7: C35/45, represe	2292	kg/m3	https://oneclick
In situ concrete C40/50	**In situ concrete mid C40/50**	**0,144**	**0**	**0,144**	**kg CO2e/**	**kg**	**direct epd**	**Ready-mix concrete, C40/50, 16 S4, vct 0.40 (**	**2400**	**kg/m3**	**https://oneclicl**
	In situ concrete C40/50 high i	0,162	0	0,162	kg CO2e/	kg	direct epd	Ready-mix concrete, group 6: 341-415 kgCO2e	2344,5	kg/m3	https://oneclick

	In situ concrete C40/50 low ir	0,096	0	0,096	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick

	Concrete (ex rebar), C40/50 (	0,165	0	0,165	kg CO2e/	kg	direct epd	Concrete (ex rebar), C40/50 (B35 M40) (Scanb	2376,3	kg/m3	https://oneclick
	Ready-mix concrete, normal-	0,160	0	0,160	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-	0,150	0	0,150	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-	0,140	0	0,140	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-	0,120	0	0,120	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, normal-	0,110	0	0,110	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
Low	Ready-mix concrete, normal-	0,096	0	0,096	kg CO2e/	kg	one click epd	Ready-mix concrete, normal-strength, generic	2400	kg/m3	https://oneclick
	Ready-mix concrete, C40/50,	0,101	0	0,101	kg CO2e/	kg	direct epd	Ready-mix concrete, C40/50, 2484 kg/m3, D0	2484	kg/m3	https://oneclick
Mean	Ready-mix concrete, C40/50,	0,144	0	0,144	kg CO2e/	kg	direct epd	Ready-mix concrete, C40/50, 16 S4, vct 0.40 (	2400	kg/m3	https://oneclick
	Ready-mix concrete, C40/50 (	0,155	0	0,155	kg CO2e/	kg	direct epd	Ready-mix concrete, C40/50 (B40 MF45), B45	1397,95	kg/m3	https://oneclick
High	Ready-mix concrete, group 6:	0,162	0	0,162	kg CO2e/	kg	direct epd	Ready-mix concrete, group 6: 341-415 kgCO2e	2344,5	kg/m3	https://oneclick
	Ready-mix concrete, C40/50,	0,158	0	0,158	kg CO2e/	kg	direct epd	Ready-mix concrete, C40/50, vct 0.40, XD3, dr	2371	kg/m3	https://oneclick
	C40/50 100% CEM1	*0,141*	*0*	*0,141*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C40/50 25% CEM1 75% CEMI	*0,072*	*0*	*0,072*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C40/50 50% CEM1 50% CEMI	*0,099*	*0*	*0,099*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C40/50 75% CEM1 25% CEMI	*0,121*	*0*	*0,121*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*

In situ concrete C50/60	**In situ concrete mid C50/60**	**0,170**	**0**	**0,170**	**kg CO2e/**	**kg**	**one click epd**	**Ready-mix concrete, high strength, generic, C**	**2400**	**kg/m3**	**https://oneclicl**
	In situ concrete C50/60 high i	0,172	0	0,172	kg CO2e/	kg	direct epd	Concrete (ex rebar), C50/60 (B35 M40) (Scanb	2348,9	kg/m3	https://oneclick
	In situ concrete C50/60low im	0,093	0	0,093	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D07571 (Transgu	2504	kg/m3	https://oneclick

High	Concrete (ex rebar), C50/60 (	0,172	0	0,172	kg CO2e/	kg	direct epd	Concrete (ex rebar), C50/60 (B35 M40) (Scanb	2348,9	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,102	0	0,102	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D06535 (Transgu	2495,5	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,110	0	0,110	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D07375 (Transgu	2489,5	kg/m3	https://oneclick
Low	Ready-mix concrete, C50/60,	0,093	0	0,093	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D07571 (Transgu	2504	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,092	0	0,092	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D07570 (Transgu	2508,5	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,092	0	0,092	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D07573 (Transgu	2503	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,132	0	0,132	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D08491 (Transgu	2461	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,103	0	0,103	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D06889 (Transgu	2492	kg/m3	https://oneclick
	Ready-mix concrete, C50/60,	0,131	0	0,131	kg CO2e/	kg	direct epd	Ready-mix concrete, C50/60, D07988 (Transgu	2481	kg/m3	https://oneclick
Mean	Ready-mix concrete, high stre	0,170	0	0,170	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	Ready-mix concrete, high stre	0,210	0	0,210	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	Ready-mix concrete, high stre	0,180	0	0,180	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	Ready-mix concrete, high stre	0,220	0	0,220	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	Ready-mix concrete, high stre	0,190	0	0,190	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	Ready-mix concrete, high stre	0,230	0	0,230	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	Ready-mix concrete, high stre	0,200	0	0,200	kg CO2e/	kg	one click epd	Ready-mix concrete, high strength, generic, C	2400	kg/m3	https://oneclick
	C50/60 100% CEM1	*0,177*	*0*	*0,177*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C50/60 75% CEM1 25% CEMI	*0,155*	*0*	*0,155*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C50/60 50% CEM1 50% CEMI	*0,125*	*0*	*0,125*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*
	C50/60 25% CEM1 75% CEMI	*0,089*	*0*	*0,089*	*kg CO2e/*	*kg*	*veracity*	*Sus. Domain Generated from MRPI Cement Data*			*http://veracity-*

Foundation	**Foundation mid**	**0,306**	**0**	**0,306**	**kg CO2e/**	**kg**	**direct EPD**	**Precast concrete piles, 275x275 mm, 209 kg/**	**209**	**kg/m**	**https://oneclicl**
	Foundation high impact	1,275	0	1,275	kg CO2e/	kg	direct EPD	Concrete piles, rectangular, 270x270 mm, C5C	189	kg/m	https://oneclick
	Foundation low impact	0,167	0	0,167	kg CO2e/	kg	direct EPD	Prefabricated reinforced concrete piles, 400 x	388	kg/m	https://oneclick

	Concrete piles with reinforcin	0,210	0	0,210	kg CO2e/	kg	direct EPD	Concrete piles with reinforcing steel, 13 m 27(			184	kg/m	https://oneclick
	Concrete piles, rectangular, 2	1,671	0	1,671	kg CO2e/	kg	direct EPD	Concrete piles, rectangular, 235x235 mm, C5C			143	kg/m	https://oneclick
	Concrete piles, rectangular, 2	1,226	0	1,226	kg CO2e/	kg	direct EPD	Concrete piles, rectangular, 270x270 mm, C5C			186	kg/m	https://oneclick
High	Concrete piles, rectangular, 2	1,275	0	1,275	kg CO2e/	kg	direct EPD	Concrete piles, rectangular, 270x270 mm, C5C			189	kg/m	https://oneclick
	Concrete piles, rectangular, 3	0,748	0	0,748	kg CO2e/	kg	direct EPD	Concrete piles, rectangular, 350x350 mm, C5C			314	kg/m	https://oneclick
	Concrete piles, rectangular, 3	0,832	0	0,832	kg CO2e/	kg	direct EPD	Concrete piles, rectangular, 350x350 mm, C5C			328	kg/m	https://oneclick
	Concrete piles/columns, reinf	0,207	0	0,207	kg CO2e/	kg	direct EPD	Concrete piles/columns, reinforcement: 56kg/			?		https://oneclick
	Precast concrete foundation		0,184	0	0,184	kg CO2e/	kg	direct EPD	Precast concrete foundation pile, with steel re			144	kg/m	https://oneclick
	Precast concrete foundation		0,183	0	0,183	kg CO2e/	kg	direct EPD	Precast concrete foundation pile, with steel re			185	kg/m	https://oneclick
	Precast concrete foundation		0,194	0	0,194	kg CO2e/	kg	direct EPD	Precast concrete foundation pile, with steel re			188	kg/m	https://oneclick
	Precast concrete foundation		0,187	0	0,187	kg CO2e/	kg	direct EPD	Precast concrete foundation pile, with steel re			340	kg/m	https://oneclick
Mean	Precast concrete piles, 275x2	0,306	0	0,306	kg CO2e/	kg	direct EPD	Precast concrete piles, 275x275 mm, 209 kg/n			209	kg/m	https://oneclick
	Precast concrete piles, 235x2	0,236	0	0,236	kg CO2e/	kg	direct EPD	Precast concrete piles, 235x235 mm, 144 kg/n			144	kg/m	https://oneclick
	Precast concrete piles, 275x2	0,227	0	0,227	kg CO2e/	kg	direct EPD	Precast concrete piles, 275x275 mm, 185 kg/n			185	kg/m	https://oneclick
	Precast concrete piles, 275x2	0,250	0	0,250	kg CO2e/	kg	direct EPD	Precast concrete piles, 275x275 mm, 188 kg/n			188	kg/m	https://oneclick
	Prefabricated foundation pilir	0,254	0	0,254	kg CO2e/	kg	direct EPD	Prefabricated foundation piling, d 355 mm, M			1088,6	kg/stk	https://oneclick
	Prefabricated foundation pilir	0,186	0	0,186	kg CO2e/	kg	direct EPD	Prefabricated foundation piling, d 555 mm, M			2310,3	kg/stk	https://oneclick
	Prefabricated reinforced conc	0,172	0	0,172	kg CO2e/	kg	direct EPD	Prefabricated reinforced concrete piles, 250 x			151	kg/m	https://oneclick
	Prefabricated reinforced conc	0,170	0	0,170	kg CO2e/	kg	direct EPD	Prefabricated reinforced concrete piles, 300 x			218	kg/m	https://oneclick
	Prefabricated reinforced conc	0,170	0	0,170	kg CO2e/	kg	direct EPD	Prefabricated reinforced concrete piles, 350 x			298	kg/m	https://oneclick
Low	Prefabricated reinforced conc	0,167	0	0,167	kg CO2e/	kg	direct EPD	Prefabricated reinforced concrete piles, 400 x			388	kg/m	https://oneclick
	Prefabricated reinforced conc	0,167	0	0,167	kg CO2e/	kg	direct EPD	Prefabricated reinforced concrete piles, 450 x			491	kg/m	https://oneclick

Steel

Material	Sub material	GWP (A1-3)	BIO GWP (A1-	TOT GWP (A1-3)	Unit	Unit	Source and expla	specific product	thichkness	unit	density	unit	link to source
Steel beams	***Beams mid***	0,908	0	0,908	kg CO2e/	kg	direct EPD	staalproductie MRPI zwaar			7850	kg/m3	https://www.du
	Beams high impact	2,390	0	2,390	kg CO2e/	kg	direct EPD	Structural steel hollow sections (HSS), D: 25-5(			7850	kg/m3	https://oneclick
	Beams low impact	0,701	0	0,701	kg CO2e/	kg	direct EPD	Steel, rebar products (concrete reinforcement			7850	kg/m3	https://oneclick
Low	Steel, rebar products (concret	0,701	0	0,701	kg CO2e/	kg	direct EPD	Steel, rebar products (concrete reinforcement			7850	kg/m3	https://oneclick
	Structural steel hollow sectio	2,5	0	2,500	kg CO2e/	kg	direct EPD	Structural steel hollow sections, D: 21.3-508 n			7850	kg/m3	https://oneclick
High	Structural steel hollow sectio	2,39	0	2,39	kg CO2e/	kg	direct EPD	Structural steel hollow sections (HSS), D: 25-5(			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	3,21	0	3,210	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 0% recycled (			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	2,75	0	2,750	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 15% recyclec			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	2,51	0	2,510	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 20% recyclec			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	2,3	0	2,300	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 40% recyclec			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	2,12	0	2,120	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 60% recyclec			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	1,36	0	1,360	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 80% recyclec			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	0,74	0	0,740	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 90% recyclec			7850	kg/m3	https://oneclick
	Structural steel profiles, gene	0,67	0	0,670	kg CO2e/	kg	one click epd	Structural steel profiles, generic, 100% recycle			7850	kg/m3	https://oneclick
Mean	Staalproductie MRPI zwaar	0,908	0	0,908	kg CO2e/	kg	direct EPD	staalproductie MRPI zwaar			7850	kg/m3	https://www.du
	Rolled European Sections (90%	*0,908*	*0*	*0,908*	*kg CO2e/*	*kg*	*Arup varacity*	*"Bouwen met staal" (MRPI) - Heavy construction Products*					*http://veracity-*
Reinforcement	**Reinforcement mid**	**1,025**	**0**	**1,025**	**kg CO2e/**	**kg**	**direct EPD**	**Reinforcement steel (rebar) (VWN)**			**7850**	**kg/m3**	**https://oneclicl**
	Reinforcement high impact	2,890	0	2,890	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 0% recy(			7850	kg/m3	https://oneclick
	Reinforcement low impact	0,240	0	0,240	kg CO2e/	kg	direct EPD	Reinforcement for concrete (rebar), diameter:			7850	kg/m3	https://oneclick
High	Reinforcement steel (rebar), g	2,89	0	2,89	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 0% recy(			7850	kg/m3	https://oneclick

	Reinforcement steel (rebar), g	1,41	0	1,41	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 60% recy			7850	kg/m3	https://oneclick
	Reinforcement steel (rebar), g	0,92	0	0,92	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 80% recy			7850	kg/m3	https://oneclick
	Reinforcement steel (rebar), g	0,67	0	0,67	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 90% recy			7850	kg/m3	https://oneclick
	Reinforcement steel (rebar), g	0,42	0	0,42	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 100% re			7850	kg/m3	https://oneclick
	Reinforcement steel (rebar), g	0,5	0	0,5	kg CO2e/	kg	one click epd	Reinforcement steel (rebar), generic, 97% recy			7850	kg/m3	https://oneclick
Low	Reinforcement for concrete (r	0,24	0	0,24	kg CO2e/	kg	direct EPD	Reinforcement for concrete (rebar), diameter			7850	kg/m3	https://oneclick
	Reinforcement steel mesh	0,31	0	0,31	kg CO2e/	kg	direct EPD	Reinforcement steel mesh			7850	kg/m3	https://oneclick
	HS2 baseline - Steel reinforce	2,5	0	2,5	kg CO2e/	kg	one click epd	HS2 baseline - Steel reinforcement Fibres, BOI			7850	kg/m3	https://oneclick
Mean	Reinforcement steel (rebar) ('	1,02515	0	1,02515	kg CO2e/	kg	direct EPD	Reinforcement steel (rebar) (VWN)			7850	kg/m3	https://oneclick
	Reinforcement steel mesh (re	0,89	0	0,89	kg CO2e/	kg	one click epd	Reinforcement steel mesh (rebar) (Van Merks			7850	kg/m3	https://oneclick
	Reinforcement NL average ve	*1,36*	*0*	*1,36*	*kg CO2e/*	*kg*	*Arup varacity*	*Vereniging Wapeningsstaal Nederland MRPI EPD*					*http://veracity-*

Non structural materials

Material	Sub material	GWP (A1-3)	BIO GWP (A1-	TOT GWP (A1-3)	Unit	Unit	Source and expla	specific product	thichkness	unit	density	unit	link to source
Minerale wol	**Minerale wol mid**	**1,244**	**0**	**1,244**	**kg CO2e/**	**kg**	**direct EPD**	**DDP2-U / DDP2 Rock Mineral Wool for Flat R**			**135**	**kg/m3**	**https://pim.kna**
	Minerale wol high impact	1,379	0	1,379	kg CO2e/	kg	direct EPD	rock mineral wool			39	kg/m3	https://pim.kna
	Minerale wol low impact	0,129	-0,008	0,121	kg CO2e/	kg	direct EPD	DDP-S, DDP-X flat roofs			160	kg/m3	https://pim.kna
	Minerale wol 1	0,805	0	0,805	kg CO2e/	kg	direct EPD	Knauf insulation mineral wool KP35			19,5	kg/m3	https://pim.kna
High	Minerale wol 2	1,379	0,000	1,379	kg CO2e/	kg	direct EPD	rock mineral wool			39	kg/m3	https://pim.kna
	Minerale wol 3	1,218	0	1,218	kg CO2e/	kg	direct EPD	Rock Mineral Wool FPL-035 / FPL-035-GS / KD			50	kg/m3	https://pim.kna
	Minerale wol 4	1,093	0	1,093	kg CO2e/	kg	direct EPD	FKD / FKD C1 Rock Mineral Wool for ETICS (Ex			140	kg/m3	https://pim.kna
	Minerale wol 5	1,134	0	1,134	kg CO2e/	kg	direct EPD	DPF-30 / TW Rock Mineral Wool for partition v			32	kg/m3	https://pim.kna
	Minerale wol 6	1,277	0	1,277	kg CO2e/	kg	direct EPD	DP7 - DP8 Multipurpose Rock Mineral Wool in			70	kg/m3	https://pim.kna
Mean	Minerale wol 7	1,244	0,000	1,244	kg CO2e/	kg	direct EPD	DDP2-U / DDP2 Rock Mineral Wool for Flat Ro			135	kg/m3	https://pim.kna
	Minerale wol 8	1,276	0	1,276	kg CO2e/	kg	direct EPD	Steinwolle Dachdämmplatten DDP Knauf Insu			145	kg/m3	https://pim.kna
	Minerale wol 9	1,285	0	1,285	kg CO2e/	kg	direct EPD	Steinwolle Dachdämmplatten DDP-RT Knauf In			130	kg/m3	https://pim.kna
Low	Minerale wol 10	0,129	-0,008	0,121	kg CO2e/	kg	direct EPD	DDP-S, DDP-X flat roofs			160	kg/m3	https://pim.kna
	Minerale wol 11	0,172	-0,006	0,166	kg CO2e/	kg	direct EPD	DDP2-U Base	120	mm	130	kg/m3	https://pim.kna
	MECAWOOL Isolant en laine r	0,222	0	0,222	kg CO2e/	kg	direct EPD	MECAWOOL Isolant en laine minérale soufflée			3,6	kg/m2	https://oneclick
	Knauf insulation	0,975	0	0,975	kg CO2e/	kg	direct EPD	Glass Mineral Wool 036-037-038 unfaced rolls			16	kg/m3	https://oneclick
	Minerale wol 12	0,162	-0,001	0,161	kg CO2e/	kg	direct EPD	Kooltherm® K3 Kingspan Insulation B.V.			35	kg/m3	file:///C:/Users/
	Flibreglass	*1,350*			*kg CO2e/*	*kg*	*veracity*				*25*	*kg/m3*	*http://veracity-*
	Glasswool insulaton	*4,000*			*kg CO2e/*	*kg*	*veracity*				*25*	*kg/m3*	*http://veracity-*
	Glasswool insulation - 100 mr	*4,040*			*kg CO2e/*	*kg*	*veracity*				*25*	*kg/m3*	*http://veracity-*
	Glasswool insulation - 80 mm	*4,000*			*kg CO2e/*	*kg*	*veracity*				*25*	*kg/m3*	*http://veracity-*
	Mineral wool	*1,280*			*kg CO2e/*	*kg*	*veracity*				*70*	*kg/m3*	*http://veracity-*
	Paper wool	*0,630*			*kg CO2e/*	*kg*	*veracity*				*65*	*kg/m3*	*http://veracity-*
	Rockwool	*1,120*			*kg CO2e/*	*kg*	*veracity*				*100*	*kg/m3*	*http://veracity-*
	Rockwool insulation	*3,800*			*kg CO2e/*	*kg*	*veracity*				*70*	*kg/m3*	*http://veracity-*
	Rockwool insulation - 100 mn	*3,771*			*kg CO2e/*	*kg*	*veracity*				*70*	*kg/m3*	*http://veracity-*
	Rockwool insulation - 80 mm	*3,768*			*kg CO2e/*	*kg*	*veracity*				*70*	*kg/m3*	*http://veracity-*
	EPS	*0,246*			*kg CO2e/*	*kg*	*veracity*	*NMD (Netherlands)*			*20*	*kg/m3*	*http://veracity-*
Gipsplaat fire resistant	**Gipsplaat mid**	**0,194**	**0**	**0,194**	**kg CO2e/**	**kg**	**direct EPD**	**Gypsum plasterboard mois**	**12,5**	**mm**	**12,1**	**kg/m2**	**https://oneclicl**
	Gipsplaat high impact	0,250	0	0,250	kg CO2e/	kg	direct EPD	Gypsum board standaard	12,500	mm	8,7	kg/m2	https://oneclick
	Gipsplaat low impact	0,077	0	0,077	kg CO2e/	kg	direct EPD	Fermacell GmbH	12,500	mm	14,8	kg/m2	https://livios-dc

	Gipskarton	2,510	0	2,510	kg CO2e/	m2	direct EPD	gipskartonplaat	12,5	mm			https://www.kr
High	Gipsplaat	0,249770115	0	0,249770115	kg CO2e/	kg	direct EPD	Gypsum board standaard	12,5	mm	8,7	kg/m2	https://oneclick
	plasterboard	0,209	0	0,209	kg CO2e/	kg	direct EPD	GYPSUM PLASTERBOARD II	12,5	mm	10	kg/m2	https://oneclick
	Gypsum board, water resistar	0,244	0	0,244	kg CO2e/	kg	direct EPD	Gypsum board, water resis	12,5	mm	9,7	kg/m2	https://oneclick
	Gypsum board, fire resistant	0,172	0	0,172	kg CO2e/	kg	direct EPD	Gypsum board, fire resistar	15	mm	12,8	kg/m2	https://oneclick
	)HUPDFHOO GmbH	0,077	0	0,077	kg CO2e/	kg	direct EPD	Gypsum Fibreboard Ferma	12,5	mm	14,75	kg/m2	https://oneclick
	Rigips Habito	0,182	0	0,182	kg CO2e/	kg	direct EPD	Gypsum plasterboard	12,5	mm	12	kg/m2	https://oneclick
Mean	Rigips Habito hydro	0,194214876	0	0,194214876	kg CO2e/	kg	direct EPD	Gypsum plasterboard mois	12,5	mm	12,1	kg/m2	https://oneclick
Low	Fermacell GmbH	0,077288136	0	0,077288136	kg CO2e/	kg	direct EPD	Fermacell GmbH	12,5	mm	14,75	kg/m2	https://livios-dc
	Genreal (gypsum)	*0,130*			*kg CO2e/*	*kg*	*veracity*	*ICE v2.0 2011 (UK)*			*1200*	*kg/m3*	*http://veracity-*
	Gypsum plaster	*0,440*			*kg CO2e/*	*kg*	*veracity*	*EPiC data*			*1956*	*kg/m3*	*http://veracity-*
Glass wool	**Glass wool mid**	**1,855**	**0**	**1,855**	**kg CO2e/**	**kg**	**direct EPD**	**Insulation, glass wool, 0.6 kg/m2, 20 kg/m3 (**			**20**	**kg/m3**	**https://oneclicl**
	Glass wool high impact	2,565	0	2,565	kg CO2e/	kg	direct EPD	Glass wool insulation, laminated, 0.030 - 0.04:			20	kg/m3	https://oneclick
	Glass wool low impact	1,070	0	1,070	kg CO2e/	kg	one click epd	Glass wool insulation panels, unfaced, generic			50	kg/m3	https://oneclick
	Glass wool insulation, L=0.03:	0,886	0	0,886	kg CO2e/	kg	direct EPD	Glass wool insulation, L=0.(	60	mm	1,84	kg/m2	https://oneclick
	Glass wool insulation panels,	2,110	0	2,110	kg CO2e/	kg	one click epd	Glass wool insulation panels, 20 mm, 1.06 kg/			45	kg/m3	https://oneclick
	Glass wool insulation panels,	1,130	0	1,130	kg CO2e/	kg	one click epd	Glass wool insulation panels, unfaced, generic			25	kg/m3	https://oneclick
Low	Glass wool insulation panels,	1,07	0	1,07	kg CO2e/	kg	one click epd	Glass wool insulation panels, unfaced, generic			50	kg/m3	https://oneclick
	Glass wool insulation panels,	1,200	0	1,200	kg CO2e/	kg	one click epd	Glass wool insulation panels, unfaced, generic			75	kg/m3	https://oneclick
	Glass wool insulation panels,	1,590	0	1,590	kg CO2e/	kg	one click epd	Glass wool insulation panels, unfaced, generic			110	kg/m3	https://oneclick
	Glass wool insulation, R=8.0 r	1,061	0	1,061	kg CO2e/	kg	direct EPD	Glass wool insulation, R=8.(	375	mm	4,24	kg/m2	https://oneclick
	Glass wool insulation, R=8.0 r	1,351	0	1,351	kg CO2e/	kg	direct EPD	Glass wool insulation, R=8.(	300	mm	4,59	kg/m2	https://oneclick
	Glass wool insulation, L = 0.0:	1,955	0	1,955	kg CO2e/	kg	direct EPD	Glass wool insulation, L = 0	80	mm	1,79	kg/m2	https://oneclick
High	Glass wool insulation, laminat	2,565	0	2,565	kg CO2e/	kg	direct EPD	Glass wool insulation, laminated, 0.030 - 0.04:			20	kg/m3	https://oneclick
Mean	Insulation, glass wool, 0.6 kg/	1,855	0	1,855	kg CO2e/	kg	direct EPD	Insulation, glass wool, 0.6 kg/m2, 20 kg/m3 (IS			20	kg/m3	https://oneclick
	Insulation, glass wool, 0.9 kg/	2,250	0	2,250	kg CO2e/	kg	direct EPD	Insulation, glass wool, 0.9 kg/m2, 30 kg/m3, U			30	kg/m3	https://oneclick
	Glaswool insulation	*4*	*0*	*4*	*kg CO2e/*	*kg*	*Arup veracity*	*EPiC data*			*25*	*kg/m3*	*http://veracity-*
	Fibreglass (Glasswool)	*1,35*	*0*	*1,35*	*kg CO2e/*	*kg*	*Arup veracity*	*ICE v3.0b 2019 (UK)*			*25*	*kg/m3*	*http://veracity-*
	Glasswool insulation - 100 mr	*4,04*	*0*	*4,04*	*kg CO2e/*	*kg*	*Arup veracity*	*EPiC data*	*100*	*mm*	*25*	*kg/m3*	*http://veracity-*
	Glasswool insulation - 80 mm	*4*	*0*	*4*	*kg CO2e/*	*kg*	*Arup veracity*	*EPiC data*	*100*	*mm*	*25*	*kg/m3*	*http://veracity-*
Washed gravel	**Washed gravel mid**	**0,004**	**0,000**	**0,004**	**kg CO2e/**	**kg**	**one click EPD**	**Gravel, wet bulk density, 2000 kg/m3**			**2000**	**kg/m3**	**https://oneclicl**
	Washed gravel high	0,007	0,000	0,007	kg CO2e/	kg	one click EPD	Crushed rock / gravel mix (50-50 %), wet bulk			2000	kg/m3	https://oneclick
	Washed gravel low	0,002	0,000	0,002	kg CO2e/	kg	direct EPD	Natural round gravel (Cascade) 4-32 mm					https://oneclick
Low	Natural round gravel (Cascad	0,002	0	0,002	kg CO2e/	kg	direct EPD	Natural round gravel (Cascade) 4-32 mm					https://oneclick
Mean	Gravel, wet bulk density, 200(	0,004	0	0,004	kg CO2e/	kg	one click EPD	Gravel, wet bulk density, 2000 kg/m3			2000	kg/m3	https://oneclick
	Gravel, dry bulk density, 168C	0,004	0	0,004	kg CO2e/	kg	one click EPD	Gravel, dry bulk density, 1680 kg/m3			1680	kg/m3	https://oneclick
High	Crushed rock / gravel mix (50	0,007	0	0,007	kg CO2e/	kg	one click EPD	Crushed rock / gravel mix (50-50 %), wet bulk			2000	kg/m3	https://oneclick
	Crushed rock / gravel mix (50	0,007	0	0,007	kg CO2e/	kg	one click EPD	Crushed rock / gravel mix (50-50 %), dry bulk (			1680	kg/m3	https://oneclick
	Aggregate (crushed gravel), g	0,003	0	0,003	kg CO2e/	kg	one click EPD	Aggregate (crushed gravel), generic, dry bulk (			1600	kg/m3	https://oneclick
	Aggregat (Gravel or Crushed r	*0,0052*	*0*	*0,0052*	*kg CO2e/*	*kg*	*Arup veracity*	*ICE v2.0 2011 (UK)*			*2240*	*kg/m3*	*http://veracity-*
MDF	**MDF mid**	**1,029**	**-1,480**	**-0,451**	**kg CO2e/**	**kg**	**direct EPD**	**25 mm E0 & E1 standard m**	**25**	**mm**	**17,5**	**kg/m2**	**https://arup.sh**

	MDF high	1,205	-1,472	-0,265	kg CO2e/	kg	direct EPD	25 mm E0 & E1 moisture re	25	mm	17,6	kg/m2	https://arup.sha
	MDF low	0,792	-1,508	-0,715	kg CO2e/	kg	direct EPD	18 mm E0 & E1 standard m	18	mm	13,0	kg/m2	https://arup.sha
	MDF (medium-density fibreb	- -		-0,032	kg CO2e/	kg	direct EPD	MDF (medium-density fibreboard) boards, 28			550	kg/m3	https://oneclick
	MDF (medium-density fibreb	- -		-0,035	kg CO2e/	kg	direct EPD	MDF (medium-density fibreboard) boards, 28			626	kg/m3	https://oneclick
	Medium density fibreboard (I	- -		-0,391	kg CO2e/	kg	direct EPD	Medium density fibreboard (MDF), uncoated,			734	kg/m3	https://oneclick
	Medium density fiberboard (I	2,943	-0,017	2,926	kg CO2e/	kg	one clik EPD	Medium density fiberboard (MDF), 9 mm, 6.8			750	kg/m3	https://oneclick
	Wooden fiberboard, medium	- -		0,457	kg CO2e/	kg	direct EPD	Wooden fiberboard, medium density (MDF), (			737,5	kg/m3	https://oneclick
	High density fiberboard, biog	- -		-0,012	kg CO2e/	kg	direct EPD	High density fiberboard, biogenic CO2 not sub			860	kg/m3	https://oneclick
	High density fiberboard, biog	- -		-0,004	kg CO2e/	kg	direct EPD	High density fiberboard, biogenic CO2 not sub			870	kg/m3	https://oneclick
	Raw and coated fiberboards,	- -		-0,877	kg CO2e/	kg	direct EPD	Raw and coated fiberboards, 810 kg/m3 (SWIS			810	kg/m3	https://oneclick
Mean	25 mm E0 & E1 standard mel	1,029	-1,480	-0,451	kg CO2e/	kg	direct EPD	25 mm E0 & E1 standard m	25	mm	17,5	kg/m2	https://arup.sha
	16 mm E0 & E1 standard mel	0,834	-1,491	-0,660	kg CO2e/	kg	direct EPD	16 mm E0 & E1 standard m	16	mm	11,6	kg/m2	https://arup.sha
Low	18 mm E0 & E1 standard mel	0,792	-1,508	-0,715	kg CO2e/	kg	direct EPD	18 mm E0 & E1 standard m	18	mm	13	kg/m2	https://arup.sha
	16 mm E0 & E1 moisture resi	1,034	-1,479	-0,444	kg CO2e/	kg	direct EPD	16 mm E0 & E1 moisture re	16	mm	11,7	kg/m2	https://arup.sha
	18 mm E0 & E1 moisture resi	1,208	-1,477	-0,273	kg CO2e/	kg	direct EPD	18 mm E0 & E1 moisture re	18	mm	13	kg/m2	https://arup.sha
High	25 mm E0 & E1 moisture resi	1,205	-1,472	-0,265	kg CO2e/	kg	direct EPD	25 mm E0 & E1 moisture re	25	mm	17,6	kg/m2	https://arup.sha
	MDF	*0,856*	*-1,500*	*-0,644*	*kg CO2e/*	*kg*	*Arub Vercity*	*ICE v3.0b 2019 (UK)*			*720*	*kg/m3*	*http://veracity-*
High density PIR insulatior	**PIR mid**	**3,990**	**0**	**3,990**	**Kg CO2e/**	**kg**	**direct EPD**	**KNAUF Thane Multti Se 12**	**120**	**mm**	**33,42**	**kg/m3**	**https://oneclicl**
	PIR high	4,510	0	4,510	Kg CO2e/	kg	direct EPD	KNAUF Steelthane 100mm	100	mm	3,37	kg/m2	https://oneclick
	PIR low	2,946	0	2,946	Kg CO2e/	kg	direct EPD	PIR INSULATION BOARD W	80	mm	2,56	kg/m2	https://oneclick
	UNILIN insulation boards PIR	3,791	0	3,791	Kg CO2e/	kg	direct EPD	UNILIN insulation boards PI	100	mm	3,2	kg/m2	https://oneclick
Low	PIR INSULATION BOARD WITH	2,946	0	2,946	Kg CO2e/	kg	direct EPD	PIR INSULATION BOARD W	80	mm	2,56	kg/m2	https://oneclick
	UNILIN PIR INSULATION BOAF	2,593	0	2,593	Kg CO2e/	kg	direct EPD	UNILIN PIR INSULATION BC	80	mm	2,91	kg/m2	https://oneclick
	Plaque isolante UTHERM 25m	4,060	0	4,060	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 2!	25	mm	1,16	kg/m2	https://oneclick
	Plaque isolante UTHERM 140	4,160	0	4,160	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 14	140	mm	4,88	kg/m2	https://oneclick
	Plaque isolante UTHERM 160	4,234	0	4,234	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 1(	160	mm	5,48	kg/m2	https://oneclick
	Plaque isolante UTHERM 162	4,153	0	4,153	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 1(	120	mm	4,19	kg/m2	https://oneclick
	Plaque isolante UTHERM 101	4,199	0	4,199	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 1(	101	mm	3,62	kg/m2	https://oneclick
	Plaque isolante UTHERM 80m	4,255	0	4,255	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 8(	80	mm	2,82	kg/m2	https://oneclick
	Plaque isolante UTHERM 57m	4,022	0	4,022	Kg CO2e/	kg	direct EPD	Plaque isolante UTHERM 5	57	mm	2,24	kg/m2	https://oneclick
	QUICKCIEL PU Façade MI 100	3,761	0	3,761	Kg CO2e/	kg	direct EPD	QUICKCIEL PU Façade MI 1(	100	mm	3,35	kg/m2	https://oneclick
	QUICKCIEL PU Façade MI 120	4,635	0	4,635	Kg CO2e/	kg	direct EPD	QUICKCIEL PU Façade MI 1	120	mm	3,97	kg/m2	https://oneclick
	KNAUF Thane Façade 82 mm	5,053	0	5,053	Kg CO2e/	kg	direct EPD	KNAUF Thane Façade 82 m	82	mm	2,81	kg/m3	https://oneclick
	QUICKCIEL Sarking 160 mm	4,203	0	4,203	Kg CO2e/	kg	direct EPD	QUICKCIEL Sarking 160 mm	160	mm	5,21	kg/m2	https://oneclick
	KNAUF Thane ET Se 130 mm	3,995	0	3,995	Kg CO2e/	kg	direct EPD	KNAUF Thane ET Se 130 mr	130	mm	4,38	kg/m2	https://oneclick
	KNAUF Steelthane 140mm	4,685	0	4,685	Kg CO2e/	kg	direct EPD	KNAUF Steelthane 140mm	140	mm	4,61	kg/m2	https://oneclick
	KNAUF Thane Dallage 132mm	3,995	0	3,995	Kg CO2e/	kg	direct EPD	KNAUF Thane Dallage 132n	132	mm	4,38	kg/m2	https://oneclick
Mean	KNAUF Thane Multti Se 120m	3,990	0	3,990	Kg CO2e/	kg	direct EPD	KNAUF Thane Multti Se 12(	120	mm	33,42	kg/m3	https://oneclick
	KNAUF Asfalthane 40mm	4,081	0	4,081	Kg CO2e/	kg	direct EPD	KNAUF Asfalthane 40mm	40	mm	1,36	kg/m2	https://oneclick
	KNAUF Steelthane 120mm	4,662	0	4,662	Kg CO2e/	kg	direct EPD	KNAUF Steelthane 120mm	120	mm	3,99	kg/m2	https://oneclick
High	KNAUF Steelthane 100mm	4,510	0	4,510	Kg CO2e/	kg	direct EPD	KNAUF Steelthane 100mm	100	mm	3,37	kg/m2	https://oneclick
Façade systems	**façade mid**	**1,291**	**0**	**1,291**	**Kg CO2e/**	**kg**	**Arup carbon insi**	**Unitised curtain wall with aluminium framing**			**150**	**kg/m2**	**http://arup-car**
	façade high	1,614	0	1,614	Kg CO2e/	kg	Arup carbon insi	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	façade low	1,243	0	1,243	Kg CO2e/	kg	Arup carbon insi	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl

	Brick façade option	0,770	0	0,770	Kg CO2e/	kg	Arup carbon insig	Brick facade option with alu -			150	kg/m2	http://arup-carl
Low	Unitised curtain wall 60%	1,243	0	1,243	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	Unitised curtain wall 45%	1,299	0	1,299	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
Mean	Unitised curtain wall 30%	1,291	0	1,291	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	Unitised curtain wall shadow	1,449	0	1,449	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	Unitised curtain wall fins;60%	1,489	0	1,489	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	Unitised curtain wall fins; 45%	1,521	0	1,521	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	Unitised curtain wall fins; 30%	1,526	0	1,526	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
High	Unitised curtain wall shadow	1,614	0	1,614	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
	Unitised curtain wall shadow	1,699	0	1,699	Kg CO2e/	kg	Arup carbon insig	Unitised curtain wall with aluminium framing,			150	kg/m2	http://arup-carl
Cementious screed	**screed mid**	0,156	0,000	0,156	Kg CO2e/	kg	direct EPD	Floor screed mortar, cement screed, 1500 kg/			1500	kg/m3	https://oneclick
	screed high	0,300	0,000	0,300	Kg CO2e/	kg	direct EPD	Leveling screed, 90 kg/m2			90	kg/m2	https://oneclick
	Screed low	0,081	0,000	0,081	Kg CO2e/	kg	direct EPD	Leveling screed for interior	50,000	mm	111	kg/m2	https://oneclick
	Leveling screed, C16 (NeMO)	0,130	0	0,130	Kg CO2e/	kg	one click LCA	Leveling screed, C16 (NeMO)			2200	kg/m3	
	Leveling screed, C12 (NeMO)	0,120	0	0,120	Kg CO2e/	kg	one click LCA	Leveling screed, C12 (NeMO)			2200	kg/m3	
Mean	Floor screed mortar, cement s	0,156	0	0,156	Kg CO2e/	kg	direct EPD	Floor screed mortar, cement screed, 1500 kg/			1500	kg/m3	https://oneclick
	Calcium sulphate screed, 150	0,110	0	0,110	Kg CO2e/	kg	one click LCA	Calcium sulphate screed, 1500 kg/m3			1500	kg/m3	
	Flooring screed, C20/25 - XC1	0,140	0	0,140	Kg CO2e/	kg	direct EPD	Flooring screed, C20/25 - XC1 - S3 - 20 CEM I			116,8	kg/m2	https://oneclick
High	Leveling screed, 90 kg/m2	0,300	0	0,300	Kg CO2e/	kg	direct EPD	Leveling screed, 90 kg/m2			90	kg/m2	https://oneclick
	Screed mortar, calcium sulpha	0,123	0	0,123	Kg CO2e/	kg	direct EPD	Screed mortar, calcium sulphate screed, 1500			1500	kg/m3	https://oneclick
	Cement-based self-levelling s	0,280		0,280	Kg CO2e/	kg	direct EPD	Cement-based self-levelling screed, weber.flo	?				https://oneclick
	Leveling screed, 1.5 kg/m2	0,465	0	0,465	Kg CO2e/	kg	direct EPD	Leveling screed, 1.5 kg/m2			1,5	kg/m2	https://oneclick
Low	Leveling screed for interior ar	0,081	0	0,081	Kg CO2e/	kg	direct EPD	Leveling screed for interior	50	mm	110,5	kg/m2	https://oneclick

Appendix F. Embodied carbon per building function

This appendix contains embodied carbon data per building function from various sources

Embodied carbon per building function per m²

Figure 92 and Figure 93 present the collected information regarding the carbon emissions per building function

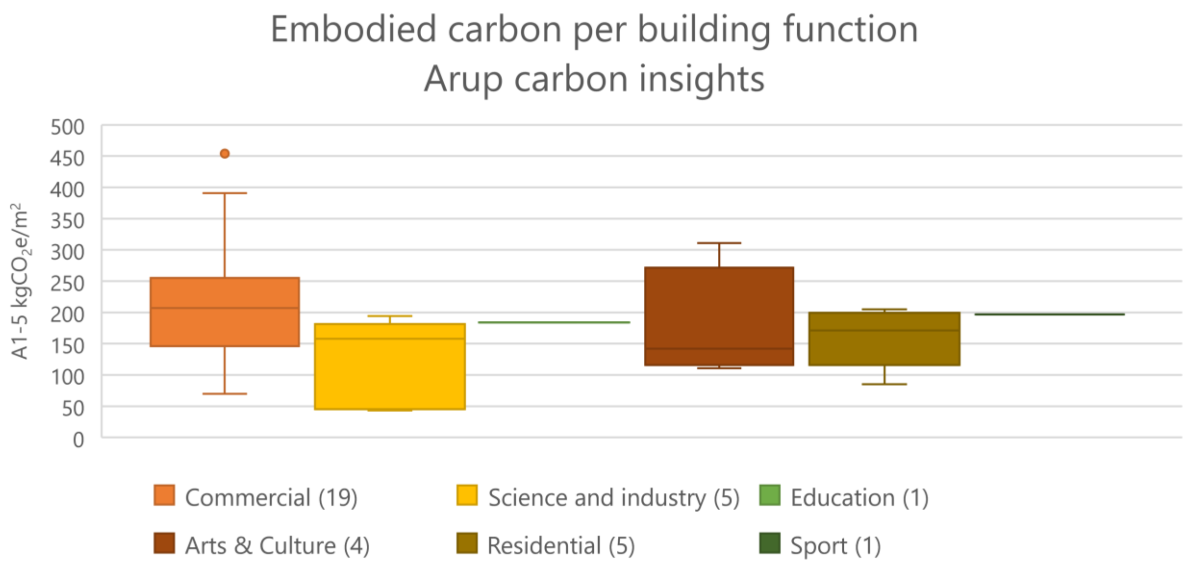


Figure 92: Embodied carbon per building function. Adapted from Arup's Carbon Insights Platform, by ARUP, 2021 (http://arup-carbon-insights.appspot.com/#/insights)

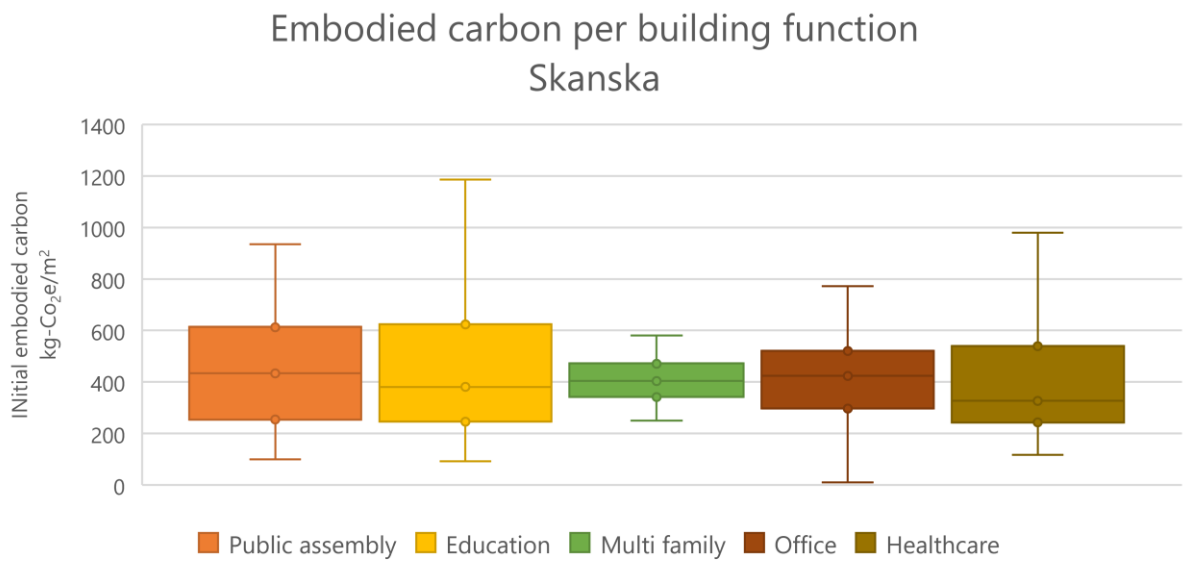


Figure 93: Embodied carbon per building function. Adapted from Quantifying the Carbon Footprint of Every Building, by Skanska, 2019, (https://www.phnw.org/assets/2019Conference/Presentations/PHnw2019_Quantifying%20the%20Carbon%20Footprint%20of%20Every%20Project_Stacy%20Smedley.pdf)

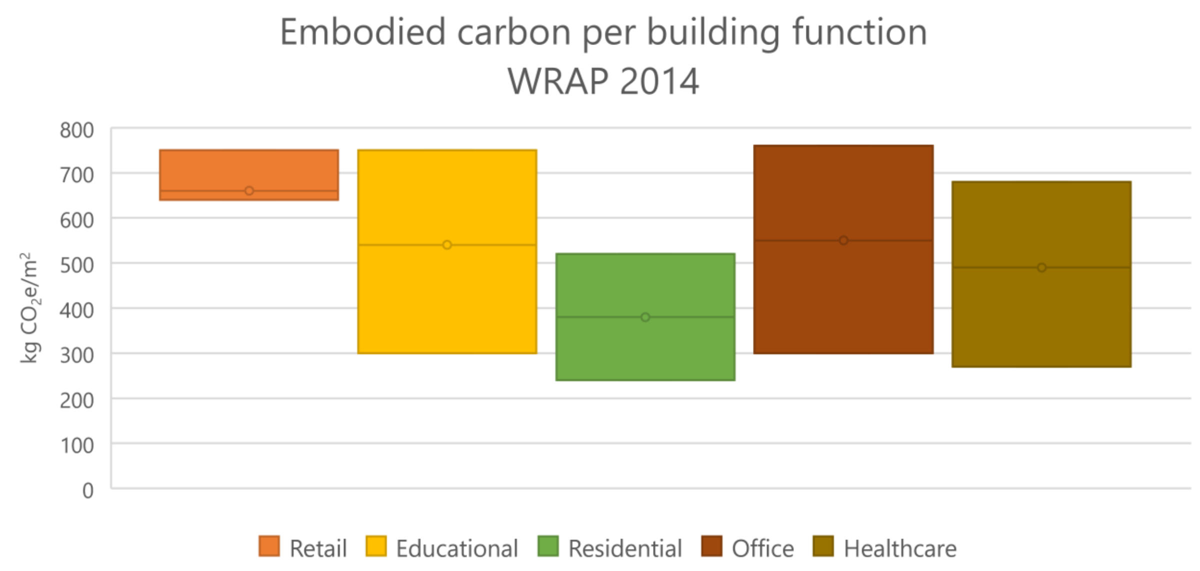


Figure 94: Embodied carbon per building function. Adapted from "Embodied Carbon Database" by WRAP, 2014

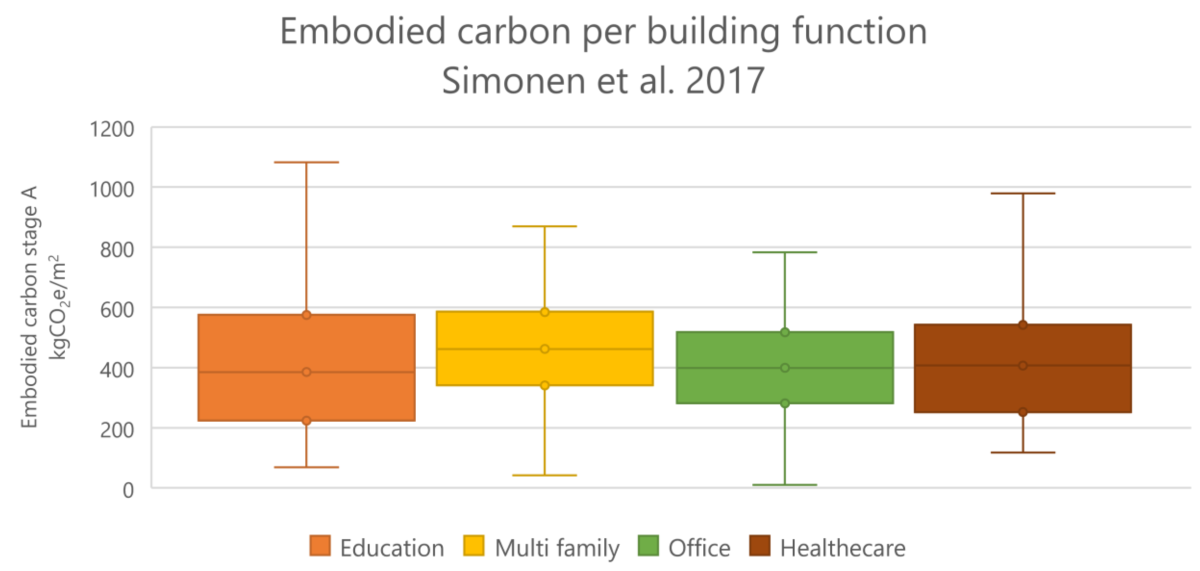


Figure 95: Embodied carbon per building function. Adapted from "Benchmarking the Embodied Carbon of Buildings," by K. Simonen et al., 2017, Technology Architecture and design, 1(2), p.212 (10.1080/24751448.2017.1354623).

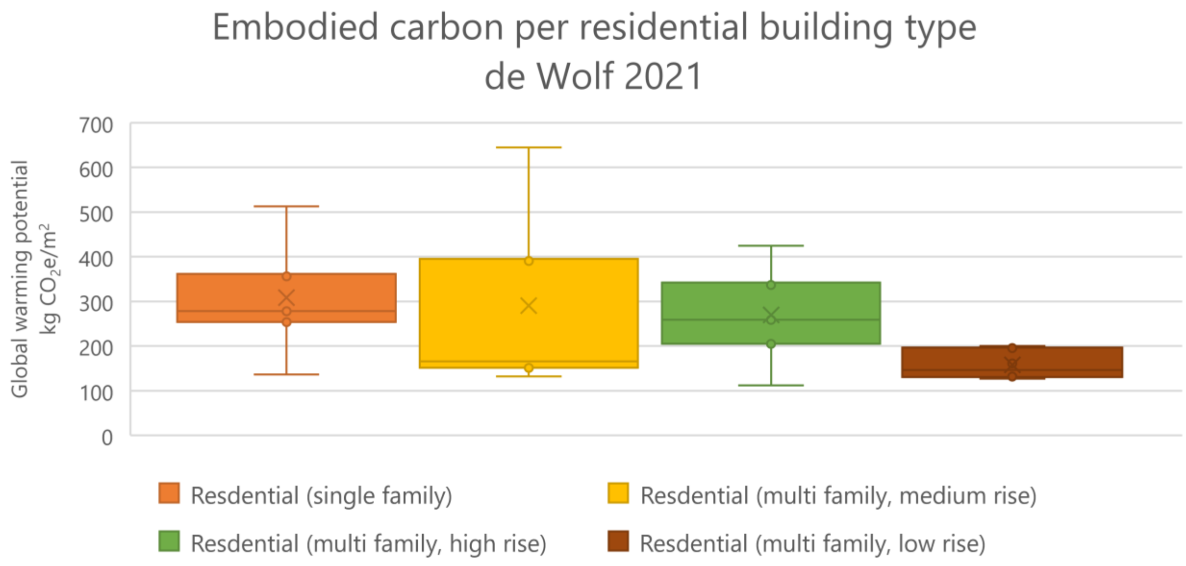


Figure 96: Embodied carbon per residential building type. Adapted from deQo database of embodied Quantity outputs, by de Wolf et al., 2021 (https://www.carbondeqo.com/database/graph)

Carbon emissions per building

If the medians of the found emissions per building function are multiplied with the average gross floor area of each function, the total CO_2 emissions per building can be found. If this information is combined with the average number of buildings that is constructed per year, the total carbon emissions can be found. This will show which building function is responsible for the highest total emissions per year.

The average emissions per m^2 are determined by taking the average of all collected medians as presented in the previous section and chapter 5.1. The average floor area is based on research by Bak (2021), Luijks et al. (2021) and Olthof (2012). The total average emissions per building can be found in Table 48. This table shows a large difference between the various functions.

Table 48: Total average emissions per building function

Building program	Average emissions [kg-CO_2eq/m^2]	Average BVO per building type	Total kg of CO_2
Healthcare	393	10294	4040395
Multifamily high rise > 15 storeys	347	11550	4004424
Mixed Residential/ Office/ Retail	421	4851	2042271
Multifamily mid rise 6 - 15 storeys	303	4851	1469853
Sports	393	10294	468423
Office	364	955	347620
Multifamily low rise < 5 storeys	159	1155	183645
Educational	387	3970	1536197
Single family	376	197	73938

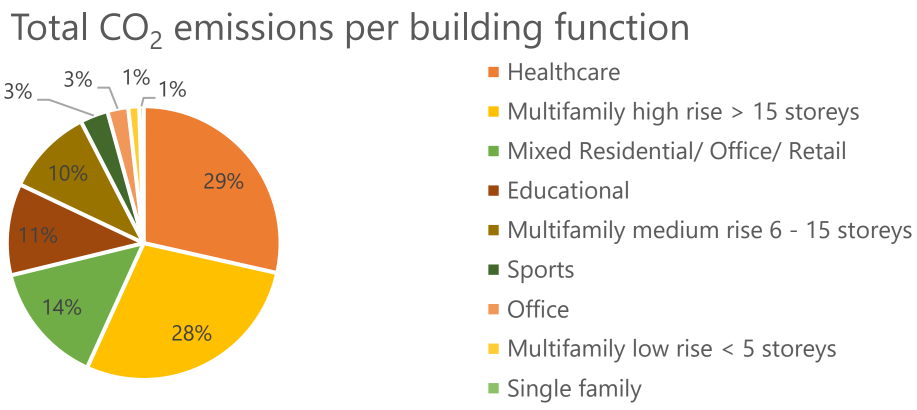


Figure 97: Total CO_2 emissions per building function per building

In Figure 97 the results of Table 48 are represented in a pie chart. This shows that one healthcare building emits almost as much as a multifamily high rise building of more than 15 storeys. Also, the mixed use, educational and mid-rise residential buildings emit a significant percentage of CO_2 per building because the buildings floor area is large.

Total emissions per building function

By combining the information on the newly constructed buildings in 2020 and the greenhouse gas emissions per building function and typology, the total emissions per building function in 2020 can be estimated. These values are given in Table 49. However, it is important to note that the numbers in this table only give an indication since there are many uncertainties in the calculation. The following assumptions were made:

- The global warming potential (GWP) per square meter is assumed to be the average of the median values from de Wolf et al. (2021), Simonen et al. (2017) and Luijks et al. (2021). All three sources showed that the embodied carbon of a building structure is highly dependent on the specific building design and that a large variation is possible within one building typology.
- The average total building area of the non-residential buildings is based on the research of H. Olthof (2012). Since this report is from 2012, the values might be different from the current average building areas. Also, for some building functions values were combined.
- The average area for single family homes is assumed to be the average of the floor areas for Rowhouses, semi-detached houses and detached houses as provided by Luijks et al. (2021).
- The total building areas of the multifamily homes are determined by assuming an apartment area of 77 m^2 as in the research by Luijks et al. (2021) and assuming that an average apartment floor contains 6 apartments (NEN, 2012). The assumed number of floors is 2.5 for multifamily low rise, 10.5 for multifamily medium rise and 25 for multifamily high rise.
- The numbers of new buildings built are based on the data provided by the CBS (2021) for all non-residential buildings
- The number of single family buildings is assumed to be 85% of the residential buildings as indicated by the CBS (2021). The remaining 15% that represents the apartment buildings is equally divided over multifamily low, medium, and high rise.

Table 49: Total GHG emissions per building function

Building function	Average GWP stage A [kg-CO_2eq/m^2]	Average total area [m^2]	Total GWP per building [kg-CO_2eq]	New built buildings 2020	Total emissions in 2020 [kg-CO_2eq]
Healthcare	393	10294	4040395	305	1 232 320 475
Multifamily high rise > 15 storeys	347	11550	4004424	3499	14 012 478 932
Mixed Residential/ Office/ Retail	421	4851	2042271	1429	2 918 405 259
Educational	387	3970	1536197	90	138 257 685
Multifamily mid rise 6 - 15 storeys	303	4851	1469853	3499	5 143 383 110
Sports	393	10294	468423	36	16 863 210
Office	364	955	347620	367	127 576 540
Multifamily low rise < 5 storeys	159	1155	183645	3499	642 619 766
Single family	376	197	73938	59557	4 403 540 289

Figure 98 shows the assumed division of total greenhouse gas emissions per building function. This shows that the vast majority greenhouse gas emissions of the newly constructed buildings in 2020 was due to multi-storey residential buildings.

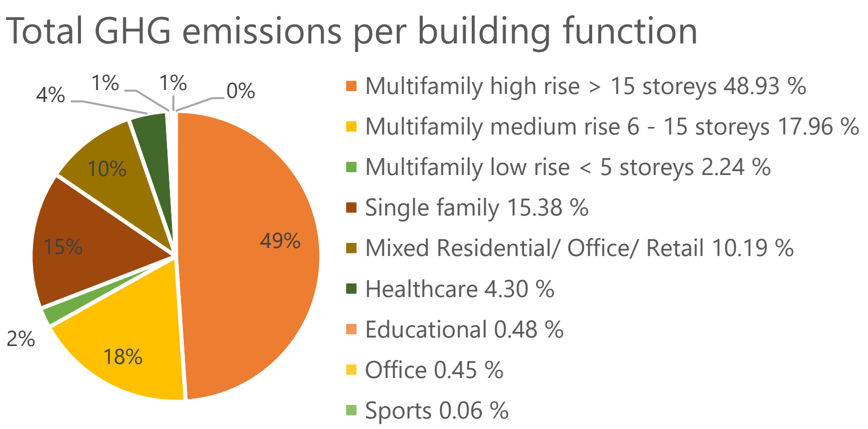


Figure 98: Total GHG emissions per building function.

Appendix G. Properties of timber

This appendix contains the material properties of solid timber, glued laminated timber, cross laminated timber, and laminated veneer lumber.

Solid timber

Table 50: Strength classes and material properties softwood. Adapted from Timber engineering, principles for design (p.102) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

N/mm^2	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30
$f_{t,90,k}$	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29
$f_{c,90,k}$	2.0	2.2	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.1	3.2
$f_{v,k}$	3.0	3.2	3.4	3.6	3.8	4.0	4.0	4.0	4.0	4.0	4.0	4.0
N/mm^2												
$E_{0,mean}$	7000	8000	9000	9500	10000	11000	11500	12000	13000	14000	15000	16000
$E_{0,05}$	4700	5400	6000	6400	6700	7400	7700	8000	8700	9400	10000	10700
$E_{90,mean}$	230	270	300	320	330	370	380	400	430	470	500	530
G_{mean}	440	500	560	590	630	690	720	750	810	880	940	1000
kg/m^3												
ρ_k	290	310	320	330	340	350	370	380	400	420	440	460
ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550

Table 51: Strength classes and material properties hardwood. Adapted from Timber engineering, principles for design (p.103) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

N/mm^2	D18	D24	D30	D35	D40	D50	D60	D70
$f_{m,k}$	18	24	30	35	40	50	60	70
$f_{t,0,k}$	11	14	18	21	24	30	36	42
$f_{t,90,k}$	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
$f_{c,0,k}$	18	21	23	25	26	29	32	34
$f_{c,90,k}$	7.5	7.8	8	8.1	8.3	9.3	10.5	13.5
$f_{v,k}$	3.4	4.0	4.0	4.0	4.0	4.0	4.5	5.0
N/mm^2								
$E_{0,mean}$	9500	10000	11000	12000	13000	14000	17000	20000
$E_{0,05}$	8000	8500	9200	10100	10900	11800	14300	16800
$E_{90,mean}$	630	670	730	800	860	930	1130	1330
G_{mean}	590	620	690	750	810	880	1060	1250
kg/m^3								
ρ_k	475	485	530	540	550	620	700	900
ρ_{mean}	570	580	640	650	660	750	840	1080

Glued laminated timber

Table 52: Material properties glued laminated timber. Adapted from Timber engineering, principles for design (p.103) by C. Sandhaas & H. Blaß, 2017, KIT Scientific Publishing (DOI: 10.5445/KSP/1000069616).

		Strength class				
Property	Symbol	GL24h	GL28h	GL32h	GL36h	Units
Bending strength	$f_{m;k}$	24	28	32	36	N/mm²
Tension strength //	$f_{t;0;k}$	16.5	19.5	22.5	26	N/mm²
Tension strength ⊥	$f_{t;90;k}$	0.4	0.45	0.5	0.6	N/mm²
Compression strength //	$f_{c;0;k}$	24	26.5	29	31	N/mm²
Compression strength ⊥	$f_{c;90;k}$	2.7	3.2	3.8	4.3	N/mm²
Shear strength	$f_{v,k}$	2.7	3	3.3	3.6	N/mm²
Modulus of elasticity //	$E_{0;mean}$	11600	12600	13700	14700	N/mm²
Modulus of elasticity //	$E_{0,05}$	9400	10200	11100	11900	N/mm²
Modulus of elasticity ⊥	$E_{90;mean}$	390	420	460	490	N/mm²
Shear modulus	G_{mean}	720	780	850	910	N/mm²
Density-char	ρ_k	380	410	430	450	kg/m³
Density-mean	ρ_{mean}	460	490	520	540	kg/m³

Cross laminated timber

Table 53: Material properties of CLT. Adapted from The CLT handbook (p. 37,38), by A. Gustafsson et al., 2019, Skogsindustrierna.

Characteristic strength values		**CLT panels with only C24**	**CLT panels with C30 in main direction of load and C14 across main direction of load**	**Unit**
Bending strength	$f_{m,x,k}$	24	30	N/mm²
	$f_{m,y,k}$	24	14	N/mm²
Bending strength, in plane	$f_{t,0,x,k}$	14.5	19	N/mm²
	$f_{t,0,y,k}$	14.5	7.2	N/mm²
Tension strength, perpendicular to the plane	$f_{t,90,x,k}$	0.4	0.4	N/mm²
	$f_{t,90,y,k}$	0.4	0.4	N/mm²
Compression strength, in plane	$f_{c,0,x,k}$	21	24	N/mm²
	$f_{c,0,y,k}$	21	16	N/mm²
Compression strength, perpendicular to the plane	$f_{c,90,z,k}$	2.5	2.7	N/mm²
Shear strength, longitudinal shear	$f_{v,090,xlay,k}$	4	4	N/mm²
	$f_{v,090,ylay,k}$	4	3	N/mm²
Shear strength, rolling shear	$f_{v,9090,xlay,k}$	1.1 or 0.7	1.1 or 0.7	N/mm²
	$f_{v,9090,ylay,k}$	1.1 or 0.7	1.1 or 0.7	N/mm²
Characteristic stiffness values				

Mean value of modulus of elasticity	$E_{0,x,mean}$	11000	12000	N/mm²
	$E_{90,x,mean}$	0 or 400	0 or 400	N/mm²
	$E_{0,y,mean}$	11000	7000	N/mm²
	$E_{90,y,mean}$	0 or 400	0 or 280	N/mm²
Fifth percentile value of modulus of elasticity	$E_{0,x,05}$	7400	8000	N/mm²
	$E_{0,y,05}$	7400	4700	N/mm²
Mean value of modulus of shear	$G_{090,xlay,mean}$	690	750	N/mm²
	$G_{090,ylay,mean}$	690	440	N/mm²
Mean value of modulus of rolling shear	$G_{9090,xlay,mean}$	50	50	N/mm²
	$G_{9090,ylay,mean}$	50	50	N/mm²
Density values				
Characteristic value	$\rho_{xlam,k}$	350	350	kg/m³
Mean value	$\rho_{xlam,mean}$	420	420	kg/m³

Laminated veneer lumber

Table 54: Material properties laminated veneer lumber without crossband veneers. Adapted from (Studiengemeinschaft Holzleimbau e.V & Federation of Finnish Woodworking Industries, 2019)

	Property	**Symbol**	**Unit**	**LVL 32P**	**LVL 35P**	**LVL 48P**	**LVL 50P**	**LVL 80P**
Bending strength	Edgewise, parallel to grain (depth 300 mm)	$f_{m,0,edge,k}$	N/mm²	27	30	44	46	75
	Flatwise, parallel to grain	$f_{m,0,flat,k}$	N/mm²	32	35	48	50	80
	Size effect parameter	s	—	0.15	0.15	0.15	0.15	0.15
Tension strength	Parallel to grain (length 3 000 mm)	$f_{t,0,k}$	N/mm²	22	22	35	36	60
	Perpendicular to grain, edgewise	$f_{t,90,edge,k}$	N/mm²	0.5	0.5	0.8	0.9	1.5
Compression strength	Parallel to grain for service class 1	$f_{c,0,k}$	N/mm²	26	30	35	42	69
	Parallel to grain for service class 2	$f_{c,0,k}$	N/mm²	21	25	29	35	57
	Perpendicular to grain, edgewise	$f_{c,90,edge,k}$	N/mm²	4	6	6	8.5	14
	Perpendicular to grain, flatwise (except pine)	$f_{c,90,flat,k}$	N/mm²	0.8	2.2	2.2	3.5	12
	Perpendicular to grain, flatwise, pine	$f_{c,90,flat,k,pine}$	N/mm²	MDV	3.3	3.3	3.5	-
Shear strength	Edgewise parallel to grain	$f_{v,0,edge,k}$	N/mm²	3.2	3.2	4.2	4.8	8
	Flatwise, parallel to grain	$f_{v,0,flat,k}$	N/mm²	2	2.3	2.3	3.2	8
Modulus of elasticity	Parallel to grain	$E_{0,mean}$	N/mm²	9600	12000	13800	15200	16800
	Parallel to grain	$E_{0,k}$	N/mm²	8000	10000	11600	12600	14900

	Perpendicular to grain, edgewise	$E_{c,90,edge,mean}$	N/mm^2	MDV	MDV	430	430	470
	Perpendicular to grain, edgewise	$E_{c,90,edge,k}$	N/mm^2	MDV	MDV	350	350	400
Shear modulus	Edgewise, parallel to grain	$G_{0,edge,mean}$	N/mm^2	500	500	600	650	760
	Edgewise, parallel to grain	$G_{0,edge,k}$	N/mm^2	300	350	400	450	630
	Flatwise, parallel to grain	$G_{0,flat,mean}$	N/mm^2	320	380	380	600	850
	Flatwise, parallel to grain	$G_{0,flat,k}$	N/mm^2	240	270	270	400	760
Density		ρ_{mean}	kg/m^3	440	510	510	580	800
		ρ_k	kg/m^3	410	480	480	550	730

Table 55: Material properties laminated veneer lumber with crossband veneers. Adapted from (Studiengemeinschaft Holzleimbau e.V & Federation of Finnish Woodworking Industries, 2019)

	Property	**Symbol**	**Unit**	**LVL 22C**	**LVL 25C**	**LVL 32C**	**LVL 36C**	**LVL 70C**	**LVL 75C**
Bending strength	Edgewise, parallel to grain (depth 300 mm)	$f_{m,0,edge,k}$	N/mm^2	19	20	28	32	54	60
	Flatwise, parallel to grain	$f_{m,0,flat,k}$	N/mm^2	22	25	32	36	70	75
	Size effect parameter	s	—	0.15	0.15	0.15	0.15	0.15	0.15
	Flatwise, perpendicular to grain	$f_{m,90,flat,k}$	N/mm^2	MDV	MDV	7	8	32	20
Tension strength	Parallel to grain (length 3 000 mm)	$f_{t,0,k}$	N/mm^2	14	15	18	22	45	51
	Perpendicular to grain, edgewise	$f_{t,90,edge,k}$	N/mm^2	4	4	5	5	16	8
Compression strength	Parallel to grain for service class 1	$f_{c,0,k}$	N/mm^2	18	18	18	26	54	64
	Parallel to grain for service class 2	$f_{c,0,k}$	N/mm^2	15	15	15	21	45	53
	Perpendicular to grain, edgewise	$f_{c,90,edge,k}$	N/mm^2	8	8	9	9	45	23
	Perpendicular to grain, flatwise (except pine)	$f_{c,90,flat,k}$	N/mm^2	1	1	2.2	2.2	16	16
	Perpendicular to grain, flatwise, pine	$f_{c,90,flat,k,pine}$	N/mm^2	MDV	MDV	3.5	3.5	—	—
Shear strength	Edgewise parallel to grain	$f_{v,0,edge,k}$	N/mm^2	3.6	3.6	4.5	4.5	7.8	7.8
	Flatwise, parallel to grain	$f_{v,0,flat,k}$	N/mm^2	1.1	1.1	1.3	1.3	3.8	3.8

	Flatwise, perpendicular to grain	$f_{v,90,flat,k}$	N/mm²	MDV	MDV	0.6	0.6	MDV	MDV
Modulus of elasticity	Parallel to grain	$E_{0,mean}$	N/mm²	6700	7200	10000	10500	11800	13200
	Parallel to grain	$E_{0,k}$	N/mm²	5500	6000	8300	8800	10900	12200
	Perpendicular to grain, edgewise	$E_{c,90,edge,mean}$	N/mm²	MDV	MDV	2400	2400	MDV	MDV
	Perpendicular to grain, edgewise	$E_{c,90,edge,k}$	N/mm²	MDV	MDV	2000	2000	MDV	MDV
	Perpendicular to grain, flatwise	$E_{m,90,flat,k}$	N/mm²	MDV	MDV	1000	1700	MDV	MDV
Shear modulus	Edgewise, parallel to grain	$G_{0,edge,mean}$	N/mm²	500	500	600	600	820	820
	Edgewise, parallel to grain	$G_{0,edge,k}$	N/mm²	300	300	400	400	660	660
	Flatwise, parallel to grain	$G_{0,flat,mean}$	N/mm²	70	70	80	120	430	430
	Flatwise, parallel to grain	$G_{0,flat,k}$	N/mm²	55	55	60	100	380	380
	Flatwise, perpendicular to grain	$G_{90,flat,mean}$	N/mm²	MDV	MDV	22	22	MDV	MDV
	Flatwise, perpendicular to grain	$G_{90,flat,k}$	N/mm²	MDV	MDV	16	16	MDV	MDV
Density		ρ_{mean}	kg/m³	440	440	510	510	800	800
		ρ_k	kg/m³	410	410	480	480	730	730

Appendix H. Analysed timber projects

This appendix contains a list of all timber buildings gathered for the analysis in chapter 7. The known characteristics of the buildings and the properties are included.

#	Building	City	Country	Costs in euro's	Cost per m2	Stored carbon	Floors (#)	Height (m)	BVO (m2)	level height	timber vollume (m3)	overall construction (weeks)	Stability system
1	Forte Tower	Melbourne	Australia			-761	10	32,2					Timber core
2	HoHo	Vienna	Austria	65000000	2600		24	84	25000		14800		Concrete core and CLT walls
3	Origine	Quebec	Canada			-3901	13	40,9	891,9				CLT walls
4	Arbora	Montreal	Canada				8		55515				CLT walls
5	Brock Commons TallWoo	Vancouver	Canada				18	53	15000				Concrete core
6	C 13 Berlin	Berlin	Germany	4700000	1005,777873		7	19,5	4673			60	
7	E3 Berlin	Berlin	Germany				7		940				CLT walls
8	Velve-lindenhof	Enschede	Netherlands				3	8,4					Timber frame
9	Plant-je-vlag		Netherlands				3						CLT walls
10	NEZZT	Purmerend	Netherlands				3						Steel frame
11	Iewan	Nijmegen	Netherlands				4						Timber frame
12	Patch 22	Amsterdam	Netherlands				6	24		4			Concrete core
13	Buiksloterham Stories	Amsterdam	Netherlands				8	34	4878	2,9			CLT walls
14	Doorman	Rotterdam	Netherlands				20						Concrete core
15	HAUT	Amsterdam	Netherlands				21	73					Concrete core and CLT walls
16	Houtbaar (remontabel bouwsysteem)		Netherlands				3						CLT walls
17	The Treet	Bergen	Norway				14	50,9	5830 of 3780			72	Timber stability frame strucutre
18	Mjøstårnet	Brumunddal	Norway				18	85,4	11300				Timber stability frame strucutre
19	Sunken Hous/ Ed's Shed	London Borough of Hackney	United Kingdom			-42	3	6,9			74	52	CLT walls
20	Cavendish Avenue	Cambridge	United Kingdom			-41	3	8,4			74	43	Timber frame
21	Woodblock House	London Borough of Hamlets	United Kingdom			-69	3	12			121	34	CLT walls
22	Mazarin House	London Borough of Redbridg	United Kingdom			-135	4	10,8			242	53	CLT walls
23	Russel street	Cambridge, Cambridgeshire	United Kingdom	2843705,567		-146	4	12			250	50	CLT walls
24	Fairmule House	London Borough of Hackney	United Kingdom	2374944,337	2225,814749	-242	5	13,8	1067		425	65	CLT walls
25	Bacton low rise	London Borough of Camden	United Kingdom	20470829,07		-977	5	17,5			1720	90	
26	Barretts Grove	London Borough of Hackney	United Kingdom	1660782,006		-144	5	18			250	52	CLT walls
27	UEA Blackdale	Norwich, Norfolk	United Kingdom	35961815,09		-2034	5	21,7			3930	62	CLT walls
28	Cobalt Palace	London Borough of Wandsw	United Kingdom	17711171,66		1458	6	19,3	15762		2575	69	
29	Whitmore Road	London Borough of Hackney	United Kingdom	2387489,555		-281	7	20,5			499	104	CLT walls
30	Kingsgate House	Royal Borough of Kensingtor	United Kingdom	12325073,82		-616	7	23	4350		1092	78	CLT walls
31	Stadthaus/ murrey grove	London Borough of Hackney	United Kingdom	4221809,034	1794,986834	-505	9	29	2352		901	49	CLT walls
32	The Cube Building	London	United Kingdom	13623978,2	2018,367141	-869	10	33	6750		1400		Concrete core
33	Dalston Works	London Borough of Hackney	United Kingdom			-2611	10	33,8	15960		4649	130	CLT walls
34	Trafalgar Palace	London Borough of Southwa	United Kingdom			-424	10	36			750	78	Timber core
	Not included because not completed or insufficient information foud												
70	Bridport House	London Borough of Hackney	United Kingdom	6789634,491		-896	8	25,6			1576	56	CLT walls
37	Tree House/ provast	Rotterdam	Netherlands				36	130	41000				Concrete core
40	The Dutch Mountains	Eindhoven	Netherlands				33	130					Concrete core
25	Woodie student hostel	Hamburg	Germany	37000000			6		13140			52	
27	Cenni di Cambiamento	Milan	Italy	15800000	#VALUE!		9	27	30325			72	
8	Puukuoka	Jyvaskyla	Finland	11000000	#VALUE!		8		5335			24	
77	Framework	Portland	United States	39534883,72	4728,487468		12	45	8361				Timber core
2	Wagramerstrasse	Vienna	Austria				7		9240			20	
7	Terrace House	Vancouver	Canada				19	71					Concrete core
9	Maison de l'Inde	Paris	France				7					28	
10	St. Diè-des-Vosges	St. Diè des Vosges	France				8						
11	Ilôt Bois et Biosourcé	Strasbourg	France				9	38	9605				
12	Ternes Villiers	Paris	France				9		17900				
13	Canopia	Bordeaux	France				17	50	17000				Timber stability frame strucutre
14	The Hyperion	Bordeaux	France				16	55	17000				Timber core
15	Silva	Bordeaux	France			-3100	18	50	17700		2500		
16	Baobab	Paris	France				35						Steel frame
24	Holz8 (H8)	Bad Aibling	Germany				8	25	803				
26	Panorama Giustinelli	Trieste	Italy				7		2900		600		
42	Abebe Court Tower	Lagos	Nigeria				26	87	40176				
43	Moholt 50/50	Trondheim	Norway				9	28	21700				
46	Strand Parken	Stockholm	Sweden				8						
47	Limnologen	Växjö	Sweden				8		10700				
48	Lagerhuset	Eslov	Sweden				10						
68	UEA (University East Ang	Norwich	United Kingdom				7		5908		1580		CLT walls
69	Sanctuary	Yoker	United Kingdom				7						
76	Carbon 12 Building	Portland	United States				8		3900				
56	St Clare's College	Oxford, Oxfordshire	United Kingdom	6130790,191		-179	3	12,8			323	66	
64	Pitfield street	London Borough of Hackney	United Kingdom	10661222,64		-301	6	18,5			533	96	
54	Cowan Court	Cambridge, Cambridgeshire	United Kingdom	12057015,82		-173	3	10			314	77	
73	Wenlock Cross	London Borough of Hackney	United Kingdom	14305177,11		-715	10	33,5			1313	108	Concrete core
60	Woodberry Down	London Borough of Hackney	United Kingdom			-284	5	15,4			503	39	
21	Walden 48	Berlin	Germany			-1361	6		7000		1633		
34	SAWA	Rotterdam	Netherlands				13	50					Concrete core
38	Elements toren	Amsterdam	Netherlands				21	70					Concrete core and walls
18	Ansbach, DE 2013	Ansbach	Germany	4340000	#VALUE!		4		3667				
20	Renovation	Augusburg	Germany	5900000	#VALUE!		6		7124			56	

#	Building	City	Country	Costs in euro's	Cost per m2	Stored carbon	Floors (#)	Height (m)	BVO (m2)	level height	timber vollume (m3)	overall construction (weeks)	Stability system
17	Terraced Houses	Munich	Germany	6360000	#VALUE!		3		3744			96	
19	Residential developmetn	Munich	Germany	8400000	#VALUE!		5		4630			28	
49	Additional storeys and cc	Zurich	Switzerland	9600000	#VALUE!		4		5127			64	
51	Badenerstraße	Zurich	Switzerland	33500000	#VALUE!		7		13876			72	
50	Zollfreilager housing com	Zurich	Switzerland	330000000	#VALUE!		6		20054			144	
39	Elements plint						4	12					CLT walls
	Not included because no residential function												
78	Pentagon II	Oslo	Norway				8			0			
79	Kulturhus Skellefteå	Skellefteå	Sweden				16	73		0			
80	Koning willlem I college	Den Bosch	Netherlands				5			0			
81	Wood Innovation Design	Prince George	Canada				7	29,6	4820	0			
82	Hotel jakarta	Amsterdam	Netherlands				12	30		0			
83	55 Southbank Boulevard	Melbourne	Australia				16			0			
84	Museum aan het water	Ijlst	Netherlands				2			0			
85	Vivialdigebouw Zuidas	Amsterdam	Netherlands					86		0			
86	Houtwerk	Utrecht	Netherlands				3	12					
87	Floating Office Rotterdam	Rotterdam	Netherlands				3			0			
88	Tamedia	Zurich	Switzerland				7	26	10120	0			
89	25 King	Brisbane	Australia				10			0			
90	DPG media	Amsterdam	Netherlands							0			
91	Triodos Bank	Driebergen- Rijsenburg	Netherlands				6	25		0			
92	Life Cycle Tower (LCT) O	Dornbirn	Austria				8	27	1765	0			
93	Barentshus	Kirkenes	Norway				20			0			
94	T3 Building	Minneapolis	United States			-3200	7		20439	0	9,5		
	Not included because only 1 floor												
95	Hurdle House	Alresford, Hampshire	United Kingdom	326925,5917		-17	1	3,5					
96	Strange House	London Borough of Lewishar	United Kingdom	208205,7563		-12	1	3,7					
97	Nurses Cottage	Milton Keynes, Buckinghams	United Kingdom	192579,2785		-16	1	3,2					
98	Huis JB	Zutphen	Netherlands				1			0			
	Not included because only 2 floors												
99	Norg	Bergakker	Netherlands				2			0			
100	Watson House	Boldre, Hampshire	United Kingdom	783833,4354		-58	2	5,3					
101	Eva Lanxmeer	Culemborg	Netherlands				2			0			
102	WonenZoals	Den Bosch	Netherlands				2			0			
103	Pannenhoef-Leemerhoef	Eindhoven	Netherlands				2			0			
104	Barli Base Uitkijkwoninge	Houten	Netherlands				2			0			
105	Lansdowne Drive Passivh	London Borough of Hackney	United Kingdom	476839,2371		-14	2	4,9					
106	Carlisle Lane	London Borough of Lambeth	United Kingdom	509535,5947		-26	2	6					
107	Carmarhen House	London Borough of Southwa	United Kingdom	352553,1673		-45	2	6,5					
108	Appartementen Finch bu	Monnickendam	Netherlands				2						
109	Heijmans ONE	Nijmegen en Veldhoven	Netherlands				2			0			
110	Optimus	Noord-Barbant	Netherlands				2	7		0			
111	Susssex House	South Downs, Sussex	United Kingdom	0		-36	2	6,5					
112	Hunsett milll	Stalham, Norfolk	United Kingdom	0		-46	2	6,5					
113	Dune House	Thorpeness, Suffolk	United Kingdom	0		-35	2	7,8					
114	Nur Holz	Weert	Netherlands				2			0			
58	142 Bremondsey street	London Borough of Southwa	United Kingdom	0		-31	2	12			55	52	
	Alleen houten gevel maar betonnen draagconstructie												
115	G8	Utrecht	Netherlands				6 and 9			0			

#	Building	Vertical system	Floor system	Floor span	Concrete plinth?	Modulair?	Construction system	Soort hout	Concerete plinth
1	Forte Tower	Timber walls	CLT		yes	no	All Timber	CLT + Concrete	Concrete plinth
2	HoHo	Timber columns	TCC	7	yes	yes	Hybrid Timber & Concrete	CLT + Glulam	
3	Origine	Timber walls	CLT	5	yes	yes	All Timber	CLT + Glulam	
4	Arbora	Timber columns	CLT	6	yes	no	All Timber		
5	Brock Commons TallWoo	Timber columns	CLT	4	yes	no	Hybrid Timber & Concrete	CLT + Glulam + Concrete > prefab	Concrete core
6	C 13 Berlin	Timber and concrete columns	CLT	5		no	Hybrid Timber, Steel & concrete	CLT floors, Glulam columns	
7	E3 Berlin	Timber walls	TCC		yes	no	Hybrid Timber & Steel		
8	Velve-lindenhof	Timber walls and columns	Casette	5	yes	no	All Timber	HSB	concrete ground level floor
9	Plant-je-vlag	Timber walls	CLT		yes	no	All Timber	CLT	
10	NEZZT	Steel columns		3,6	no	yes	Hybrid Timber & Steel	?	
11	Iewan	Timber columns	Wooden beam layer		yes	no	Hybrid HSB + strobouw	HSB + strobouw	
12	Patch 22	Timber walls and columns	TCC	4,8	yes	no	All Timber	CLT + Glulam	
13	Buiksloterham Stories	Timber walls	CLT	4,8	yes	yes	Hybrid Timber & Concrete	CLT + Concrete	concrete plinth
14	Doorman	Steel columns	TCC	4	yes	no	Hybrid Timber & Steel	HSB + Steel	use of existing concrete plinth
15	HAUT	Timber walls	CLT	6	yes	no	Hybrid Timber & Concrete	CLT + Glulam	
16	Houtbaar (remontabel bo	Timber walls	CLT	5	no	no	All Timber Modulair	?	
17	The Treet	Timber walls	CLT	4	yes	yes	All Timber	CLT + Glulam + Concrete > modular + prefab	Concrete plinth
18	Mjøstårnet	Timber walls	Casette	7,5	Concrete ground floor	no	All Timber	CLT + Glulam	
19	Sunken Hous/ Ed's Shed	Timber walls	CLT	Unknown	Concrete ground floor	no	All Timber	CLT	
20	Cavendish Avenue	Timber columns	CLT	Unknown	no	no	All timber	CLT + Glulam	
21	Woodblock House	Timber walls	CLT	Unknown	no	no	All Timber	CLT	
22	Mazarin House	Timber walls	CLT	Unknown		no	All Timber	CLT	
23	Russel street	Timber walls	CLT	Unknown	Concrete ground floor	no	All Timber	CLT	
24	Fairmule House	Timber walls	CLT	Unknown	Concrete ground floor	no	All Timber	CLT	
25	Bacton low rise						Hybrid Timber & ?	CLT + ?	
26	Barretts Grove	Timber walls	CLT	6	Concrete ground floor	no	All Timber	CLT	
27	UEA Blackdale	Timber walls	Timber and concrete floors		no	no	All Timber	CLT	
28	Cobalt Palace	Timber walls	CLT				All Timber	CLT + ?	
29	Whitmore Road	Timber walls	CLT	Unknown	yes	no	All Timber	CLT	
30	Kingsgate House	Timber walls	CLT	Unknown		no	All Timber	CLT	
31	Stadthaus/ murrey grove	Timber walls	CLT	Unknown	Concrete ground floor	no	All Timber	CLT	
32	The Cube Building	Steel columns	CLT		yes	no	Hybrid Timber, Steel & Concrete	CLT + Steel	
33	Dalston Works	Timber walls	CLT	4	yes	no	All Timber	CLT	
34	Trafalgar Palace	Timber walls	CLT		yes	no	All Timber	CLT	

Not included because not completed or insufficient information foud

70	Bridport House	Timber walls	CLT	Unknown	no	no	All Timber	CLT	
37	Tree House/ provast	Timber walls and columns					Hybrid Timber & Concerte	CLT + Concrete	
40	The Dutch Mountains	Concrete columns	TCC	7	yes	no	Hybrid Timber & Concerte core	CLT + Concrete	concrete plinth
25	Woodie student hostel		Concrete floor			yes		Modular CLT	prefab concrete floors
27	Cenni di Cambiamento						All Timber	CLT	
8	Puukuoka					yes	All Timber	Plywood > modular + prefab	
77	Framework	Timber columns	CLT		no	no	Hybrid Timber & Steel	CLT + Glulam + Concrete	
2	Wagramerstrasse						Hybrid Timber & Concrete	CLT + Concrete	
7	Terrace House	Timber columns			yes	no	Hybrid Timber & Concrete		
9	Maison de l'Inde						Hybrid Timber & Concrete	GLulam	
10	St. Diè-des-Vosges						All Timber	CLT + Glulam	
11	Ilôt Bois et Biosourcé						Unknown		
12	Ternes Villiers						All Timber		
13	Canopia		CLT			no	All Timber		
14	The Hyperion	Timber columns	CLT		yes	no	Hybrid Timber & Concrete	CLT + Concrete	
15	Silva						Unknown		
16	Baobab	Timber walls and columns			yes	yes	Hybrid Timber & Steel		
24	Holz8 (H8)						All Timber		
26	Panorama Giustinelli						All Timber except stairs and lift	Glulam	
42	Abebe Court Tower	Timber columns	LVL	Unknown	yes	no		LVL!	
43	Moholt 50/50						All Timber	CLT	
46	Strand Parken						All Timber	prefabricated units	
47	Limnologen				yes		Hybrid Timber & Concrete	CLT	All timber above concrete plinth
48	Lagerhuset						All Timber		
68	UEA (University East Ang	Timber walls	CLT	Unknown	no	no	All Timber		
69	Sanctuary						All Timber		
76	Carbon 12 Building						All Timber		
56	St Clare's College						All Timber	CLT	
64	Pitfield street						Hybrid Timber & ?	CLT + ?	
54	Cowan Court						All Timber	CLT + Glulam	
73	Wenlock Cross	Steel columns	CLT	Unknown	no	no	Hybrid Timber & Steel	CLT + Steel	
60	Woodberry Down						All Timber	CLT	
21	Walden 48								
34	SAWA	Timber walls and columns	CLT	6	yes	no	All Timber	CLT	
38	Elements toren	Steel columns and concrete walls	Timber and concrete floors	6	yes	no	Hybrid Timber, Steel & Concrete		
18	Ansbach, DE 2013							Spruce plywood	
20	Renovation						Hybrid Timber & Concrete		

17	Terraced Houses						Hybrid Timber & Steel	Timber panels + steel	
19	Residential developmetn above car park						Hybrid Timber & concrete	Plywood	
49	Additional storeys and conversion			5			Hybrid Timber, Steel & Concrete	Glulam	
51	Badenerstraße						Hybrid Timber & Concrete	Solid wood + Plywood	
50	Zollfreilager housing complex A						Hybrid Timber & Concrete	Solid wood + osb panels > modular?	
39	Elements plint	Timber and concrete columns	TCC	6	no	no			
	Not included because no residential function								
78	Pentagon II						Unknown		
79	Kulturhus Skellefteå						Hybrid Timber & Steel	CLT + Glulam	
80	Koning willlem I college						All Timber	CLT	
81	Wood Innovation Design Centre						All Timber	CLT + Glulam + mass timber	
82	Hotel jakarta						Hybrid Timber & Concerte	CLT + Concrete > modular	
83	55 Southbank Boulevard						Hybrid Timber & Concrete		
84	Museum aan het water						All Timber	HSB	
85	Vivialdigebouw Zuidas						?	?	
86	Houtwerk						All Timber	CLT + Glulam	
87	Floating Office Rotterdam (FOR)						All Timber	CLT + HSB + vuren	
88	Tamedia						All Timber	Prestressed laminated beams	
89	25 King						All Timber		
90	DPG media						Hybrid timber	?	
91	Triodos Bank						Hybrid Timber	CLT	
92	Life Cycle Tower (LCT) One						Hybrid Timber & Concrete		
93	Barentshus						Hybrid Timber & Steel		
94	T3 Building						All Timber	NLT + Glulam	
	Not included because only 1 floor								
95	Hurdle House						All Timber	CLT + ?	
96	Strange House						All Timber	CLT	
97	Nurses Cottage						All Timber	CLT	
98	Huis JB						Hybrid HSB + stone	HSB	
	Not included because only 2 floors								
99	Norg						All Timber	HSB	
100	Watson House						Hybrid Timber & Concrete	CLT + Concrete	
101	Eva Lanxmeer						All Timber	HSB	
102	WonenZoals						All Timber	CLT + HSB	
103	Pannenhoef-Leemerhoef						All Timber	CLT	
104	Barli Base Uitkijkwoningen						All Timber	HSB	
105	Lansdowne Drive Passivhaus						All Timber	CLT	
106	Carlisle Lane						All Timber	CLT	
107	Carmarhen House						All Timber	CLT	
108	Appartementen Finch buildings						All Timber	CLT	
109	Heijmans ONE						Hybrid Timber & Steel	Sandwich panels	
110	Optimus						All Timber	CLT + HSB	
111	Susssex House						Hybrid Timber & Concrete	CLT + Concrete	
112	Hunsett milll						All Timber	CLT	
113	Dune House						Hybrid Timber & Concrete	CLT + Concrete	
114	Nur Holz						All Timber	CLT	
58	142 Bremondsey street						All Timber	CLT	
	Alleen houten gevel maar betonnen draagconstructie								
115	G8						Hybrid Timber & Concerte	HSB + Concrete	
#	**Building**	**Vertical system**	**Floor system**	**Floor span**	**Concrete plinth?**	**Modulair?**	**Construction system**	**Soort hout**	**Concerete plinth**

#	Building	Functie	Status	Completion date	Source
1	Forte Tower	Residential + Retail	Completed	2013	(CTBUH Journal, 2017)
2	HoHo	Residential + Commercial	Completed	2017	(CTBUH Journal, 2017)
3	Origine	Residential	Under Construction	2017	(CTBUH Journal, 2017)
4	Arbora	Residential	Completed	2016	(CTBUH Journal, 2017)
5	Brock Commons TallWoo	Residential	Topped Out	2017	(CTBUH Journal, 2017)
6	C 13 Berlin	Residential + Office	Completed	2013	Manual of Multi-Storey Timber Construction 2018
7	E3 Berlin	Residential	Completed	2008	(CTBUH Journal, 2017)
8	Velve-lindenhof	Residential	Completed	2012	(Bronsvoort et al., 2020)
9	Plant-je-vlag	Residential	Completed	2019	(van Roosmalen et al., 2021)
10	NEZZT	Residential	Completed	2020	(van Roosmalen et al., 2021)
11	Iewan	Residential	Completed	2015	(van Roosmalen et al., 2021)
12	Patch 22	Residential + Office	Completed	2014	
13	Buiksloterham Stories	Residential + ofice space	Completed	2021	https://www.stedebouwarchitectuur.nl/artikel/woontoren-stories-e
14	Doorman	Residential	Completed		(CTBUH Journal, 2017)
15	HAUT	Residential	Proposed	2019	(CTBUH Journal, 2017)
16	Houtbaar (remontabel bo	Residential	3 completed	2021	https://www.houtbaar.nl/
17	The Treet	Residential	Completed	2015	(CTBUH Journal, 2017)
18	Mjøstårnet	Residential + Office + Hotel	Completed	2018	(CTBUH Journal, 2017)
19	Sunken Hous/ Ed's Shed	Residential	Completed	2007	100 Projects UK CLT
20	Cavendish Avenue	Residential	Completed	2008	100 Projects UK CLT
21	Woodblock House	Residential	Completed	2013	100 Projects UK CLT
22	Mazarin House	Residential	Completed	2014	100 Projects UK CLT
23	Russel street	Residential	Completed	2009	100 Projects UK CLT
24	Fairmule House	Residential + Office	Completed	2006	100 Projects UK CLT
25	Bacton low rise	Residential	Completed	2017	100 Projects UK CLT
26	Barretts Grove	Residential	Completed	2016	100 Projects UK CLT
27	UEA Blackdale	Residential	Completed	2016	100 Projects UK CLT
28	Cobalt Palace	Residential	Completed	2015	100 Projects UK CLT
29	Whitmore Road	Residential	Completed	2012	100 Projects UK CLT
30	Kingsgate House	Residential	Completed	2014	100 Projects UK CLT
31	Stadthaus/ murrey grove	Residential	Completed	2009	100 Projects UK CLT
32	The Cube Building	Residential + Commerical	Completed	2015	(CTBUH Journal, 2017)
33	Dalston Works	Residential + Commercial + Offi	Completed	2017	100 Projects UK CLT
34	Trafalgar Palace	Residential	Completed	2015	100 Projects UK CLT
	Not included because not completed or insufficient information foud				
70	Bridport House	Residential	Completed	2011	100 Projects UK CLT
37	Tree House/ provast	Residential + Office	Under Development		
40	The Dutch Mountains	Residential + Office + Hotel	Under Development	2021	
25	Woodie student hostel	Residential		2017	
27	Cenni di Cambiamento	Residential	Completed	2013	(CTBUH Journal, 2017)
8	Puukuoka	Residential	Completed	2015	(CTBUH Journal, 2017)
77	Framework	Residential + Office + Retail	Proposed	2018	(CTBUH Journal, 2017)
2	Wagramerstrasse	Residential	Completed	2013	(CTBUH Journal, 2017)
7	Terrace House	Residential	Proposed		(CTBUH Journal, 2017)
9	Maison de l'Inde	Residential	Completed	2013	(CTBUH Journal, 2017)
10	St. Diè-des-Vosges	Residential	Completed	2014	(CTBUH Journal, 2017)
11	Ilôt Bois et Biosourcé	Residential + Commercial	Proposed		(CTBUH Journal, 2017)
12	Ternes Villiers	Residential + Office + Retail	Proposed		(CTBUH Journal, 2017)
13	Canopia	Residential + Office + Commerc	Proposed		(CTBUH Journal, 2017)
14	The Hyperion	Residential + Office + Retail	Proposed	2019	(CTBUH Journal, 2017)
15	Silva	Residential + Office + Retail	Proposed	2020	(CTBUH Journal, 2017)
16	Baobab	Residential + Facilities	Proposed		(CTBUH Journal, 2017)
24	Holz8 (H8)	Residential	Completed	2011	(CTBUH Journal, 2017)
26	Panorama Giustinelli	Residential	Completed	2013	(CTBUH Journal, 2017)
42	Abebe Court Tower	Residential + Facilities	Proposed		(CTBUH Journal, 2017)
43	Moholt 50/50	Residential	Completed	2016	(CTBUH Journal, 2017)
46	Strand Parken	Residential	Completed	2014	(CTBUH Journal, 2017)
47	Limnologen	Residential	Completed	2009	(CTBUH Journal, 2017)
48	Lagerhuset	Residential	Completed	2008	(CTBUH Journal, 2017)
68	UEA (University East Ang	Residential	Completed	2016	(CTBUH Journal, 2017)
69	Sanctuary	Residential	Under Construction	2017	(CTBUH Journal, 2017)
76	Carbon 12 Building	Residential + Retail	Proposed		(CTBUH Journal, 2017)
56	St Clare's College	Residential	Completed	2015	100 Projects UK CLT
64	Pitfield street	Residential	Completed	2018	100 Projects UK CLT
54	Cowan Court	Residential	Completed	2016	100 Projects UK CLT
73	Wenlock Cross	Residential	Completed	2015	100 Projects UK CLT
60	Woodberry Down	Residential	Completed	2016	100 Projects UK CLT
21	Walden 48	Residential			houtblad
34	SAWA	Residential	Proposed	2017	https://mei-arch.eu/projecten-archief/sawa/
38	Elements toren	Residential	Under Development	2021	https://www.architectuur.nl/nieuws/amstelkwartier-krijgt-woontor
18	Ansbach, DE 2013	Residential		2013	Manual of Multi-Storey Timber Construction 2018
20	Renovation	Residential	Completed	2014	Manual of Multi-Storey Timber Construction 2018

17	Terraced Houses	Residential	Completed	2011	Manual of Multi-Storey Timber Construction 2018
19	Residential developmetn	Residential	Completed	2016	Manual of Multi-Storey Timber Construction 2018
49	Additional storeys and cc	Residential	Completed	2013	Manual of Multi-Storey Timber Construction 2018
51	Badenerstraße	Residential + Office	Completed	2010	Manual of Multi-Storey Timber Construction 2018
50	Zollfreilager housing com	Residential			Manual of Multi-Storey Timber Construction 2018
39	Elements plint		Under Development		
	Not included because no residential function				
78	Pentagon II	Unknown	Completed	2013	(CTBUH Journal, 2017)
79	Kulturhus Skellefteå	Commerical + Hotel	Proposed	2019	(CTBUH Journal, 2017)
80	Koning willlem I college	Educational		2021	(Bronsvoort et al., 2020)
81	Wood Innovation Design	Educational	Completed	2014	(CTBUH Journal, 2017)
82	Hotel jakarta	Hotel	Completed	2018	thesis van Wijnen
83	55 Southbank Boulevard	Hotel	Proposed	2020	(CTBUH Journal, 2017)
84	Museum aan het water	Museum	Completed	?	https://onix.nl/project/museum-houtstad-ijlst/
85	Vivialdigebouw Zuidas	Office			(Gemeente Amsterdam, 2020)
86	Houtwerk	Office	Planned	2021	https://www.m-architects.nl/houtwerk/
87	Floating Office Rotterdam	Office		2021	(Bronsvoort et al., 2020)
88	Tamedia	Office	Completed	2013	(CTBUH Journal, 2017)
89	25 King	Office	Proposed	2018	(CTBUH Journal, 2017)
90	DPG media	Office	Under Construction		(Bronsvoort et al., 2020)
91	Triodos Bank	Office	Completed	2019	(Van Wijnen, 2020)
92	Life Cycle Tower (LCT) O	Office	Completed	2012	(CTBUH Journal, 2017)
93	Barentshus	Office	Proposed		(CTBUH Journal, 2017)
94	T3 Building	Office + retail	Completed	2016	(CTBUH Journal, 2017)
	Not included because only 1 floor				
95	Hurdle House	Residential	Completed	2016	100 Projects UK CLT
96	Strange House	Residential	Completed	2010	100 Projects UK CLT
97	Nurses Cottage	Residential	Completed	2014	100 Projects UK CLT
98	Huis JB	Residential	Completed	2019	(van Roosmalen et al., 2021)
	Not included because only 2 floors				
99	Norg	Residential	Completed	2020	(van Roosmalen et al., 2021)
100	Watson House	Residential	Completed	2010	100 Projects UK CLT
101	Eva Lanxmeer	Residential	Completed	2000	(van Roosmalen et al., 2021)
102	WonenZoals	Residential	Under Construction	2021	(van Roosmalen et al., 2021)
103	Pannenhoef-Leemerhoef	Residential	Completed	2021	(van Roosmalen et al., 2021)
104	Barli Base Uitkijkwoninge	Residential	Completed	2017	(van Roosmalen et al., 2021)
105	Lansdowne Drive Passivh	Residential	Completed	2015	100 Projects UK CLT
106	Carlisle Lane	Residential	Completed	2005	100 Projects UK CLT
107	Carmarhen House	Residential	Completed	2017	100 Projects UK CLT
108	Appartementen Finch bu	Residential			(Bronsvoort et al., 2020)
109	Heijmans ONE	Residential	Completed	2016	(van Roosmalen et al., 2021)
110	Optimus	Residential	Under Construction	2021	(van Roosmalen et al., 2021)
111	Susssex House	Residential	Completed	2013	100 Projects UK CLT
112	Hunsett milll	Residential	Completed	2009	100 Projects UK CLT
113	Dune House	Residential	Completed	2010	100 Projects UK CLT
114	Nur Holz	Residential	Completed	2020	(van Roosmalen et al., 2021)
58	142 Bremondsey street	Residential	Completed	2015	100 Projects UK CLT
	Alleen houten gevel maar betonnen draagconstructie				
115	G8	Residential	Under Development	2022	(van Roosmalen et al., 2021)
#	**Building**	**Functie**	**Status**	**Completion date**	**Source**

Appendix I. Potential profit *De Scharnier*

This appendix contains the full cost and carbon calculation of *De Scharnier*

Full calculation costs *De Scharnier*

	level 1	*level 2*	*Level 3*			
				Concrete variant	***Hybrid variant***	***Timber variant***
B	Building costs					
	1	Engineering works				
		A	Foundation	€ 1.400.437	€ 1.375.853	€ 1.338.976
		B	Frame	€ 5.779.211	€ 7.062.588	€ 7.299.588
		E	Interior wall finishing	€ 758.350	€ 758.350	€ 941.400
		F	Floor finishing	€ 858.812	€ 1.846.445	€ 1.846.445
		H	Ceiling finishing	€ 1.374.098	€ 1.202.336	€ 1.202.336
		-	**Total engineering works**	**€ 10.170.909**	**€ 12.245.572**	**€ 12.628.745**
	5	General execution costs				
		A	Other subjects	€ 1.017.091	€ 1.224.557	€ 1.262.874
		B	General execution costs	€ 3.091.721	€ 2.799.210	€ 2.799.210
		-	**Total general execution costs**	**€ 4.108.812**	**€ 4.023.767**	**€ 4.062.085**
	-	**Total building costs**		**€ 14.279.721**	**€ 16.269.339**	**€ 16.690.829**
G	Financing costs					
	2	Financing costs building				
		A	Construction interest	€ 428.392	€ 463.676	€ 475.689
		-	**Total financing costs building**	**€ 428.392**	**€ 463.676**	**€ 475.689**
	-	**Total financing costs**		**€ 428.392**	**€ 463.676**	**€ 475.689**
Z	Revenue					
	2	Revenue building project				
		A	Periodic revenue	€ -	€ -	€ -
		B	One-off revenue 0%	€ 58.704.200	€ 58.704.200	€ 58.704.200
			One-off revenue 1%		€ 59.016.460	€ 59.016.460
			One-off revenue 2%		€ 59.328.720	€ 59.328.720
			One-off revenue 4%		€ 59.953.240	€ 59.953.240
		-	**Total Revenue building project**	**€ 58.704.200**	**€ 58.704.200**	**€ 58.704.200**
	-	**Total revenue**		**€ 58.704.200**	**€ 58.704.200**	**€ 58.704.200**
	1	Additional costs				
		A	Land costs	€ 1.464.241	€ 1.464.241	€ 1.464.241
		X	Unforeseen	€ 571.189	€ 650.774	€ 667.633
		B	Professional fees	€ 1.399.413	€ 1.594.395	€ 1.635.701
		C	Connection fees	€ 471.231	€ 536.888	€ 550.797
		D	Taxes	€ 285.594	€ 325.387	€ 333.817
		H	Developer fees	€ 1.042.420	€ 1.187.662	€ 1.218.431
		I	Selling fees	€ 171.357	€ 195.232	€ 200.290
		-	**Total additional costs**	**€ 5.405.443**	**€ 5.954.578**	**€ 6.070.909**
	-	**Total additional costs**		**€ 5.405.443**	**€ 5.954.578**	**€ 6.070.909**
		Total compared costs		**€ 20.113.556**	**€ 22.687.594**	**€ 23.237.428**
		Total potential profit		**€ 38.590.644**	**€ 36.016.606**	**€ 35.466.772**

Figure 99: Overview costs three variants of De Scharnier

footprint/ bouwoppervlak	1768,63 m²			
BVO	17176,23 m²	Koop GO	6005	m2
GO	12707 m²	Huur GO	3163	m2
Wandoppervlak afweking	5230 m²	overig GO	3539	m2

code	omschrijving	d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	Difference concrete and hybrid
	CONCRETE		17176,23		€ 856		€ 14.708.112	€ 2.024.903
B1	**Bouwkundige werken**		**17.176,23**				**€ 10.170.909**	
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	Difference concrete and hybrid
1A	**FUNDERING CONCRETE**		**17176,23**	**m²**	**€ 82**		**€ 1.400.437**	-€ 24.585
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
10	**Voorzieningen bouwput**							
	MAATVOEREN:							
	maatvoering onderbouw		1768,63	tbb	€ 2,50	€ 4.421,58		€ 0
	totaal voorzieningen bouwput						**€ 4.421,58**	**€ 0**
11	**Bodemvoorzieningen**							
	GRONDWERK							
	terrein uitvlakken		1768,63	m²	€ 1,50	€ 2.652,95		€ 0
	totaal bodemvoorzieningen		**1768,63**	**m²**			**€ 2.652,95**	**€ 0**
13/23	**Laagste vloer, op grondslag / vrijdragend**							
	VRIJDRAGENDE VLOEREN:							
	kanaalplaatvloer	0,26	1768,63	m²	€ 84,00	€ 148.564,92		€ 0
	totaal laagste vloer, op grondslag / v		**1768,63**	**m²**			**€ 148.564,92**	**€ 0**
16	**Funderingsconstructie**							
	FUNDERINGSCONSTRUCTIE							
	funderingsconstructie, totaal	0%	17176,23	bvo	€ 25,00	€ 429.405,75		-€ 8.588
	totaal funderingsconstructie		**1768,63**	**m²**	**€ 242,79**		**€ 429.405,75**	**-€ 8.588**
17	**Paalfunderingen**							
	PAALFUNDERINGEN:							
	paalfunderingen, totaal (gron	0%	17176,23	bvo	€ 40,06	€ 688.079,77		-€ 13.762
	totaal paalfunderingen		**17176**	**st**	**€ 40,06**		**€ 688.079,77**	**-€ 13.762**
5A	**Nader te detailleren over fundering**							
	nader te detailleren		0,1	over	€ 1.273.124,96	€ 127.312,50		-€ 2.235
	totaal nader te detailleren over fundering						**€ 127.312,50**	**-€ 2.235**
	TOTAAL FUNDERING						**€ 1.400.437**	**-€ 24.585**
1B	**SKELET CONCRETE**		**17.176,23**	**m²**	**€ 336,47**		**€ 5.779.211**	
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
21.2	**Buitenwanden; constructief**							
22.2	**Binnenwanden; constructief**							
	BINNENWANDEN:							
	prefab betonwand (bruto) tpv	0,3	705,264	m²	€ 228	€ 160.800		€ 0
	prefab betonwand (bruto) tpv	0,3	3564,565	m²	€ 228	€ 812.721		€ 0
	prefab betonwand (bruto) tpv	0,3	5229,57	m²	€ 219	€ 1.145.276		€ 0
	totaal binnenwanden; constructief		**9499,399**	**m²**	**€ 223**		**€ 2.118.797**	**€ 0**
23.2	**Vloeren; constructief**							
	VLOEREN:							
	breedplaat	0,25	3326,4	m²	€ 107	€ 355.925		€ 0
	breedplaat met balkbodems	0,3	3082,78	m²	€ 204	€ 628.887		€ 0
	Breedplaat ipv CLT	0,25	8998,42	m²	€ 107	€ 962.831		€ 998.825
	Breedplaat als balkons ipv CLT	0,25	1512,45	m²	€ 107	€ 161.832		€ 167.882
	stalen balkoen tbv balkons		51723,7	kg	€ 3	€ 142.240		€ 0
	totaal vloeren; constructief		**59645,33**	**m²**	**€ 38**		**€ 2.251.715**	**€ 1.166.707**
24	**Trappen & hellingen constructief**							
27.2	**Daken; constructief**							
	VLAKKE DAKEN:							
	breedplaat	0,28	674,53	m²	€ 110	€ 74.198		€ 0
	breedplaat incl. balkbodems	0,3	447,51	m²	€ 215	€ 96.215		€ 0
	totaal daken; constructief		**1122,04**	**m²**	**€ 152**		**€ 170.413**	**€ 0**
28	**Hoofddraagconstructie**							
	MAATVOEREN:							
	maatvoering bovenbouw		15407,6	bvo	€ 2	€ 36.978		€ 0
	KOLOMMEN							
	betonkolom prefab tpv woningen		741,2	m¹	€ 146	€ 108.215		€ 0
	betonkolom prefab tpv plint		462	m¹	€ 228	€ 105.336		€ 0
								€ 0
	LIGGERS							
	betonbalk prefab tpv kopgevels		406,25	m¹	€ 216	€ 87.750		€ 0
	Glulam ligger		1470,1	m¹	€ 187	€ 274.909		€ 0
	wand-/vakwerkligger tbv overgangsc		40,8	m¹	€ 2.444	€ 99.715		€ 0
	totaal hoofddraagconstructie		**17176,23**	**m²**	**€ 42**		**€ 712.903**	**€ 0**
5A	**Nader te detailleren over skelet**							
	nader te detailleren		0,1	over	€ 5.253.828	€ 525.383		€ 116.671
	totaal nader te detailleren over skelet						**€ 525.383**	**€ 116.671**
	TOTAAL SKELET		**17.176**	**m²**			**€ 5.779.211**	**€ 1.283.377**
1E	**BINNENWAND AFBOUW CONC**		**5.230**	**m²**	**€ 145**		**€ 758.350**	€ 0
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Binnenwand afwerking		5230,00	m2	€ 145,00	€ 758.350,00		€ 0
	Totaal binnenwand afbouw						**€ 758.350**	€ 0

		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
1F	**VLOERAFBOUW CONCRETE**		**17.176,23**	**m²**	**€ 50**		**€ 858.812**	**€ 987.633**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Vloerafbouw		17176,23	m²	€ 50,00	€ 858.811,50		€ 343.525
								€ 644.109
	Totaal vloerafbouw						**€ 858.812**	**€ 987.633**
1H	**PLAFONDS BINNEN/ BUI**	**bvo**	**17.176,23**	**m²**	**€ 80**		**€ 1.374.098**	**-€ 171.762**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Plafonds binnen		17176,23	m²	€ 80,00	€ 1.374.098,40		-€ 171.762
	Plafonds buiten, buiten beschouwing							€ 0
	Totaal plafonds binnen/ buiten						**€ 1.374.098**	**-€ 171.762**
B5	**Algemene uitvoering:**	**bvo**	**17.176,23**	**m²**	**€ 239,22**		**€ 4.108.812**	**-€ 85.045**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
5A	**DIVERSEN CONCRETE**	**bco**	**17.176,23**	**m²**	**€ 59**		**€ 1.017.091**	**€ 207.466**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Diversen,10% van totaal bouwkundig	€	10.170.908,51		10%	€ 1.017.090,85		€ 207.466
	Totaal diversen						**€ 1.017.091**	**€ 207.466**
5B	**ALGEMENE UITVOERING**	**bvo**	**17.176,23**	**m²**	**€ 180**		**€ 3.091.721**	**-€ 292.511**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Algemene uitvoeringskosten		17.176,23	m²	€ 180,00	€ 3.091.721,40		-€ 292.511
	Totaal algemene uitvoeringskosten						**€ 3.091.721**	**-€ 292.511**
G2	**Financieringskosten b**	**bvo**	**17.176,23**	**m²**	**€ 24,94**		**€ 428.392**	**€ 35.285**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Bouwrente		3,0%		€ 14.279.720,76	€ 428.391,62		€ 35.285
	Totaal financieringskosten						**€ 428.392**	**€ 35.285**
Z2	**Baten bouw concrete**	**bvo**	**17.176,23**	**m²**	**€ -3.417,76**		**€ -58.704.200**	**€ 0**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Baten verkoop vrije sector		6005	m²	€ 5.200,00	€ -31.226.000,00		€ 0
	Baten verkoop sociale huur		3163	m²	€ 4.100,00	€ -12.968.300,00		
	Baten verkoop overig		3539	m²	€ 4.100,00	€ -14.509.900,00		
	Totaal baten						**€ -58.704.200**	**€ 0**
X	**Additional costs**	**bvo**	**17.176,23**	**m²**	**€ 314,70**		**€ 5.405.443**	**€ 549.135**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
A	Grondkosten	laag	€ 14.279.721		6,0%			
		mid	€ 14.279.721		7,5%			
		hoog	€ 14.279.721		9,0%	€ 1.464.241		
	totaal grondkosten		**17176,23**	**m²**	**€ 85**		**€ 1.464.241**	**€ 0**
X	Onvoorzien	laag	€ 14.279.721		3,0%			
		mid	€ 14.279.721		4,0%	€ 571.189		
		hoog	€ 14.279.721		5,0%			
	totaal onvoorzien		**17176,23**	**m²**	**€ 33**		**€ 571.189**	**€ 79.585**
B	Honoraria	laag	€ 14.279.721		6,7%			
		mid	€ 14.279.721		9,8%	€ 1.399.413		
		hoog	€ 14.279.721		17,3%			
	totaal honoraria		**17176,23**	**m²**	**€ 81**		**€ 1.399.413**	**€ 194.983**
C	Aansluitkosten	laag	€ 14.279.721		2,1%			
		mid	€ 14.279.721		3,3%	€ 471.231		
		hoog	€ 14.279.721		5,0%			
	totaal aansluitkosten		**17176,23**	**m²**	**€ 27**		**€ 471.231**	**€ 65.657**
D	Heffingen	laag	€ 14.279.721		1,0%			
		mid	€ 14.279.721		2,0%	€ 285.594		
		hoog	€ 14.279.721		5,0%			
	totaal hefftingen		**17176,23**	**m²**	**€ 17**		**€ 285.594**	**€ 39.792**
H	Ontwikkelaarskosten	laag	€ 14.279.721		3,5%			
		mid	€ 14.279.721		7,3%	€ 1.042.420		
		hoog	€ 14.279.721		18,5%			
	totaal ontwikkelaarskosten		**17176,23**	**m²**	**€ 61**		**€ 1.042.420**	**€ 145.242**
I	Verkoopkosten	laag	€ 14.279.721		1,2%			
		mid	€ 14.279.721		1,2%	€ 171.357		
		hoog	€ 14.279.721		2,7%			
	totaal verkoopkosten		**17176,23**	**m²**	**€ 10**		**€ 171.357**	**€ 23.875**
	Totaal additional costs						**€ 5.405.443**	**€ 549.135**

footprint/ bouwoppervlak	1768,63 m²		
BVO	17176,23 m²	Koop GO	6005 m2
GO	12707 m²	Huur GO	3163 m2
Wandoppervlak afweking	5230 m²	overig GO	3539 m2

Difference concrete and hybrid			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	Difference hybrid and timber
€ 2.024.903		HYBRID		17176,23		€ 974		€ 16.733.016	€ 433.503
	B1	**Bouwkundige werken**						€ **12.245.572**	
-€ 24.585	**1A**	**FUNDERING CONCRETE**		**17176,23**	**m²**	**€ 80**		**€ 1.375.853**	-€ 1.375.853
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	10	**Voorzieningen bouwput**							
		MAATVOEREN:							
€ 0		maatvoering onderbouw		1768,63	tbb	€ 2,50	€ 4.421,58		€ 0
€ 0		**totaal voorzieningen bouwput**						**€ 4.421,58**	€ 0
	11	**Bodemvoorzieningen**							
		GRONDWERK							
€ 0		terrein uitvlakken		1768,63	m²	€ 1,50	€ 2.652,95		€ 0
€ 0		**totaal bodemvoorzieningen**		**1768,63**	**m²**			**€ 2.652,95**	€ 0
	13/23	**Laagste vloer, op grondslag / vrijdragend**							
		VRIJDRAGENDE VLOEREN:							
€ 0		kanaalplaatvloer	0,26	1768,63	m²	€ 84,00	€ 148.564,92		€ 0
€ 0		**totaal laagste vloer, op grondslag / vrijdra**		**1768,63**	**m²**			**€ 148.564,92**	€ 0
	16	**Funderingsconstructie**							
		FUNDERINGSCONSTRUCTIE							
-€ 8.588		funderingsconstructie, totaal ii	2%	17176,23	bvo	€ 24,50	€ 420.817,64		-€ 12.882
-€ 8.588		**totaal funderingsconstructie**		**1768,63**	**m²**	**€ 237,93**		**€ 420.817,64**	-€ 12.882
	17	**Paalfunderingen**							
		PAALFUNDERINGEN:							
-€ 13.762		paalfunderingen, totaal (gronc	2%	17176,23	bvo	€ 39,26	€ 674.318,18		-€ 20.642
-€ 13.762		**totaal paalfunderingen**		**17176**	**st**	**€ 39,26**		**€ 674.318,18**	-€ 20.642
	5A	**Nader te detailleren over fundering**							
-€ 2.235		nader te detailleren		0,1	over	€ 1.250.775,25	€ 125.077,53		-€ 3.352
-€ 2.235		**totaal nader te detailleren over fundering**						**€ 125.077,53**	-€ 3.352
-€ 24.585		**TOTAAL FUNDERING**						**€ 1.375.853**	-€ 36.877
	1B	**SKELET HYBRID**		**17.176,23**	**m²**	**€ 411,18**		**€ 7.062.588**	
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	21.2	**Buitenwanden; constructief**							€ 68.793
	22.2	**Binnenwanden; constructief**							
		BINNENWANDEN:							
€ 0		prefab betonwand (bruto) tpv	0,3	705,264	m²	€ 228	€ 160.800		€ 0
€ 0		prefab betonwand (bruto) tpv	0,3	3564,565	m²	€ 228	€ 812.721		€ 0
€ 0		prefab betonwand (bruto) tpv	0,3	5229,57	m²	€ 219	€ 1.145.276		-€ 1.145.276
€ 0		**totaal binnenwanden; constructief**		**4269,829**	**m²**	**€ 496**		**€ 2.118.797**	-€ 1.145.276
	23.2	**Vloeren; constructief**							
		VLOEREN:							
€ 0		breedplaat	0,25	3326,4	m²	€ 107	€ 355.925		€ 0
€ 0		breedplaat met balkbodems	0,3	3082,78	m²	€ 204	€ 628.887		€ 0
€ 998.825		Hybride CLT-vloer (200+100)	0,3	8998,42	m²	€ 218	€ 1.961.656		€ 332.942
€ 167.882		Hybride CLT-vloer (200+100) a	0,3	1512,45	m²	€ 218	€ 329.714		€ 55.961
€ 0		stalen balkoen tbv balkons		51723,7	kg	€ 3	€ 142.240		€ 0
€ 1.166.707		**totaal vloeren; constructief**		**59645,33**	**m²**	**€ 57**		**€ 3.418.422**	€ 388.902
	24	**Trappen & hellingen constructief**							
	27.2	**Daken; constructief**							
		VLAKKE DAKEN:							
€ 0		breedplaat	0,28	674,53	m²	€ 110	€ 74.198		€ 0
€ 0		breedplaat incl. balkbodems	0,3	447,51	m²	€ 215	€ 96.215		€ 0
€ 0		**totaal daken; constructief**		**1122,04**	**m²**	**€ 152**		**€ 170.413**	€ 0
	28	**Hoofddraagconstructie**							
		MAATVOEREN:							
€ 0		maatvoering bovenbouw		15407,6	bvo	€ 2	€ 36.978		€ 0
		KOLOMMEN							
€ 0		betonkolom prefab tpv woningen		741,2	m¹	€ 146	€ 108.215		-€ 47.666
€ 0		betonkolom prefab tpv plint		462	m¹	€ 228	€ 105.336		€ 0
€ 0									€ 831.560
		LIGGERS							
€ 0		betonbalk prefab tpv kopgevels		406,25	m¹	€ 216	€ 87.750		-€ 87.750
€ 0		Glulam ligger		1470,1	m¹	€ 187	€ 274.909		€ 77.845
€ 0		wand-/vakwerkligger tbv overgangsconstr.		40,8	m¹	€ 2.444	€ 99.715		€ 197.839
€ 0		**totaal hoofddraagconstructie**		**17176,23**	**m²**	**€ 42**		**€ 712.903**	€ 971.828
	5A	**Nader te detailleren over skelet**							
€ 116.671		nader te detailleren		0,1	over	€ 6.420.535	€ 642.053		€ 21.545
€ 116.671		**totaal nader te detailleren over skelet**						**€ 642.053**	€ 21.545
€ 1.283.377		**TOTAAL SKELET**		**17.176**	**m²**			**€ 7.062.588**	€ 237.000
€ 0	**1E**	**BINNENWAND AFBOUW CONCRETE**		**5.230**	**m²**			**€ 758.350**	€ 183.050
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
€ 0		Binnenwand afwerking		5230	m2	€ 145,00	€ 758.350,00		€ 183.050
€ 0		**Totaal binnenwand afbouw**						**€ 758.350**	€ 183.050

€ 987.633	1F	**VLOERAFBOUW CONCRETE**		**17.176,23**	**m²**	**€ 107,50**		**€ 1.846.445**	€ 0
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
€ 343.525		Vloerafbouw		17176,23	m²	€ 70,00	€ 1.202.336,10		€ 0
€ 644.109		Sprinkler installatie		17176,23	m²	€ 37,50	€ 644.108,63		€ 0
€ 987.633		**Totaal vloerafbouw**						€ 1.846.445	€ 0
-€ 171.762	1H	**PLAFONDS BINNEN/ BUI**	**bvo**	**17.176,23**	**m²**			**€ 1.202.336**	€ 0
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
-€ 171.762		Plafonds binnen		17176,23	m²	€ 70,00	€ 1.202.336,10		€ 0
€ 0		Plafonds buiten, buiten beschouwing							€ 0
-€ 171.762		**Totaal plafonds binnen/ buiten**						€ 1.202.336	€ 0
-€ 85.045	B5	**Algemene uitvoerings**	**bvo**	**17.176,23**	**m²**	**€ 234,26**		**€ 4.023.767**	€ 38.317
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
€ 207.466	5A	**DIVERSEN HYBRID**	**bco**	**17.176,23**	**m²**			**€ 1.224.557**	€ 38.317
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
€ 207.466		Diversen,10% van totaal bouwkundige wer		€ 12.245.571,98	10%		€ 1.224.557,20		€ 38.317
€ 207.466		**Totaal diversen**						€ 1.224.557	€ 38.317
-€ 292.511	5B	**ALGEMENE UITVOERING!**	**bvo**	**17.176,23**	**m²**	**€ 162,97**		**€ 2.799.210**	€ 0
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
-€ 292.511		Algemene uitvoeringskosten diversen		17.176,23	m²	€ 162,97	€ 2.799.210,20		€ 0
			90,5%	€ 162,97					
-€ 292.511		**Totaal uitvoeringskosten**						€ 2.799.210	€ 0
€ 35.285	G2	**Financieringskosten b**	**bvo**	**17.176,23**	**m²**	**€ 27,00**		**€ 463.676**	€ 12.012
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
€ 35.285		Bouwrente		5%	2,85%	€ 16.269.339,38	€ 463.676,17		€ 12.012
				5%	3,15%	€ 16.269.339,38	€ 512.484,19		
€ 35.285		**Totaal financieringskosten**						€ 463.676	€ 12.012
€ 0	Z2	**Baten bouw concrete**	**bvo**	**17.176,23**	**m²**	**€ -3.417,76**		**€ -58.704.200**	€ 0
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
€ 0		Baten verkoop vrije sector	0,0%	6005	m²	€ 5.200,00	€ -31.226.000,00	€ -58.704.200	€ 0
			1,0%	6005	m²	€ 5.252,00	€ -31.538.260,00	€ -59.016.460	
			2,0%	6005	m²	€ 5.304,00	€ -31.850.520,00	€ -59.328.720	
			4,0%	6005	m²	€ 5.408,00	€ -32.475.040,00	€ -59.953.240	
		Baten verkoop sociale huur		3163	m²	€ 4.100,00	€ -12.968.300,00		
		Baten verkoop school		3539	m²	€ 4.100,00	€ -14.509.900,00		
€ 0		**Totaal baten**					0,0%	€ -58.704.200	€ 0
€ 549.135	Z2	**Additional costs**	**bvo**	**17.176,23**	**m²**	**€ 346,68**		**€ 5.954.578**	€ 116.331
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	A	Grondkosten	laag	€ 16.269.339		6,0%			
			mid	€ 16.269.339		7,5%			
			hoog	€ 16.269.339		9,0%	€ 1.464.241		
€ 0		**totaal grondkosten**		**17176,23**	**m²**	**€ 85**		**€ 1.464.241**	€ 0
	X	Onvoorzien	laag	€ 16.269.339		3,0%			
			mid	€ 16.269.339		4,0%	€ 650.774		
			hoog	€ 16.269.339		5,0%			
€ 79.585		**totaal onvoorzien**		**17176,23**	**m²**	**€ 38**		**€ 650.774**	€ 16.860
	B	Honoraria	laag	€ 16.269.339		6,7%			
			mid	€ 16.269.339		9,8%	€ 1.594.395		
			hoog	€ 16.269.339		17,3%			
€ 194.983		**totaal honoraria**		**17176,23**	**m²**	**€ 93**		**€ 1.594.395**	€ 41.306
	C	Aansluitkosten	laag	€ 16.269.339		2,1%			
			mid	€ 16.269.339		3,3%	€ 536.888		
			hoog	€ 16.269.339		5,0%			
€ 65.657		**totaal aansluitkosten**		**17176,23**	**m²**	**€ 31**		**€ 536.888**	€ 13.909
	D	Heffingen	laag	€ 16.269.339		1,0%			
			mid	€ 16.269.339		2,0%	€ 325.387		
			hoog	€ 16.269.339		5,0%			
€ 39.792		**totaal hefftingen**		**17176,23**	**m²**	**€ 19**		**€ 325.387**	€ 8.430
	H	Ontwikkelaarskosten	laag	€ 16.269.339		3,5%			
			mid	€ 16.269.339		7,3%	€ 1.187.662		
			hoog	€ 16.269.339		18,5%			
€ 145.242		**totaal ontwikkelaarskosten**		**17176,23**	**m²**	**€ 69**		**€ 1.187.662**	€ 30.769
	I	Verkoopkosten	laag	€ 16.269.339		1,2%			
			mid	€ 16.269.339		1,2%	€ 195.232		
			hoog	€ 16.269.339		2,7%			
€ 23.875		**totaal verkoopkosten**		**17176,23**	**m²**	**€ 11**		**€ 195.232**	€ 5.058
€ 549.135		**Totaal additional costs**						€ 5.954.578	€ 116.331

footprint/ bouwoppervlak	1768,63 m²			
BVO	17176,23 m²	Koop GO	6005	m2
GO	12707 m²	Huur GO	3163	m2
Wandoppervlak afweking	5230 m²	overig GO	3539	m2

Difference hybrid and timber	Code	Omschrijving	d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 433.503		TIMBER		17176,23		€ 999		€ 17.166.518
	B1	**Bouwkundige werken**						€ **12.628.745**
-€ 1.375.853	1A	**FUNDERING HOUT**		**17176,23**	**m²**	**€ 78**		**€ 1.338.976**
	10	**Voorzieningen bouwput**						
		MAATVOEREN:						
€ 0		maatvoering onderbouw		1768,63	tbb	€ 3	€ 4.422	
€ 0		**totaal voorzieningen bouwput**						**€ 4.422**
	11	**Bodemvoorzieningen**						
		GRONDWERK						
€ 0		terrein uitvlakken		1768,63	m²	€ 1,50	€ 2.653	
€ 0		**totaal bodemvoorzieningen**		**1768,63**	**m²**			**€ 2.653**
	13/23	**Laagste vloer, op grondslag / vrijdragend**						
		VRIJDRAGENDE VLOEREN:						
€ 0		kanaalplaatvloer	0,26	1768,63	m²	€ 84,00	€ 148.565	
€ 0		**totaal laagste vloer, op grondslag / vr**		**1768,63**	**m²**			**€ 148.565**
	16	**Funderingsconstructie**						
		FUNDERINGSCONSTRUCTIE						
-€ 12.882		funderingsconstructie, totaal i	5%	17176,23	bvo	€ 23,75	€ 407.935	
-€ 12.882		**totaal funderingsconstructie**		**1768,63**	**m²**	**€ 230,7**		**€ 407.935**
	17	**Paalfunderingen**						
		PAALFUNDERINGEN:						
-€ 20.642		paalfunderingen, totaal (gronc	5%	17176,23	bvo	€ 38,06	€ 653.676	
-€ 20.642		**totaal paalfunderingen**		**17176,23**	**st**	**€ 38,06**		**€ 653.676**
	5A	**Nader te detailleren over fundering**						
-€ 3.352		nader te detailleren		0,1	over	€ 1.217.251	€ 121.725	
-€ 3.352		**totaal nader te detailleren over fundering**						**€ 121.725**
-€ 36.877		**TOTAAL FUNDERING**						**€ 1.338.976**
	1B	**SKELET HOUT**		**17176,23**	**m²**	**€ 425**		**€ 7.299.588**
€ 68.793	21.2	**Buitenwanden; constructief**						
	22.2	**Binnenwanden; constructief**						
		BINNENWANDEN:						
€ 0		prefab betonwand (bruto) tpv	0,3	705,264	m²	€ 228	€ 160.800	
€ 0		prefab betonwand (bruto) tpv	0,3	3564,565	m²	€ 228	€ 812.721	
-€ 1.145.276								
-€ 1.145.276		**totaal binnenwanden; constructief**		**4269,829**	**m²**	**€ 228**		**€ 973.521**
	23.2	**Vloeren; constructief**						
		VLOEREN:						
€ 0		breedplaat	0,25	3326,4	m²	€ 107	€ 355.925	
€ 0		breedplaat met balkbodems	0,3	3082,78	m²	€ 204	€ 628.887	
€ 332.942		Hybride CLT-vloer (240+80)	0,32	8998,42	m²	€ 255	€ 2.294.597	
€ 55.961		Hybride CLT-vloer (200+100) a	0,3	1512,45	m²	€ 255	€ 385.675	
€ 0		stalen balkoen tbv balkons		51723,7	kg	€ 3	€ 142.240	
€ 388.902		**totaal vloeren; constructief**		**59645,33**	**m²**	**€ 64**		**€ 3.807.324**
	24	**Trappen & hellingen constructief**						
	27.2	**Daken; constructief**						
		VLAKKE DAKEN:						
€ 0		breedplaat	0,28	674,53	m²	€ 110	€ 74.198	
€ 0		breedplaat incl. balkbodems	0,3	447,51	m²	€ 215	€ 96.215	
€ 0		**totaal daken; constructief**		**1122,04**	**m²**	**€ 152**		**€ 170.413**
	28	**Hoofddraagconstructie**						
		MAATVOEREN:						
€ 0		maatvoering bovenbouw		15407,6	bvo	€ 2	€ 36.978	
		KOLOMMEN						
-€ 47.666		betonkolom prefab tpv woning	0,4	414,72	m¹	€ 146	€ 60.549	
€ 0		betonkolom prefab tpv plint (C	0,5	462	m¹	€ 228	€ 105.336	
€ 831.560		CLT kolom (0,6 x 0,6)	0,6	1857,6	m¹	€ 448	€ 831.560	
		LIGGERS						
-€ 87.750								
€ 77.845		Glulam ligger (0,6 x 0,3)		1876,35	m¹	€ 188	€ 352.754	
€ 197.839		wand-/vakwerkligger tbv overgangsco		122,4	m¹	€ 2.431	€ 297.554	
€ 971.828		**totaal hoofddraagconstructie**		**17176,23**	**m²**	**€ 98**		**€ 1.684.731**
	5A	**Nader te detailleren over skelet**						
€ 21.545		nader te detailleren		0,1	over	€ 6.635.989	€ 663.599	
€ 21.545		**totaal nader te detailleren over skelet**						**€ 663.599**
€ 237.000		**TOTAAL SKELET**		**17.176**	**m²**	**€ 424,98**		**€ 7.299.588**
€ 183.050	1E	**BINNENWAND AFBOUW HOUT**		**5230**				**€ 941.400**
€ 183.050		Binnenwand afwerking		5230	m²	€ 180	€ 941.400	
€ 183.050		**Totaal binnenwand afbouw**						**€ 941.400**

			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 0	1F	**VLOERAFBOUW HOUT**		**17176,23**	**m²**	**€ 108**		**€ 1.846.445**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 0		Vloerafbouw		17176,23	m²	€ 70,00	€ 1.202.336,10	
€ 0		Sprinkler installatie		17176,23	m²	€ 37,50	€ 644.108,63	
€ 0		**Totaal vloerafbouw**						**€ 1.846.445**
€ 0	1H	**PLAFONDS BINNEN/ BUI bvo**		**17176,23**	**m²**			**€ 1.202.336**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 0		Plafonds binnen		17176,23	m²	€ 70,00	€ 1.202.336,10	
€ 0		Plafonds buiten, buiten beschouwing						
€ 0		**Totaal plafonds binnen/ buiten**						**€ 1.202.336**
€ 38.317	B5	**Algemene uitvoerings bvo**		**17176,23**	**m²**	**€ 236,49**		**€ 4.062.085**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 38.317	5A	**DIVERSEN HOUT**		**17176,23**				**€ 1.262.874**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 38.317		Diversen,10% van totaal bouwkundige	€	12.628.744,78	10%		€ 1.262.874,48	
€ 38.317		**Totaal diversen**						**€ 1.262.874**
€ 0	5B	**ALGEMENE UITVOERING: bvo**		**17176,23**	**m²**	**€ 163**		**€ 2.799.210**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 0		Algemene uitvoeringskosten diversen		17.176,23	m²	€ 162,97	€ 2.799.210,20	
€ 0		**Totaal uitvoeringskosten**						**€ 2.799.210**
€ 12.012	G2	**Financieringskosten b bvo**		**17176,23**	**m²**	**€ 27,69**		**€ 475.689**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 12.012		Bouwrente	5%	2,85%		€ 16.690.829,46	€ 475.688,64	
		Bouwrente	5%	3,15%		€ 16.690.829,46	€ 525.761,13	
€ 12.012		**Totaal financieringskosten**						**€ 475.689**
€ 0	G2	**Baten bouw hout bvo**		**17176,23**	**m²**	**€ -3.417,76**		**€ -58.704.200**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
€ 0		Baten verkoop vrije sector	0,0%	6005	m²	€ 5.200,00	€ -31.226.000,00	€ -58.704.200
			1,0%	6005	m²	€ 5.252,00	€ -31.538.260,00	€ -59.016.460
			2,0%	6005	m²	€ 5.304,00	€ -31.850.520,00	€ -59.328.720
			4,0%	6005	m²	€ 5.408,00	€ -32.475.040,00	€ -59.953.240
		Baten verkoop sociale huur		3163	m²	€ 4.100,00	€ -12.968.300,00	
		Baten verkoop school		3539	m²	€ 4.100,00	€ -14.509.900,00	
€ 0		**Totaal baten**					**0,0%**	**€ -58.704.200**
€ 116.331	G2	**Additional costs bvo**		**17.176,23**	**m²**	**€ 353,45**		**€ 6.070.909**
			d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
	A	Grondkosten	laag	€ 16.690.829		6,0%		
			mid	€ 16.690.829		7,5%		
			hoog	€ 16.690.829		9,0%	€ 1.464.241	
€ 0		**totaal grondkosten**		**17176,23**	**m²**	**€ 85**		**€ 1.464.241**
	X	Onvoorzien	laag	€ 16.690.829		3,0%		
			mid	€ 16.690.829		4,0%	€ 667.633	
			hoog	€ 16.690.829		5,0%		
€ 16.860		**totaal onvoorzien**		**17176,23**	**m²**	**€ 39**		**€ 667.633**
	B	Honoraria	laag	€ 16.690.829		6,7%		
			mid	€ 16.690.829		9,8%	€ 1.635.701	
			hoog	€ 16.690.829		17,3%		
€ 41.306		**totaal honoraria**		**17176,23**	**m²**	**€ 95**		**€ 1.635.701**
	C	Aansluitkosten	laag	€ 16.690.829		2,1%		
			mid	€ 16.690.829		3,3%	€ 550.797	
			hoog	€ 16.690.829		5,0%		
€ 13.909		**totaal aansluitkosten**		**17176,23**	**m²**	**€ 32**		**€ 550.797**
	D	Heffingen	laag	€ 16.690.829		1,0%		
			mid	€ 16.690.829		2,0%	€ 333.817	
			hoog	€ 16.690.829		5,0%		
€ 8.430		**totaal hefftingen**		**17176,23**	**m²**	**€ 19**		**€ 333.817**
	H	Ontwikkelaarskosten	laag	€ 16.690.829		3,5%		
			mid	€ 16.690.829		7,3%	€ 1.218.431	
			hoog	€ 16.690.829		18,5%		
€ 30.769		**totaal ontwikkelaarskosten**		**17176,23**	**m²**	**€ 71**		**€ 1.218.431**
	I	Verkoopkosten	laag	€ 16.690.829		1,2%		
			mid	€ 16.690.829		1,2%	€ 200.290	
			hoog	€ 16.690.829		2,7%		
€ 5.058		**totaal verkoopkosten**		**17176,23**	**m²**	**€ 12**		**€ 200.290**
€ 116.331		**Totaal additional costs**						**€ 6.070.909**

Full calculations embodied carbon *De Scharnier*

BVO		Concrete reference						Hybrid						timber			
17176,23	m2																
			emissions	capturec	total		bio incuded?		emissions	captured	total		bio incuded?		emissions	captured	total
		low	2648473	0	2648473		100%	low	1907026	-1820779	86990		100%	low	1652688	-2862015	-1208221
		mid	4040382	0	4040382			mid	3570530	-1794807	1775780			mid	3028847	-2826958	201742
		high	6099904	0	6099904			high	5789360	-2050478	3738883			high	5153936	-3204612	1949325
							50%	low	1907026	-1820779	996636		50%	low	1652688	-2862015	221680
								mid	3570530	-1794807	2673126			mid	3028847	-2826958	1615368
								high	5789360	-2050478	4764122			high	5153936	-3204612	3551630
							0%	low	1907026	-1820779	1907026		0%	low	1652688	-2862015	1652688
								mid	3570530	-1794807	3570530			mid	3028847	-2826958	3028847
								high	5789360	-2050478	5789360			high	5153936	-3204612	5153936
	per m2 BVO						per m2 BVO						per m2 BVO				
			emissions	capturec	total				emissions	captured	total				emissions	captured	total
		low	154	0	154		100%	low	111	-106	5		100%	low	96	-167	-70
		mid	235	0	235			mid	208	-104	103			mid	176	-165	12
		high	355	0	355			high	337	-119	218			high	300	-187	113
							50%	low	111	-106	58		50%	low	96	-167	13
								mid	208	-104	156			mid	176	-165	94
								high	337	-119	277			high	300	-187	207
							0%	low	111	-106	111		0%	low	96	-167	96
								mid	208	-104	208			mid	176	-165	176
								high	337	-119	337			high	300	-187	300

Figure 100: Carbon emissions 3 variants De Scharnier

level 1 *level 2* *Level 3*

CONCRETE

grondopper *1768,63*

BVO 17176,23 m2

Bouwkosten

Bouwkundige werken

										Output embodied carbon low A1-A3 [kg-CO2eq]			Output embodied carbon medium A1-A3 [kg-CO2eq]			Output embodied carbon high A1-A3 [kg-CO2eq]		
										excl. bigenic car	only bigenic	incl. biogenic carbon	excl. bigenic ca	only bigenic	incl. biogenic carbon	excl. bigenic carl	only bigenic	incl. biogenic carbon
		materiaal	breedte (m)	dikte (m)	wapenir	density ehd.	hoeveelheid ehd.	hoeveelheid 2 ehd.		GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP
A	**Fundering**																	
13/23	laagste vloer, op grondslag / vrijdragend	kanaalplaat (geisoleerd)		0,26		258 kg/m2	1768,63 m^2	456307 kg	*Hollow core slab*	54620		54620	62017		62017	78058		78058
		druklaag		0,07			1768,63 m^2											
		Concrete compressive layer conrete part		0,07		2400 kg/m3		297130 kg	*In situ concrete C30/37*	15570		15570	24157		24157	37574		37574
		Concrete compressive layer reinforcement			100	7 kg/m2		12380 kg	*Reinforcement*	2971		2971	12692		12692	35779		35779
16	funderingsconstructie	funderingsconstructie, totaal incl. grondwerk		0,3		2400 kg/m3	1768,63 m^2	1273414 kg	*In situ concrete C30/37*	66727		66727	103529		103529	161033		161033
17	paalfunderingen	Fundexpalen, ø580 mm en paallengte, 26 m^1				210 st	5460 m											
		100% *betonmortel*		0,2642079 m2		2400 kg/m3		3462181 kg	*In situ concrete C35/45*	245757		245757	283423		283423	506002		506002
#REF!		*wapening rond 25 6x 6,5 m*		0,0004909 m2		8190 m	7850 kg/m3	31559 kg	*Reinforcement*	7574		7574	32353		32353	91206		91206
		wapening rond 16 6x 19,5 m		0,0002011 m2		24570 m	7850 kg/m3	38780 kg	*Reinforcement*	9307		9307	39755		39755	112073		112073
	TOTAL FOUNDATION									**402526**		**402526**	**557924**		**557924**	**1021726**		**1021726**
B	**Skelet**																	
22.2	Binnenwanden; constructief	prefab betonwand (bruto) tpv plint		0,3		2400 kg/m3	705,264 m^2	507790 kg	*Precast concrete incl rebar*	43055		43055	95972		95972	123901		123901
		prefab beton				2400 kg/m3												
		wapening prefab betonwand (bruto) tpv plint			125	37,5 kg/m2	705,264 m^2											
		prefab betonwand (bruto) tpv kernen		0,3		2400 kg/m3	3564,565 m^2	2566487 kg	*Precast concrete incl rebar*	217610		217610	485066		485066	626223		626223
		prefab beton																
		wapening prefab betonwand (bruto) tpv kernen			125	37,5 kg/m2	3564,565 m^2											
		prefab betonwand (bruto) tpv woningen (WSW)		0,3		2400 kg/m3	5229,57 m^2	3765290 kg	*Precast concrete incl rebar*	319255		319255	711640		711640	918731		918731
		prefab beton																
		wapening prefab betonwand (bruto) tpv woningen (WSW			100	30 kg/m2	5229,57 m^2	kg										
	total binnenwanden									579920		579920	1292678		1292678	1668854		1668854
22.3	Vloeren; constructief	breedplaat		0,25			13837,27 m^2											
		prefabbeton breedplaat		0,05		2400 0	13837,27 m^2	1660472 kg	*Precast plank floor*	272317		272317	290137		290137	308848		308848
		in situ beton breeedplaat		0,2		2400 kg/m3	13837,27 m^2	6641890 kg	*In situ concrete C30/37*	348035		348035	539986		539986	839917		839917
		Wapening breedplaat			80	20 kg/m2	13837,27 m^2	276745 kg	*Reinforcement*	66419		66419	283706		283706	799794		799794
		breedplaat met balkbodems		0,3			3082,78 m^2											
		prefab beton breedplaat met balkbodems		0,05		2400 0	3082,78 m^2	369934 kg	*Precast plank floor*	60669		60669	64639		64639	68808		68808
		insitu beton druklaag		0,25		2400 kg/m3	3082,78 m^2	1849668 kg	*In situ concrete C30/37*	96923		96923	150378		150378	233904		233904
		Wapening breedplaat met balkbodems			100	30 kg/m2	3082,78 m^2	92483 kg	*Reinforcement*	22196		22196	94809		94809	267277		267277
		Vloer was CLT nu bredplaat					*8998,42 m^2*											
		Vloer als balkons was CLT nu breeedplaat					*1512,45 m^2*											
		stalen balken tbv balkons					51723,7 kg	51724 kg	*Steel beams*	36247		36247	46965		46965	123620		123620
	total vloeren									902806		902806	1470620		1470620	2642167		2642167
27.2	Daken; constructief	breedplaat		0,28			674,53 m^2											
		prefabbeton breedplaat		0,05		2400 kg/m3	674,53 m^2	80944 kg	*Precast plank floor*	13275		13275	14143		14143	15056		15056
		in situ beton breeedplaat		0,23		2400 kg/m3	674,53 m^2	372341 kg	*In situ concrete C30/37*	19511		19511	30271		30271	47085		47085
		Wapening breedplaat			100	28 kg/m2	674,53 m^2	18887 kg	*Reinforcement*	4533		4533	19362		19362	54583		54583
		breedplaat incl. balkbodems		0,3			447,51 m^2											
		prefab beton breedplaat met balkbodems		0,05		2400 kg/m3	447,51 m^2	53701 kg	*Precast plank floor*	8807		8807	9383		9383	9988		9988
		insitu beton druklaag		0,25		2400 kg/m3	447,51 m^2	268506 kg	*In situ concrete C30/37*	14070		14070	21830		21830	33955		33955
		wapening breedplaat incl. balkbodems			120	36 kg/m2	447,51 m^2	16110 kg	*Reinforcement*	3866		3866	16516		16516	46559		46559
	total daken									64061		64061	111505		111505	207226		207226
18	Hoofdstraagconstructie	betonkolom prefab tpv woningen	0,4	0,4		2400 kg/m3	741,2 m^1	284621 kg	*Precast concrete incl rebar*	24133		24133	53793		53793	69447		69447
		Beton betonkolom prefab																
		wapening betonkolom prefab tpv woningen			250	40 kg/m1	741,2 m^1											
		betonkolom prefab tpv plint	0,5	0,5		2400 kg/m3	462 m^1	277200 kg	*Precast concrete incl rebar*	23504		23504	52391		52391	67637		67637
		Beton betonkolom prefab																
		wapening betonkolom prefab tpv plint			250	62,5 kg/m1	462 m^1											
		betonbalk prefab tpv kopgevels	0,4	0,5		2400 kg/m3	406,25 m^1	195000 kg	*Precast concrete incl rebar*	16534		16534	36855		36855	47580		47580
		Beton betonkolom prefab																
		wapening betonbalk prefab tpv kopgevels				0 kg/m1	406,25 m^1	0 kg										
		Concrete beam	0,43	0,3		2400 kg/m3	1470,1 m^1	455143 kg	*Precast concrete incl rebar*	38591		38591	86022		86022	111055		111055
							40,8 m^1											
	total hoofddraagconstructie									102761		102761	229061		229061	295719		295719
	TOTAL SKELET									**1649549**		**1649549**	**3103864**		**3103864**	**4813967**		**4813967**
E	**Binnenwand afbouw**																	
22.1	Binnenwanden; niet constructief																	
		plaster work		0,005 m		968 kg/m3	9499 m2	45977 kg	*Gipsplaat fire resistant*	3553		3553	8929		8929	11484		11484
		plaster work		0,005 m		968 kg/m3	9499 m2	45977 kg	*Gipsplaat fire resistant*	3553		3553	8929		8929	11484		11484
	total binnenwandafbouw									7107		7107	17859		17859	22967		22967
F	**Vloerafbouw**																	
		zandcement vloer Assumed in situ concrete C25/30		0,07 m		1500 kg/m3	16920 m2	1776605 kg	*Cementious screed*	532982		532982	277150		277150	144283		144283
		PIR insulation		0,03 m		33,4 kg/m3	16920 m2	16962 kg	*High density PIR insulation*	49979		49979	67680		67680	76507		76507
	total vloerafbouw									582961		582961	344831		344831	220790		220790
H	**Plafonds binnen/buiten**																	
		plaster work		0,005 m		968 kg/m3	16920 m2	81893 kg	*Gipsplaat fire resistant*	6329		6329	15905		15905	20454		20454
	total plafonds									6329		6329	15905		15905	20454		20454
	TOTAL						**incl substrucutre**	**27344101 kg**	**TOTAL**	**2648473**		**2648473**	**4040382**		**4040382**	**6099904**		**6099904**
	TOTAL / m2							**1592 kg/m2**	**Total / m2**	**154**	**0**	**154**	**235**	**0**	**235**	**355**	**0**	**355**

	Level 3												Output embodied carbon			Output embodied carbon			Output embodied carbon		
		HYBRID	BVO	17176,23	m2								low A1-A3 [kg-CO2eq]			medium A1-A3 [kg-CO2eq]			high A1-A3 [kg-CO2eq]		
													excl. bigenic car	only bigenic (	incl. biogenic carbon	excl. bigenic ca	only bigenic car	incl. biogenic carbon	excl. bigenic car	only bigenic (	incl. biogenic carbon
		materiaal	breedte (m)	dikte (m)	wapenir	density	ehd.	hoeveelheid	ehd.	hoeveelheid 2	ehd.		GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP
A	**Fundering**																				
13/23	laagste vloer, op grondslag /	kanaalplaat (geisoleerd)		0,26		258	kg/m2	1768,63	m2	456307	kg	*Hollow core slab*	54620		54620	62017		62017	78058		78058
		druklaag		0,07				1768,63	m2												
		Concrete compressive layer conrete part		0,07		2400	kg/m3			297130	kg	*In situ concrete C30/37*	15570		15570	24157		24157	37574		37574
		Concrete compressive layer reinforcement			100	7	kg/m2			12380	kg	*Reinforcement*	2971		2971	12692		12692	35779		35779
16	funderingsconstructie	funderingsconstructie, totaal incl. grondwerk	assumed 85	0,3		2400	kg/m3	1768,63	m2	1273414	kg	*In situ concrete C30/37*	66727		66727	103529		103529	161033		161033
17	paalfunderingen	Fundexpalen, ø497 mm en paallengte, 26 m^1				210	st	5460	m												
		99,74% *betonmortel C35/45*		0,2635103		2400	kg/m3			3453039	kg	*In situ concrete C35/45*	245108		245108	282674		282674	504666		504666
		wapening rond 25 6x 6,5 m 86%		0,0004896	m2	8190	m	7850	kg/m3	31476	kg	*Reinforcement*	7554		7554	32267		32267	90965		90965
		wapening rond 16 6x 19,5 m 86%		0,0002005	m2	24570	m	7850	kg/m3	38677	kg	*Reinforcement*	9283		9283	39650		39650	111777		111777
	TOTAL FOUNDATION												**401833**		**401833**	**556985**		**556985**	**1019853**		**1019853**
B	**Skelet**																				
22.2	Binnenwanden; constructief	prefab betonwand (bruto) tpv plint		0,3		2400	kg/m3	705,264	m^2	507790,08	kg	*Precast concrete incl re*	43055		43055	95972		95972	123901		123901
		prefab beton				551	kg/m3														
		wapening prefab betonwand (bruto) tpv plint			125	37,5	kg/m2	705,264	m^2		kg										
		prefab betonwand (bruto) tpv kernen		0,3		2400	kg/m3	3564,565	m^2	2566486,8	kg	*Precast concrete incl re*	217610		217610	485066		485066	626223		626223
		prefab beton																			
		wapening prefab betonwand (bruto) tpv kernen			125	37,5	kg/m2	3564,565	m^2		kg										
		prefab betonwand (bruto) tpv woningen (WSW)		0,3		2400	kg/m3	5229,57	m^2	3765290,4	kg	*Precast concrete incl re*	319255		319255	711640		711640	918731		918731
		prefab beton																			
		wapening prefab betonwand (bruto) tpv woningen (WSW			100	30	kg/m2	5229,57	m^2		kg										
	total binnenwanden												579920		579920	1292678		1292678	1668854		1668854
22.3	Vloeren; constructief	breedplaat		0,25				3326,4	m^2												
		prefabbeton breedplaat		0,05		2400	kg/m3	3326,4	m^2	399168	kg	*Precast plank floor*	65464		65464	69747		69747	74245		74245
		in situ beton breeedplaat		0,2		2400	kg/m3	3326,4	m^2	1596672	kg	*In situ concrete C30/37*	83666		83666	129809		129809	201911		201911
		Wapening breedplaat			80	20	kg/m2	3326,4	m^2	66528	kg	*Reinforcement*	15967		15967	68201		68201	192266		192266
		breedplaat met balkbodems		0,3				3082,78	m^2												
		prefab beton breedplaat met balkbodems		0,05		2400	kg/m3	3082,78	m^2	369933,6	kg	*Precast plank floor*	60669		60669	64639		64639	68808		68808
		insitu beton druklaag		0,25		2400	kg/m3	3082,78	m^2	1849668	kg	*In situ concrete C30/37*	96923		96923	150378		150378	233904		233904
		Wapening breedplaat met balkbodems			100	30	kg/m2	3082,78	m^2	92483,4	kg	*Reinforcement*	22196		22196	94809		94809	267277		267277
		Hybride CLT-vloer (200+100)		0,3				8998,42	m^2												
		Hybride CLT-vloer (200 CLT deel)		0,2		470	kg/m3	8998,42	m^2	845851,48	kg	*CLT*	98349	-1371359	-1272377	230360	-1365960	-1135601	506784	-1576724	-1069941
		Hybride CLT-vloer (100 beton deel)		0,1		2400	kg/m3	8998,42	m^2	2159620,8	kg	*In situ concrete C30/37*	113164		113164	175577		175577	273100		273100
		wapening beton deel			100	10	kg/m2	8998,42	m^2	89984,2		*Reinforcement*	21596		21596	92247		92247	260054		260054
		Hybride CLT-vloer (200+100) als balkons						1512,45	m^2												
		Hybride CLT-vloer (200 CLT deel) als balkons		0,2		470	kg/m3	1512,45	m^2	142170,3	kg	*CLT*	16530	-230497	-213860	38719	-229590	-190871	85180	-265015	-179835
		Hybride CLT-vloer (100 beton deel) als balko		0,1		2400	kg/m3	1512,45	m^2	362988	kg	*In situ concrete C30/37*	19021		19021	29511		29511	45903		45903
		wapening beton deel			100	10	kg/m2	1512,45	m^2	15124,5		*Reinforcement*	3630		3630	15505		15505	43710		43710
		stalen balken tbv balkons						51723,7	kg	51723,7	kg	*Steel beams*	36247		36247	46965		46965	123620		123620
	total vloeren												653421	-1601857	-947696	1206468	-1595550	-389082	2376762	-1841740	535022
27.2	Daken; constructief	breedplaat		0,28				674,53	m^2												
		prefabbeton breedplaat		0,05		2400	kg/m3	674,53	m^2	80943,6	kg	*Precast plank floor*	13275		13275	14143		14143	15056		15056
		in situ beton breeedplaat		0,23		2400	kg/m3	674,53	m^2	372340,56	kg	*In situ concrete C30/37*	19511		19511	30271		30271	47085		47085
		Wapening breedplaat			100	28	kg/m2	674,53	m^2	18886,84	kg	*Reinforcement*	4533		4533	19362		19362	54583		54583
		breedplaat incl. balkbodems		0,3				447,51	m^2												
		prefab beton breedplaat met balkbodems		0,05		2400	kg/m3	447,51	m^2	53701,2	kg	*Precast plank floor*	8807		8807	9383		9383	9988		9988
		insitu beton druklaag		0,25		2400	kg/m3	447,51	m^2	268506	kg	*In situ concrete C30/37*	14070		14070	21830		21830	33955		33955
		wapening breedplaat incl. balkbodems			120	36	kg/m2	447,51	m^2	16110,36	kg	*Reinforcement*	3866		3866	16516		16516	46559		46559
	total daken												64061		64061	111505		111505	207226		207226
18	Hoofdstraagconstructie	betonkolom prefab tpv woningen	0,4	0,4		2400	kg/m3	741,2	m^1	284620,8	kg	*Precast concrete incl re*	24133		24133	53793		53793	69447		69447
		Beton betonkolom prefab																			
		wapening betonkolom prefab tpv woningen			250	40	kg/m1	741,2	m^1		kg										
		betonkolom prefab tpv plint	0,5	0,5		2400	kg/m3	462	m^1	277200	kg	*Precast concrete incl re*	23504		23504	52391		52391	67637		67637
		Beton betonkolom prefab																			
		wapening betonkolom prefab tpv plint			250	62,5	kg/m1	462	m^1		kg										
		betonbalk prefab tpv kopgevels	0,4	0,5		2400	kg/m3	406,25	m^1	195000	kg	*Precast concrete incl re*	16534		16534	36855		36855	47580		47580
		Beton betonkolom prefab																			
		wapening betonbalk prefab tpv kopgevels				0	kg/m1	406,25	m^1	0	kg										
		Glulam ligger	0,6	0,3		470	kg/m3	1470,1	m^1	124370,46	kg	*Glulam*	30750	-218923	-188170	38312	-199257	-160888	50524	-208738	-158214
								40,8	m^1												
	total hoofddraagconstructie												94920	-218923	-124000	181351	-199257	-17849	235189	-208738	26450
	TOTAL SKELET												**1392323**	**-1820779**	**-427714**	**2792002**	**-1794807**	**997252**	**4488030**	**-2050478**	**2437552**
E	**Binnenwand afbouw**																				
22.1	Binnenwanden; niet constructief																				
		plaster work		0,005	m	968	kg/m3	9499	m2	45977	kg	*Gipsplaat fire resistant*	3553		3553	8929		8929	11484		11484
		plaster work		0,005	m	968	kg/m3	9499	m2	45977	kg	*Gipsplaat fire resistant*	3553		3553	8929		8929	11484		11484
	total binnenwandafbouw												7107		7107	17859		17859	22967		22967
F	**Vloerafbouw**																				
		fermacel gisverzelplaat		0,0375	m	968	kg/m3	16920,05	m2	614198	kg	*Gipsplaat fire resistant*	47470		47470	119286		119286	153408		153408
		PIR insulatoon		0,03	m	33,417	kg/m3	16920,05	m2	16962	kg	*High density PIR insulat*	49979		49979	67680		67680	76507		76507
		Mass layer		0,13	m	2000	kg/m3	16920,05	m2	4399213	kg	*Washed gravel*	8315		8315	16717		16717	28595		28595
	total vloerafbouw												105764		105764	203684		203684	258510		258510
H	**Plafonds binnen/buiten**																				
	total plafonds																				
	TOTAL							**incl substrucutre**		**27257913**	**kg**	**TOTAL**	**1907026**	**-1820779**	**86990**	**3570530**	**-1794807**	**1775780**	**5789360**	**-2050478**	**3738883**
	TOTAL / m2									**1587**	**kg/m2**	**Total / m2**	**111**	**-106**	**5**	**208**	**-104**	**103**	**337**	**-119**	**218**

Level 3

TIMBER — BVO 17176,23 m2

		materiaal	breedte (m	dikte (m)	wapening	density	ehd.	hoeveelheid	ehd.	hoeveelheid 2	ehd.		Output embodied carbon low A1-A3 [kg-CO2eq]			Output embodied carbon medium A1-A3 [kg-CO2eq]			Output embodied carbon high A1-A3 [kg-CO2eq]		
													excl. bigenic carbo	only bigenic car	incl. biogenic carbon	excl. bigenic ca	only bigenic car	incl. biogenic carbon	excl. bigenic car	only bigenic	incl. biogenic carbon
													GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP
A	**Fundering**																				
13/23	laagste vloer, op grondslag / vrijdragend	kanaalplaat (geisoleerd)		0,26		258	kg/m2	1768,63	m2	456307	kg	*Hollow core slab*	54620		54620	62017		62017	78058		78058
		druklaag		0,07				1768,63	m2												
		Concrete compressive layer conrete pa		0,07		2400	kg/m3			297130	kg	*In situ concrete C30/37*	15570		15570	24157		24157	37574		37574
		Concrete compressive layer reinforcement			100	7	kg/m2			12380	kg	*Reinforcement*	2971		2971	12692		12692	35779		35779
16	funderingsconstructie	funderingsconstructie, totaal incl. grondwerk	assumed 78	0,3		2400	kg/m3	1768,63	m2	1273414	kg	*In situ concrete C30/37*	66727		66727	103529		103529	161033		161033
17	paalfunderingen	Fundexpalen, ø455 mm en paallengte, 29 m^1				210	st	5460	m												
		87,8% *betonmortel C35/45*		0,231902		2400	kg/m3			3038839	kg	*In situ concrete C35/45*	215707		215707	248767		248767	444130		444130
		wapening rond 25 6x 6,5 m 71%		0,000431 m2		8190	m	7850	kg/m3	27700	kg	*Reinforcement*	6648		6648	28397		28397	80053		80053
		wapening rond 16 6x 19,5 m 71%		0,000176 m2		24570	m	7850	kg/m3	34038	kg	*Reinforcement*	8169		8169	34894		34894	98369		98369
	TOTAL FOUNDATION												**370412**		**370412**	**514451**		**514451**	**934997**		**934997**
B	**Skelet**																				
22.2	Binnenwanden; constructief	prefab betonwand (bruto) tpv plint		0,3		2400	kg/m3	705,264	m^2	507790	kg	*Precast concrete incl rebar*	43055		43055	95972		95972	123901		123901
		prefab beton																			
		wapening prefab betonwand (bruto) tpv plint			125	37,5	kg/m2	705,264	m^2												
		prefab betonwand (bruto) tpv kernen		0,3		2400	kg/m3	3564,565	m^2	2566487	kg	*Precast concrete incl rebar*	217610		217610	485066		485066	626223		626223
		prefab beton																			
		wapening prefab betonwand (bruto) tpv kernen			125	37,5	kg/m2	3564,565	m^2												
		CLT kolom	0,6	0,6		470	kg/m3	1857,6	m^1	314306	kg	*CLT*	36545	-509577	-472796	85598	-507571	-421972	188313	-585888	-397574
	total binnenwanden												297210	-509577	-212131	666637	-507571	159066	938437	-585888	352549
22.3	Vloeren; constructief	breedplaat		0,25				3326,4	m^2												
		prefabbeton breedplaat		0,05		2400	kg/m3	3326,4	m^2	399168	kg	*Precast plank floor*	65464		65464	69747		69747	74245		74245
		in situ beton breeedplaat		0,2		2400	kg/m3	3326,4	m^2	1596672	kg	*In situ concrete C30/37*	83666		83666	129809		129809	201911		201911
		Wapening breedplaat			80	20	kg/m2	3326,4	m^2	66528	kg	*Reinforcement*	15967		15967	68201		68201	192266		192266
		breedplaat met balkbodems		0,3				3082,78	m^2												
		prefab beton breedplaat met balkbode		0,05		2400	kg/m3	3082,78	m^2	369934	kg	*Precast plank floor*	60669		60669	64639		64639	68808		68808
		insitu beton druklaag		0,25		2400	kg/m3	3082,78	m^2	1849668	kg	*In situ concrete C30/37*	96923		96923	150378		150378	233904		233904
		Wapening breedplaat met balkbodems			100	30	kg/m2	3082,78	m^2	92483	kg	*Reinforcement*	22196		22196	94809		94809	267277		267277
		Hybride CLT-vloer (240+80)		0,32				8998,42													
		Hybride CLT-vloer (240 CLT deel)		0,24		470	kg/m3	8998,42	m^2	1015022	kg	*CLT*	118019	-1645631	-1526852	276431	-1639152	-1362721	608140	-1892069	-1283929
		Hybride CLT-vloer (80 beton deel)		0,08		2400	kg/m3	8998,42	m^2	1727697	kg	*In situ concrete C30/37*	90531		90531	140462		140462	218480		218480
		wapening beton deel			100	8	kg/m2	8998,42	m2	71987	kg	*Reinforcement*	17277		17277	73798		73798	208043		208043
		Hybride CLT-vloer (200+100) als balkons		0,3				1512,45	m^2												
		Hybride CLT-vloer (200 CLT deel) als ba		0,2		470	kg/m3	1512,45	m^2	142170	kg	*CLT*	16530	-230497	-213860	38719	-229590	-190871	85180	-265015	-179835
		Hybride CLT-vloer (100 beton deel) als		0,1		2400	kg/m3	1512,45	m^2	362988	kg	*In situ concrete C30/37*	19021		19021	29511		29511	45903		45903
		wapening beton deel			100	10	kg/m2	1512,45	m^2	15125	kg	*Reinforcement*	3630		3630	15505		15505	43710		43710
		stalen balken tbv balkons						51723,7	kg	51724	kg	*Steel beams*	36247		36247	46965		46965	123620		123620
	total vloeren												646139	-1876128	-1229123	1198975	-1868742	-669767	2371487	-2157084	214403
27.2	Daken; constructief	breedplaat		0,28				674,53	m^2												
		prefabbeton breedplaat		0,05		2400	kg/m3	674,53	m^2	80944	kg	*Precast plank floor*	13275		13275	14143		14143	15056		15056
		in situ beton breeedplaat		0,23		2400	kg/m3	674,53	m^2	372341	kg	*In situ concrete C30/37*	19511		19511	30271		30271	47085		47085
		Wapening breedplaat			100	28	kg/m2	674,53	m^2	18887	kg	*Reinforcement*	4533		4533	19362		19362	54583		54583
		breedplaat incl. balkbodems		0,3				447,51	m^2												
		prefab beton breedplaat met balkbode		0,05		2400	kg/m3	447,51	m^2	53701		*Precast plank floor*	8807		8807	9383		9383	9988		9988
		insitu beton druklaag		0,25		2400	kg/m3	447,51	m^2	268506		*In situ concrete C30/37*	14070		14070	21830		21830	33955		33955
		wapening breedplaat incl. balkbodems			120	36	kg/m2	447,51	m^2	16110	kg	*Reinforcement*	3866		3866	16516		16516	46559		46559
	total daken												64061		64061	111505		111505	207226		207226
18	Hoofdstraagconstructie	betonkolom prefab tpv woningen	0,4	0,4		2400	kg/m3	414,72	m^1	159252	kg	*Precast concrete incl rebar*	13503		13503	30099		30099	38858		38858
		Beton betonkolom prefab																			
		wapening betonkolom prefab tpv woningen			250	100	kg/m2	414,72	m^1												
		betonkolom prefab tpv plint	0,5	0,5		2400	kg/m3	462	m^1	277200	kg	*Precast concrete incl rebar*	23504		23504	52391		52391	67637		67637
		Beton betonkolom prefab																			
		wapening betonkolom prefab tpv plint			250	125	kg/m2	462	m^1												
		Glulam ligger tpv kopgevels	0,6	0,3		470	kg/m3	406,25	m^1	34369	kg	*Glulam*	8497	-60497	-51999	10587	-55063	-44460	13962	-57683	-43721
		Glulam ligger	0,6	0,3		470	kg/m3	1470,1	m^1	124370	kg	*Glulam*	30750	-218923	-188170	38312	-199257	-160888	50524	-208738	-158214
								122,4	m^1												
	total hoofddraagconstructie												76253	-279420	-203163	131388	-254320	-122858	170981	-266421	-95441
	TOTAL SKELET												**1083664**	**-2665125**	**-1580356**	**2108505**	**-2630633**	**-522055**	**3688131**	**-3009393**	**678737**
E	**Binnenwand afbouw**																				
22.1	Binnenwanden; niet constructief	timber wall system						9499,399	m2												
		Gipsplaten		0,025 m		968	kg/m3	9499,399	m2	229885	kg	*Gipsplaat fire resistant*	17767		17767	44647		44647	57419		57419
		HSB frame				6,41915	kg/m2	9499,399	m2	60978	kg	*Softwood*	4262	-98445	-94183	14166	-98163	-84108	20252	-97609	-77357
		glaswol		0,12 m		20	kg/m3	9499,399	m2	22799	kg	*Glass wool*	24394		24394	42291		42291	58478		58478
		HSB frame				6,41915	kg/m2	9499,399		60978	kg	*Softwood*	4262	-98445	-94183	14166	-98163	-84108	20252	-97609	-77357
		glaswol		0,12 m		20	kg/m3	9499,399	m2	22799	kg	*Glass wool*	24394		24394	42291		42291	58478		58478
		Gipsplaten		0,025 m		968	kg/m3	9499,399	m2	229885	kg	*Gipsplaat fire resistant*	17767		17767	44647		44647	57419		57419
	total binnenwandafbouw												46424	-98445	-52021	101104	-98163	2831	136149	-97609	38540
F	**Vloerafbouw**																				
		fermacel gisverzelplaat		0,0375 m		968	kg/m3	16920,05	m2	614198	kg	*Gipsplaat fire resistant*	47470		47470	119286		119286	153408		153408
		PIR insulatoon		0,03 m		33,41667	kg/m3	16920,05	m2	16962	kg	*High density PIR insulation*	49979		49979	67680		67680	76507		76507
		Mass layer		0,13 m		2000	kg/m3	16920,05	m2	4399213	kg	*Washed gravel*	8315		8315	16717		16717	28595		28595
	total vloerafbouw	mass layer											105764		105764	203684		203684	258510		258510
H	**Plafonds binnen/buiten**																				
	total plafonds																				
	TOTAL							**incl substrucutre**		**23352933**	**kg**	**TOTAL**	**1652688**	**-2862015**	**-1208221**	**3028847**	**-2826958**	**201742**	**5153936**	**-3204612**	**1949325**
	TOTAL / m2									**1360**	**kg/m2**	**Total / m2**	**96,2**	**-166,6**	**-70,3**	**176,3**	**-164,6**	**11,7**	**300,1**	**-186,6**	**113,5**

Appendix J. Performed calculations for the element sizing of the base design scenario.

This appendix contains a description of the performed calculations for the sizing of the floor and walls of the variants analysed in the parameter study.

Introduction

To study the influence of the floor span and building height on the total building costs and the embodied carbon, the required floor and wall thicknesses for multiple variants must be determined. This appendix contains an overview of these calculations and the assumptions that are made.

The method that is described in this appendix is used for all design variations; the numbers that are given correspond to the calculations for variant 6. This variant has 5 storeys and a floor span of 4.8 meters. The building that is studied is a multi-storey residential building with CLT floors and CLT walls. A floorplan and section can be found in Figure 101 and Figure 102. All timber is protected from weather and wetting and therefore falls under use class 1 and service class 1.

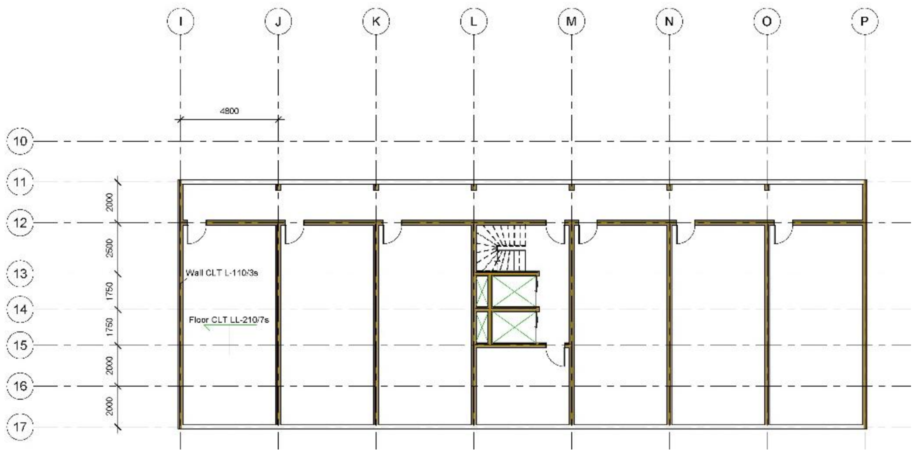


Figure 101: Floorplan variant 6

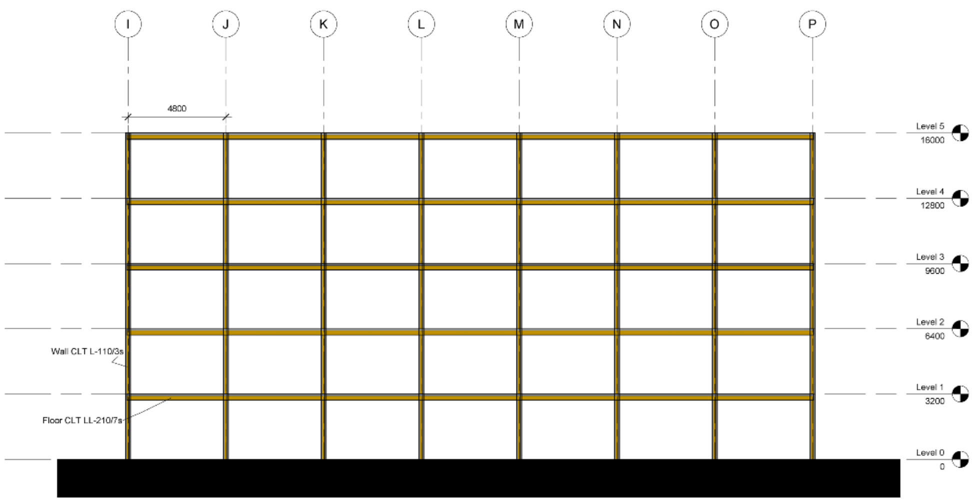


Figure 102: Section variant 6

References

The following references were used for the calculation:

- Calculatis by Stora Enso. (2021). *Airborne sound insulation*. https://calculatis.storaenso.com/EingabeBauphysik/Edit/6197
- Gustafsson, A., Crocetti, R., Just, A., Landel, P., Olsson, J., Pousette, A., Silfverhielm, M., & Östman, B. (2019). The CLT Handbook. In E. Borgström & J. Fröbel (Eds.), *Föreningen Sveriges Skogsindustrier* (1st ed.). Skogsindustrierna.
- Porteous, J., & Kermani, A. (2007*). Structural Timber Design to Eurocode 5*. Blackwell publishing.
- NEN 1990, NEN 1991, NEN 1992, NEN 1995
- Wallner-Novak, M., Koppelhuber, J., & Pock, K. (2014). *Pro:Holz Cross-Laminated Timber Structural Design*. www.proholz.at

Floor design and assumptions

The floors of the apartment building are made of CLT and span 4.8 meters. The assumed width of one panel is 2.25 meter, all panels are assumed to be connected and be able to transfer lateral forces. The loads are transferred from the floors to the walls using angle braces. A hinged connection is assumed between the floors and the walls. This gives the mechanical scheme of a simply supported beam, as is shown in Figure 103 and Figure 104. The calculations are done assuming a reference slab that is 1 meter wide. The build-up of the CLT panel and the floor can be found in Figure 105. This shows that the timber is exposed on the underside of the floor, therefore calculations assuming a reduced floor thickness in the case of fire is performed. The impact sound insulation level of the floor (L) is 44 dB and the airborne sound insulation level (D) is 63 dB (Gustafsson et al., 2019). The assumed damping is 2.5% since the floor acts as a simply supported beam.

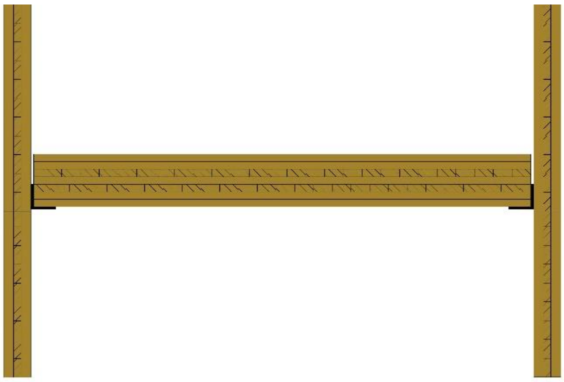


Figure 103: Section floor and walls

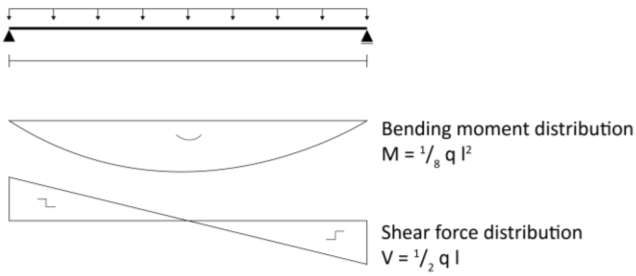


Figure 104: Mechanical scheme floor

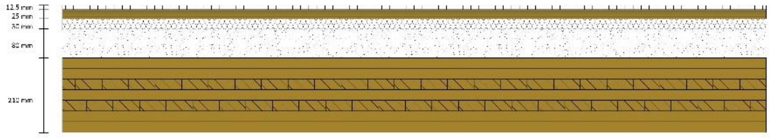


Figure 105: Floor build-up variant 6

Wall design and assumptions

The walls are also constructed out of CLT. In variant 6 the walls will transfer both the horizontal and the vertical loads. In the variants with more than 5 storeys the CLT walls will only transfer the vertical loads and a concrete stability element are added for the horizontal loads. The walls are assumed to be rigidly connected to the foundation. This results in the mechanical scheme as shown in Figure 106. The height of the wall elements is assumed to be equal to the height of one building storey. The wall elements are connected using angled screws. Due to the required wall openings at the side of the building with the circulation routes the structural depth of the walls is assumed to be 2 meters less than the building depth. To reduce the risks in the case of fire, both sides of the walls are covered with fireproof gypsum boards, therefore no calculation with a reduced element thickness is made for the walls. The wall build-up can be found in Figure 107. The airborne sound insulation level (D) is 62 dB (Calculatis by Stora Enso, 2021). This build-up is used for the walls of all variants. The calculations are performed for both the end wall (axis A) and the second wall (axis B). These walls are indicated in Figure 108.

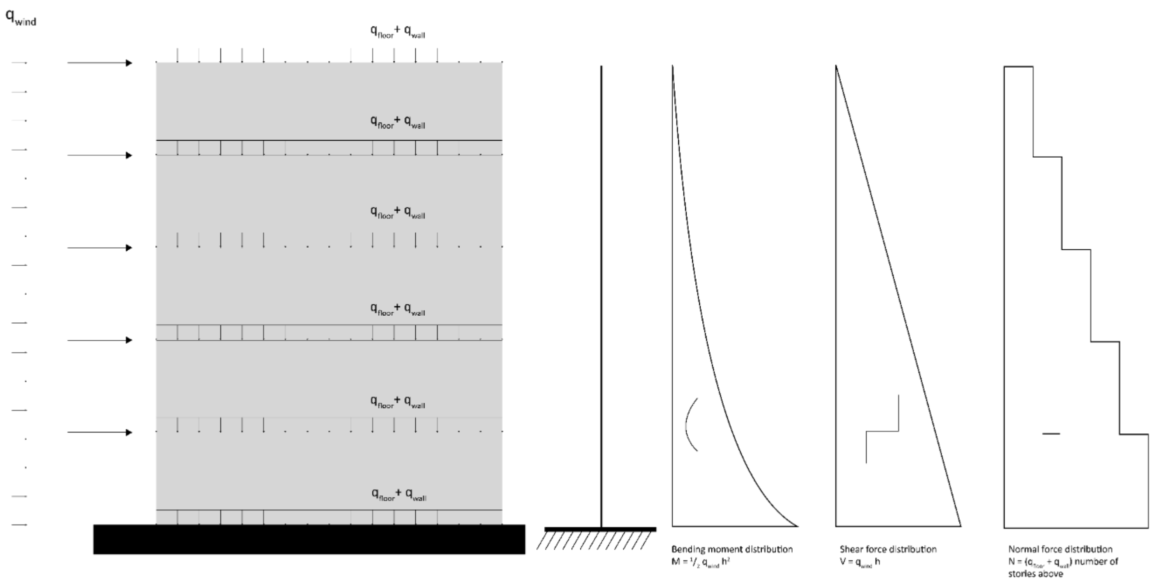


Figure 106: Mechanical scheme walls

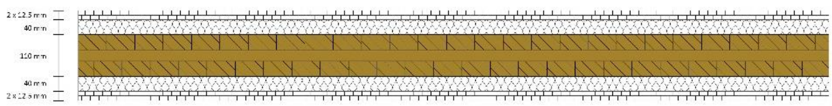


Figure 107: Wall build-up variant 6

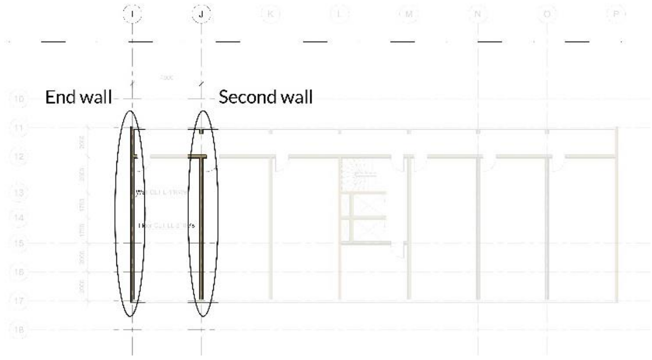


Figure 108: End wall and second wall used for the calculation

Characteristics base scenario

The following values correspond to the design of variant 6

Table 56: Characteristics base scenario

Floor span	4.8 m
Number of bays	7
Total building width	33.6 m
Storey height	3.2 m
Number of storeys	5
Total building height	16 m
Depth	12 m
Gross floor area	2016 m^2
Net floor area	1825 m^2

Load and stability calculation

Based on the assumptions that are described before the following calculations are made.

Load factors

The following load factors are used.

Table 57: load factors

Load combinations	Permanent loads		Main variable load	Remaining variable loads
	Normal	Beneficial		
ULS Combination 1	1.35	0.9	1	$1.5 \cdot \psi_{0,i}$
ULS Combination 2	1.2	0.9	1.5	$1.5 \cdot \psi_{0,i}$
ULS in case of fire	1	0.9	$1 \cdot \psi_{1,i}$	-
SLS load combination	1		1	$1 \cdot \psi_{0,i}$
Vibrations load combination	1		0.1	

Psi factors

The following ψ factors are used.

Table 58: psi factors

ψ0	0.4

ψ1	0.5
ψ2	0.3

K-mod

The following factors are used for k_{mod}. The k_{mod} factor must be chosen according to the shortest acting load in the load combination.

Table 59: k mod factors

	Permanent	Long	Medium	Short	Instantaneous
Service class 1 and 2	0.6	0.7	0.8	0.9	1.1

Other factors

The following factors are used for $\gamma_{M.}$

Table 60: γM factors

Material	γM
CLT	1.25
Concrete	1.5

The following factors are used for k_{def}.

Table 61: k def factors

	Service class		
Material	1	2	3
Solid timber and glued laminated timber (also used for CLT)	0.60	0.80	2.00

Material specifications

The material characteristics of the CLT floors, CLT walls and concrete walls are described.

CLT elements

All CLT elements that are used in the design consist of timber elements in the strength class C24, this translates to the following timber properties.

Table 62: Material properties timber

$f_{m,k}$	24	N/mm^2
$f_{c,90,xlay,k}$	2.5	N/mm^2
$E_{0,x,mean}$	11000	N/mm^2
$E_{90,x,mean}$	400	N/mm^2
$E_{0,x,0.5}$	7400	N/mm^2
$E_{0,y,0.5}$	7400	N/mm^2
$G_{090,xlay\ mean}$	690	N/mm^2
$G_{9090,xlay\ mean}$	50	N/mm^2
$f_{v,090,ylay,k}$	4	N/mm^2
$f_{v,9090,xlay,k}$	1.1	N/mm^2

$f_{c,0,xlay,k}$	21	N/mm²
$f_{c,0,ylay,k}$	21	N/mm²

CLT floors

Chosen floor is CLT LL-210/7s as produced by Derix, these floors are built up out of 7 layers of 30 mm thick. The direction of the layers is shown in Figure 103. The following calculations were performed to determine the properties of the floor.

Table 63: Properties timber floor

$I_{x,net} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \sum \frac{E_{x,i}}{E_{ref}} \cdot b_x t_i a_i^2$	$I_{x,net} = 7.13\text{E} + 08\ mm^4$
$I_{y,net} = \sum \frac{E_{y,i}}{E_{ref}} \cdot \frac{b_y t_i^3}{12} + \sum \frac{E_{y,i}}{E_{ref}} \cdot b_y t_i a_i^2$	$I_{y,net} = 5.85\text{E} + 07\ mm^4$
$W_{x,net} = \frac{2 \cdot I_{x,net}}{h_{CLT}}$ With $h_{CLT} = h_x + h_y$	$W_{x,net} = 6.79\text{E} + 06\ mm^3$ $h_{CLT} = 7 \cdot 30 = 210\ mm$
$W_{y,net} = \frac{2 \cdot I_{y,net}}{h_{CLT}}$ With $h_{CLT} = h_x + h_y$	$W_{y,net} = 5.57\text{E} + 05\ mm^3$ $h_{CLT} = 7 \cdot 30 = 220\ mm$
$S_{R,x,\text{ net}} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i$	$S_{R,x,\text{ net}} = 5.40\text{E} + 06\ mm^3$ $(between\ third\ and\ fourth\ layer)$
$S_{x,\text{ net}} = \sum_{i=1}^{k_L} \frac{E_{y,i}}{E_{ref}} b_y t_i a_i + b_y \frac{\left(\frac{t_k}{2} - a_k\right)^2}{2}$	$S_{x,\text{ net}} = 2.75\text{E} + 06 mm^3$ (at middle layer)
$A_{x,net} = b_x h_x$	$A_{x,net} = 1.50E + 05\ mm^2$
$A_{y,net} = b_y h_y$	$A_{y,net} = 6.00E + 04\ mm^2$
$EI_{net} = \sum E_i I_i + E_i A_i a_i^2$	$EI_{x,net} = 7846\ kNm^2$ $EI_{y,net} = 644\ kNm^2$
$\text{GA}_\text{s} = \kappa \sum \text{G}_\text{i} \text{b}_\text{i} \text{t}_\text{i}$ With: $\kappa = \frac{\left(\sum(EI+EAa^2)\right)^2}{\sum G_i b t_i \cdot \int \frac{S^2(z)E^2(z)}{G(z)b(z)} dz}$ Or according to Table 64. Or according to page 191 Wallner-Novak et al., 2014	$\text{GA}_\text{s} = 1.91\text{E} + 07\ N$ $\kappa_\text{x} = 0.179$

Table 64: Shear correction factors. From: "The CLT Handbook", by A. Gustafsson et al., 2019, p.43.

Dimension	Thickness per layer					Strength class per layer					Shear correction factor	
h_{CLT}	t_1	t_2	t_3	t_4	t_5	s_1	s_2	s_3	s_4	s_5	κ_x	κ_y
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(SS-EN 338)					–	–
60	20	20	20			C24	C24	C24			0.163	0.722
70	20	30	20			C24	C24	C24			0.161	0.756
80	20	40	20			C24	C24	C24			0.168	0.774
80	30	20	30			C24	C24	C24			0.178	0.677
90	30	30	30			C24	C24	C24			0.163	0.722
100	30	40	30			C24	C24	C24			0.161	0.747
100	40	20	40			C24	C24	C24			0.196	0.637
110	40	30	40			C24	C24	C24			0.172	0.691
120	40	40	40			C24	C24	C24			0.163	0.722
100	20	20	20	20	20	C24	C24	C24	C24	C24	0.194	0.152
120	20	30	20	30	20	C24	C24	C24	C24	C24	0.197	0.169
140	20	40	20	40	20	C24	C24	C24	C24	C24	0.208	0.189
110	20	20	30	20	20	C24	C24	C24	C24	C24	0.212	0.150
130	20	30	30	30	20	C24	C24	C24	C24	C24	0.207	0.156
150	20	40	30	40	20	C24	C24	C24	C24	C24	0.213	0.166
120	20	20	40	20	20	C24	C24	C24	C24	C24	0.234	0.157
140	20	30	40	30	20	C24	C24	C24	C24	C24	0.221	0.153
160	20	40	40	40	20	C24	C24	C24	C24	C24	0.221	0.157
120	30	20	20	20	30	C24	C24	C24	C24	C24	0.188	0.147
140	30	30	20	30	30	C24	C24	C24	C24	C24	0.184	0.165
160	30	40	20	40	30	C24	C24	C24	C24	C24	0.189	0.186
130	30	20	30	20	30	C24	C24	C24	C24	C24	0.204	0.146
150	30	30	30	30	30	C24	C24	C24	C24	C24	0.194	0.152
170	30	40	30	40	30	C24	C24	C24	C24	C24	0.195	0.163
140	30	20	40	20	30	C24	C24	C24	C24	C24	0.221	0.152
160	30	30	40	30	30	C24	C24	C24	C24	C24	0.206	0.150
180	30	40	40	40	30	C24	C24	C24	C24	C24	0.203	0.155
140	40	20	20	20	40	C24	C24	C24	C24	C24	0.189	0.142
160	40	30	20	30	40	C24	C24	C24	C24	C24	0.179	0.162
180	40	40	20	40	40	C24	C24	C24	C24	C24	0.179	0.182
150	40	20	30	20	40	C24	C24	C24	C24	C24	0.203	0.141
170	40	30	30	30	40	C24	C24	C24	C24	C24	0.189	0.149
190	40	40	30	40	40	C24	C24	C24	C24	C24	0.186	0.160
160	40	20	40	20	40	C24	C24	C24	C24	C24	0.219	0.147
180	40	30	40	30	40	C24	C24	C24	C24	C24	0.199	0.146
200	40	40	40	40	40	C24	C24	C24	C24	C24	0.194	0.152

CLT walls

The walls are constructed out of CLT L-110/3s panels as manufactured by Derix, the outer layers have a thickness of 40 mm, and the centre layer is 30 mm thick. The build-up of the layers and the direction is illustrated in Figure 103. The following calculations were performed to determine the properties of the CLT walls.

Table 65: Properties timber walls

$I_{x,net,out\ of\ plane} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \sum \frac{E_{x,i}}{E_{ref}} \cdot b_x t_i a_i^2$	$I_{x,net,out\ of\ plane} = 1.09\text{E} + 09\ mm^4$
$I_{y,net,out\ of\ plane} = \sum \frac{E_{y,i}}{E_{ref}} \cdot \frac{b_y t_i^3}{12} + \sum \frac{E_{y,i}}{E_{ref}} \cdot b_y t_i a_i^2$	$I_{y,net,out\ of\ plane} = 2.25\text{E} + 07\ mm^4$
$W_{x,net,out\ of\ plane} = \frac{2 \cdot I_{x,net,out\ of\ plane}}{h_{CLT}}$ With $h_{CLT} = h_x + h_y$	$W_{x,net,out\ of\ plane} = 1.98\text{E} + 07\ mm^3$ $h_{CLT} = 40 + 30 + 40 = 110\ mm$
$W_{y,net,out\ of\ plane} = \frac{2 \cdot I_{y,net,out\ of\ plane}}{h_{CLT}}$ With $h_{CLT} = h_x + h_y$	$W_{y,net,out\ of\ plane} = 4.09\text{E} + 05\ mm^3$ $h_{CLT} = 40 + 30 + 40 = 110\ mm$
$I_{x,net,in\ plane} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{t_i b_x^3}{12}$	$I_{x,net,in\ plane} = 6.67\text{E} + 12\ mm^4$
$I_{y,net,in\ plane} = \sum \frac{E_{y,i}}{E_{ref}} \cdot \frac{t_i b_y^3}{12}$	$I_{y,net,in\ plane} = 2.50\text{E} + 12\ mm^4$
$W_{x,net,in\ plane} = \frac{2 \cdot I_{x,net,in\ plane}}{h_{CLT}}$	$W_{x,net,in\ plane} = 1.33\text{E} + 09\ mm^3$
$W_{y,net,in\ plane} = \frac{2 \cdot I_{y,net,in\ plane}}{h_{CLT}}$	$W_{Y,net,in\ plane} = 5.00\text{E} + 08\ mm^3$
$A_{x,net} = b_x h_x$	$A_{x,net} = 8.00\text{E} + 05\ mm^2$
$A_{y,net} = b_y h_y$	$A_{y,net} = 3.00\text{E} + 05\ mm^2$
$\text{GA}_s = \kappa \sum \text{G}_i \text{b}_i \text{t}_i$ With $\kappa = \frac{\left(\sum(EI + EAa^2)\right)^2}{\sum G_i b t_i \cdot \int \frac{S^2(z) E^2(z)}{G(z) b(z)} dz}$ Or according to Table 64.	$\text{GA}_s = 9.75\text{E} + 06\ \text{N}$ $\kappa_x = 0.172$ $\kappa_y = 0.691$

Concrete stability walls

The assumed strength class for all concrete stability elements is C30/37, this translated to the following material properties. In variant 6 no concrete stability walls are applied. Section 9.2 describes the method that is used to determine the dimensions of the concrete stability elements.

Table 66: Material properties concrete

E_{cm}	33000	N/mm^2

$E_{cracked}$	11000	N/mm^2
f_{cm}	38	N/mm^2
f_{ck}	30	N/mm^2
$f_{ck,cube}$	37	N/mm^2
f_{ctm}	2.9	N/mm^2
$f_{ctk;0,05}$	2	N/mm^2

Stability

For variant 6 the wind loads on the long façade will be transferred via the floors to the CLT walls it the direction perpendicular to the long facade. The wind force distribution over the walls of the lang facade is shown in Figure 109.

The wind loads on the short façade will be transferred by the CLT walls in the direction perpendicular to the short façade.

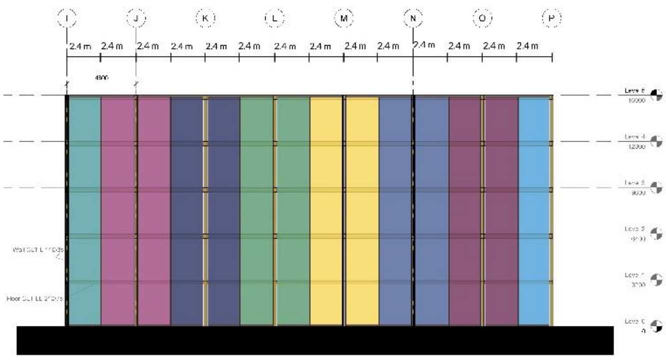


Figure 109: Wind force distribution stability walls

Loads

The permanent loads applied to the floors can be found in Table 28. The assumed variable floor load is 1.75 kN/m^2 0.8 kN/m^2 is added for separation walls, which brings the total variable load to 2.55 kN/m^2. The load combinations for the floors can be found in Table 67. An additional check for the influence of k_{mod} is performed by dividing combination 1 and 2 over 0.9 and creating a third combination with only permanent loading and k,mod =0.6

Table 67: load combinations floors

ULS load combination 1:	$\gamma_{G1} \cdot G_k + \gamma_{Q1;1} \cdot Q_{1;k} + \Sigma(\gamma_{Q:i} \cdot \Psi_{0;i} \cdot Q_{i;k})$
	$1.35 \cdot 2.86 + 1 \cdot 2.55 = 6.4\ kN/m^2$
ULS load combination 2:	$\gamma_{G2} \cdot G_k + \gamma_{Q2;1} \cdot Q_{1;k} + \Sigma(\gamma_{Q:i} \cdot \Psi_{0;i} \cdot Q_{i;k})$
	$1.2 \cdot 2.86 + 1.5 \cdot 2.55 = 7.3\ kN/m^2$
ULS load combination 3:	$\gamma_{G1} \cdot G_k$
	$1.35 \cdot 2.86 = 3.9\ kN/m^2$
Fire load combination:	$\gamma_{G1} \cdot G_k + Q_{1;k} \cdot \Psi_{1;i}$
	$1 \cdot 2.86 + 2.55 \cdot 0.5 = 4.1\ kN/m^2$
SLS load combination:	$G_k + \gamma \cdot Q_{1:k} + \Sigma(\Psi_{0;i} \cdot Q_{i;k})$
	$2.86 + 1 \cdot 2.55 = 5.4\ kN/m^2$
Vibrations load combination:	$G_k + 0.1 \cdot Q_{1:k}$
	$2.86 + 0.1 \cdot 2.55 = 3.1\ kN/m^2$

Wind load combination (floor load works beneficial):	$0.9 \cdot \mathrm{G}_k + 0 \cdot Q_{1:k}$
	$0.9 \cdot 2.86 + 2.55 \cdot 0 = 2.6\ kN/mm^2$

The permanent loads due to the walls can be found in Table 30. The load combinations for the walls can be found in Table 68.

Table 68: Load combinations walls

ULS load combination 1:	$\gamma_{G1} \cdot \mathrm{G}_k + \gamma_{Q1;1} \cdot Q_{1;k} + \Sigma(\gamma_{Q:i} \cdot \Psi_{0;i} \cdot Q_{i;k})$
	$1.35 \cdot 1.09 = 1.5\ kN/m^2$
ULS load combination 2:	$\gamma_{G2} \cdot \mathrm{G}_k + \gamma_{Q2;1} \cdot Q_{1;k} + \Sigma(\gamma_{Q:i} \cdot \Psi_{0;i} \cdot Q_{i;k})$
	$1.2 \cdot 1.09 = 1.3\ kN/m^2$
SLS load combination:	$G_k + \gamma \cdot Q_{1:k} + \Sigma(\Psi_{0;i} \cdot Q_{i;k})$
	$1.09 = 1.09\ \mathrm{l}N/m^2$
Wind load combination (floor load works beneficial):	$0.9 \cdot \mathrm{G}_k + 0 \cdot Q_{1:k}$
	$0.9 \cdot 1.09 = 1.0\ kN/m^2$

The façade loads are assumed to be 1.5 kN/m2 façade area, these are taken by the walls as a normal force distributed over the full length of the wall. This results in a horizontal load of 46.1 kN for the second wall. Since this load is very small it is neglected in the calculations for the wall thickness.

To determine the wind loads the following calculations are performed. All variants are assumed to be in wind area II on rural terrain. $q_p(z_e)$ is determined using linear interpolation between the given values in NEN 1991, table NB-5. The reference height for variant 6 is 16 meters.

Table 69: Wind loads

Wind load:	For the second wall	For the end wall:	Wind on the short facade
$F_{wind} = F_{we} + F_{wi} + F_{fr}$			
	$q_p(z_e) = 0.998$	$q_p(z_e) = 0.998$	
$F_{we} = A_{ref} \cdot q_p(z_e) \cdot (c_{peD} - c_{peE}) \cdot c_{correlation}$	$F_{we,second} = 78.2 \cdot 0.998 \cdot (0.8 + 0.5) \cdot 1 = 87.0\ kN$	$F_{we,end} = 38.4 \cdot 0.998 \cdot (0.8 + 0.5) \cdot 1 = 43.5\ kN$	$F_{we,short} = 192 \cdot 0.998 \cdot (0.8 + 0.5) \cdot 0.85 = 214.5\ kN$
F_{wi} The internal wind pressure us assumed to be equal on all sides and is therefore neglected.			
F_{fr} The wind friction can be neglected if the total area of all surfaces parallel to the wind direction are smaller than four times the total area of all exterior surfaces' perpendicular to the wind direction. This was true for the wind force on the long façade but not true for the wind force on the short façade. Therefore, the			$F_{fr,short} = 0.998 \cdot 0.04 \cdot (403.2 + 1075.2) = 59.0\ kN$

friction force is included in the calculation of the wind force on the short façade.			
	$q_{wind,second} = \frac{97.9}{16} = 5.4\ kN/m$	$q_{wind,end} = \frac{32.6}{16} = 2.7\ kN/m$	$q_{wind,short} = \frac{214.5 + 59.0}{16} = 17.1\ kN/m$

ULS calculation floors

In the table below the calculations to check the ultimate limit state of the floors can be found.

Table 70: ULS calculation floors

Bending Check	
$\frac{\sigma_{m,y,d}}{f_{m,xlay,d}} \leq 1$	$\frac{3.07}{19.43} = 0.158 \leq 1$
$f_{m,xlay,d} = k_{sys} \cdot k_{mod} \frac{f_{m,xlay,k}}{\gamma_M}$	$f_{m,xlay,d} = 1.15 \cdot 0.8 \cdot \frac{24}{1.25} = 19.43$
$\sigma_{m,y,d} = \frac{M_{y,d}}{W_{x,net}}$	$\sigma_{m,y,d} = \frac{20886422}{6792857} = 3.07$
Shear check	
$\frac{\tau_{V,d}}{f_{V,d}} \leq 1$	$\frac{0.067}{2.56} = 0.026 \leq 1$
$\tau_{V,d} = \frac{V_{0,d} \cdot S_{0,V,net}}{I_{0,net} \cdot b}$	$\tau_{V,d} = \frac{17405 \cdot 2745000}{713250000 \cdot 1000} = 0.067$
$f_{V,d} = k_{mod} \cdot \frac{f_{V,k}}{\gamma_M}$	$f_{V,d} = 0.80 \cdot \frac{4}{1.25} = 2.56$
Rolling shear check	
$\frac{\tau_{V,R,d}}{f_{V,R,d}} \leq 1$	$\frac{0.132}{0.70} = 0.187 \leq 1$
$\tau_{V,R,d} = \frac{V_{0,d} \cdot S_{0,R,net}}{I_{0,net} \cdot b}$	$\tau_{V,R,d} = \frac{17405 \cdot 5400000}{713250000 \cdot 1000} = 0.132$
$f_{V,R,d} = k_{mod} \cdot \frac{f_{V,R,k}}{\gamma_M}$	$f_{V,R,d} = 0.80 \cdot \frac{1.10}{1.25} = 0.70$
Reaction force at the support	
$\frac{\sigma_{c,90,d}}{f_{c,90,d}} \leq 1$	$\frac{0.64}{1.60} = 0.403 \leq 1$
$\sigma_{c,90,d} = \frac{N_{90,d}}{k_{c,90} \cdot A_{ef}}$	$\sigma_{c,90,d} = \frac{17405}{1.40 \cdot 27000} = 0.64$ With support area $= 150 \cdot (150 + 30)$ mm
$f_{c,90,d} = k_{mod} \cdot \frac{f_{c,90,k}}{\gamma_M}$	$f_{c,90,d} = 0.80 \cdot \frac{2.5}{1.25} = 1.60$
Floor checks under fire load	

$d_{char,n} = \beta_0 \cdot t$ $\beta_n = \beta_0 = 0.65mm/min$	$d_{char,n} = 0.65 \cdot 90 = 58.50$
$d_{ef} = d_{char,n} + k_0 d_0$	$d_{ef} = 58.50 + 7 = 65.50$
Remaining cross section	t1 = 30 t2 = 30 t3 = 30 t4 = 30 t5 = 24.5 t6 = 0 t7 = 0
Bending under fire	
$\frac{\sigma_{m,y,f}}{f_{m,xlay,f}} \leq 1$	$\frac{5.39}{27.60} = 0.195 \leq 1$
$\sigma_{m,y,f} = \frac{M_{y,f}}{W_{x,net}}$	$\sigma_{m,y,f} = \frac{11897352}{2208036} = 5.39$
$f_{m,xlay,f} = k_{fi} \cdot k_{mod,fi} \frac{f_{m,xlay,k}}{\gamma_{M,fi}}$	$f_{m,xlay,f} = 1.15 \cdot 1 \frac{24}{1} = 27.60$
Shear check under fire	
$\frac{\tau_{V,f}}{f_{V,f}} \leq 1$	$\frac{0.162}{4.60} = 0.035 \leq 1$
$\tau_{V,f} = \frac{V_{0,d} \cdot S_{0,V,\ net}}{I_{0,\ net} \cdot b}$	$\tau_{V,f} = \frac{9914 \cdot 2610031}{159530625 \cdot 1000} = 0.162$
$f_{V,d} = k_{fi} \cdot k_{mod,fi} \cdot \frac{f_{V,k}}{\gamma_{M,fi}}$	$f_{V,d} = 1.15 \cdot 1 \cdot \frac{4}{1} = 4.6$
Rolling shear check under fire	
$\frac{\tau_{V,R,f}}{f_{V,R,f}} \leq 1$	$\frac{0.158}{1.27} = 0.125 \leq 1$
$\tau_{V,R,f} = \frac{V_{0,d} \cdot S_{0,R,net}}{I_{0,\ net} \cdot b}$	$\tau_{V,R,f} = \frac{9914 \cdot 2535000}{159530625 \cdot 1000} = 0.158$
$f_{V,R,f} = k_{fi} \cdot k_{mod,fi} \cdot \frac{f_{V,R,k}}{\gamma_{M,fi}}$	$f_{V,R,f} = 1.15 \cdot 1 \cdot \frac{1.1}{1} = 1.27$
Reaction force at the support under fire	
$\frac{\sigma_{c,90,f}}{f_{c,90,f}} \leq 1$	$\frac{0.37}{2.88} = 0.128 \leq 1$
$\sigma_{c,90,f} = \frac{N_{90,d}}{k_{c,90} \cdot A_{ef}}$	$\sigma_{c,90,f} = \frac{9914}{1.4 \cdot 27000} = 0.37$ With support area = 150 · (150 + 30) mm
$f_{c,90,f} = k_{fi} \cdot k_{mod,fi} \cdot \frac{f_{c,90,k}}{\gamma_{M,fi}}$	$f_{c,90,f} = 1.15 \cdot 1 \cdot \frac{2.5}{1} = 2.88$

SLS calculation floors

In the table below the calculations to check the serviceability limit state of the floors can be found.

Table 71: SLS calculation floors

Deflections	
$w = \frac{5ql^4}{384EI} + \frac{ql^2}{8GA_G}$	
$w_{inst,qs} = w_G + \sum_{i\geq 1} \psi_{2,i} \cdot w_{Q,i}$	$w_{inst,qs} = 2.95 + 0.3 \cdot 2.63 = 3.74\ mm$
$W_{fin,qs} = W_{inst,qs} \cdot (1 + k_{def}) \leq \frac{\ell}{250}$	$W_{fin,qs} = 3.74 \cdot (1 + 0.8) = 6.73 \leq 19.20\ mm$
$W_{creep} = k_{def} \cdot W_{inst,\ qs}$	$W_{creep} = 2.99\ mm$
$w_{inst} = (w_{g,1} + w_{g,2}) + w_{q,1} + \sum_{i>1} \psi_{0,i} \cdot w_{q,i} \leq \frac{\ell}{300}$	$w_{inst} = 5.58 \leq 16\ mm$
$w_{fin} = w_{inst} + w_{creep} \leq \frac{\ell}{200}$	$w_{fin} = 8.57 \leq 24\ mm$
Vibrations	
First natural frequency	
$\frac{8\ Hz}{f_{1,\ beam}} \leq 1$	$\frac{8\ Hz}{10.83\ Hz} = 0.739 \leq 1$
$f_{1,\ beam} = \frac{\pi}{2 \cdot \ell^2} \cdot \sqrt{\frac{E \cdot I_0}{m}}$	$f_{1,\ beam} = \frac{\pi}{2 \cdot 4.8^2} \cdot \sqrt{\frac{11000 \cdot 713250000}{311}} = 10.83$
Stiffness criterion	
$\frac{w_{1kN}}{0.25\ mm} \leq 1$	$\frac{0.131}{0.25} = 0.522 \leq 1$
$w_{1kN} = \frac{1kN \cdot \ell^3}{48 \cdot E \cdot I_{ef}}$ I_{ef} *over one floor panel with a width of 2.25m*	$w_{1kN} = \frac{1kN \cdot 4800^3}{48 \cdot 11000 \cdot 1604812500} = 0.131$
Limit acceleration	
$\frac{a_{ms}}{0.05\ m/s^2} \leq 1$	$\frac{0.043}{0.05} = 0.867 \leq 1$
$a_{ms} = \frac{0.4 \cdot a \cdot F_0}{M \cdot 2 \cdot D}$	$a = e^{-0.47 \cdot f_1}$ $F_0 = 700\ N$ $M \approx \frac{8}{15} \cdot m \cdot \ell$ D = 0.025 according to Table 72.

Table 72: Suggested values for relative damping in floor structures made from wood and CLT. From: "The CLT Handbook", by A. Gustafsson et al., 2019, p.98.

Material and composition	Relative damping
Wooden floor structure	1.0 percent
Bonded boards with cast layer	2.0 percent
Composite structure with nailed wooden joists and cast layer	3.0 percent
CLT floor structure with or without additional lightweight top layer, two-sided supported	2.5 percent
CLT floor structure with cast layer, two-sided supported	2.5 percent
CLT floor structure with cast layer, four-sided supported	3.5 percent
CLT floor structure with cast layer, four-sided supported on stud walls	4.0 percent

ULS calculation walls

In the table below the calculations to check the ultimate limit state of the timber walls can be found.

Table 73: ULS calculation timber walls

Bending and compression in plane	Second wall	End wall
$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1$	$\frac{3.25}{1 \cdot 10.08} + \frac{0.78}{15.36} = 0.374 \leq 1$	$\frac{1.89}{1 \cdot 10.08} + \frac{0.39}{15.36} = 0.213 \leq 1$
$\sigma_{c,0,d} = \frac{N_{0,d}}{A_{0,\,net}}$	$\sigma_{c,0,d} = \frac{2371689}{800000} = 2.96$	
$N_{0,d} = f_b \cdot N_{d,hor}$ $N_{d,hor} = N_{floor\ loads} + N_{wall\ loads}$	$N_{0,d} = 1 \cdot (2088642 + 283046 + 230400) = 2602089\ N$	
$f_b = \frac{b_0}{b_{eff}}$	$f_b = \frac{10000}{10000} = 1$	
$f_{c,0,d} = k_{sys} \cdot k_{mod} \frac{f_{c,0,k}}{\gamma_M}$	$f_{c,0,d} = 1 \cdot 0.6 \frac{21}{1.25} = 10.08$	
$\sigma_{m,d} = \frac{M_d}{W_{0,\,net}}$	$\sigma_{m,d} = \frac{1044498816}{1333333333} = 0.78$	
$M_d = \frac{1}{2} \cdot q_{d,wind} \cdot b_{eff}^2$	$M_d = \frac{1}{2} \cdot 8.16 \cdot 16000^2 = 1044498816$	
$f_{m,d} = k_{sys} \cdot k_{mod} \frac{f_{m,k}}{\gamma_M}$	$f_{m,d} = 1 \cdot 0.8 \frac{24}{1.25} = 15.36$	
$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}}$	$k_{c,y} = 1$	
$k_y = 0.5[(1 + \beta_c(\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2)]$ $\beta_c = 0.1$	$k_y = 0.49$	
$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0,05}}}$	$\lambda_{rel,y} = 0.02$	
$\lambda_y = \frac{\ell_{k,i}}{i_{y,0,ef}}$	$\lambda_y = 1.11$	

$i_{y,0,ef} = \sqrt{\frac{I_{y,0,ef}}{A_{0,net}}}$	$i_{y,0,ef} = 2887$	
Check if there is tension in the foundation		
$\frac{F_{tension}}{F_{compression}} \leq 1$	$\frac{104450}{897530} = 0.116 \leq 1$	$\frac{52225}{558838} = 0.093 \leq 1$
$F_{tension} = \frac{M_d}{b_{eff}}$	$F_{tension} = \frac{1044498816}{10000} = 104450\ N$	
$F_{compression} = N_{0,d}$	$F_{compression} = 897530\ N$	
Shear check		
Mechanism 1:		
$\frac{\tau_{V,S,d}}{f_{V,S,d}} \leq 1$	$\frac{0.44}{2.56} = 0.170 \leq 1$	$\frac{0.14}{0.70} = 0.193 \leq 1$
$\tau_{V,S,d} = \frac{T}{A_{S,\ net}}$	$\tau_{V,S,d} = \frac{130562}{300000} = 0.44$	
$A_s = min\begin{cases}A_{0,net}\\A_{90,net}\end{cases}$	$A_s = min\begin{cases}800000\\300000\end{cases}$	
$f_{V,S,d} = k_{mod} \cdot \frac{f_{V,S,k}}{\gamma_M}$	$f_{V,S,d} = 0.80 \cdot \frac{4}{1.25} = 2.56$	
Mechanism 2:		
$\frac{\tau_{V,d}}{f_{V,d}} \leq 1$	$\frac{0.10}{0.70} = 0.145 \leq 1$	$\frac{0.09}{0.70} = 0.121 \leq 1$
$\tau_{V,d} = \frac{T}{A_{gross}}$	$\tau_{V,d} = \frac{130562}{1280000} = 0.10$	
$f_{V,d} = k_{mod} \cdot \frac{f_{V,k}}{\gamma_M}$	$f_{V,d} = 0.80 \cdot \frac{1.1}{1.25} = 0.70$	
Bending and compression out of plane		
$\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1$	$\frac{3.25}{0.42 \cdot 13.44} + \frac{0.03}{15.36} = 0.576 \leq 1$	$\frac{1.89}{0.42 \cdot 13.44} + \frac{0.05}{15.36} = 0.336 \leq 1$
$\sigma_{c,0,d} = \frac{N_d}{A_{net}}$	$\sigma_{c,0,d} = \frac{2602089}{800000} = 3.25$	
$\sigma_{m,d} = \frac{M_d}{W_{net}}$	$\sigma_{m,d} = \frac{617999}{29700000} = 0.03$ M_d due to eccentricity of the floor load	
$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}}$	$k_{c,y} = 0.42$	

$k_y = 0.5[(1 + \beta_c(\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2)]$ $\beta_c = 0.1$	$k_y = 1.64$	
$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0,05}}}$	$\lambda_{rel,y} = 1.47$	
$\lambda_y = \frac{\ell_{k,i}}{i_{y,0,ef}}$	$\lambda_y = 86.83$	
$i_{y,0,ef} = \sqrt{\frac{I_{y,0,ef}}{A_{0,net}}}$	$i_{y,0,ef} = 36.86$	
$f_{c,0,d} = k_{sys} \cdot k_{mod} \frac{f_{c,0,k}}{\gamma_M}$	$f_{c,0,d} = 1 \cdot 0.8 \frac{21}{1.25} = 13.44$	
$f_{m,d} = k_{sys} \cdot k_{mod} \frac{f_{m,k}}{\gamma_M}$	$f_{m,d} = 1 \cdot 0.8 \frac{24}{1.25} = 15.36$	

SLS calculation walls

In the table below the calculations to check the serviceability limit state of the timber walls can be found. The assumption has been made that the wind load can be modelled as a distributed load over the full length of the wall. The connections are modelled as screws on a centre to enter distance of 40 mm with a k_{ser} of 0.5 kN/mm.

Table 74: SLS calculation timber walls

Deformations	Second wall	End wall
$\delta_{shear} = \frac{q_k \cdot h^2}{2 \cdot GA_s}$	$\delta_{shear,second} = 0.76\ mm$	$\delta_{shear,end} = 0.38\ mm$
$\delta_{bend} = \frac{q_k \cdot h^4}{8 \cdot E_{mean} \cdot I}$	$\delta_{bend,\ second} = 0.61\ mm$	$\delta_{bend,\ second} = 0.30\ mm$
$\delta_{connections} = \frac{k_{ser}}{F_{wind}} \cdot \frac{h}{b}$	$\delta_{connections} = 0.20$	$\delta_{connections} = 0.10\ mm$
$\delta_{tot} = \delta_{shear} + \delta_{bend} + \delta_{connections} + \delta_{foundation} \leq \frac{h_{tot}}{500}$ The assumption is made that the foundations will cause half the deformations this results in the following check: $\delta_{tot,part1} = \delta_{shear} + \delta_{bend} + \delta_{connections} \leq \frac{h_{tot}}{1000}$		
$\delta_{tot,part1} = \delta_{shear} + \delta_{bend} \leq \frac{h_{tot}}{1000}$	$\delta_{tot,second} = 0.76 + 0.61 + 0.20 = 1.57 \leq 16\ mm$	$\delta_{tot,second} = 0.38 + 0.30 + 0.10 = 0.79 \leq 16\ mm$

Summary of results

Figure 110 shows a summary of the unity checks. In Appendix K a summary of the unity checks for all sixteen variants can be found.

Floor	LL-210/7s		0,867	Governing is:	Limit acceleration
Floor ULS	**Unity Check**		**0,403**	Governing is:	Reaction force at supports
		Utilisation			
Bending stresses	0,158	16%			
Shear stresses	0,026	3%			
Roling shear stresses	0,187	19%			
Reaction force at supports	0,403	40%			
Fire and bending stresses	0,195	20%			
Fire and shear stresses	0,035	4%			
Fire and roling shear stresses	0,125	12%			
Fire and reaction force at supports	0,128	13%			
Floor SLS	**Unity check**		**0,867**	Governing is:	Limit acceleration
		Utilisation			
Deformation Quasi-permanent design situation	0,350	35%			
Deformation Characteristic design situation initial deformation	0,349	35%			
Deformation Characteristic design situation final deformation	0,357	36%			
Frequency criterion	0,739	74%			
Stifness cirterion	0,522	52%			
Limit acceleration	0,867	87%			
Wall	**L110/3s**		**0,576**	Governing is:	**Bending and compression out of plane**
Wall ULS	**Unity check**		**0,576**	**Governing is:**	**Bending and compression out of plane**
		Utilisation			
second wall					
Bending and compression in plane	0,374	37%			
Stresses due to normal force	0,323	32%			
Stressees due to bending moment	0,051	5%			
Check tension in the foundation	0,116	12%			
Shear force check	0,170	17%			
Mechanism 1	0,170	17%			
Mechanism 3	0,145	14%			
Bending and compression out of plane	0,576	58%			
Compression part	0,574	57%			
Bending part	0,002	0%			
end wall					
Bending and compression in plane	0,240	24%			
Stresses due to normal force	0,215	21%			
Stressees due to bending moment	0,026	3%			
Check tension in the foundation	0,093	9%			
Shear force check	0,193	19%			
Mechanism 1	0,193	19%			
Mechanism 3	0,121	12%			
Bending and compression out of plane	0,385	38%			
Compression part	0,382	38%			
Bending part	0,003	0%			
Wall SLS	**Unity check**		**0,098**	**Governing is:**	**second wall**
		Utilisation			
second wall					
Total deflections	0,098	10%			
end wall					
Total deflections	0,049	5%			

Figure 110: Unity checks CLT walls and floors variant 6

Appendix K. Unity checks all variants parameter study

This appendix contains an overview of the unity checks for all variants included in the parameter study.

span	3,6	Storeys	3

Floor

Floor	L160/5s	0,613	Governing is:	Frequency criterion

Floor ULS

Floor ULS	Unity Check	Utilisation	0,291 Governing is:	Reaction force at supports
Bending stresses	0,153	15%		
Shear stresses	0,052	5%		
Roling shear stresses	0,176	18%		
Reaction force at supports	0,291	29%		
Fire and bending stresses	0,135	13%		
Fire and shear stresses	0,023	2%		
Fire and roling shear stresses	0,085	8%		
Fire and reaction force at supports	0,188	19%		

Floor SLS

Floor SLS	Unity check	Utilisation	0,613 Governing is:	Frequency criterion
Deformation Quasi-permanent design situation	0,314	31%		
Deformation Characteristic initial deformation	0,320	32%		
Deformation Characteristic final deformation	0,325	32%		
Frequency criterion	0,613	61%		
Stifness cirterion	0,517	52%		
Limit acceleration	0,438	44%		

Wall

Wall	L100/3s	0,479	Governing is:	Bending and compression out of pla

Wall ULS

Wall ULS	Unity check	Utilisation	0,479 Governing is:	Bending and compression out of plane
second wall				
Bending and compression in plane	0,208	21%		
Stresses due to normal force	0,193	19%		
Stressees due to bending moment	0,015	1%		
Check tension in the foundation	0,057	6%		
Shear force check	0,116	12%		
Mechanism 1	0,046	5%		
Mechanism 3	0,116	12%		
Bending and compression out of plane	0,479	48%		
Compression part	0,477	48%		
Bending part	0,002	0%		
end wall				
Bending and compression in plane	0,146	15%		
Stresses due to normal force	0,139	14%		
Stressees due to bending moment	0,007	1%		
Check tension in the foundation	0,043	4%		
Shear force check	0,091	9%		
Mechanism 1	0,087	9%		
Mechanism 3	0,091	9%		
Bending and compression out of plane	0,345	34%		
Compression part	0,342	34%		
Bending part	0,003	0%		

Wall SLS

Wall SLS	Unity check	Utilisation	0,045 Governing is:	second wall
second wall				
Total deflections	0,045	5%		
end wall				
Total deflections	0,023	2%		

	span	4,8	Storeys	3

Floor — LL-210/7s — 0,867 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,403 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,158	16%
Shear stresses	0,026	3%
Roling shear stresses	0,187	19%
Reaction force at supports	0,403	40%
Fire and bending stresses	0,178	18%
Fire and shear stresses	0,034	3%
Fire and roling shear stresses	0,123	12%
Fire and reaction force at supports	0,265	27%

Floor SLS — Unity check — 0,867 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,350	35%
Deformation Characteristic initial deformation	0,349	35%
Deformation Characteristic final deformation	0,357	36%
Frequency criterion	0,739	74%
Stifness cirterion	0,522	52%
Limit acceleration	0,867	87%

Wall — L100/3s — 0,636 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,636 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,277	28%
Stresses due to normal force	0,257	26%
Stressees due to bending moment	0,020	2%
Check tension in the foundation	0,057	6%
Shear force check	0,155	16%
Mechanism 1	0,061	6%
Mechanism 3	0,155	16%
Bending and compression out of plane	0,636	64%
Compression part	0,634	63%
Bending part	0,002	0%
end wall		
Bending and compression in plane	0,180	18%
Stresses due to normal force	0,170	17%
Stressees due to bending moment	0,010	1%
Check tension in the foundation	0,046	5%
Shear force check	0,121	12%
Mechanism 1	0,116	12%
Mechanism 3	0,121	12%
Bending and compression out of plane	0,424	42%
Compression part	0,420	42%
Bending part	0,004	0%

Wall SLS — Unity check — 0,328 Governing is: middle wall

		Utilisation
second wall		
Total deflections	0,060	6%
end wall		
Total deflections	0,030	3%

span	5,4 Storeys	3

Floor — LL-240/7s — 0,872 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,463 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,150	15%
Shear stresses	0,028	3%
Roling shear stresses	0,178	18%
Reaction force at supports	0,463	46%
Fire and bending stresses	0,166	17%
Fire and shear stresses	0,035	3%
Fire and roling shear stresses	0,126	13%
Fire and reaction force at supports	0,308	31%

Floor SLS — Unity check — 0,872 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,318	32%
Deformation Characteristic initial deformation	0,313	31%
Deformation Characteristic final deformation	0,322	32%
Frequency criterion	0,764	76%
Stifness cirterion	0,476	48%
Limit acceleration	0,872	87%

Wall — L100/3s — 0,720 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,720 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,313	31%
Stresses due to normal force	0,291	29%
Stressees due to bending moment	0,022	2%
Check tension in the foundation	0,056	6%
Shear force check	0,175	17%
Mechanism 1	0,069	7%
Mechanism 3	0,175	17%
Bending and compression out of plane	0,720	72%
Compression part	0,717	72%
Bending part	0,003	0%
end wall		
Bending and compression in plane	0,198	20%
Stresses due to normal force	0,187	19%
Stressees due to bending moment	0,011	1%
Check tension in the foundation	0,046	5%
Shear force check	0,136	14%
Mechanism 1	0,131	13%
Mechanism 3	0,136	14%
Bending and compression out of plane	0,466	47%
Compression part	0,462	46%
Bending part	0,004	0%

Wall SLS — Unity check — 0,338 Governing is: middle wall

		Utilisation
second wall		
Total deflections	0,068	7%
end wall		
Total deflections	0,034	3%

span	6 Storeys	3

Floor — LL-280/7s — 0,858 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,529 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,149	15%
Shear stresses	0,026	3%
Roling shear stresses	0,184	18%
Reaction force at supports	0,529	53%
Fire and bending stresses	0,156	16%
Fire and shear stresses	0,033	3%
Fire and roling shear stresses	0,119	12%
Fire and reaction force at supports	0,356	36%

Floor SLS — Unity check — 0,858 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,320	32%
Deformation Characteristic initial deformation	0,310	31%
Deformation Characteristic final deformation	0,320	32%
Frequency criterion	0,786	79%
Stifness cirterion	0,430	43%
Limit acceleration	0,858	86%

Wall — L110/3s — 0,587 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,587 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,265	27%
Stresses due to normal force	0,247	25%
Stressees due to bending moment	0,018	2%
Check tension in the foundation	0,053	5%
Shear force check	0,146	15%
Mechanism 1	0,102	10%
Mechanism 3	0,146	15%
Bending and compression out of plane	0,587	59%
Compression part	0,585	58%
Bending part	0,003	0%
end wall		
Bending and compression in plane	0,165	16%
Stresses due to normal force	0,155	16%
Stressees due to bending moment	0,009	1%
Check tension in the foundation	0,045	4%
Shear force check	0,202	20%
Mechanism 1	0,194	19%
Mechanism 3	0,202	20%
Bending and compression out of plane	0,372	37%
Compression part	0,368	37%
Bending part	0,004	0%

Wall SLS — Unity check — 0,327 Governing is: middle wall

		Utilisation
second wall		
Total deflections	0,068	7%
end wall		
Total deflections	0,034	3%

span	3,6	Storeys	5

Floor

Floor	L160/5s	0,613	Governing is:	Frequency criterion

Floor ULS

Floor ULS	Unity Check	Utilisation	0,302 Governing is:	Fire and bending stresses
Bending stresses	0,153	15%		
Shear stresses	0,052	5%		
Roling shear stresses	0,176	18%		
Reaction force at supports	0,291	29%		
Fire and bending stresses	0,302	30%		
Fire and shear stresses	0,048	5%		
Fire and roling shear stresses	0,169	17%		
Fire and reaction force at supports	0,188	19%		

Floor SLS

Floor SLS	Unity check	Utilisation	0,613 Governing is:	Frequency criterion
Deformation Quasi-permanent design situation	0,314	31%		
Deformation Characteristic initial deformation	0,320	32%		
Deformation Characteristic final deformation	0,325	32%		
Frequency criterion	0,613	61%		
Stifness cirterion	0,517	52%		
Limit acceleration	0,438	44%		

Wall

Wall	L100/3s	0,797	Governing is:	Bending and compression out of pla

Wall ULS

Wall ULS	Unity check	Utilisation	0,797 Governing is:	Bending and compression out of plane
second wall				
Bending and compression in plane	0,373	37%		
Stresses due to normal force	0,322	32%		
Stressees due to bending moment	0,051	5%		
Check tension in the foundation	0,119	12%		
Shear force check	0,145	14%		
Mechanism 1	0,096	10%		
Mechanism 3	0,145	14%		
Bending and compression out of plane	0,797	80%		
Compression part	0,795	80%		
Bending part	0,002	0%		
end wall				
Bending and compression in plane	0,257	26%		
Stresses due to normal force	0,231	23%		
Stressees due to bending moment	0,026	3%		
Check tension in the foundation	0,090	9%		
Shear force check	0,109	11%		
Mechanism 1	0,109	11%		
Mechanism 3	0,068	7%		
Bending and compression out of plane	0,573	57%		
Compression part	0,570	57%		
Bending part	0,003	0%		

Wall SLS

Wall SLS	Unity check	Utilisation	0,436 Governing is:	middle wall
second wall				
Total deflections	0,087	9%		
end wall				
Total deflections	0,043	4%		

span 4,8 Storeys 5

Floor — LL-210/7s — 0,867 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,403 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,158	16%
Shear stresses	0,026	3%
Roling shear stresses	0,187	19%
Reaction force at supports	0,403	40%
Fire and bending stresses	0,195	20%
Fire and shear stresses	0,035	4%
Fire and roling shear stresses	0,125	12%
Fire and reaction force at supports	0,128	13%

Floor SLS — Unity check — 0,867 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,350	35%
Deformation Characteristic initial deformation	0,349	35%
Deformation Characteristic final deformation	0,357	36%
Frequency criterion	0,739	74%
Stifness cirterion	0,522	52%
Limit acceleration	0,867	87%

Wall — L110/3s — 0,576 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,576 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,374	37%
Stresses due to normal force	0,323	32%
Stressees due to bending moment	0,051	5%
Check tension in the foundation	0,116	12%
Shear force check	0,170	17%
Mechanism 1	0,170	17%
Mechanism 3	0,145	14%
Bending and compression out of plane	0,576	58%
Compression part	0,574	57%
Bending part	0,002	0%
end wall		
Bending and compression in plane	0,240	24%
Stresses due to normal force	0,215	21%
Stressees due to bending moment	0,026	3%
Check tension in the foundation	0,093	9%
Shear force check	0,193	19%
Mechanism 1	0,193	19%
Mechanism 3	0,121	12%
Bending and compression out of plane	0,385	38%
Compression part	0,382	38%
Bending part	0,003	0%

Wall SLS — Unity check — 0,098 Governing is: second wall

		Utilisation
second wall		
Total deflections	0,098	10%
end wall		
Total deflections	0,049	5%

	span	5,4	Storeys	5

Floor

Floor	LL-240/7s	0,872	Governing is:	Limit acceleration

Floor ULS

Floor ULS	Unity Check	Utilisation	0,463 Governing is:	Reaction force at supports
Bending stresses	0,150	15%		
Shear stresses	0,028	3%		
Roling shear stresses	0,178	18%		
Reaction force at supports	0,463	46%		
Fire and bending stresses	0,182	18%		
Fire and shear stresses	0,035	4%		
Fire and roling shear stresses	0,128	13%		
Fire and reaction force at supports	0,308	31%		

Floor SLS

Floor SLS	Unity check	Utilisation	0,872 Governing is:	Limit acceleration
Deformation Quasi-permanent design situation	0,318	32%		
Deformation Characteristic initial deformation	0,313	31%		
Deformation Characteristic final deformation	0,322	32%		
Frequency criterion	0,764	76%		
Stifness cirterion	0,476	48%		
Limit acceleration	0,872	87%		

Wall

Wall	L120/3s	0,701	Governing is:	Bending and compression out of pla

Wall ULS

Wall ULS	Unity check	Utilisation	**0,701 Governing is:**	**Bending and compression out of plane**
second wall				
Bending and compression in plane	0,424	42%		
Stresses due to normal force	0,366	37%		
Stressees due to bending moment	0,057	6%		
Check tension in the foundation	0,114	11%		
Shear force check	0,163	16%		
Mechanism 1	0,143	14%		
Mechanism 3	0,163	16%		
Bending and compression out of plane	0,701	70%		
Compression part	0,699	70%		
Bending part	0,002	0%		
end wall				
Bending and compression in plane	0,266	27%		
Stresses due to normal force	0,237	24%		
Stressees due to bending moment	0,029	3%		
Check tension in the foundation	0,093	9%		
Shear force check	0,163	16%		
Mechanism 1	0,163	16%		
Mechanism 3	0,102	10%		
Bending and compression out of plane	0,456	46%		
Compression part	0,453	45%		
Bending part	0,003	0%		

Wall SLS

Wall SLS	Unity check	Utilisation	**0,367 Governing is:**	**middle wall**
second wall				
Total deflections	0,106	11%		
end wall				
Total deflections	0,053	5%		

Span	6	Storeys	5

Floor — LL-280/7s — 0,858 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,529 Governing is: Reaction force at supports

	Unity Check	Utilisation
Bending stresses	0,149	15%
Shear stresses	0,026	3%
Roling shear stresses	0,184	18%
Reaction force at supports	0,529	53%
Fire and bending stresses	0,171	17%
Fire and shear stresses	0,035	3%
Fire and roling shear stresses	0,125	13%
Fire and reaction force at supports	0,356	36%

Floor SLS — Unity check — 0,858 Governing is: Limit acceleration

	Unity check	Utilisation
Deformation Quasi-permanent design situation	0,320	32%
Deformation Characteristic initial deformation	0,310	31%
Deformation Characteristic final deformation	0,320	32%
Frequency criterion	0,786	79%
Stifness cirterion	0,430	43%
Limit acceleration	0,858	86%

Wall — L120/3s — 0,790 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,790 Governing is: Bending and compression out of plane

	Unity check	Utilisation
second wall		
Bending and compression in plane	0,476	48%
Stresses due to normal force	0,412	41%
Stressees due to bending moment	0,064	6%
Check tension in the foundation	0,110	11%
Shear force check	0,181	18%
Mechanism 1	0,159	16%
Mechanism 3	0,181	18%
Bending and compression out of plane	0,790	79%
Compression part	0,788	79%
Bending part	0,002	0%
end wall		
Bending and compression in plane	0,292	29%
Stresses due to normal force	0,260	26%
Stressees due to bending moment	0,032	3%
Check tension in the foundation	0,092	9%
Shear force check	0,181	18%
Mechanism 1	0,181	18%
Mechanism 3	0,113	11%
Bending and compression out of plane	0,501	50%
Compression part	0,497	50%
Bending part	0,004	0%

Wall SLS — Unity check — 0,377 Governing is: middle wall

	Unity check	Utilisation
second wall		
Total deflections	0,118	12%
end wall		
Total deflections	0,059	6%

span	3,6	Storeys	9

Floor — L160/5s — 0,613 Governing is: Frequency criterion

Floor ULS — Unity Check — 0,402 Governing is: Fire and bending stresses

		Utilisation
Bending stresses	0,153	15%
Shear stresses	0,052	5%
Roling shear stresses	0,176	18%
Reaction force at supports	0,291	29%
Fire and bending stresses	0,402	40%
Fire and shear stresses	0,050	5%
Fire and roling shear stresses	0,182	18%
Fire and reaction force at supports	0,188	19%

Floor SLS — Unity check — 0,613 Governing is: Frequency criterion

		Utilisation
Deformation Quasi-permanent design situation	0,314	31%
Deformation Characteristic initial deformation	0,320	32%
Deformation Characteristic final deformation	0,325	32%
Frequency criterion	0,613	61%
Stifness cirterion	0,517	52%
Limit acceleration	0,438	44%

Wall — L120/3s — 0,842 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,842 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,440	44%
Stresses due to normal force	0,440	44%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,842	84%
Compression part	0,841	84%
Bending part	0,001	0%
end wall		
Bending and compression in plane	0,317	32%
Stresses due to normal force	0,317	32%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,608	61%
Compression part	0,606	61%
Bending part	0,002	0%

span	4,8	Storeys	9

Floor — LL-210/7s — 0,867 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,403 Governing is: Reaction force at supports

	Unity Check	Utilisation
Bending stresses	0,158	16%
Shear stresses	0,027	3%
Roling shear stresses	0,187	19%
Reaction force at supports	0,403	40%
Fire and bending stresses	0,195	20%
Fire and shear stresses	0,031	3%
Fire and roling shear stresses	0,111	11%
Fire and reaction force at supports	0,265	27%

Floor SLS — Unity check — 0,867 Governing is: Limit acceleration

	Unity check	Utilisation
Deformation Quasi-permanent design situation	0,350	35%
Deformation Characteristic initial deformation	0,349	35%
Deformation Characteristic final deformation	0,357	36%
Frequency criterion	0,739	74%
Stifness cirterion	0,522	52%
Limit acceleration	0,867	87%

Wall — L-140/5s — 0,765 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,765 Governing is: Bending and compression out of plane

	Unity check	Utilisation
second wall		
Bending and compression in plane	0,471	47%
Stresses due to normal force	0,471	47%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,765	77%
Compression part	0,764	76%
Bending part	0,002	0%
end wall		
Bending and compression in plane	0,315	32%
Stresses due to normal force	0,315	32%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,514	51%
Compression part	0,511	51%
Bending part	0,003	0%

span	5,4	Storeys	9

Floor — LL-240/7s — 0,872 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,463 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,150	15%
Shear stresses	0,029	3%
Roling shear stresses	0,178	18%
Reaction force at supports	0,463	46%
Fire and bending stresses	0,187	19%
Fire and shear stresses	0,032	3%
Fire and roling shear stresses	0,117	12%
Fire and reaction force at supports	0,308	31%

Floor SLS — Unity check — 0,872 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,318	32%
Deformation Characteristic initial deformation	0,313	31%
Deformation Characteristic final deformation	0,322	32%
Frequency criterion	0,764	76%
Stifness cirterion	0,476	48%
Limit acceleration	0,872	87%

Wall — L-140/5s — 0,864 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,864 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,531	53%
Stresses due to normal force	0,531	53%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,864	86%
Compression part	0,862	86%
Bending part	0,002	0%
end wall		
Bending and compression in plane	0,345	35%
Stresses due to normal force	0,345	35%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,564	56%
Compression part	0,561	56%
Bending part	0,003	0%

	span	6 Storeys	9

Floor

Floor	**LL-280/7s**	**0,858**	Governing is:	**Limit acceleration**

Floor ULS

Floor ULS	**Unity Check**	Utilisation	**0,529** Governing is:	Reaction force at supports
Bending stresses	0,149	15%		
Shear stresses	0,026	3%		
Roling shear stresses	0,184	18%		
Reaction force at supports	0,529	53%		
Fire and bending stresses	0,183	18%		
Fire and shear stresses	0,036	4%		
Fire and roling shear stresses	0,126	13%		
Fire and reaction force at supports	0,356	36%		

Floor SLS

Floor SLS	**Unity check**	Utilisation	**0,858** Governing is:	Limit acceleration
Deformation Quasi-permanent design situation	0,320	32%		
Deformation Characteristic initial deformation	0,310	31%		
Deformation Characteristic final deformation	0,320	32%		
Frequency criterion	0,786	79%		
Stifness cirterion	0,430	43%		
Limit acceleration	0,858	86%		

Wall

Wall	**L160/5s**	**0,717**	Governing is:	**Bending and compression out of pla**

Wall ULS

Wall ULS	**Unity check**	Utilisation	**0,717 Governing is:**	**Bending and compression out of plane**
second wall				
Bending and compression in plane	0,502	50%		
Stresses due to normal force	0,502	50%		
Stressees due to bending moment	0,000	0%		
Check tension in the foundation	0,000	0%		
Shear force check	0,000	0%		
Mechanism 1	0,000	0%		
Mechanism 3	0,000	0%		
Bending and compression out of plane	0,717	72%		
Compression part	0,715	71%		
Bending part	0,002	0%		
end wall				
Bending and compression in plane	0,319	32%		
Stresses due to normal force	0,319	32%		
Stressees due to bending moment	0,000	0%		
Check tension in the foundation	0,000	0%		
Shear force check	0,000	0%		
Mechanism 1	0,000	0%		
Mechanism 3	0,000	0%		
Bending and compression out of plane	0,457	46%		
Compression part	0,454	45%		
Bending part	0,003	0%		

span	3,6	Storeys	20

Floor — L160/5s — 0,613 Governing is: Frequency criterion

Floor ULS — Unity Check — 0,402 Governing is: Fire and bending stresses

		Utilisation
Bending stresses	0,153	15%
Shear stresses	0,052	5%
Roling shear stresses	0,176	18%
Reaction force at supports	0,291	29%
Fire and bending stresses	0,402	40%
Fire and shear stresses	0,050	5%
Fire and roling shear stresses	0,182	18%
Fire and reaction force at supports	0,188	19%

Floor SLS — Unity check — 0,613 Governing is: Frequency criterion

		Utilisation
Deformation Quasi-permanent design situation	0,314	31%
Deformation Characteristic initial deformation	0,320	32%
Deformation Characteristic final deformation	0,325	32%
Frequency criterion	0,613	61%
Stifness cirterion	0,517	52%
Limit acceleration	0,438	44%

Wall — L-180/5s — 0,824 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,824 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,676	68%
Stresses due to normal force	0,676	68%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,824	82%
Compression part	0,823	82%
Bending part	0,001	0%
end wall		
Bending and compression in plane	0,493	49%
Stresses due to normal force	0,493	49%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,602	60%
Compression part	0,601	60%
Bending part	0,002	0%

	span	4,8	Storeys	20

Floor — LL-210/7s — 0,867 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,403 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,158	16%
Shear stresses	0,027	3%
Roling shear stresses	0,187	19%
Reaction force at supports	0,403	40%
Fire and bending stresses	0,195	20%
Fire and shear stresses	0,031	3%
Fire and roling shear stresses	0,111	11%
Fire and reaction force at supports	0,265	27%

Floor SLS — Unity check — 0,867 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,350	35%
Deformation Characteristic initial deformation	0,349	35%
Deformation Characteristic final deformation	0,357	36%
Frequency criterion	0,739	74%
Stifness cirterion	0,522	52%
Limit acceleration	0,867	87%

Wall — LL-190/7s — 0,848 Governing is: Bending and compression out of pla

Wall ULS — Unity check — 0,848 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,713	71%
Stresses due to normal force	0,713	71%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,848	85%
Compression part	0,847	85%
Bending part	0,001	0%
end wall		
Bending and compression in plane	0,482	48%
Stresses due to normal force	0,482	48%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,575	57%
Compression part	0,573	57%
Bending part	0,002	0%

	span	5,4	Storeys	20

Floor

	LL-240/7s	0,872	Governing is:	Limit acceleration

Floor ULS

	Unity Check	Utilisation
	0,463 Governing is: Reaction force at supports	
Bending stresses	0,150	15%
Shear stresses	0,029	3%
Roling shear stresses	0,178	18%
Reaction force at supports	0,463	46%
Fire and bending stresses	0,187	19%
Fire and shear stresses	0,032	3%
Fire and roling shear stresses	0,117	12%
Fire and reaction force at supports	0,308	31%

Floor SLS

	Unity check	Utilisation
	0,872 Governing is: Limit acceleration	
Deformation Quasi-permanent design situation	0,318	32%
Deformation Characteristic initial deformation	0,313	31%
Deformation Characteristic final deformation	0,322	32%
Frequency criterion	0,764	76%
Stifness cirterion	0,476	48%
Limit acceleration	0,872	87%

Wall

	LL-210/7s	0,900	Governing is:	Bending and compression out of pla

Wall ULS

	Unity check	Utilisation
	0,900 Governing is: Bending and compression out of plane	
second wall		
Bending and compression in plane	0,809	81%
Stresses due to normal force	0,809	81%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,900	90%
Compression part	0,898	90%
Bending part	0,001	0%
end wall		
Bending and compression in plane	0,534	53%
Stresses due to normal force	0,534	53%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,594	59%
Compression part	0,592	59%
Bending part	0,002	0%

span	6 Storeys	20

Floor — LL-280/7s — 0,858 Governing is: Limit acceleration

Floor ULS — Unity Check — 0,529 Governing is: Reaction force at supports

		Utilisation
Bending stresses	0,149	15%
Shear stresses	0,027	3%
Roling shear stresses	0,184	18%
Reaction force at supports	0,529	53%
Fire and bending stresses	0,183	18%
Fire and shear stresses	0,036	4%
Fire and roling shear stresses	0,126	13%
Fire and reaction force at supports	0,356	36%

Floor SLS — Unity check — 0,858 Governing is: Limit acceleration

		Utilisation
Deformation Quasi-permanent design situation	0,320	32%
Deformation Characteristic initial deformation	0,310	31%
Deformation Characteristic final deformation	0,320	32%
Frequency criterion	0,786	79%
Stifness cirterion	0,430	43%
Limit acceleration	0,858	86%

Wall — LL-240/7s — 0,746 Governing is: Bending and compression out of pla

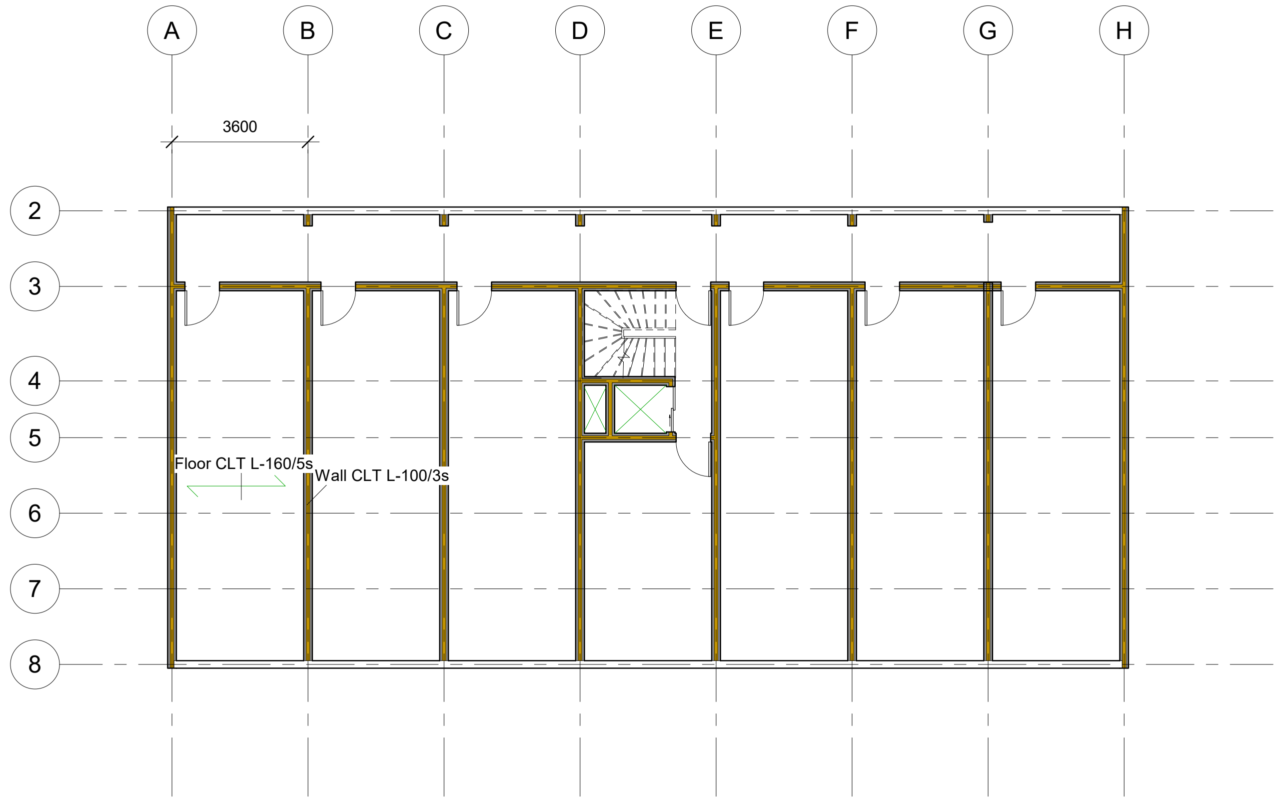
Wall ULS — Unity check — 0,746 Governing is: Bending and compression out of plane

		Utilisation
second wall		
Bending and compression in plane	0,688	69%
Stresses due to normal force	0,688	69%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,746	75%
Compression part	0,745	75%
Bending part	0,001	0%
end wall		
Bending and compression in plane	0,444	44%
Stresses due to normal force	0,444	44%
Stressees due to bending moment	0,000	0%
Check tension in the foundation	0,000	0%
Shear force check	0,000	0%
Mechanism 1	0,000	0%
Mechanism 3	0,000	0%
Bending and compression out of plane	0,483	48%
Compression part	0,481	48%
Bending part	0,002	0%

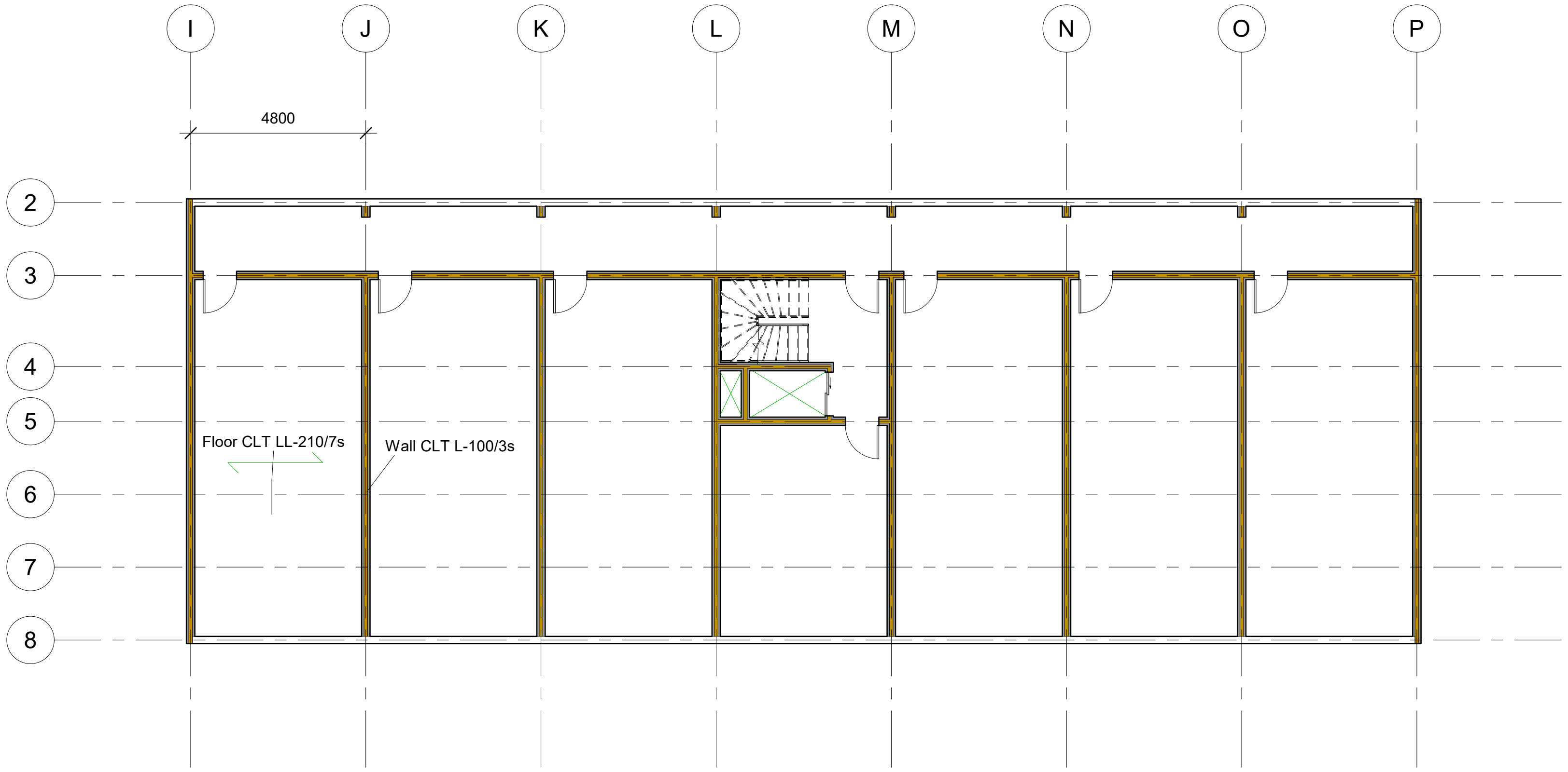
Appendix L. Floorplans and sections parameter study

This appendix contains all floorplans and sections of the sixteen variants included in the parameter study.

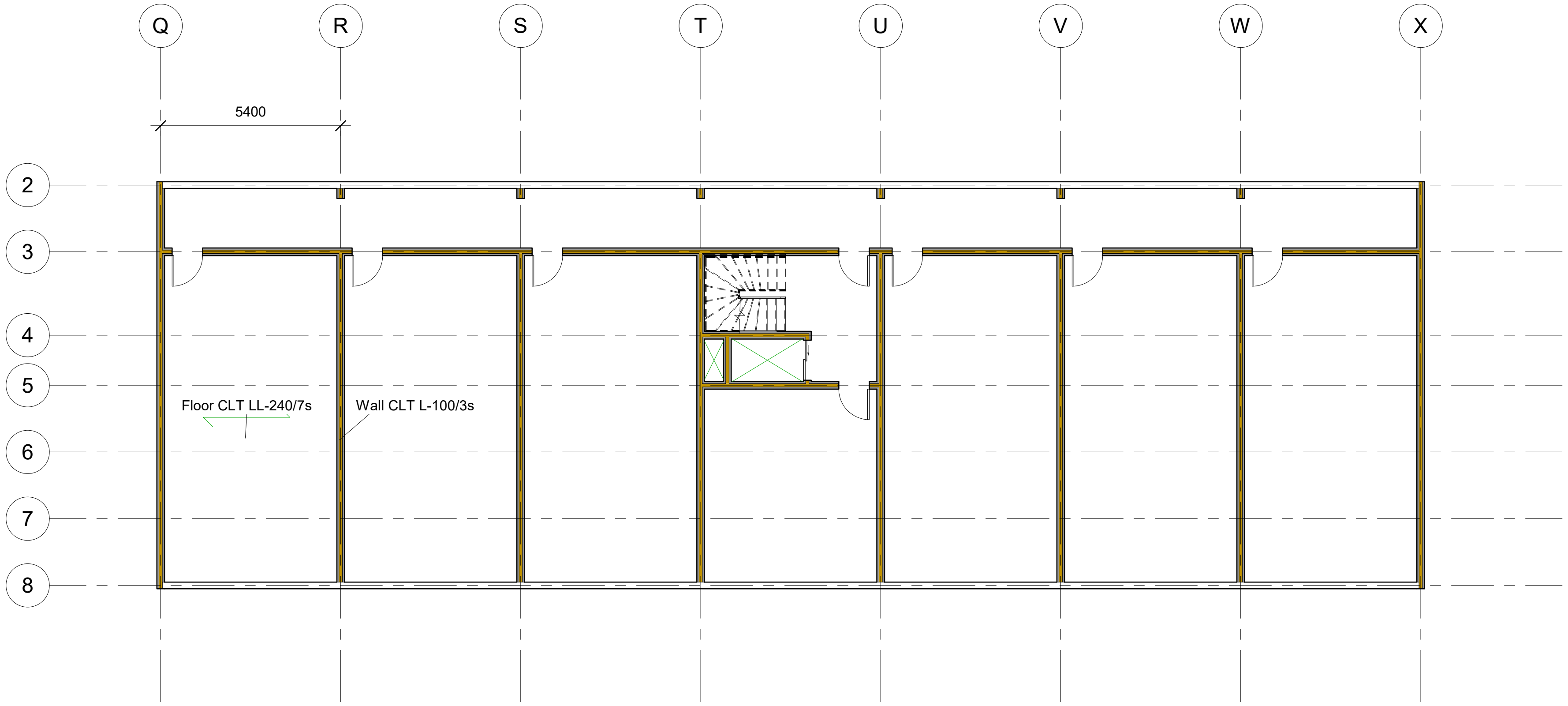
Timber 1



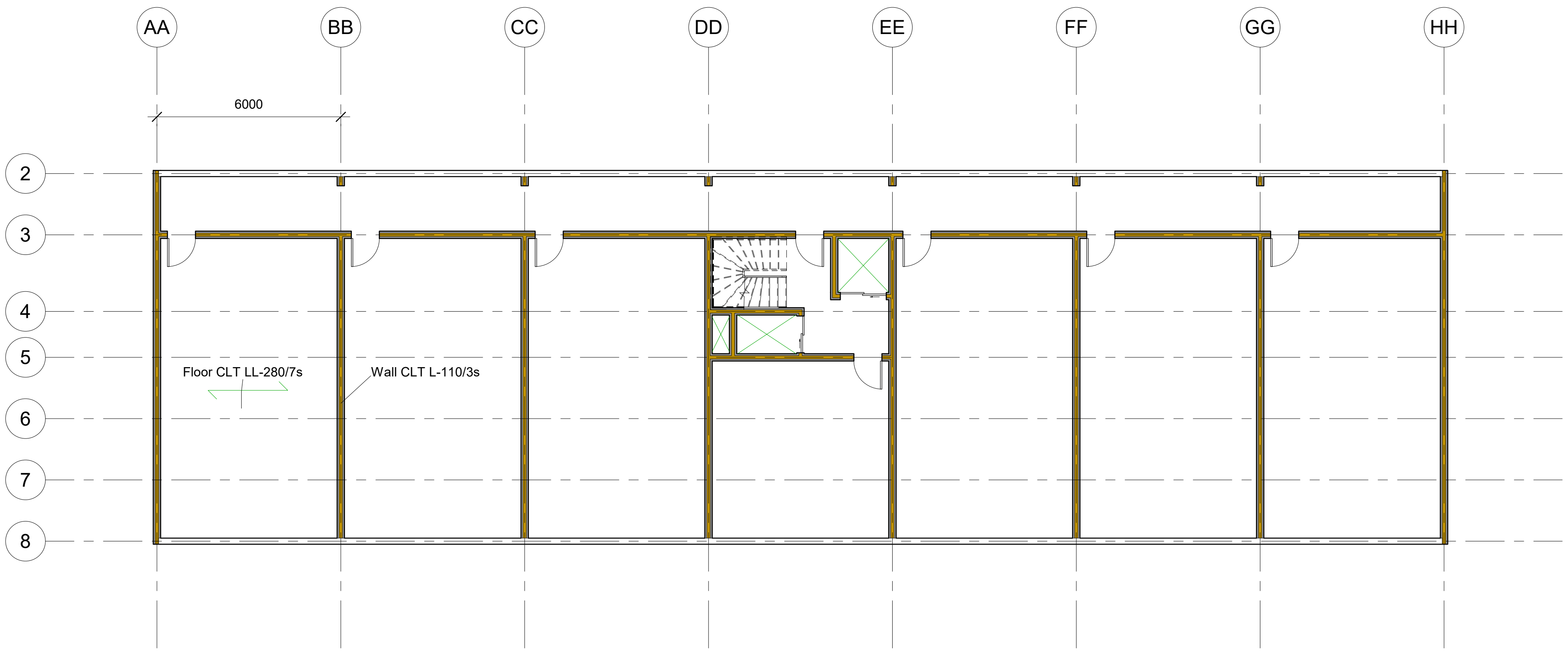
Timber 2



Timber 3



Timber 4



AA
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CC
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6000
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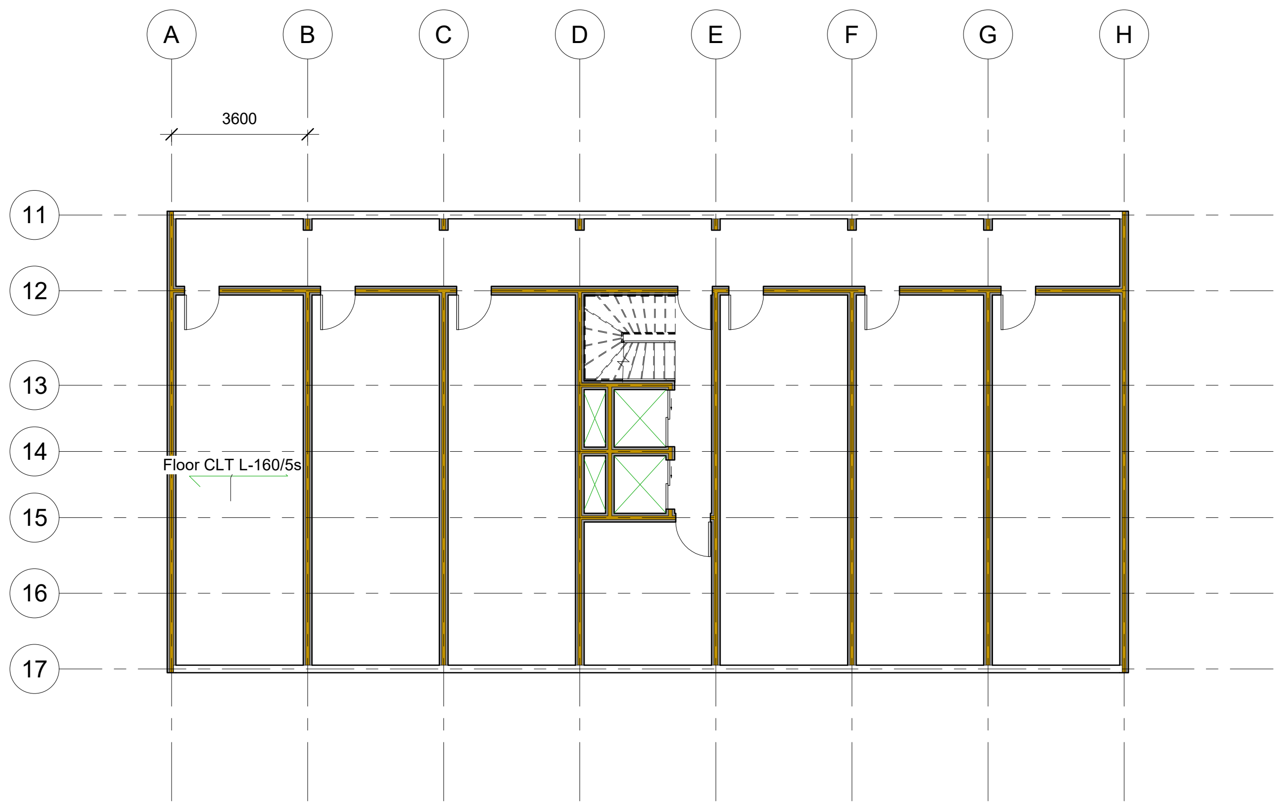
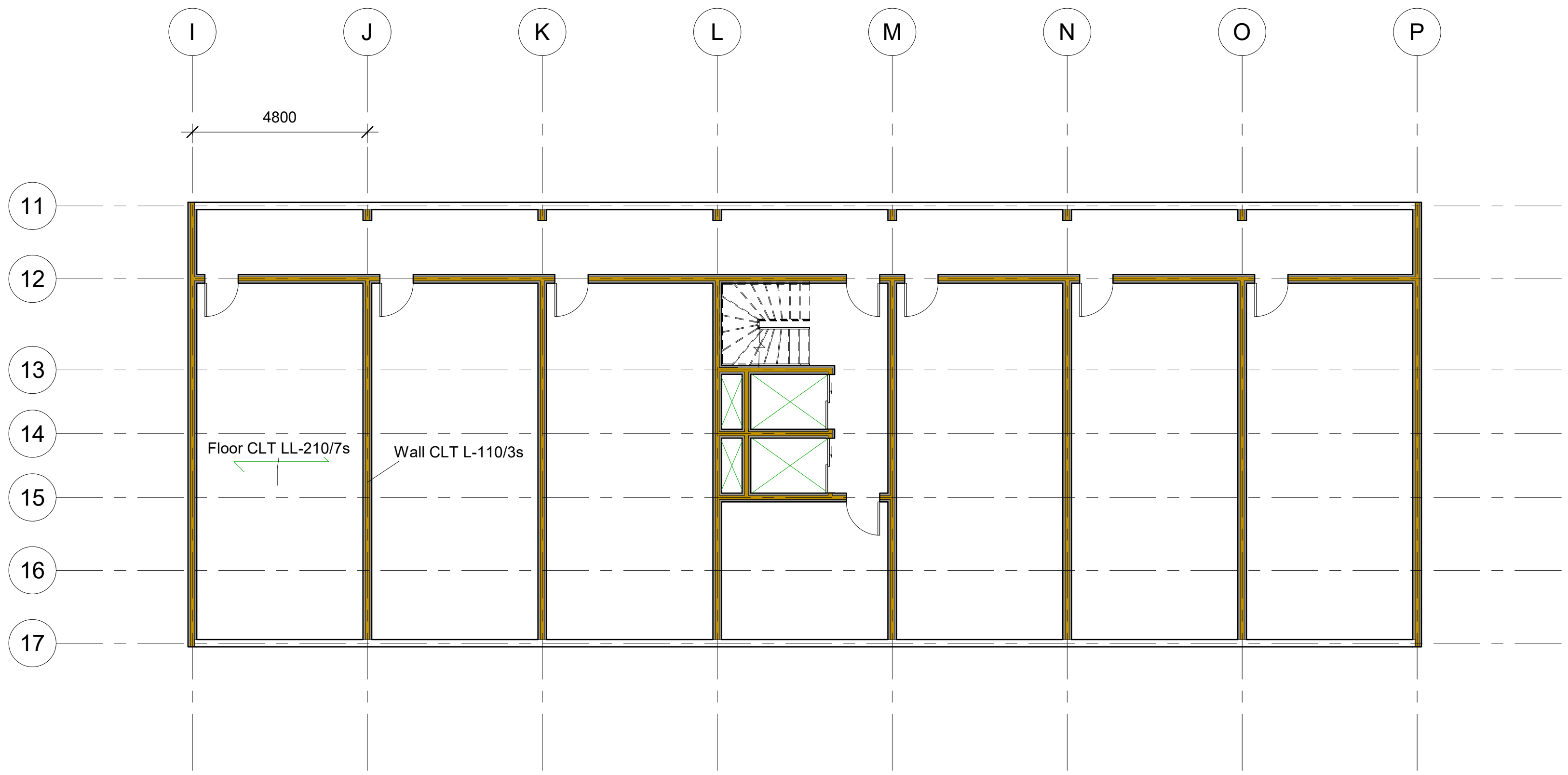
Floor CLT LL-280/7s
Wall CLT L-110/3s

Timber 5



Timber 6



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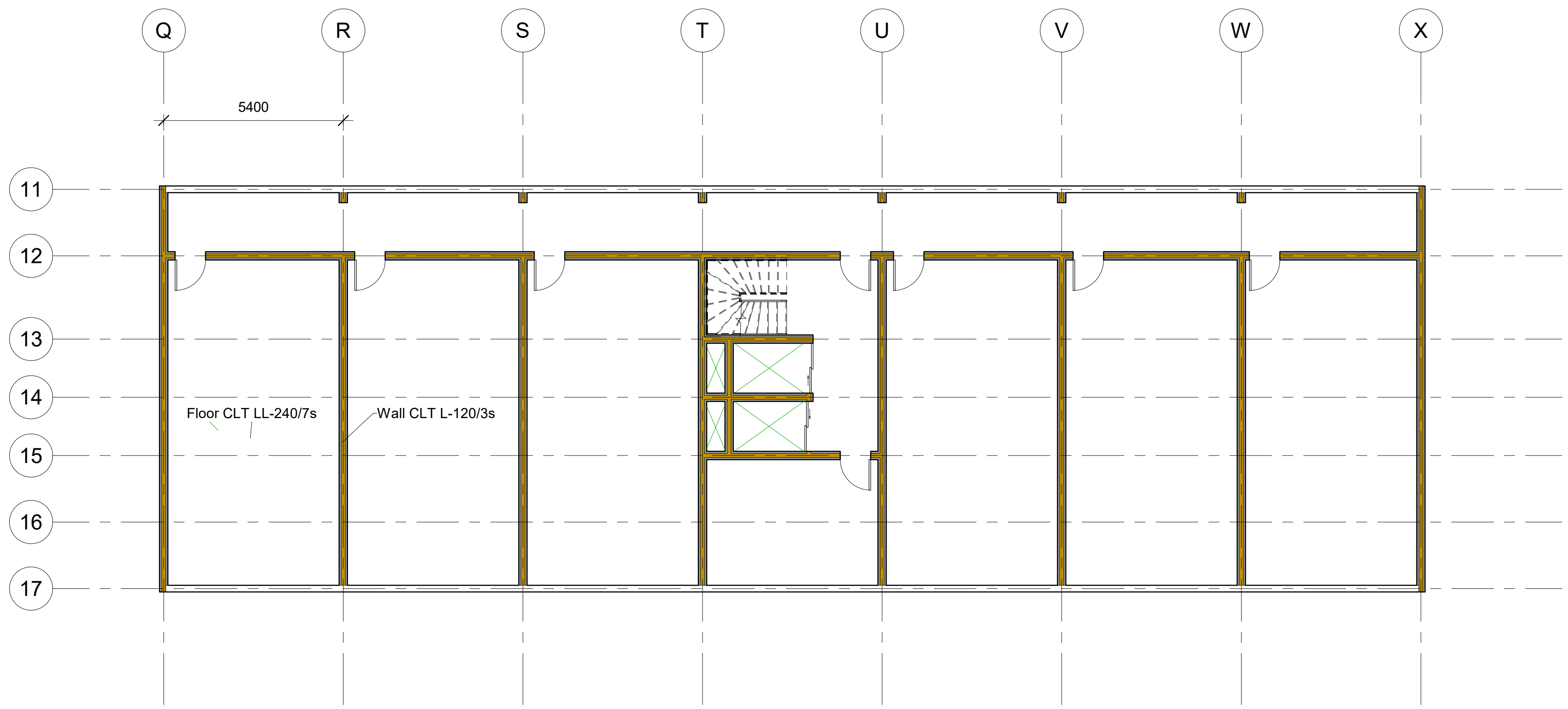
Floor CLT LL-210/7s
Wall CLT L-110/3s

Timber 7



Q
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5400
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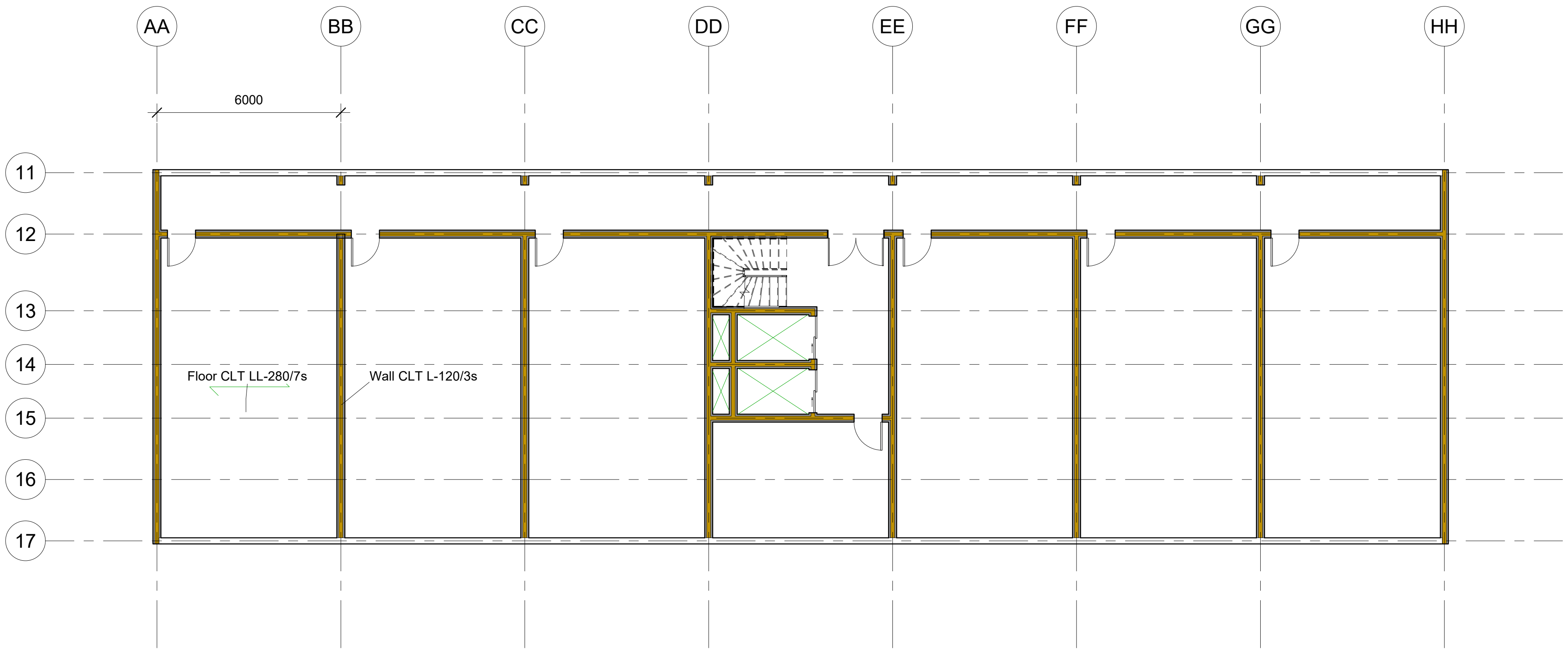
Floor CLT LL-240/7s
Wall CLT L-120/3s

Timber 8



AA
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6000
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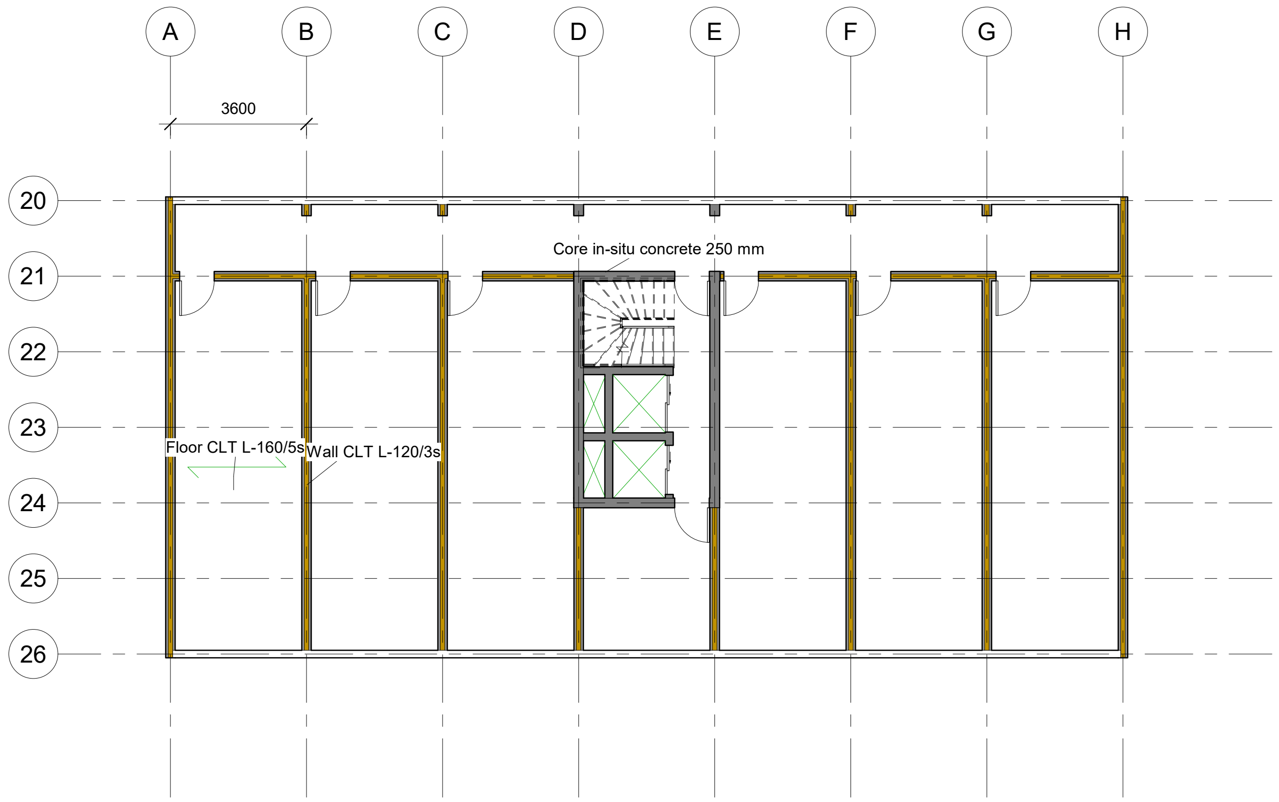
Floor CLT LL-280/7s
Wall CLT L-120/3s

Timber 9



A
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3600
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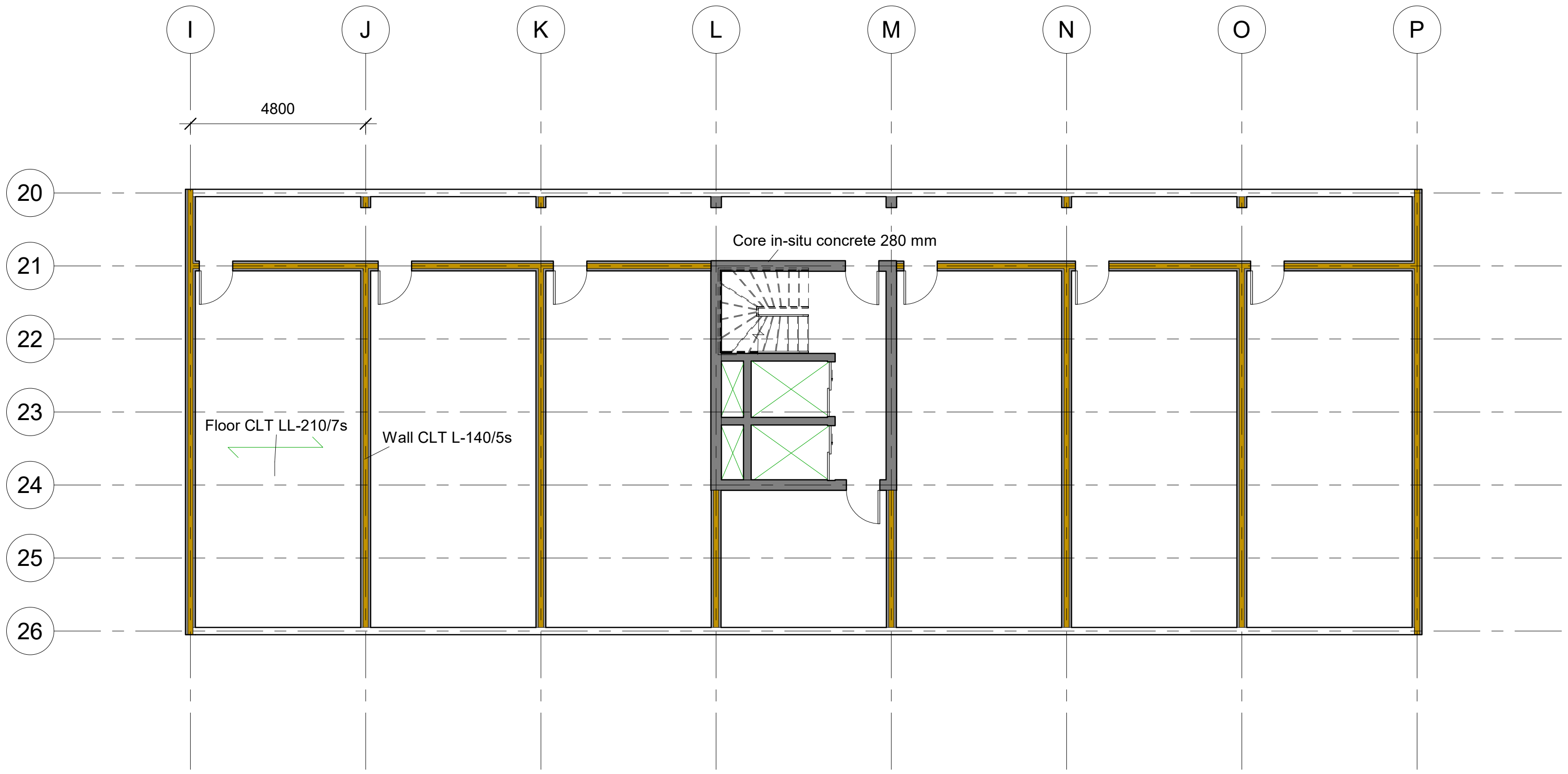
Core in-situ concrete 250 mm
Floor CLT L-160/5s
Wall CLT L-120/3s

Timber 10



I
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4800
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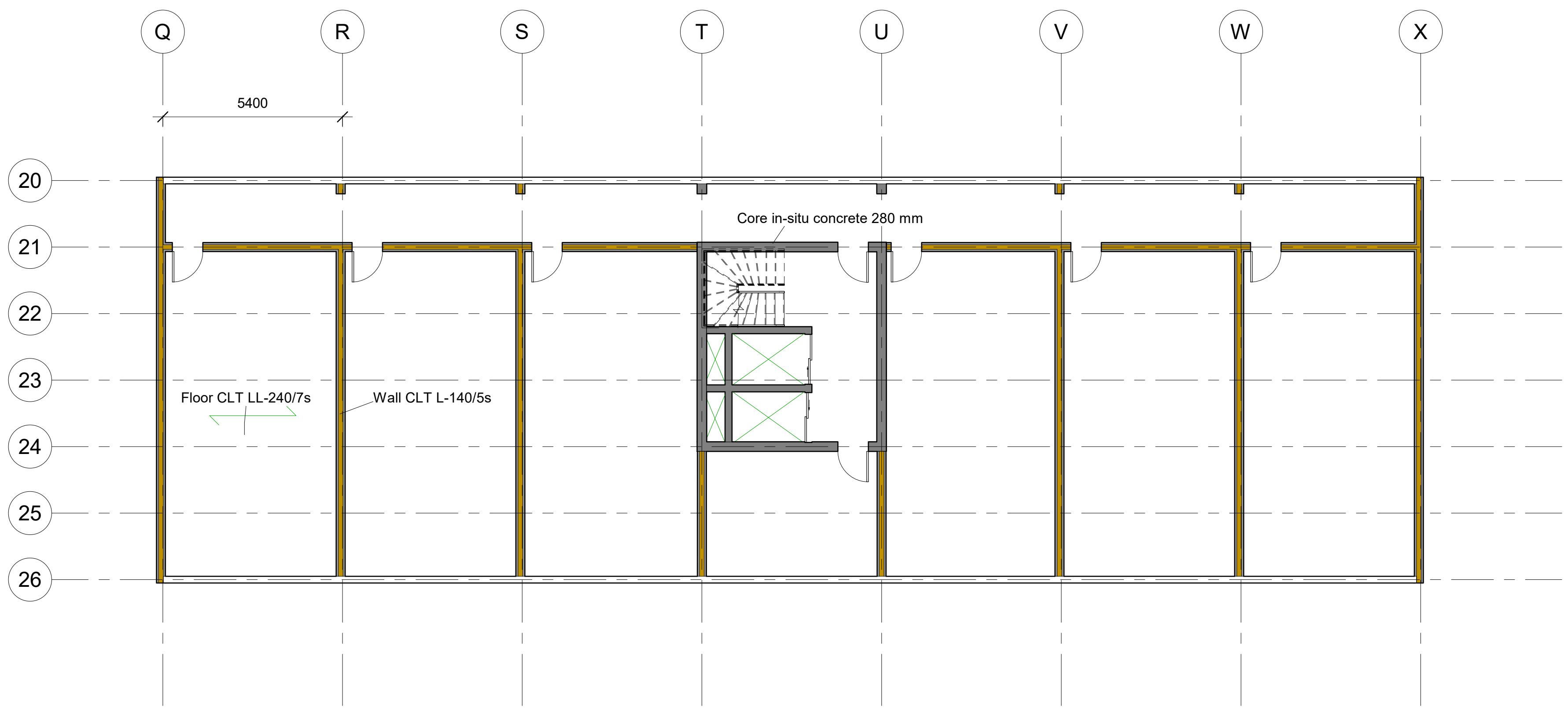
Core in-situ concrete 280 mm
Floor CLT LL-210/7s
Wall CLT L-140/5s

Timber 11



Q
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X
5400
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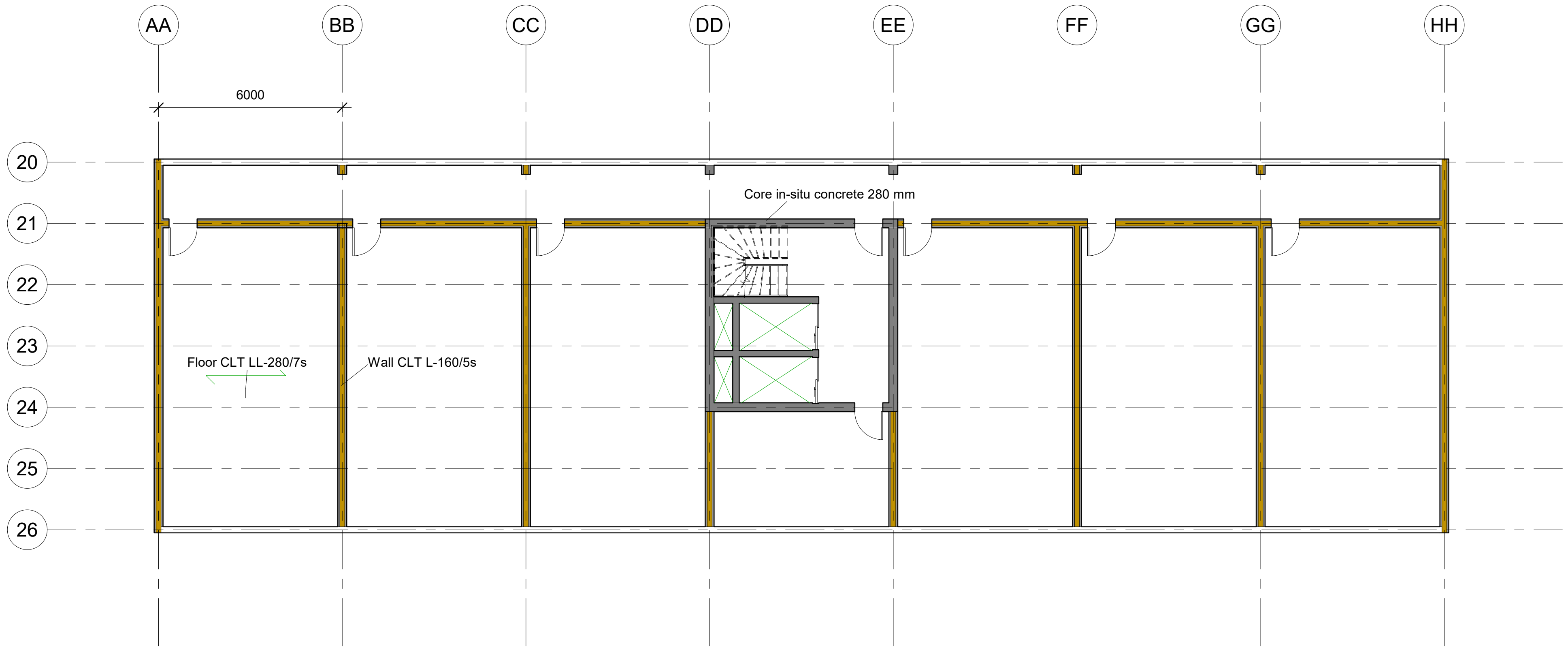
25
26
Core in-situ concrete 280 mm
Floor CLT LL-240/7s
Wall CLT L-140/5s

Timber 12



AA
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GG
HH
6000
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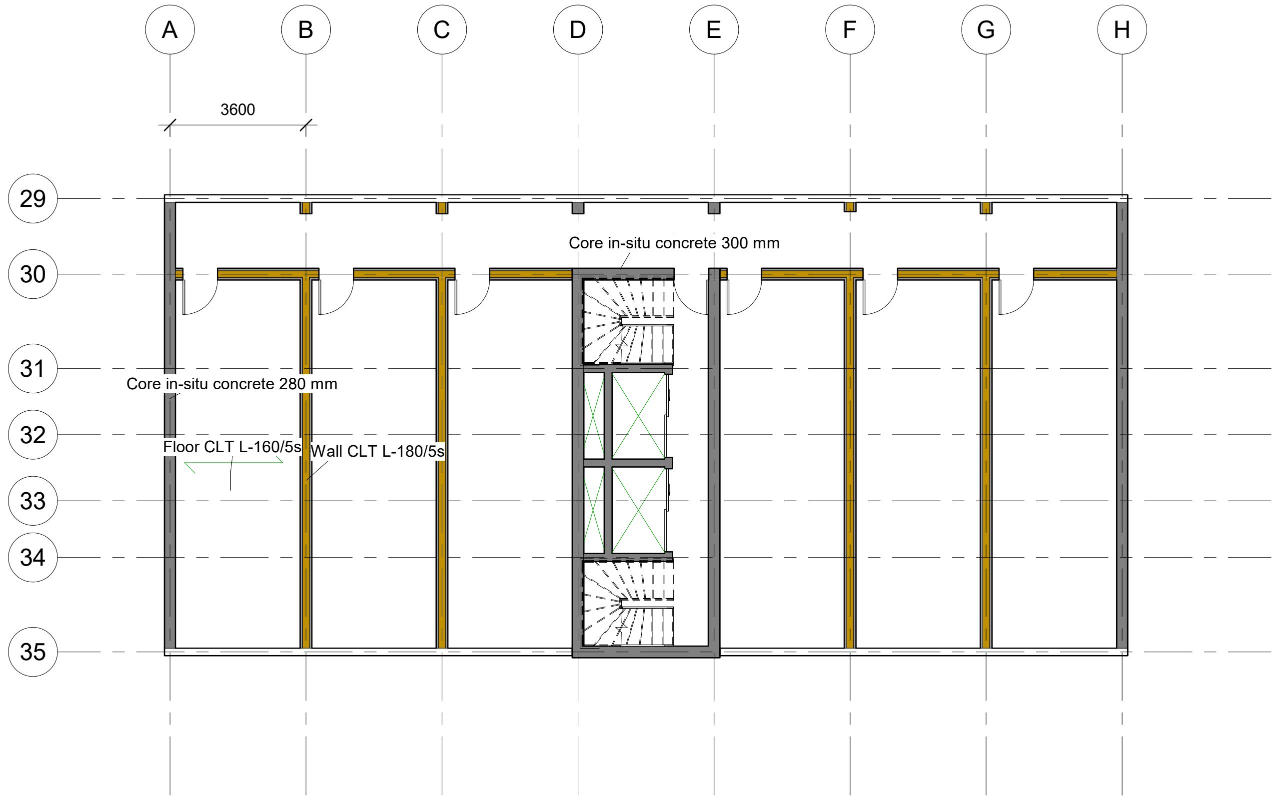
24
25
26
Core in-situ concrete 280 mm
Floor CLT LL-280/7s
Wall CLT L-160/5s

Timber 13



A
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3600
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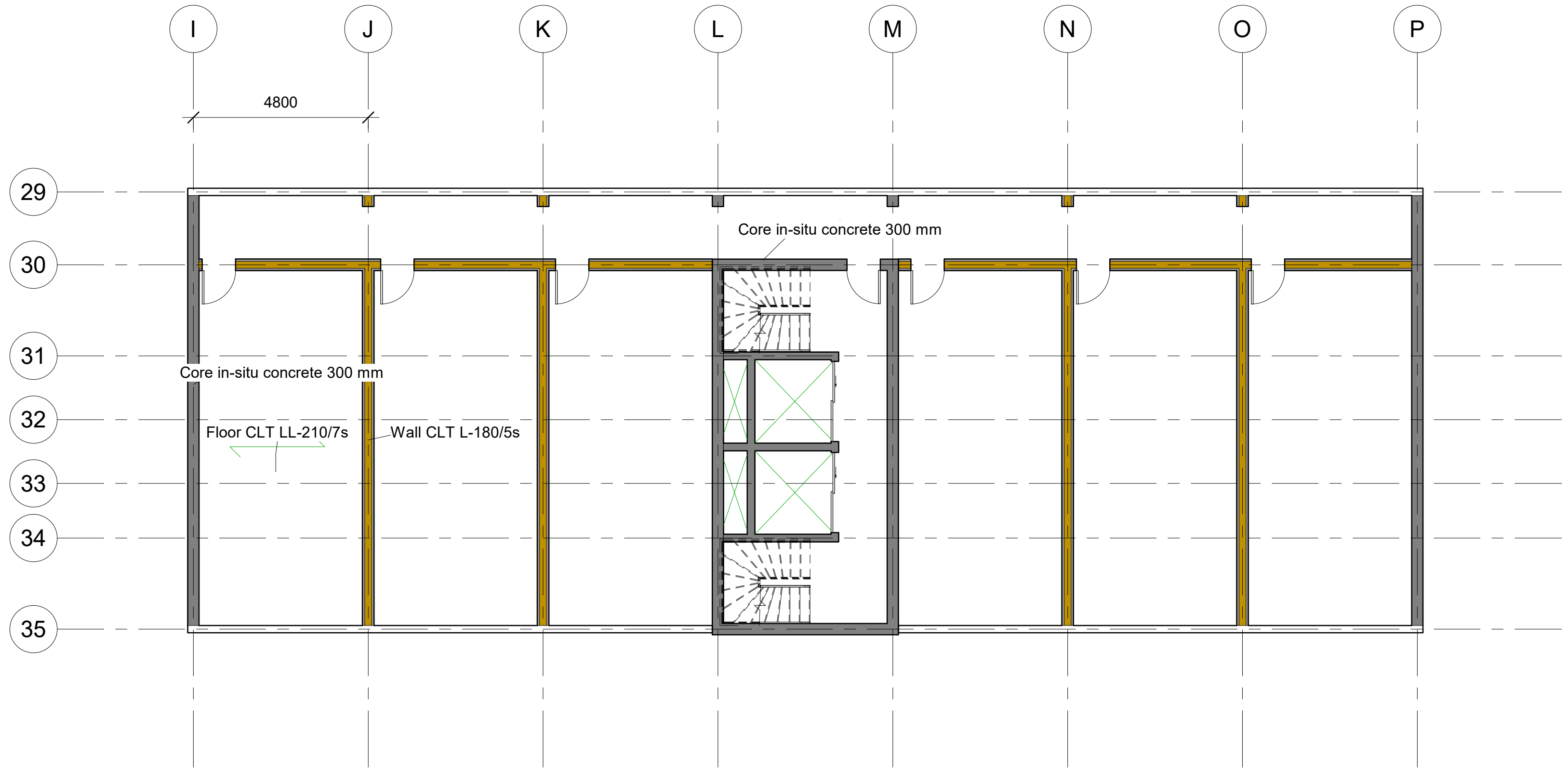
Core in-situ concrete 300 mm
Core in-situ concrete 280 mm
Floor CLT L-160/5s
Wall CLT L-180/5s

Timber 14



I
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4800
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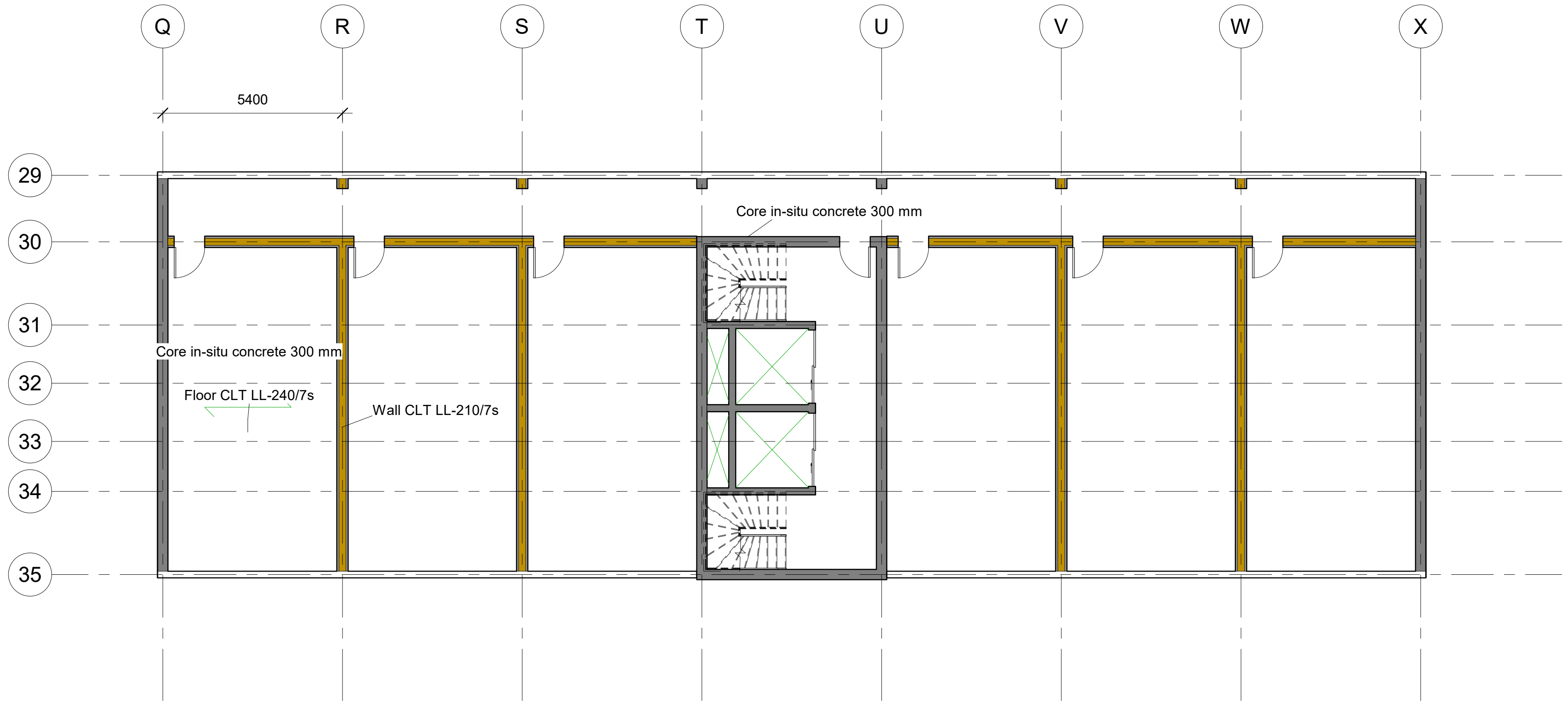
35
Core in-situ concrete 300 mm
Core in-situ concrete 300 mm
Floor CLT LL-210/7s
Wall CLT L-180/5s

Timber 15



Q
R
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X
5400
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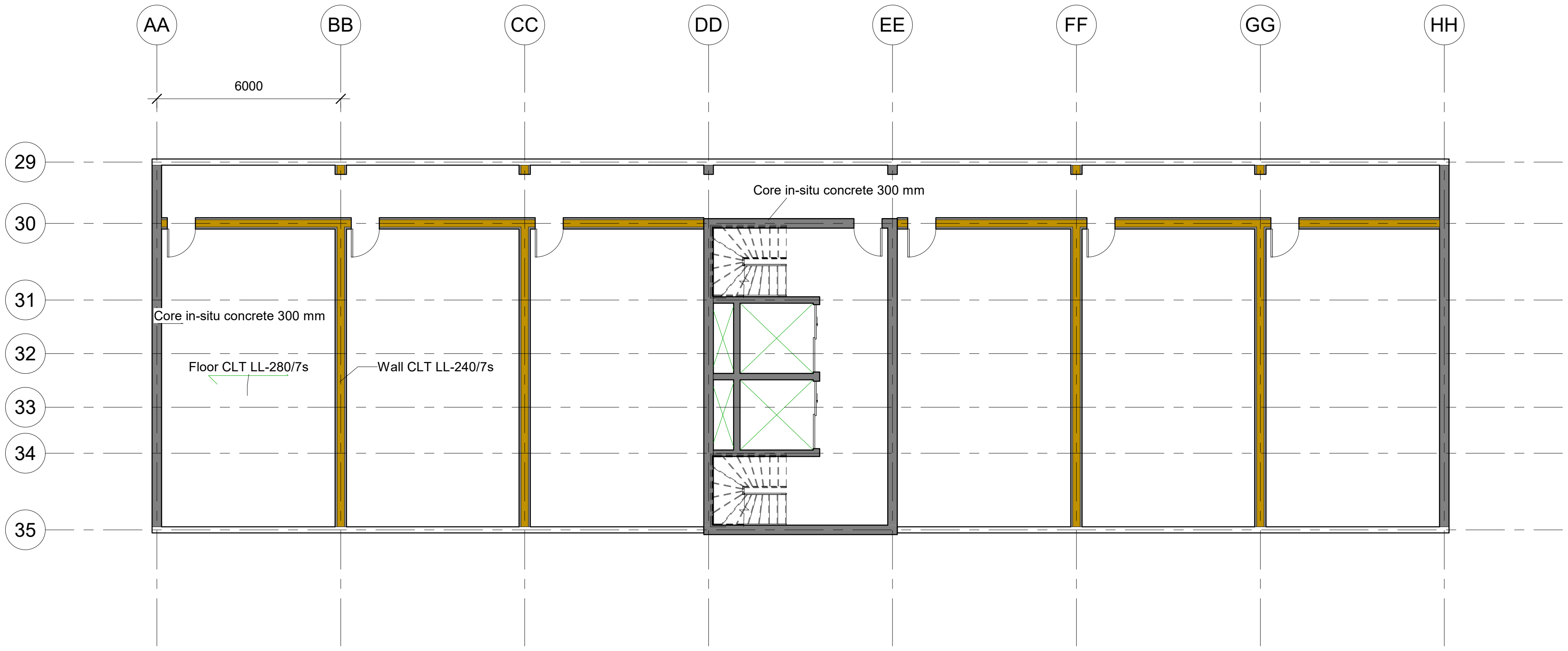
Core in-situ concrete 300 mm
Core in-situ concrete 300 mm
Floor CLT LL-240/7s
Wall CLT LL-210/7s

Timber 16



AA
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CC
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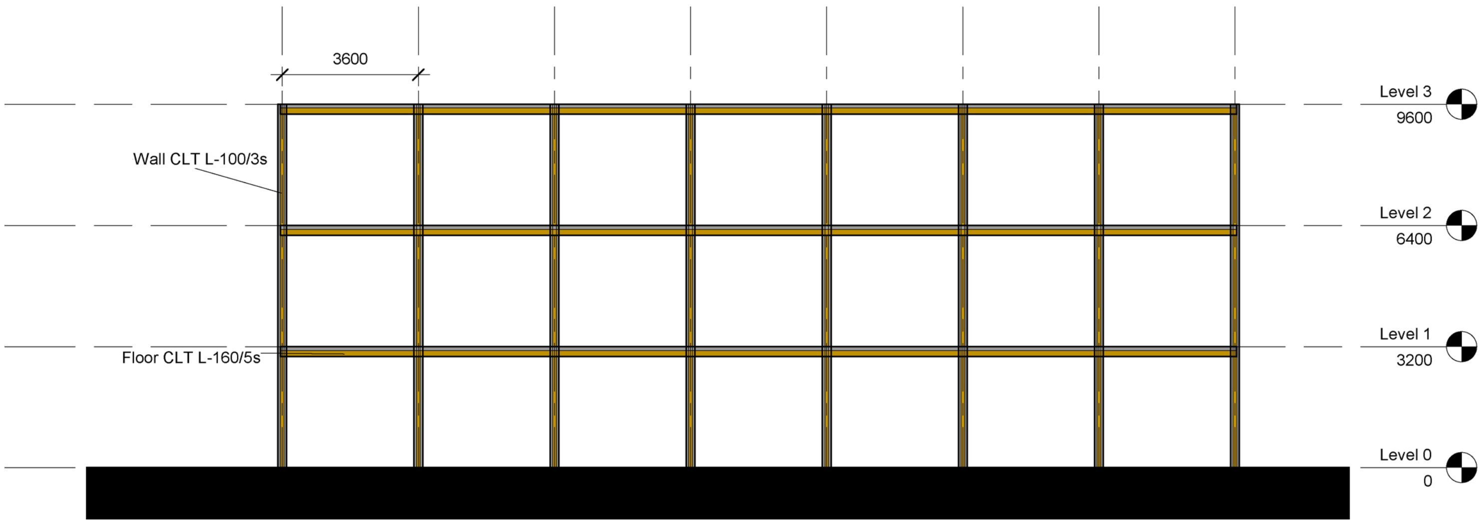
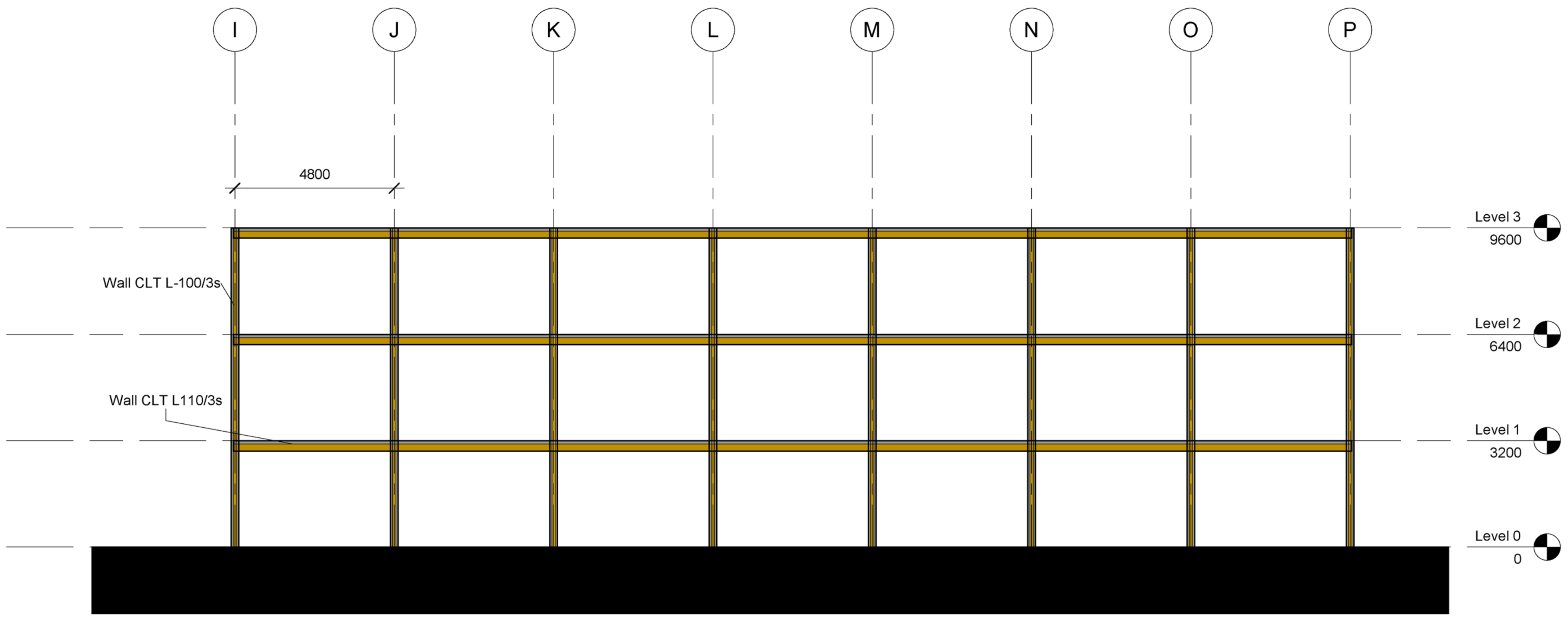
EE
FF
GG
HH
6000
29
30
31
32
33
34
35
Core in-situ concrete 300 mm
Core in-situ concrete 300 mm
Floor CLT LL-280/7s
Wall CLT LL-240/7s

Timber 1



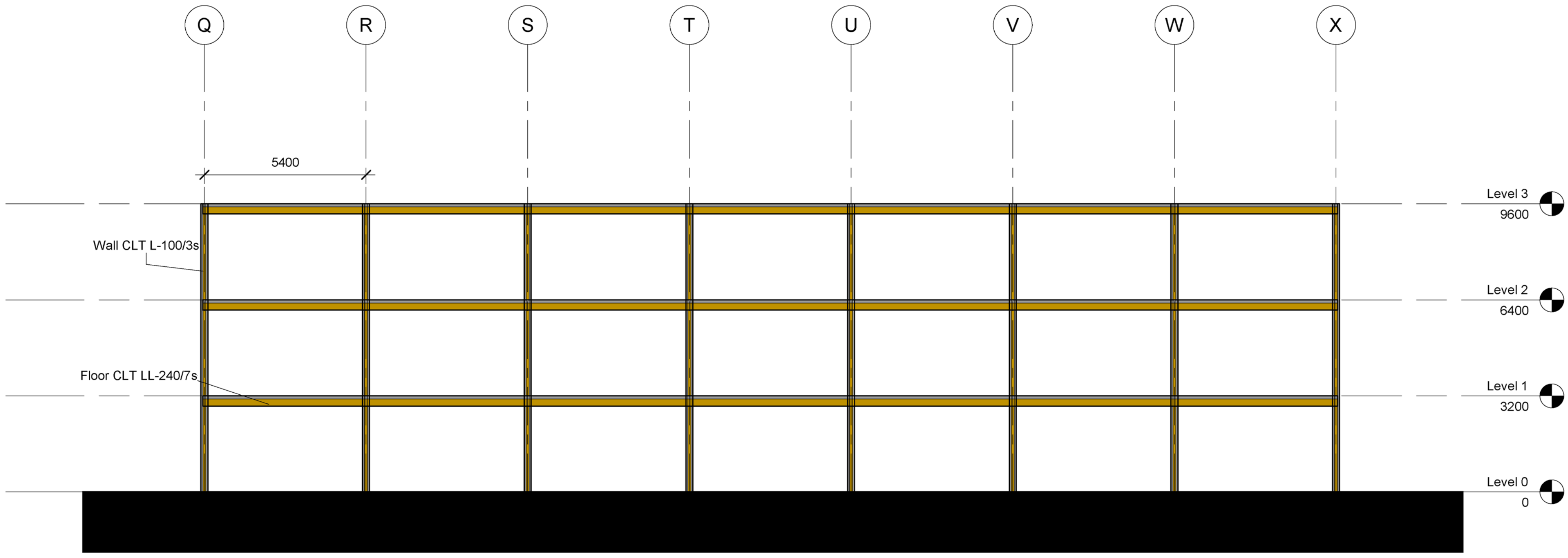
A
B
C
D
E
F
G
H
3600
Level 3
9600
Wall CLT L-100/3s
Level 2
6400
Level 1
3200
Floor CLT L-160/5s
Level 0
0

Timber 2



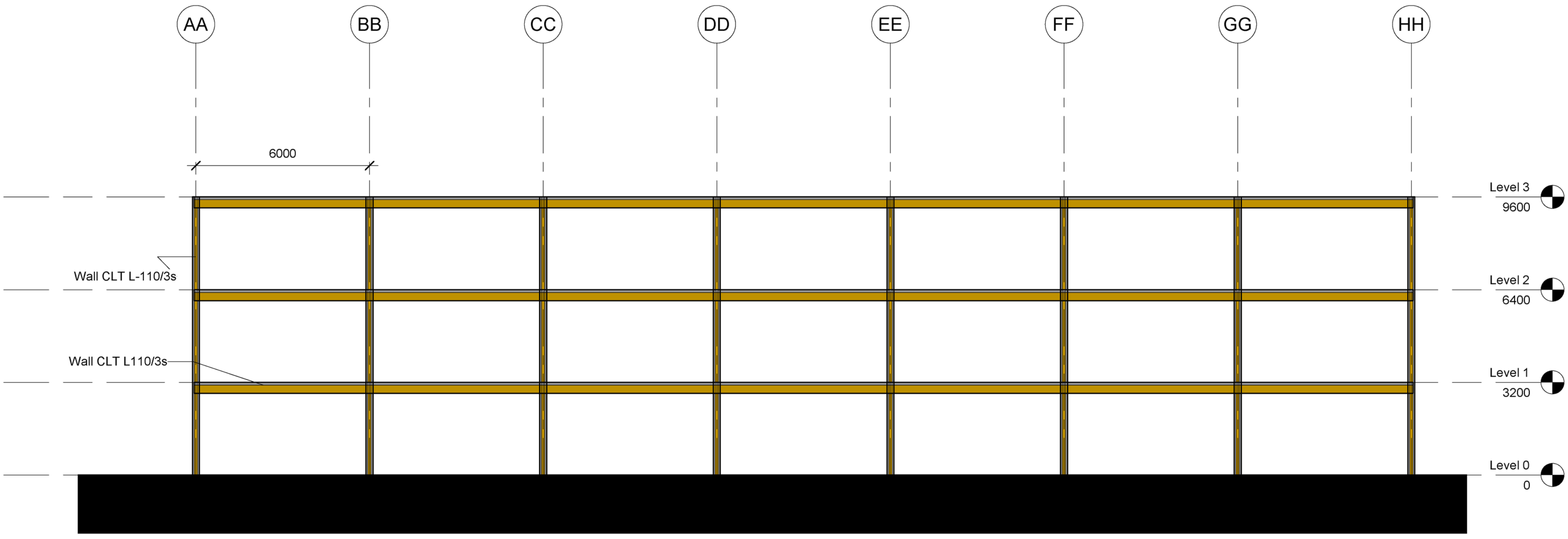
I
J
K
L
M
N
O
P
4800
Wall CLT L-100/3s
Wall CLT L110/3s
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0

Timber 3



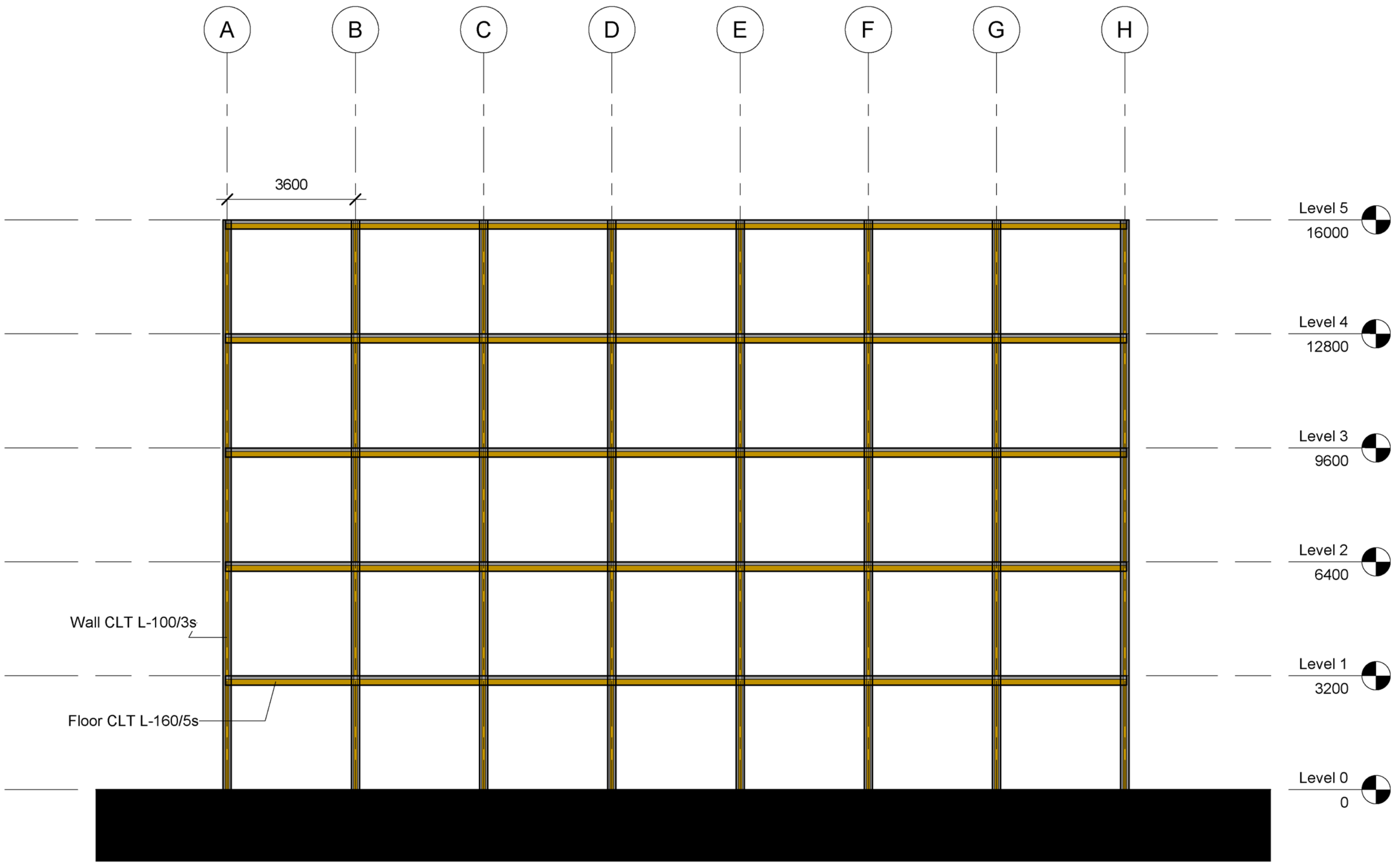
Q
R
S
T
U
V
W
X
5400
Wall CLT L-100/3s
Floor CLT LL-240/7s
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0

Timber 4



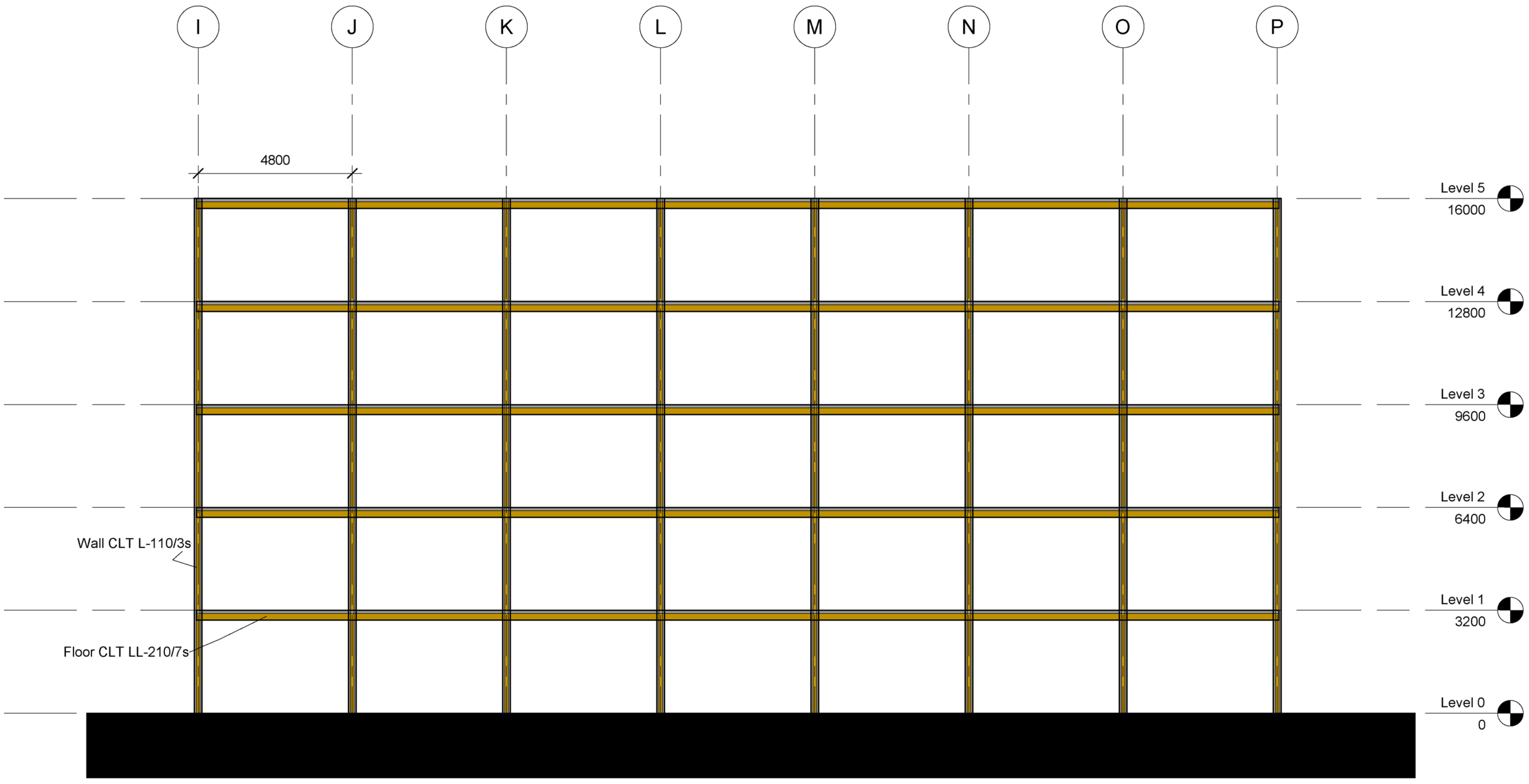
AA
BB
CC
DD
EE
FF
GG
HH
6000
Wall CLT L-110/3s
Wall CLT L110/3s
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0

Timber 5

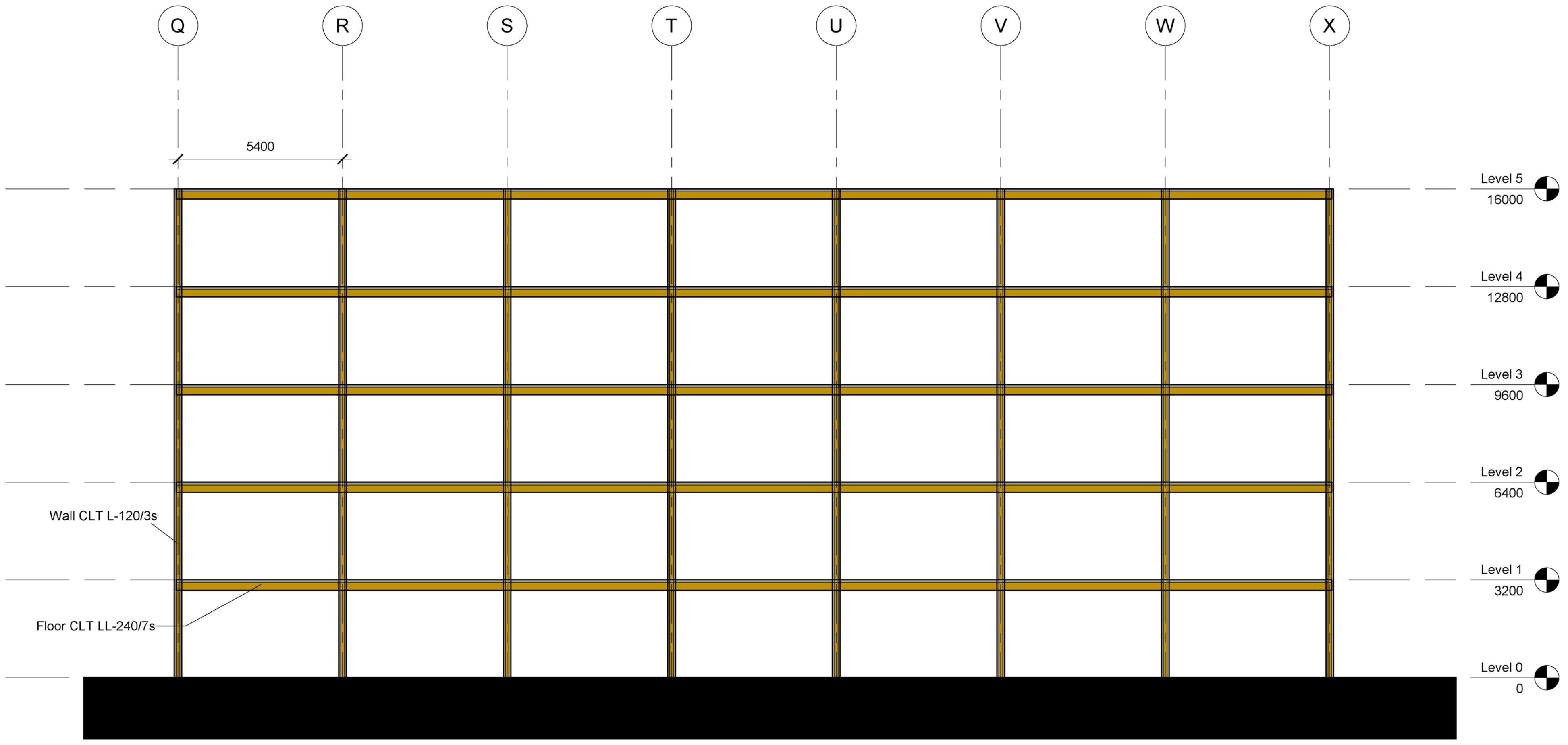


A
B
C
D
E
F
G
H
3600
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-100/3s
Floor CLT L-160/5s

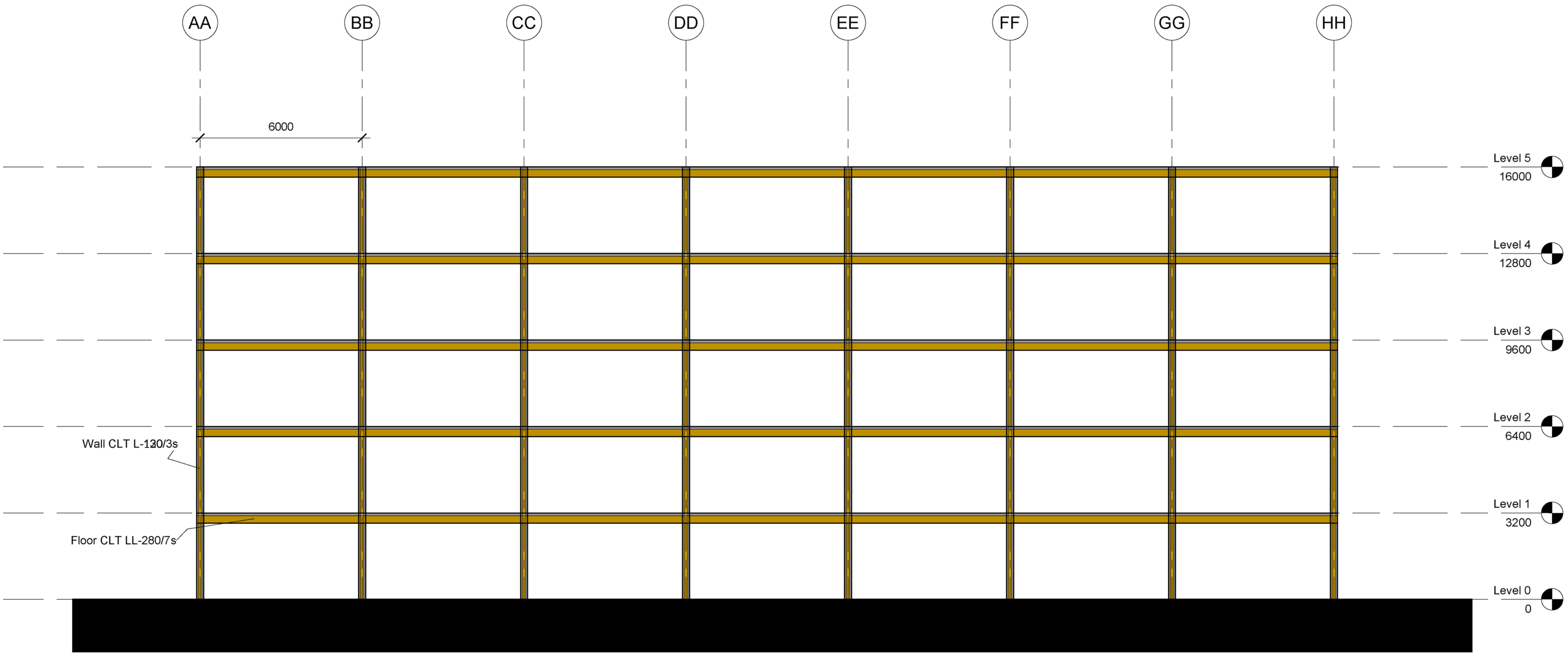
Timber 6


I
J
K
L
M
N
O
P
4800
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-110/3s
Floor CLT LL-210/7s

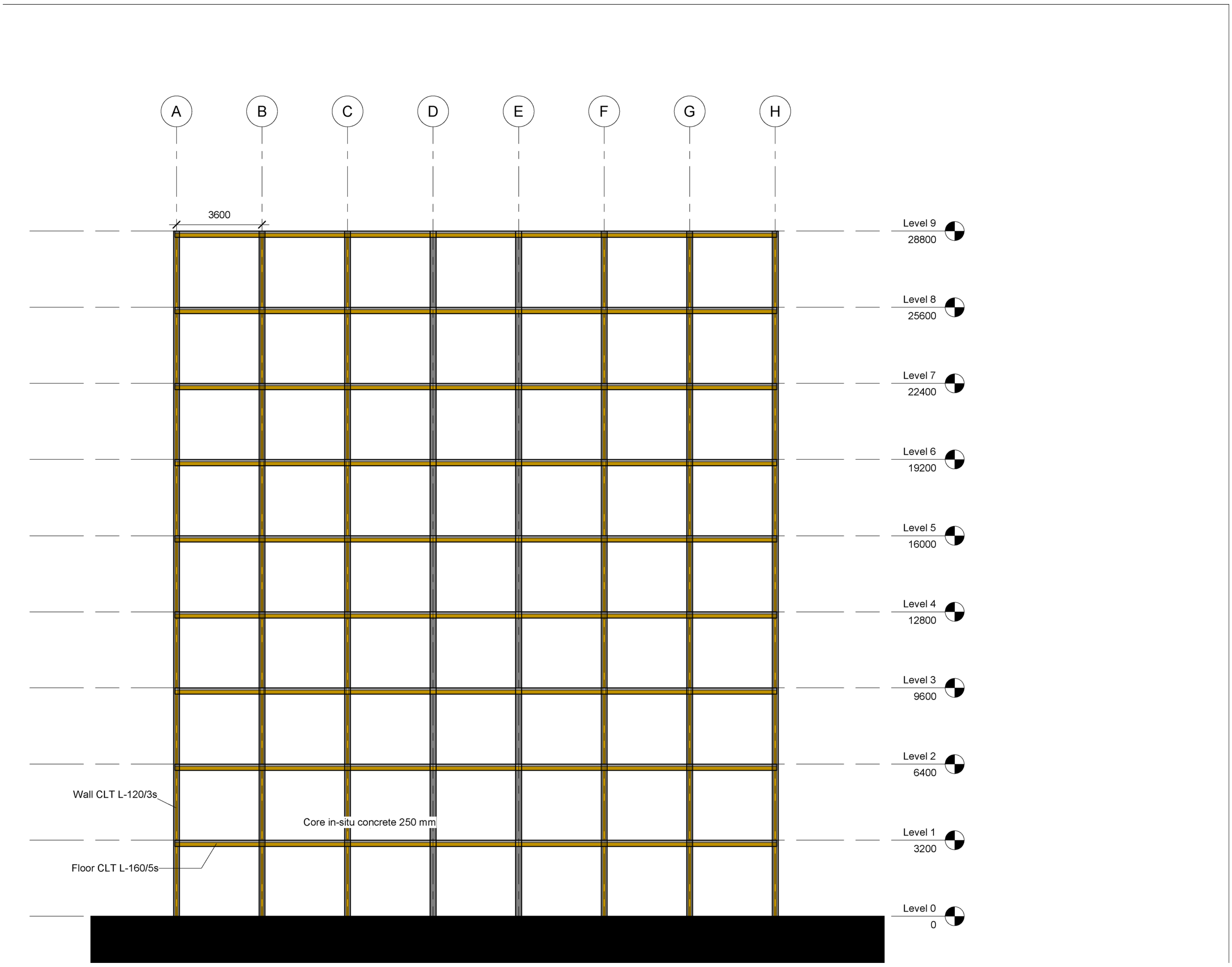
Timber 7


Q
R
S
T
U
V
W
X
5400
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-120/3s
Floor CLT LL-240/7s

Timber 8

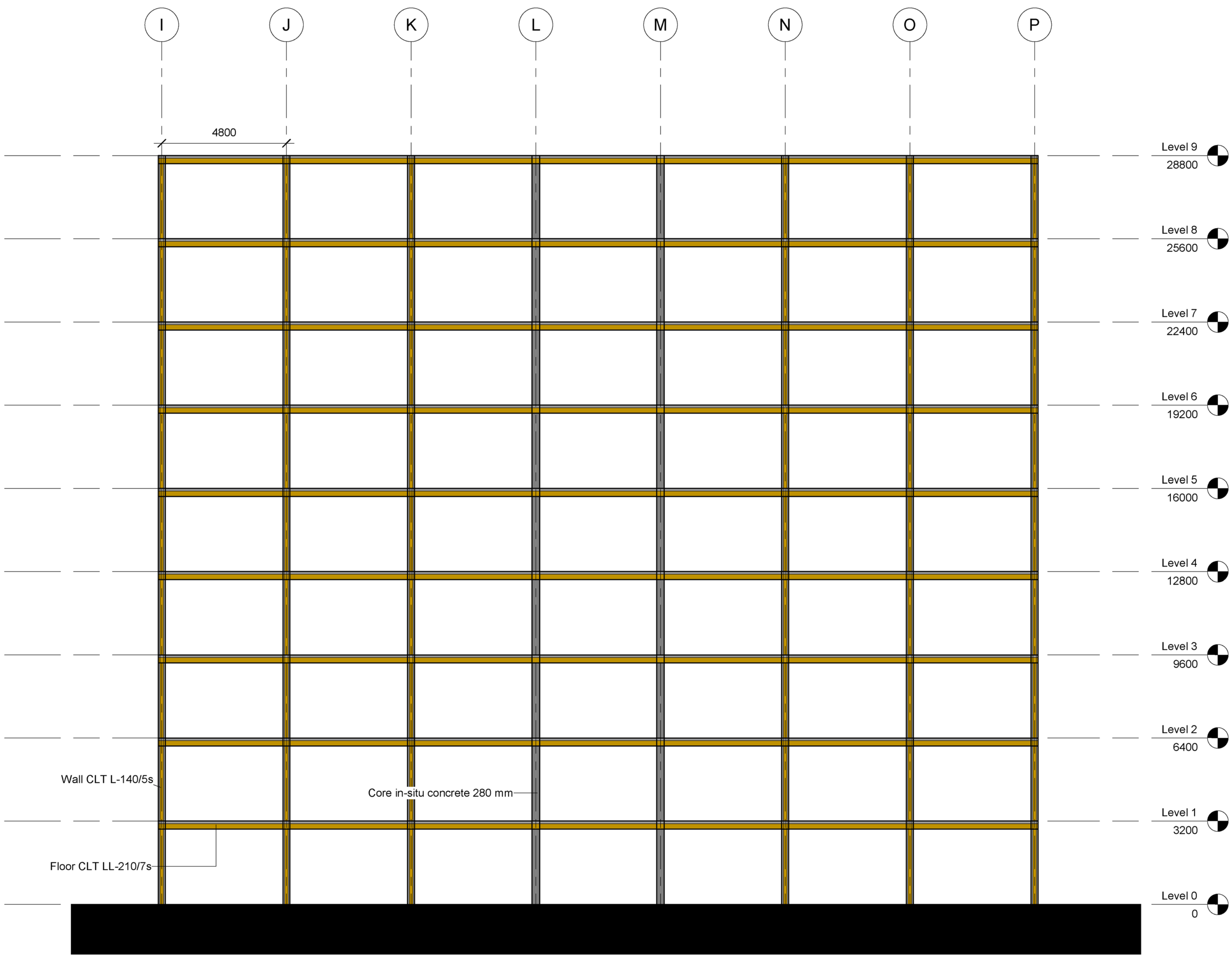

AA
BB
CC
DD
EE
FF
GG
HH
6000
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-120/3s
Floor CLT LL-280/7s

Timber 9



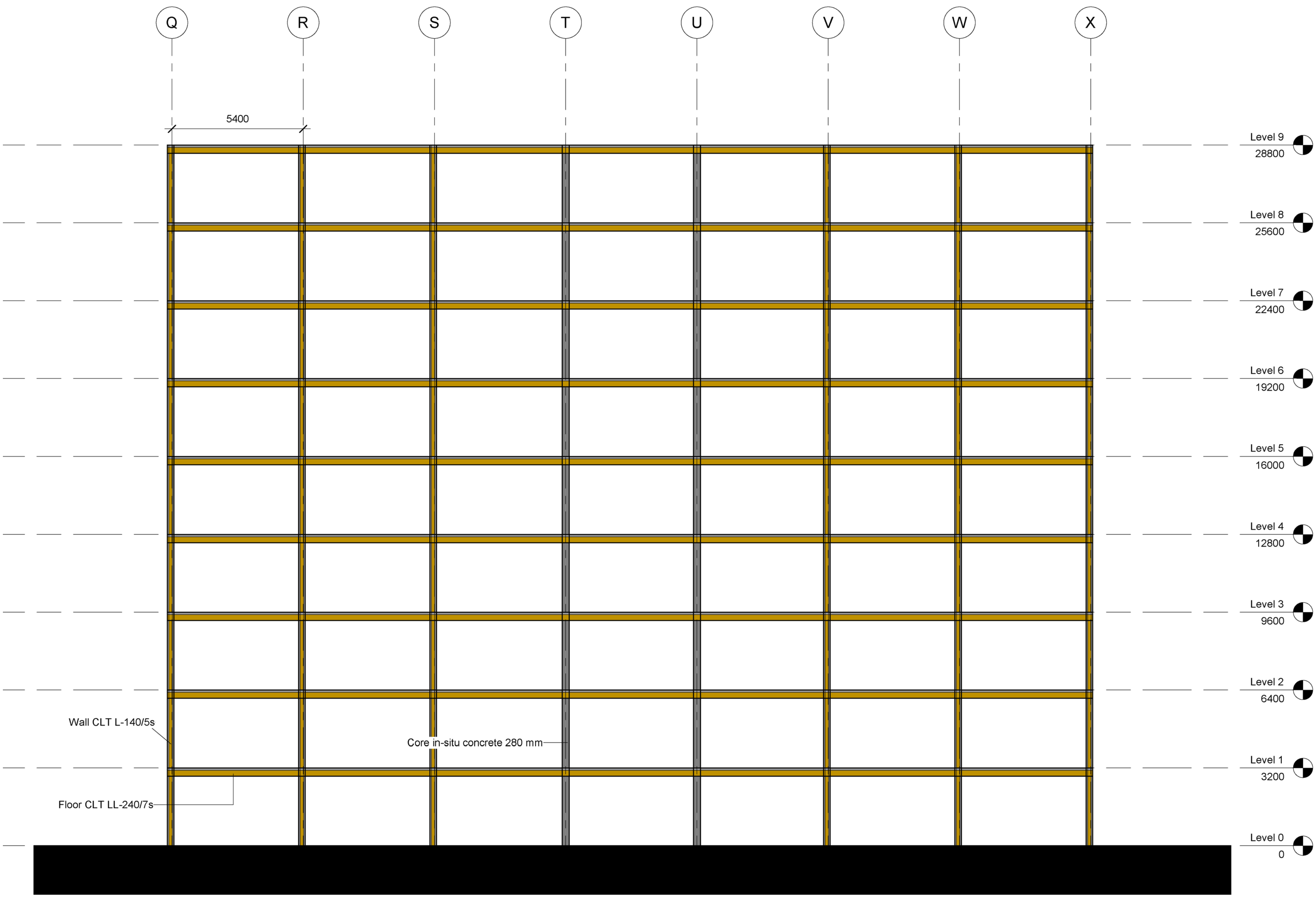
A
B
C
D
E
F
G
H
3600
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Wall CLT L-120/3s
Core in-situ concrete 250 mm
Level 1
3200
Floor CLT L-160/5s
Level 0
0

Timber 10



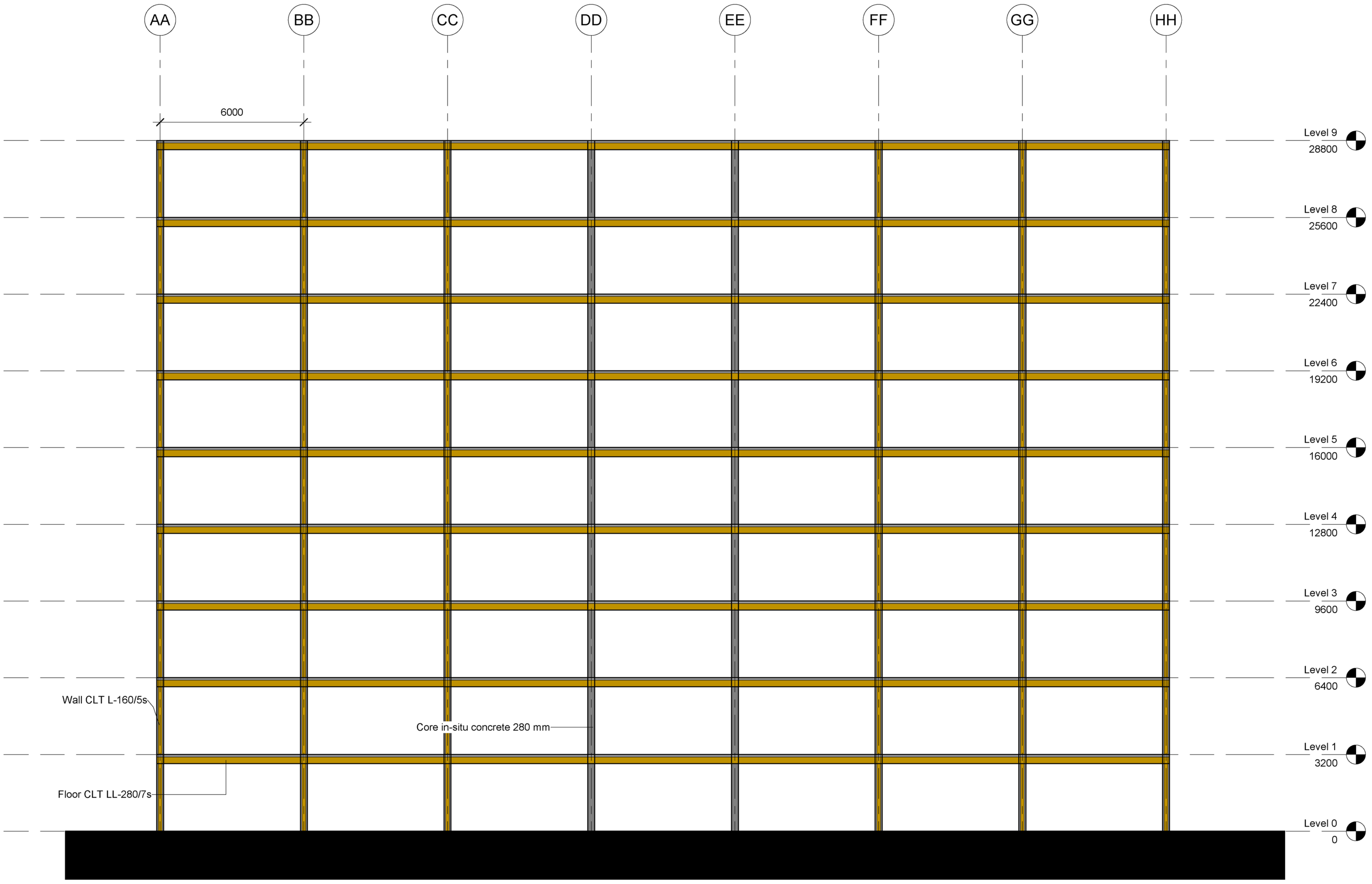
I
J
K
L
M
N
O
P
4800
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-140/5s
Core in-situ concrete 280 mm
Floor CLT LL-210/7s

Timber 11



Q
R
S
T
U
V
W
X
5400
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-140/5s
Core in-situ concrete 280 mm
Floor CLT LL-240/7s

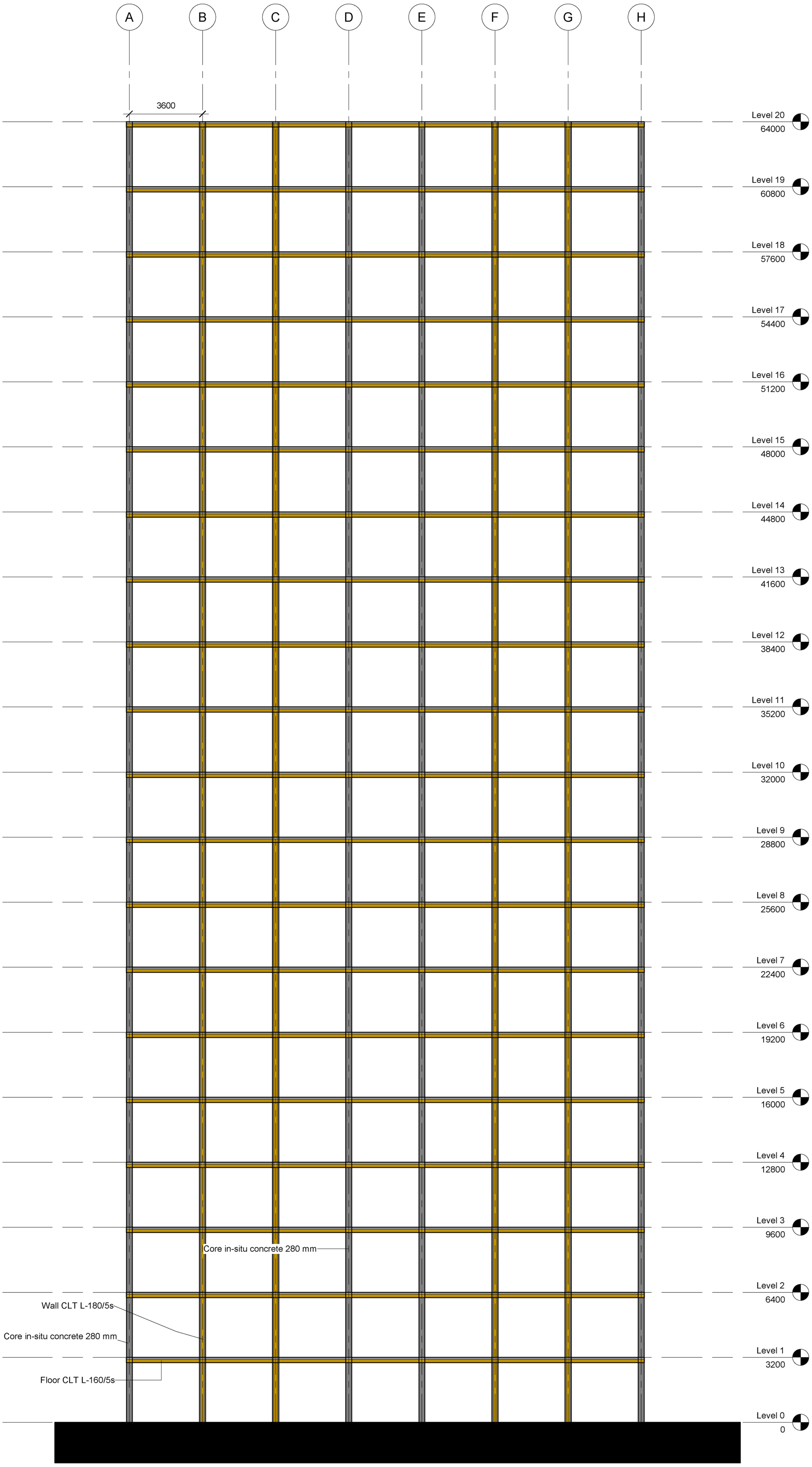
Timber 12



AA
BB
CC
DD
EE
FF
GG
HH
6000
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-160/5s
Core in-situ concrete 280 mm
Floor CLT LL-280/7s

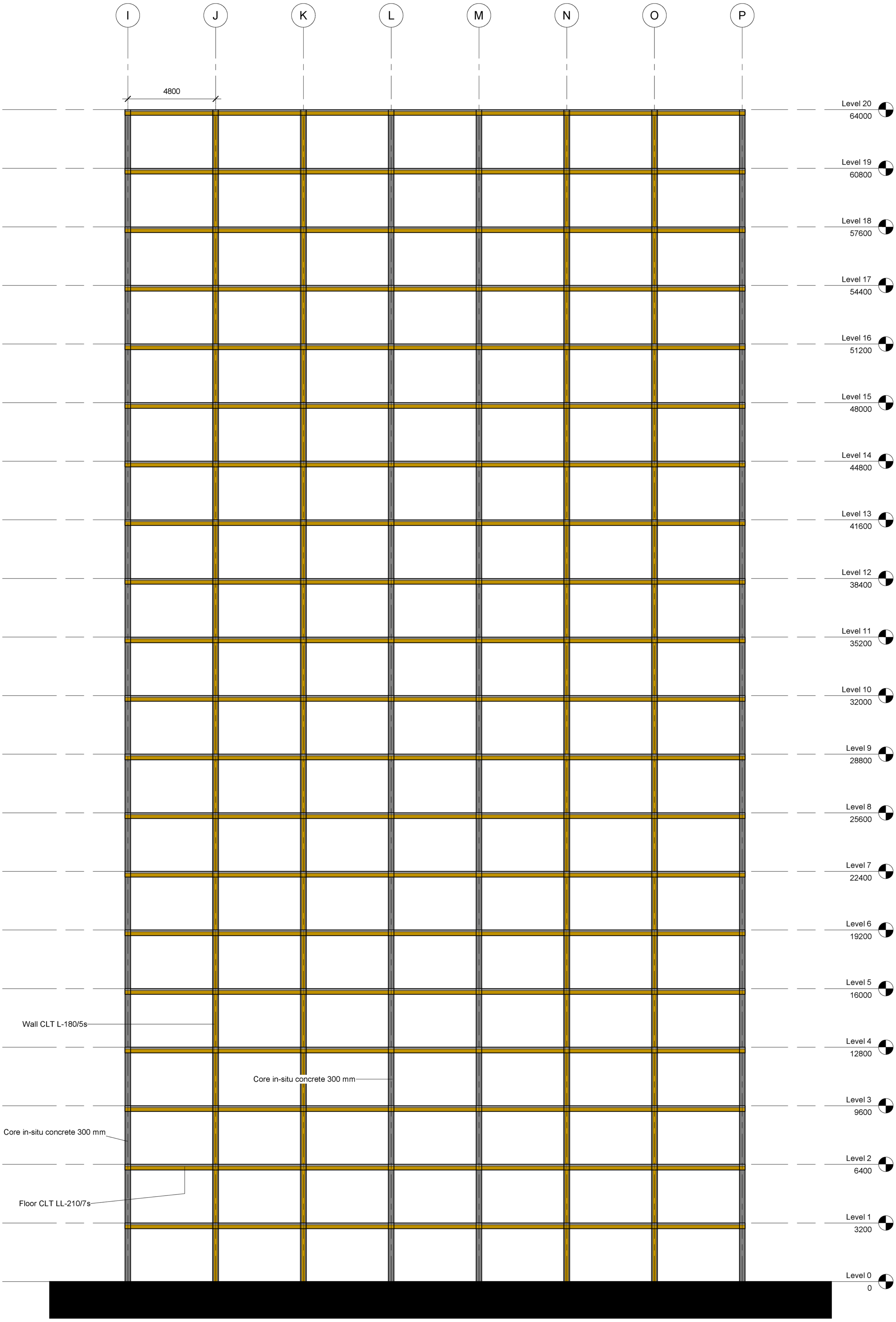
test

Timber 13

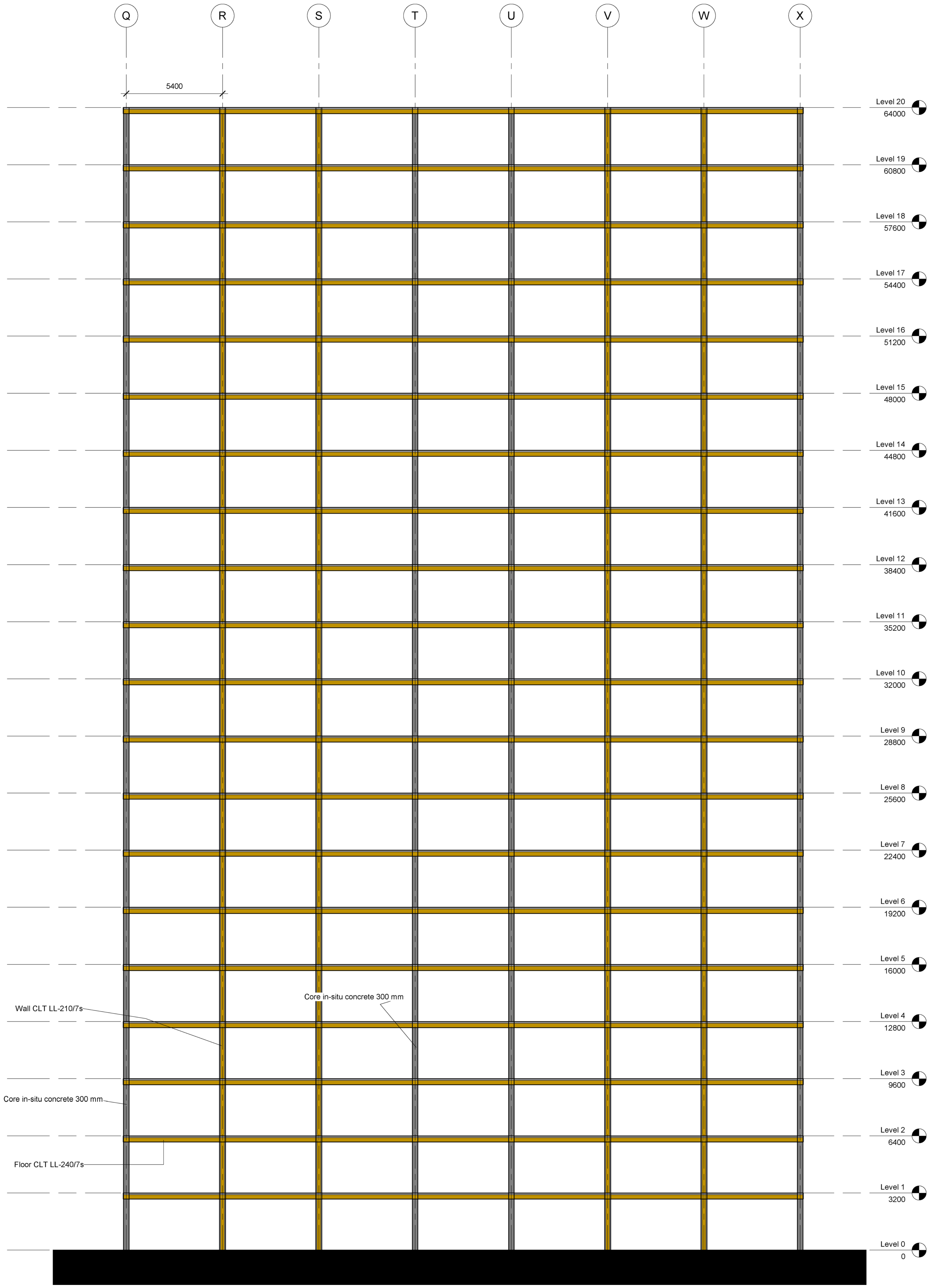


A
B
C
D
E
F
G
H
3600
Level 20
64000
Level 19
60800
Level 18
57600
Level 17
54400
Level 16
51200
Level 15
48000
Level 14
44800
Level 13
41600
Level 12
38400
Level 11
35200
Level 10
32000
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Core in-situ concrete 280 mm
Level 2
6400
Wall CLT L-180/5s
Core in-situ concrete 280 mm
Level 1
3200
Floor CLT L-160/5s
Level 0
0

Timber 14

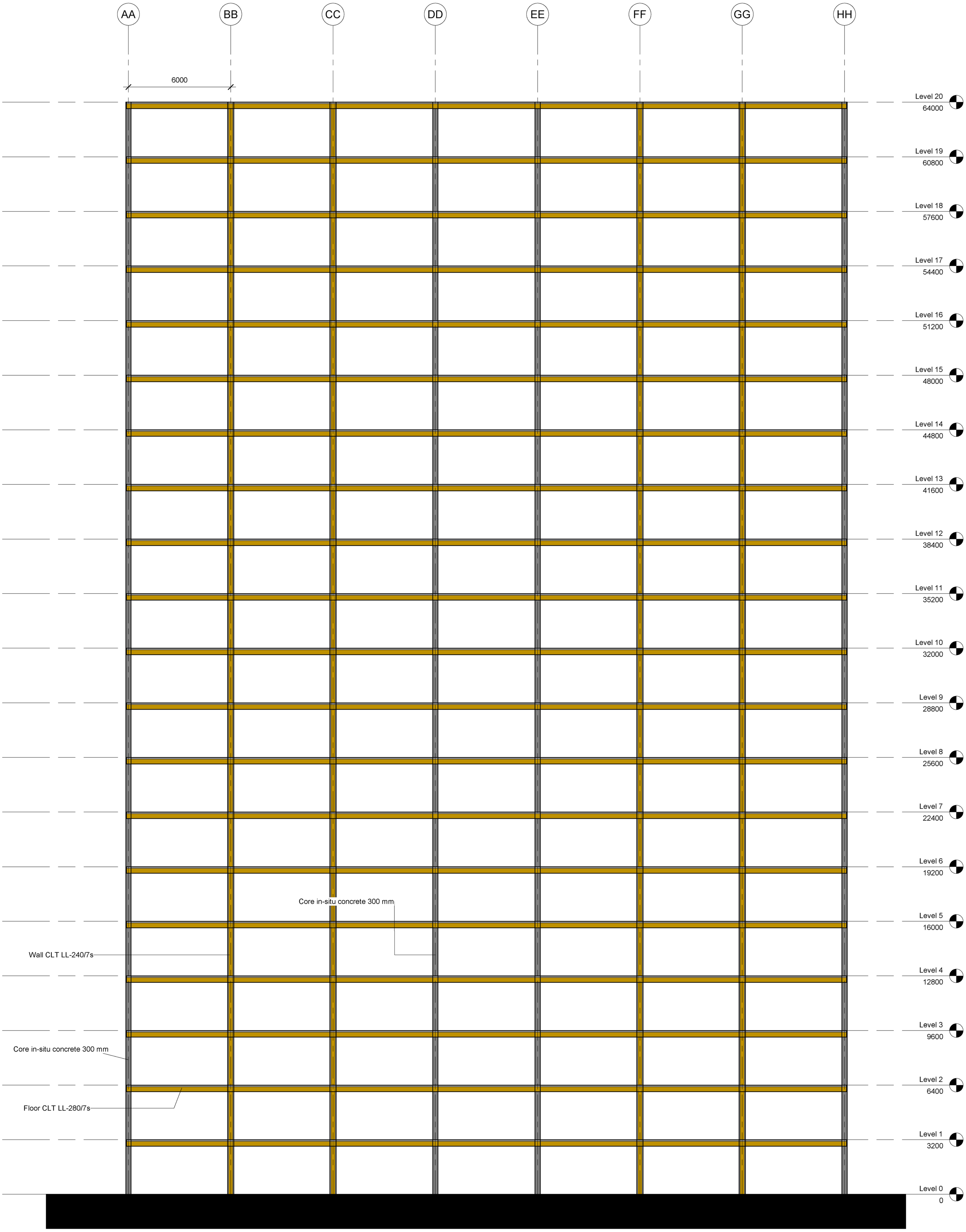

I
J
K
L
M
N
O
P
4800
Level 20
64000
Level 19
60800
Level 18
57600
Level 17
54400
Level 16
51200
Level 15
48000
Level 14
44800
Level 13
41600
Level 12
38400
Level 11
35200
Level 10
32000
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT L-180/5s
Core in-situ concrete 300 mm
Core in-situ concrete 300 mm
Floor CLT LL-210/7s

Timber 15



Q
R
S
T
U
V
W
X
5400
Level 20
64000
Level 19
60800
Level 18
57600
Level 17
54400
Level 16
51200
Level 15
48000
Level 14
44800
Level 13
41600
Level 12
38400
Level 11
35200
Level 10
32000
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Level 5
16000
Level 4
12800
Level 3
9600
Level 2
6400
Level 1
3200
Level 0
0
Wall CLT LL-210/7s
Core in-situ concrete 300 mm
Core in-situ concrete 300 mm
Floor CLT LL-240/7s

Timber 16


AA
BB
CC
DD
EE
FF
GG
HH
6000
Level 20
64000
Level 19
60800
Level 18
57600
Level 17
54400
Level 16
51200
Level 15
48000
Level 14
44800
Level 13
41600
Level 12
38400
Level 11
35200
Level 10
32000
Level 9
28800
Level 8
25600
Level 7
22400
Level 6
19200
Core in-situ concrete 300 mm
Level 5
16000
Wall CLT LL-240/7s
Level 4
12800
Level 3
9600
Core in-situ concrete 300 mm
Level 2
6400
Floor CLT LL-280/7s
Level 1
3200
Level 0
0

Appendix M. Overview cost and carbon calculation parameter study variant 6

This appendix contains the cost and carbon calculation of variant 6 of the parameter study.

footprint/ bouwoppervlak	403,2 m²		
BVO	2016 m²	Koop GO	908,4 m2
GO	1816,8 m²	Huur GO	908,4 m2
Wandoppervlak afweking	3763,2 m²	overig GO	
woninsheidende wanden	2073,6 m²		
wanden stabiliteit beton	0 m²		
Gevel oppervlak	1459 m²		
lengte balk	456 m1		

	Concrete reference	6	2016		€ 2.278		€ 4.591.890	€ 380.541
B1	**Bouwkundige werken**		**2.016**		**€ 1.336**		**€ 2.692.879**	
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	Verschil met concrete
1A	**FUNDERING CONCRETE**		**2016**	**m²**	**€ 91**		**€ 183.307**	**-€ 38.194**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
10	**Voorzieningen bouwput**							
	MAATVOEREN:							
	maatvoering onderbouw		403,2	tbb	€ 2,50	€ 1.008		**€ 0**
	totaal voorzieningen bouwput				**€ 0,50**		**€ 1.008**	**€ 0**
11	**Bodemvoorzieningen**							
	GRONDWERK							
	terrein uitvlakken		403,2	m²	€ 1,50	€ 605		**€ 0**
	totaal bodemvoorzieningen		**403,2**	**m²**			**€ 605**	**€ 0**
13/23	**Laagste vloer, op grondslag / vrijdragend**							
	VRIJDRAGENDE VLOEREN:							
	kanaalplaatvloer	0,26	403,2	m²	€ 84,00	€ 33.869		**€ 0**
	totaal laagste vloer, op grondslag / vrijdragend		**403,2**	**m²**			**€ 33.869**	**€ 0**
16	**Funderingsconstructie**							
	FUNDERINGSCONSTRUCTIE							
	funderingsconstructie, totaal incl. grond\	0%	2016	bvo	€ 25,00	€ 50.400		**-€ 13.342**
	totaal funderingsconstructie		**2016**	**m²**	**€ 25,00**		**€ 50.400**	**-€ 13.342**
17	**Paalfunderingen**							
	PAALFUNDERINGEN:							
	paalfunderingen, totaal (grondgevormde	0%	2016	bvo	€ 40,06	€ 80.761		**-€ 21.380**
	totaal paalfunderingen		**17176**	**st**	**€ 4,70**		**€ 80.761**	**-€ 21.380**
5A	**Nader te detailleren over fundering**							
	nader te detailleren		0,1	over	€ 166.642,56	€ 16.664		**-€ 3.472**
	totaal nader te detailleren over fundering						**€ 16.664**	**-€ 3.472**
	TOTAAL FUNDERING						**€ 183.307**	**-€ 38.194**
1B	**SKELET CONCRETE**		**2.016,00**	**m²**	**€ 446,07**		**€ 899.268**	**€ 171.542**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
21.2	**Buitenwanden; constructief**							
22.2	**Binnenwanden; constructief**							
	BINNENWANDEN:							
	prefab betonwand kernen	0,00	0,00	m²	€ 228,00	€ -		**€ 0**
	prefab betonwand woningen (WSW)	0,25	2073,6	m²	€ 219,00	€ 454.118		**-€ 454.118**
								€ 273.715
	totaal binnenwanden; constructief		**2073,6**	**m²**	**€ 219,00**		**€ 454.118**	**-€ 180.403**
23.2	**Vloeren; constructief**							
	VLOEREN:							
	breedplaat	0,25	2016	m²	€ 107,00	€ 215.712		**-€ 215.712**
	breedplaat met balkbodems		0	m²	€ 204,00	€ -		**€ 0**
								€ 508.032
								€ 0
	totaal vloeren; constructief		**2016**	**m²**	**€ 107,00**		**€ 215.712**	**€ 292.320**
24	**Trappen & hellingen constructief**							

footprint/ bouwoppervlak	403,2 m²		
BVO	2016 m²	Koop GO	912,6 m2
GO	1825,2 m²	Huur GO	912,6 m2
Wandoppervlak afweking	3763,2 m²		
woninsheidende wanden	2073,6 m²		
wanden stabiliteit beton	0 m²		
Gevel oppervlak	1459 m²		
lengte balk	456 m1		

	Timber Variant	6	2016		€ 2.466		€ 4.972.431
B1	**Bouwkundige werken**		**€ 2.016**		**€ 1.477,23**		**€ 2.978.099**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
1A	**FUNDERING CONCRETE**		**2016**	**m²**	**€ 72**		**€ 145.113**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
10	**Voorzieningen bouwput**						
	MAATVOEREN:						
	maatvoering onderbouw		403,2	tbb	€ 2,50	€ 1.008	
	totaal voorzieningen bouwput						**€ 1.008**
11	**Bodemvoorzieningen**						
	GRONDWERK						
	terrein uitvlakken		403,2	m²	€ 1,50	€ 605	
	totaal bodemvoorzieningen		**403,2**	**m²**			**€ 605**
13/23	**Laagste vloer, op grondslag / vrijdragend**						
	VRIJDRAGENDE VLOEREN:						
	kanaalplaatvloer	0,26	403,2	m²	€ 84,00	€ 33.869	
	totaal laagste vloer, op grondslag / vrijdragend		**403,2**	**m²**			**€ 33.869**
16	**Funderingsconstructie**						
	FUNDERINGSCONSTRUCTIE						
	funderingsconstructie, totaal incl. grondw	**26%**	2016	bvo	€ 18,38	€ 37.058	
	totaal funderingsconstructie		**2016**	**m²**	**€ 18,38**		**€ 37.058**
17	**Paalfunderingen**						
	PAALFUNDERINGEN:						
	paalfunderingen, totaal (grondgevormde ¡	**26%**	2016	bvo	€ 29,46	€ 59.381	
	totaal paalfunderingen		**17176**	**st**	**€ 3,46**		**€ 59.381**
5A	**Nader te detailleren over fundering**						
	nader te detailleren		0,1	over	€ 131.920,64	€ 13.192	
	totaal nader te detailleren over fundering						**€ 13.192**
	TOTAAL FUNDERING						**€ 145.113**
1B	**SKELET HYBRID**		**2.016,00**	**m²**	**€ 531,16**		**€ 1.070.810**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
21.2	**Buitenwanden; constructief**						
22.2	**Binnenwanden; constructief**						
	BINNENWANDEN:						
	prefab betonwand kernen	0	0	m²	€ 228,00	€ -	
	Prijs CLT	€ 1.200 *per m3*					
	CLT wand woningen	0,11	2073,6	m²	€ 132,00	€ 273.715	
	totaal binnenwanden; constructief		**2073,6**	**m²**	**€ 132,00**		**€ 273.715**
23.2	**Vloeren; constructief**						
	VLOEREN:						
	breedplaat						
	breedplaat met balkbodems		0	m²	€ 204,00	€ -	
	CLT vloer	0,21	2016	m²	€ 252,00	€ 508.032	
	totaal vloeren; constructief		**2016**	**m²**	**€ 252,00**		**€ 508.032**
24	**Trappen & hellingen constructief**						

Code	Omschrijving	d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
27.2	**Daken; constructief**							
	VLAKKE DAKEN:							
	breedplaat	0,25	403,2	m²	€ 110,00	€ 44.352		-€ 44.352
								€ 101.606
	totaal daken; constructief		**403,2**	**m²**	**€ 110,00**		**€ 44.352**	**€ 57.254**
28	**Hoofddraagconstructie**							
	MAATVOEREN:							
	maatvoering bovenbouw		2016	bvo	€ 2,40	€ 4.838		€ 0
	KOLOMMEN							
	betonkolom prefab tpv woningen		0	m¹	€ 146,00	€ -		€ 0
	betonkolom prefab tpv plint		0	m¹	€ 228,00	€ -		€ 0
								€ 0
	LIGGERS							
	betonbalk prefab tpv gevels		456	m¹	€ 216,00	€ 98.496		-€ 98.496
	Glulam ligger gevels			m¹	€ 187,00	€ -		€ 85.272
								€ 0
	totaal hoofddraagconstructie		**2016**	**m²**	**€ 51,26**		**€ 103.334**	**-€ 13.224**
5A	**Nader te detailleren over skelet**							
	nader te detailleren		0,1	over	€ 817.516,80	€ 81.752		€ 15.595
	totaal nader te detailleren over skelet				**€ 40,55**		**€ 81.752**	**€ 15.595**
	TOTAAL SKELET		**2.016**	**m²**	**€ 446,07**		**€ 899.268**	**€ 171.542**
1E	**BINNENWAND AFBOUW CONCRETE**		**3.763**	**m²**	**€ 145,00**		**€ 545.664**	**€ 131.712**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Binnenwand afwerking		3763,20	m2	€ 145,00	€ 545.664		€ 131.712
	Totaal binnenwand afbouw						**€ 545.664**	**€ 131.712**
1F	**VLOERAFBOUW CONCRETE**		**2.016,00**	**m²**	**€ 50**		**€ 100.800**	**€ 40.320**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Vloerafbouw		2016	m²	€ 50,00	€ 100.800		€ 40.320
								€ 0
	Totaal vloerafbouw						**€ 100.800**	**€ 40.320**
1D	**GEVELS**	**bvo**	**2.016,00**	**m²**	**€ 398**		**€ 802.560**	**€ 0**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	gevels		1459	m²	€ 550,00	€ 802.560		€ 0
								€ 0
	Totaal gevels						**€ 802.560**	**€ 0**
1H	**PLAFONDS BINNEN/ BUITEN CON**	**bvo**	**2.016,00**	**m²**	**€ 80**		**€ 161.280**	**-€ 20.160**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Plafonds binnen		2016	m²	€ 80,00	€ 161.280		-€ 20.160
	Plafonds buiten, buiten beschouwing							€ 0
	Totaal plafonds binnen/ buiten						**€ 161.280**	**-€ 20.160**
B5	**Algemene uitvoeringskosten,**	**bvo**	**2.016,00**	**m²**	**€ 313,58**		**€ 632.168**	**-€ 5.750**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
5A	**DIVERSEN CONCRETE**	**bco**	**2.016,00**	**m²**	**€ 133,58**		**€ 269.288**	**€ 28.522**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot	
	Diversen,10% van totaal bouwkundige werken n	€ 2.692.879,30			10%	€ 269.288		€ 28.522

Code	Omschrijving	d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
27.2	**Daken; constructief**						
	VLAKKE DAKEN:						
	CLT	0,21	403,2	m²	€ 252,00	€ 101.606	
	totaal daken; constructief		**403,2**	**m²**	**€ 252,00**		**€ 101.606**
28	**Hoofddraagconstructie**						
	MAATVOEREN:						
	maatvoering bovenbouw		2016	bvo	€ 2,40	€ 4.838	
	KOLOMMEN						
	betonkolom prefab tpv woningen		0	m¹	€ 146,00	€ -	
	betonkolom prefab tpv plint		0	m¹	€ 228,00	€ -	
	LIGGERS						
	betonbalk prefab tpv gevels			m¹	€ 216,00	€ -	
	Glulam ligger gevels		456	m¹	€ 187,00	€ 85.272	
	totaal hoofddraagconstructie		**2016**	**m²**			**€ 90.110**
5A	**Nader te detailleren over skelet**						
	nader te detailleren		0,1	over	€ 973.464,00	€ 97.346	
	totaal nader te detailleren over skelet						**€ 97.346**
	TOTAAL SKELET		**2.016**	**m²**	**€ 531,16**		**€ 1.070.810**
1E	**BINNENWAND AFBOUW CONCRETE**		**3.763**	**m²**			**€ 677.376**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
	Binnenwand afwerking		3763,2	m2	€ 180,00	€ 677.376	
	Totaal binnenwand afbouw						**€ 677.376**
1F	**VLOERAFBOUW CONCRETE**		**2.016,00**	**m²**	**€ 70,00**		**€ 141.120**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
	Vloerafbouw		2016	m²	€ 70,00	€ 141.120	
	Sprinkler installatie	0	2016	m²	€ 37,50	€ -	
	Totaal vloerafbouw						**€ 141.120**
1D	**GEVELS**	**bvo**	**2.016,00**	**m²**	**€ 398,10**		**€ 802.560**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
	gevels		1459	m²	€ 550,00	€ 802.560	
	Totaal gevels						**€ 802.560**
1H	**PLAFONDS BINNEN/ BUITEN CONC**	**bvo**	**2.016,00**	**m²**	**€ 70,00**		**€ 141.120**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
	Plafonds binnen		2016	m²	€ 70,00	€ 141.120	
	Plafonds buiten, buiten beschouwing						
	Totaal plafonds binnen/ buiten						**€ 141.120**
B5	**Algemene uitvoeringskosten/**	**bvo**	**2.016,00**	**m²**	**€ 310,72**		**€ 626.418**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
5A	**DIVERSEN HYBRID**	**bco**	**2.016,00**	**m²**			**€ 297.810**
		d (m)	hoeveelh.	ehd	€ / ehd	subtot	tot
	Diversen,10% van totaal bouwkundige werken nader te	€ 2.978.099,11	10%			€ 297.810	

	Totaal diversen							**€**	**269.288**	**€ 28.522**
5B	**ALGEMENE UITVOERINGSKOSTEN**	**bvo**	**2.016,00**	**m²**	**€**	**180**		**€**	**362.880**	**-€ 34.272**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot		
	Algemene uitvoeringskosten		2.016	m²	€	180,00	€ 362.880			-€ 34.272
	Totaal algemene uitvoeringskosten							**€**	**362.880**	**-€ 34.272**
G2	**Financieringskosten bouw co**	**bvo**	**2.016,00**	**m²**	**€**	**49,48**		**€**	**99.751**	**€ 2.977**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot		
	Bouwrente		3,0%		€	3.325.047	€ 99.751			€ 2.977
	Totaal financieringskosten							**€**	**99.751**	**€ 2.977**
Z2	**Baten bouw concrete**	**bvo**	**2.016,00**	**m²**	**€**	**-2.838,75**		**€**	**-5.722.920**	**-€ 26.460**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot		
	Baten verkoop vrije sector		908,4	m²	€	3.400,00	€ -3.088.560			-€ 14.280
	Baten verkoop sociale huur		908,4	m²	€	2.900,00	€ -2.634.360			
	Baten verkoop overig		0	m²	€	4.100,00	€ -			
	Totaal baten							**€**	**-5.722.920**	**-€ 26.460**
X	**Additional costs**	**bvo**	**2.016,00**	**m²**	**€**	**578,91**		**€**	**1.167.092**	**€ 98.094**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot		
A	Grondkosten	laag	€ 3.325.047			6,0%				
		mid	€ 3.325.047			7,5%	€ 249.379			
		hoog	€ 3.325.047			9,0%				
	totaal grondkosten		**2016**	**m²**	**€**	**124**		**€**	**249.379**	**€ 20.960**
X	Onvoorzien	laag	€ 3.325.047			3,0%				
		mid	€ 3.325.047			4,0%	€ 133.002			
		hoog	€ 3.325.047			5,0%				
	totaal onvoorzien		**2016**	**m²**	**€**	**66**		**€**	**133.002**	**€ 11.179**
B	Honoraria	laag	€ 3.325.047			6,7%				
		mid	€ 3.325.047			9,8%	€ 325.855			
		hoog	€ 3.325.047			17,3%				
	totaal honoraria		**2016**	**m²**	**€**	**162**		**€**	**325.855**	**€ 27.388**
C	Aansluitkosten	laag	€ 3.325.047			2,1%				
		mid	€ 3.325.047			3,3%	€ 109.727			
		hoog	€ 3.325.047			5,0%				
	totaal aansluitkosten		**2016**	**m²**	**€**	**54**		**€**	**109.727**	**€ 9.223**
D	Heffingen	laag	€ 3.325.047			1,0%				
		mid	€ 3.325.047			2,0%	€ 66.501			
		hoog	€ 3.325.047			5,0%				
	totaal hefftingen		**2016**	**m²**	**€**	**33**		**€**	**66.501**	**€ 5.589**
H	Ontwikkelaarskosten	laag	€ 3.325.047			3,5%				
		mid	€ 3.325.047			7,3%	€ 242.728			
		hoog	€ 3.325.047			18,5%				
	totaal ontwikkelaarskosten		**2016**	**m²**	**€**	**120**		**€**	**242.728**	**€ 20.401**
I	Verkoopkosten	laag	€ 3.325.047			1,2%				

	Totaal diversen							**€**	**297.810**
5B	**ALGEMENE UITVOERINGSKOSTEN**	**bvo**	**2.016,00**	**m²**	**€**	**163,00**		**€**	**328.608**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot	
	Algemene uitvoeringskosten diversen		2.016	m²	€	163,00	€ 328.608		
	Totaal uitvoeringskosten							**€**	**328.608**
G2	**Financieringskosten bouw cor**	**bvo**	**2.016,00**	**m²**	**€**	**50,96**		**€**	**102.729**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot	
	Bouwrente	5%	2,85%		€	3.604.517	€ 102.729		
	Totaal financieringskosten							**€**	**102.729**
Z2	**Baten bouw timber**	**bvo**	**2.016,00**	**m²**	**€**	**-2.851,88**		**€**	**-5.749.380**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot	
	Baten verkoop vrije sector	0,00%	912,6	m²	€	3.400,00	€ -3.102.840		
		2,00%	912,6	m²	€	3.468,00	€ -3.164.897		
		4,00%	912,6	m²	€	3.536,00	€ -3.226.954		
	Baten verkoop sociale huur		912,6	m²	€	2.900,00	€ -2.646.540		
	Baten verkoop overig		0	m²	€	4.100,00	€ -		
	Totaal baten							**€**	**-5.749.380**
Z2	**Additional costs**	**bvo**	**2.016,00**	**m²**	**€**	**627,57**		**€**	**1.265.185**
		d (m)	hoeveelh.	ehd	€ / ehd		subtot	tot	
A	Grondkosten	laag	€ 3.604.517			6,0%			
		mid	€ 3.604.517			7,5%	€ 270.339		
		hoog	€ 3.604.517			9,0%			
	totaal grondkosten		**2016**	**m²**	**€**	**134**		**€**	**270.339**
X	Onvoorzien	laag	€ 3.604.517			3,0%			
		mid	€ 3.604.517			4,0%	€ 144.181		
		hoog	€ 3.604.517			5,0%			
	totaal onvoorzien		**2016**	**m²**	**€**	**72**		**€**	**144.181**
B	Honoraria	laag	€ 3.604.517			6,7%			
		mid	€ 3.604.517			9,8%	€ 353.243		
		hoog	€ 3.604.517			17,3%			
	totaal honoraria		**2016**	**m²**	**€**	**175**		**€**	**353.243**
C	Aansluitkosten	laag	€ 3.604.517			2,1%			
		mid	€ 3.604.517			3,3%	€ 118.949		
		hoog	€ 3.604.517			5,0%			
	totaal aansluitkosten		**2016**	**m²**	**€**	**59**		**€**	**118.949**
D	Heffingen	laag	€ 3.604.517			1,0%			
		mid	€ 3.604.517			2,0%	€ 72.090		
		hoog	€ 3.604.517			5,0%			
	totaal hefftingen		**2016**	**m²**	**€**	**36**		**€**	**72.090**
H	Ontwikkelaarskosten	laag	€ 3.604.517			3,5%			
		mid	€ 3.604.517			7,3%	€ 263.130		
		hoog	€ 3.604.517			18,5%			
	totaal ontwikkelaarskosten		**2016**	**m²**	**€**	**131**		**€**	**263.130**
I	Verkoopkosten	laag	€ 3.604.517			1,2%			

	mid	€	3.325.047		1,2%	€ 39.901		
	hoog	€	3.325.047		2,7%			
totaal verkoopkosten			**2016 m²**	**€**	**20**		**€ 39.901**	**€ 3.354**
Totaal additional costs							**€ 1.167.092**	**€ 98.094**

	mid	€	3.604.517		1,2%	€ 43.254	
	hoog	€	3.604.517		2,7%		
totaal verkoopkosten			**2016 m²**	**€**	**21**		**€ 43.254**
Totaal additional costs							**€ 1.265.185**

	footprint/ bouwoppervlak	403,2	m²		
	BVO	2016	m²		
0,033	GO	1825,2	m²		*In situ concrete C30/37*
	Wandoppervlak afweking	3763,2	m²		
	woninsheidende wanden	2073,6	m²		*In situ concrete C40/50*
	wanden kern	0	m²	#######	
	lengte balk	456	m1		
	Gevel oppervlak	1459,2	m2		

Level 3

Concrete reference

BVO 2016 m2

				breedte (m)	dikte (m)	wapenir	density	ehd.	hoeveelheid	ehd.	hoeveelheid 2	ehd.		Output embodied carbon low A1-A3 [kg-CO2eq] excl. bigenic car GWP	only bigenic BIO GWP	incl. biogenic carbon TOT GWP	Output embodied carbon medium A1-A3 [kg-CO2eq] excl. bigenic c GWP	only bigenic BIO GWP	incl. biogenic carbon TOT GWP	Output embodied carbon high A1-A3 [kg-CO2eq] excl. bigenic car GWP	only bigenic BIO GWP	incl. biogenic TOT GWP
		materiaal																				
A	**Fundering**																					
13/23	laagste vloer, op grondslag	kanaalplaat (geisoleerd)			0,26		258	kg/m2	403,2	m²	104026	kg	*Hollow core slab*	12452		12452	**14138**		**14138**	17795		17795
		druklaag			0,07				403,2	m²												
			Concrete compressive layer conrete part		0,07		2400	kg/m3			67738	kg	*In situ concrete C30/37*	3549		3549	**5507**		**5507**	8566		8566
			Concrete compressive layer reinforcement			100	7	kg/m2			2822	kg	*Reinforcement*	677		677	**2893**		**2893**	8157		8157
16	funderingsconstructie	funderingsconstructie, totaal incl. grondwerk			0,3		2400	kg/m3	403,2	m²	290304	kg	*In situ concrete C30/37*	15212		15212	**23602**		**23602**	36711		36711
17	paalfunderingen	Fundexpalen, ø300 mm en paallengte, 26 m¹		diameter	0,3		33,0	st	26	m	858	m										
			betonmortel		0,0706858	m2	2400	kg/m3			145556	kg	*In situ concrete C35/45*	10332		10332	**11916**		**11916**	21273		21273
			wapening korf			assumed	4	kg/m1			3432	kg	*Reinforcement*	824		824	**3518**		**3518**	9918		9918
			wapening			assumed	16	kg/m1			13728	kg	*Reinforcement*	3295		3295	**14073**		**14073**	39674		39674
	TOTAL FOUNDATION										**627606**	**kg**		**46341**		**46341**	**75647**		**75647**	**142095**		**142095**
B	**Skelet**																					
22.2	Binnenwanden; constructie	prefab betonwand (bruto) tpv kernen			0		2400	kg/m3	0	m²	0	kg	*Precast concrete incl rebar*									
			in situ concrete C35/45		0		2400	kg/m3	0	m²	0	kg	*In situ concrete C30/37*									
			wapening in situ betonwand (bruto) tpv kern		200	kg/m3	7850	kg/m3	0	m²	0	kg	*Reinforcement*									
	prefab betonwand (bruto)	prefab betonwand (bruto) tpv woningen			0,25		2400	kg/m3	2073,6	m²	1244160	kg	*Precast concrete incl rebar*	105491		105491	**235146**		**235146**	303575		303575
			prefab beton																			
			wapening prefab betonwand (bruto) tpv woningen (WSW)							m²												
		CLT wand					470	kg/m3	0	m²	0	kg	*CLT*									
	total binnenwanden										**1244160**	**kg**		105491		105491	**235146**		**235146**	303575		303575
22.3	Vloeren; constructief	breedplaat			0,25				2016	m²												
			prefabbeton breedplaat		0,05		2400	kg/m3	2016	m²	241920	kg	*Precast plank floor*	39675		39675	**42271**		**42271**	44997		44997
			in situ beton breeedplaat		0,2		2400	kg/m3	2016	m²	967680	kg	*In situ concrete C30/37*	50706		50706	**78672**		**78672**	122370		122370
			Wapening breedplaat			100	25	kg/m2	2016	m²	50400	kg	*Reinforcement*	12096		12096	**51668**		**51668**	145656		145656
		CLT vloer			0		470	kg/m3	0	m²	0	kg	*CLT*									
	total vloeren										**1260000**	**kg**		102477		102477	**172611**		**172611**	313023		313023
27.2	Daken; constructief	breedplaat			0,25				403,2	m²												
			prefabbeton breedplaat		0,05		2400	kg/m3	403,2	m²	48384	kg	*Precast plank floor*	7935		7935	**8454**		**8454**	8999		8999
			in situ beton breeedplaat		0,2		2400	kg/m3	403,2	m²	193536	kg	*In situ concrete C30/37*	10141		10141	**15734**		**15734**	24474		24474
			Wapening breedplaat			100	25	kg/m2	403,2	m²	10080	kg	*Reinforcement*	2419		2419	**10334**		**10334**	29131		29131
		CLT					470	kg/m3	0	m²	0	kg	*CLT*									
	total daken										**252000**	**kg**		20495		20495	**34522**		**34522**	62605		62605
18	Hoofddraagconstructie	betonbalk prefab gevels		0,3	0,2		2400	kg/m3	456	m¹	65664	kg	*Precast concrete incl rebar*	5568		5568	**12410**		**12410**	16022		16022
			Beton betonkolom prefab																			
			wapening betonbalk prefab tpv kopgevels																			
		Glulam beam gevels					470	kg/m3	0	m¹	0	kg	*Glulam*									
	total hoofddraagconstructie										**65664**	**kg**		5568		5568	**12410**		**12410**	16022		16022
	TOTAL SKELET										**2821824**	**kg**		**234031**		**234031**	**454690**		**454690**	**695225**		**695225**
E	**Binnenwand afbouw**																					
22.1	Binnenwanden; niet constructief																					
		plaster			0,005		968	kg/m3	2073,6	m2	10036	kg	*Gipsplaat fire resistant*	776		776	**1949**		**1949**	2507		2507
		Plaster			0,005		968	kg/m3	2073,6	m2	10036	kg	*Gipsplaat fire resistant*	776		776	**1949**		**1949**	2507		2507
	total binnenwandafbouw										**20072**	**kg**		1551		1551	**3898**		**3898**	5013		5013
F	**Vloerafbouw + plafondafbouw**																					
		zandcement vloer	Assumed in situ concrete C25/30		0,07	m	1500	kg/m3	2016	m2	211680	kg	*Cementious screed*	17191		17191	**33022**		**33022**	63504		63504
		PIR insulation			0,03	m	33,4	kg/m3	2016	m2	2021	kg	*High density PIR insulation*	5955		5955	**8064**		**8064**	9116		9116
	total vloerafbouw										**213701**	**kg**		23146		23146	**41086**		**41086**	72620		72620
	TOTAL								**incl substrucutre**		**3902083**	**kg**	*TOTAL*	**305070**		**305070**	**575322**		**575322**	**914953**		**914953**
	TOTAL / m2										**1936**	**kg/m2**	*Total / m2*	**151,3**	**0,0**	**151,3**	**285,4**	**0,0**	**285,4**	**453,8**	**0,0**	**453,8**

footprint/ bouwoppervlak 403,2 m^2
BVO 2016 m^2
GO 1825,2 m^2
Wandoppervlak afweking 3763,2 m^2
woninsheidende wanden 2073,6 m^2
wanden kern 0 m^2
lengte balk 456 m1
Gevel oppervlak 1459,2 m2

Timber Variant 6 BVO 2016 m2

													Output embodied carbon low A1-A3 [kg-CO2eq]			Output embodied carbon medium A1-A3 [kg-CO2eq]			Output embodied carbon high A1-A3 [kg-CO2eq]		
													excl. bigenic car	only bigenic (	incl. biogenic carbon	excl. bigenic ca	only bigenic car	incl. biogenic carbon	excl. bigenic carl	only bigenic (	incl. biogenic carbon
	materiaal		breedte (m)	dikte (m)	wapenir	density	ehd.	hoeveelheid	ehd.	hoeveelheid 2	ehd.		GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP	GWP	BIO GWP	TOT GWP
A																					
13/23	kanaalplaat (geisoleerd)			0,26		258	kg/m2	403,2	m2	104026	kg	*Hollow core slab*	12452		12452	14138		14138	17795		17795
	druklaag			0,07				403,2	m2												
		Concrete compressive layer conrete part		0,07		2400	kg/m3			67738	kg	*In situ concrete C30/37*	3549		3549	5507		5507	8566		8566
		Concrete compressive layer reinforcement			100	7	kg/m2			2822	kg	*Reinforcement*	677		677	2893		2893	8157		8157
16	funderingsconstructie, totaal incl. grondwerk		assumed re	0,2205817		2400	kg/m3	403,2	m2	213453	kg	*In situ concrete C30/37*	11185		11185	17354		17354	26993		26993
17	Fundexpalen, ø300 -14% mm en paallengte, 29 m^1					33,0	st	26		858	m										
	74%	*betonmortel*		0,0519733		2400	kg/m3			107024	kg	*In situ concrete C35/45*	7597		7597	8761		8761	15642		15642
		wapening korf			assumec	4	kg/m1			3432	kg	*Reinforcement*	824		824	3518		3518	9918		9918
		wapening			assumec	16	kg/m1			13728	kg	*Reinforcement*	3295		3295	14073		14073	39674		39674
										512222	**kg**		**39579**		**39579**	**66245**		**66245**	**126745**		**126745**
B																					
22.2	prefab betonwand (bruto) tpv kernen			0		2400	kg/m3	0	m^2	0	kg	*Precast concrete incl rebar*									
		in situ concrete C35/45		0		2400	kg/m3	0	m^2	0	kg	*In situ concrete C30/37*									
		wapening in situ betonwand (bruto) tpv kern		200	kg/m2	7850	kg/m3	0	m^2	0	kg	*Reinforcement*									
	prefab betonwand (bruto) tpv woningen					2400	kg/m3	0	m^2	0	kg	*Precast concrete incl rebar*									
		prefab beton																			
		wapening prefab betonwand (bruto) tpv woningen (WSW)							m^2												
	CLT wand			0,11		470	kg/m3	2073,6	m^2	107205	kg	*CLT*	12465	-173809	-161264	29196	-173125	-143929	64231	-199838	-135607
										107205	**kg**		12465	-173809	-161264	29196	-173125	-143929	64231	-199838	-135607
22.3	breedplaat																				
		prefabbeton breedplaat				2400	kg/m3			0	kg	*Precast plank floor*									
		in situ beton breeedplaat				2400	kg/m3			0	kg	*In situ concrete C30/37*									
		Wapening breedplaat				0	kg/m2			0	kg	*Reinforcement*									
	CLT vloer			0,21		470	kg/m3	2016	m^2	198979	kg	*CLT*	23136	-322600	-299316	54190	-321330	-267140	119216	-370911	-251694
										198979	**kg**		23136	-322600	-299316	54190	-321330	-267140	119216	-370911	-251694
27.2	breedplaat							0	m^2												
		prefabbeton breedplaat				2400	kg/m3		m^2	0	kg	*Precast plank floor*									
		in situ beton breeedplaat				2400	kg/m3		m^2	0	kg	*In situ concrete C30/37*									
		Wapening breedplaat			100	0	kg/m2		m^2	0	kg	*Reinforcement*									
	CLT			0,21 m		470	kg/m3	403,2	m^2	39796	kg	*CLT*	4627	-64520	-59863	10838	-64266	-53428	23843	-74182	-50339
										39796	**kg**		4627	-64520	-59863	10838	-64266	-53428	23843	-74182	-50339
18	betonbalk prefab gevels					258	kg/m2		m^1	0	kg										
		Beton betonkolom prefab																			
		wapening betonbalk prefab tpv kopgevels																			
	Glulam beams gevels		0,3	0,2		470	kg/m3	456	m^1	12859	kg	*Glulam*	3179	-22635	-19456	3961	-20602	-16635	5224	-21582	-16358
										12859	**kg**		3179	-22635	-19456	3961	-20602	-16635	5224	-21582	-16358
										358839	**kg**		**43407**	**-583565**	**-539898**	**98186**	**-579323**	**-481132**	**212515**	**-666513**	**-453998**
E																					
22.1								2073,6													
	Gpsum board	2 platen per kant		25 mm		24,2	kg/m2	2073,6	m2	50181	kg	*Gipsplaat fire resistant*	3878		3878	9746		9746	12534		12534
	Mineral wool			0,04 m		135	kg/m3	2073,6	m2	11197	kg	*Minerale wol*	1443	-94	1351	13935		13935	15447		15447
	Mineral wool			0,04 m		135	kg/m3	2073,6	m2	11197	kg	*Minerale wol*	1443	-94	1351	13935		13935	15447		15447
	Gpsum board	2 platen per kant		25 mm		24,2	kg/m2	2073,6	m2	50181	kg	*Gipsplaat fire resistant*	3878		3878	9746		9746	12534		12534
										122757	kg		10643	-188	10458	47361		47361	55961		55961
F																					
	Gpsum board			0,0125 m		12,1	kg/m2	2016	m2	24394	kg	*Gipsplaat fire resistant*	1885		1885	4738		4738	6093		6093
	MDF			0,025 m		17,5	kg/m2	2016	m2	35280	kg	*MDF*	27953	-53191	-25212	36288	-52214	-15926	42496	-51918	-9361
	PIR insulation			0,03 m		33,417	kg/m2	2016	m2	2021	kg	*High density PIR insulation*	5955		5955	8064		8064	9116		9116
	Washed gravel 8-10 mm			0,08 m		2000	kg/m3	2016	m2	322560	kg	*Washed gravel*	610		610	1226		1226	2097		2097
										160											
										384255	kg		36403	-53191	-16762	50315	-52214	-1899	59801	-51918	7944
								incl substrucutre		**1546772**	**kg**	*TOTAL*	**130031**	**-636944**	**-506623**	**252361**	**-631538**	**-379171**	**442488**	**-718431**	**-275883**
										767	**kg/m2**	*Total / m2*	**64,5**	**-315,9**	**-251,3**	**125,2**	**-313,3**	**-188,1**	**219,5**	**-356,4**	**-136,8**

Appendix N. Results parameter study sensitivity analysis.

Table 75: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, base scenario

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.70	€1.06	€2.18	€0.90	€1.41	€3.33	€1.05	€1.69	€4.39	€1.24	€2.06	€6.15
	2%	€0.77	€1.17	€2.41	€0.97	€1.53	€3.60	€1.11	€1.80	€4.68	€1.30	€2.17	€6.48
	0%	€0.85	€1.28	€2.64	€1.04	€1.64	€3.88	€1.18	€1.91	€4.97	€1.37	€2.28	€6.81
9 storeys	4%	**€0.05**	**€0.07**	€0.13	€0.42	€0.65	€1.36	€0.56	€0.87	€1.97	€0.78	€1.26	€3.23
	2%	€0.12	€0.17	€0.31	€0.49	€0.75	€1.58	€0.62	€0.97	€2.21	€0.85	€1.36	€3.50
	0%	€0.19	€0.27	€0.49	€0.56	€0.85	€1.80	€0.69	€1.08	€2.45	€0.91	€1.47	€3.76
5 storeys	4%	€-0.13	€-0.18	€-0.32	€0.24	€0.36	€0.71	€0.44	€0.68	€1.47	€0.62	€0.97	€2.30
	2%	€-0.06	€-0.09	€-0.16	€0.31	€0.46	€0.90	€0.51	€0.78	€1.68	€0.68	€1.07	€2.53
	0%	€0.00	€0.00	€0.00	€0.37	€0.55	€1.10	€0.57	€0.88	€1.89	€0.74	€1.16	€2.76
3 storeys	4%	€-0.09	€-0.12	€-0.21	€0.24	€0.35	€0.68	€0.40	€0.61	€1.29	€0.63	€0.99	€2.33
	2%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.87	€0.47	€0.71	€1.49	€0.69	€1.08	€2.54
	0%	**€0.04**	**€0.05**	€0.09	€0.36	€0.54	€1.05	€0.53	€0.80	€1.69	€0.75	€1.17	€2.76

Table 76: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, CLT price +10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.85	€1.29	€2.67	€1.07	€1.68	€3.96	€1.22	€1.98	€5.13	€1.42	€2.37	€7.08
	2%	€0.93	€1.41	€2.90	€1.14	€1.80	€4.23	€1.29	€2.09	€5.43	€1.49	€2.48	€7.41
	0%	€1.00	€1.52	€3.13	€1.21	€1.91	€4.50	€1.36	€2.20	€5.72	€1.56	€2.59	€7.74
9 storeys	4%	€0.19	€0.28	€0.50	€0.58	€0.89	€1.88	€0.72	€1.13	€2.56	€0.96	€1.55	€3.97
	2%	€0.26	€0.38	€0.69	€0.65	€1.00	€2.10	€0.79	€1.23	€2.80	€1.02	€1.65	€4.23
	0%	€0.33	€0.48	€0.87	€0.72	€1.10	€2.32	€0.86	€1.34	€3.04	€1.09	€1.75	€4.49
5 storeys	4%	**€0.01**	**€0.01**	**€0.02**	€0.40	€0.59	€1.17	€0.61	€0.93	€2.02	€0.79	€1.24	€2.94
	2%	**€0.07**	€0.10	€0.18	€0.46	€0.69	€1.36	€0.67	€1.03	€2.23	€0.85	€1.34	€3.17
	0%	€0.14	€0.20	€0.34	€0.53	€0.79	€1.55	€0.74	€1.13	€2.44	€0.91	€1.44	€3.40
3 storeys	4%	**€0.05**	**€0.07**	€0.13	€0.39	€0.58	€1.13	€0.57	€0.86	€1.81	€0.80	€1.26	€2.97
	2%	€0.11	€0.16	€0.28	€0.45	€0.67	€1.31	€0.63	€0.96	€2.01	€0.86	€1.35	€3.18
	0%	€0.18	€0.25	€0.43	€0.51	€0.77	€1.49	€0.69	€1.05	€2.21	€0.92	€1.45	€3.40

Table 77: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, CLT price -10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.54	€0.82	€1.69	€0.73	€1.15	€2.71	€0.87	€1.40	€3.64	€1.05	€1.75	€5.23
	2%	€0.61	€0.93	€1.92	€0.80	€1.26	€2.98	€0.94	€1.51	€3.93	€1.12	€1.86	€5.56
	0%	€0.69	€1.04	€2.15	€0.87	€1.38	€3.25	€1.01	€1.63	€4.23	€1.18	€1.97	€5.88
9 storeys	4%	€-0.10	€-0.14	€-0.25	€0.26	€0.40	€0.85	€0.39	€0.61	€1.38	€0.61	€0.98	€2.50
	2%	€-0.03	€-0.04	€-0.07	€0.33	€0.50	€1.07	€0.46	€0.71	€1.62	€0.67	€1.08	€2.76
	0%	**€0.04**	**€0.06**	€0.11	€0.40	€0.61	€1.29	€0.52	€0.82	€1.86	€0.73	€1.18	€3.03
5 storeys	4%	€-0.27	€-0.38	€-0.65	€0.09	€0.13	€0.26	€0.28	€0.43	€0.93	€0.44	€0.70	€1.66
	2%	€-0.20	€-0.29	€-0.50	€0.15	€0.23	€0.45	€0.34	€0.53	€1.14	€0.51	€0.80	€1.89
	0%	€-0.14	€-0.19	€-0.34	€0.22	€0.32	€0.64	€0.41	€0.63	€1.35	€0.57	€0.89	€2.12
3 storeys	4%	€-0.23	€-0.32	€-0.55	**€0.08**	€0.12	€0.24	€0.24	€0.37	€0.77	€0.46	€0.72	€1.69
	2%	€-0.16	€-0.23	€-0.40	€0.14	€0.21	€0.42	€0.30	€0.46	€0.97	€0.52	€0.81	€1.91
	0%	€-0.10	€-0.14	€-0.25	€0.21	€0.31	€0.60	€0.36	€0.56	€1.17	€0.57	€0.90	€2.12

Table 78: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Floor and wall finishing costs timber + 10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.89	€1.35	€2.78	€1.05	€1.66	€3.91	€1.18	€1.91	€4.96	€1.36	€2.26	€6.75
	2%	€0.96	€1.46	€3.01	€1.12	€1.77	€4.18	€1.25	€2.02	€5.25	€1.42	€2.37	€7.08
	0%	€1.04	€1.57	€3.24	€1.20	€1.89	€4.45	€1.32	€2.13	€5.54	€1.49	€2.48	€7.40
9 storeys	4%	€0.22	€0.32	€0.57	€0.56	€0.86	€1.81	€0.68	€1.06	€2.41	€0.89	€1.44	€3.69
	2%	€0.29	€0.41	€0.75	€0.63	€0.96	€2.03	€0.75	€1.17	€2.65	€0.96	€1.54	€3.95
	0%	€0.36	€0.51	€0.93	€0.70	€1.06	€2.25	€0.82	€1.28	€2.89	€1.02	€1.64	€4.22
5 storeys	4%	**€0.03**	**€0.04**	**€0.07**	€0.37	€0.55	€1.10	€0.56	€0.86	€1.86	€0.72	€1.14	€2.70
	2%	€0.09	€0.13	€0.23	€0.44	€0.65	€1.29	€0.63	€0.96	€2.07	€0.78	€1.23	€2.92
	0%	€0.16	€0.23	€0.39	€0.50	€0.75	€1.48	€0.69	€1.06	€2.28	€0.84	€1.33	€3.15
3 storeys	4%	**€0.06**	€0.09	€0.15	€0.36	€0.53	€1.04	€0.52	€0.79	€1.65	€0.73	€1.15	€2.70
	2%	€0.12	€0.18	€0.31	€0.42	€0.63	€1.22	€0.58	€0.88	€1.85	€0.79	€1.24	€2.91
	0%	€0.19	€0.27	€0.46	€0.48	€0.72	€1.41	€0.64	€0.97	€2.05	€0.85	€1.33	€3.13

Table 79: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Thickness concrete floors - 10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.51	€0.77	€1.58	€0.74	€1.17	€2.76	€0.91	€1.47	€3.82	€1.12	€1.86	€5.56
	2%	€0.58	€0.88	€1.81	€0.82	€1.29	€3.03	€0.98	€1.58	€4.11	€1.18	€1.97	€5.89
	0%	€0.65	€0.99	€2.04	€0.89	€1.40	€3.30	€1.05	€1.69	€4.40	€1.25	€2.08	€6.21
9 storeys	4%	€-0.12	€-0.18	€-0.32	€0.29	€0.44	€0.92	€0.43	€0.67	€1.52	€0.67	€1.08	€2.77
	2%	€-0.05	€-0.08	€-0.14	€0.35	€0.54	€1.14	€0.50	€0.78	€1.76	€0.74	€1.18	€3.04
	0%	**€0.02**	**€0.02**	**€0.04**	€0.42	€0.64	€1.36	€0.57	€0.88	€2.00	€0.80	€1.29	€3.30
5 storeys	4%	€-0.29	€-0.41	€-0.71	€0.11	€0.17	€0.33	€0.33	€0.50	€1.08	€0.51	€0.81	€1.91
	2%	€-0.22	€-0.32	€-0.55	€0.18	€0.26	€0.52	€0.39	€0.60	€1.29	€0.57	€0.90	€2.14
	0%	€-0.16	€-0.22	€-0.39	€0.24	€0.36	€0.71	€0.45	€0.70	€1.50	€0.63	€1.00	€2.36
3 storeys	4%	€-0.24	€-0.34	€-0.58	€0.11	€0.17	€0.32	€0.29	€0.44	€0.93	€0.53	€0.83	€1.96
	2%	€-0.17	€-0.25	€-0.43	€0.17	€0.26	€0.51	€0.35	€0.54	€1.13	€0.59	€0.93	€2.18
	0%	€-0.11	€-0.16	€-0.27	€0.24	€0.35	€0.69	€0.41	€0.63	€1.33	€0.65	€1.02	€2.39

Table 80: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Thickness concrete walls - 10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.72	€1.10	€2.34	€0.91	€1.46	€3.57	€1.06	€1.74	€4.71	€1.26	€2.11	€6.60
	2%	€0.79	€1.21	€2.59	€0.99	€1.58	€3.86	€1.13	€1.85	€5.02	€1.32	€2.22	€6.95
	0%	€0.87	€1.33	€2.84	€1.06	€1.69	€4.15	€1.21	€1.97	€5.34	€1.39	€2.34	€7.30
9 storeys	4%	**€0.05**	**€0.08**	€0.14	€0.43	€0.67	€1.48	€0.57	€0.90	€2.13	€0.80	€1.30	€3.50
	2%	€0.12	€0.18	€0.34	€0.50	€0.78	€1.72	€0.64	€1.01	€2.39	€0.86	€1.41	€3.78
	0%	€0.19	€0.28	€0.53	€0.57	€0.89	€1.95	€0.71	€1.12	€2.65	€0.93	€1.51	€4.07
5 storeys	4%	€-0.13	€-0.19	€-0.34	€0.25	€0.38	€0.77	€0.46	€0.71	€1.60	€0.63	€1.01	€2.49
	2%	€-0.06	€-0.09	€-0.17	€0.32	€0.48	€0.98	€0.52	€0.81	€1.82	€0.69	€1.10	€2.74
	0%	€0.00	€0.00	**€0.01**	€0.38	€0.58	€1.19	€0.59	€0.91	€2.05	€0.75	€1.20	€2.98
3 storeys	4%	€-0.09	€-0.13	€-0.23	€0.24	€0.36	€0.74	€0.41	€0.64	€1.39	€0.64	€1.02	€2.51
	2%	€-0.02	€-0.03	€-0.06	€0.31	€0.46	€0.93	€0.48	€0.73	€1.60	€0.70	€1.12	€2.74
	0%	**€0.04**	**€0.06**	€0.10	€0.37	€0.56	€1.13	€0.54	€0.83	€1.82	€0.76	€1.21	€2.97

Table 81: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Decreases core reinforcement -10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.70	€1.06	€2.18	€0.90	€1.41	€3.33	€1.05	€1.69	€4.39	€1.24	€2.06	€6.15
	2%	€0.77	€1.17	€2.41	€0.97	€1.53	€3.60	€1.11	€1.80	€4.68	€1.30	€2.17	€6.48
	0%	€0.84	€1.28	€2.64	€1.04	€1.64	€3.88	€1.18	€1.91	€4.97	€1.37	€2.28	€6.81
9 storeys	4%	**€0.05**	**€0.07**	€0.13	€0.42	€0.65	€1.36	€0.56	€0.87	€1.97	€0.78	€1.26	€3.23
	2%	€0.12	€0.17	€0.31	€0.49	€0.75	€1.58	€0.62	€0.97	€2.21	€0.85	€1.36	€3.50
	0%	€0.19	€0.27	€0.49	€0.56	€0.85	€1.80	€0.69	€1.08	€2.45	€0.91	€1.47	€3.76
5 storeys	4%	€-0.13	€-0.18	€-0.32	€0.24	€0.36	€0.71	€0.44	€0.68	€1.47	€0.62	€0.97	€2.30
	2%	€-0.06	€-0.09	€-0.16	€0.31	€0.46	€0.90	€0.51	€0.78	€1.68	€0.68	€1.07	€2.53
	0%	€0.00	€0.00	€0.00	€0.37	€0.55	€1.10	€0.57	€0.88	€1.89	€0.74	€1.16	€2.76
3 storeys	4%	€-0.09	€-0.12	€-0.21	€0.24	€0.35	€0.68	€0.40	€0.61	€1.29	€0.63	€0.99	€2.33
	2%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.87	€0.47	€0.71	€1.49	€0.69	€1.08	€2.54
	0%	**€0.04**	**€0.05**	€0.09	€0.36	€0.54	€1.05	€0.53	€0.80	€1.69	€0.75	€1.17	€2.76

Table 82: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Decreases concrete slab floors reinforcement -10%

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.69	€1.05	€2.13	€0.89	€1.40	€3.25	€1.04	€1.67	€4.27	€1.23	€2.04	€5.98
	2%	€0.77	€1.16	€2.36	€0.96	€1.51	€3.52	€1.11	€1.78	€4.56	€1.30	€2.15	€6.30
	0%	€0.84	€1.27	€2.58	€1.04	€1.63	€3.78	€1.18	€1.89	€4.84	€1.36	€2.26	€6.61
9 storeys	4%	**€0.05**	**€0.07**	€0.12	€0.42	€0.64	€1.34	€0.55	€0.86	€1.92	€0.78	€1.25	€3.16
	2%	€0.12	€0.17	€0.30	€0.49	€0.74	€1.55	€0.62	€0.96	€2.16	€0.84	€1.35	€3.41
	0%	€0.18	€0.27	€0.48	€0.56	€0.85	€1.77	€0.69	€1.07	€2.39	€0.90	€1.45	€3.67
5 storeys	4%	€-0.13	€-0.18	€-0.31	€0.24	€0.36	€0.70	€0.44	€0.68	€1.44	€0.61	€0.96	€2.25
	2%	€-0.06	€-0.09	€-0.16	€0.30	€0.45	€0.89	€0.50	€0.77	€1.65	€0.67	€1.06	€2.47
	0%	€0.00	€0.00	€0.00	€0.37	€0.55	€1.08	€0.57	€0.87	€1.85	€0.73	€1.15	€2.70
3 storeys	4%	€-0.09	€-0.12	€-0.21	€0.23	€0.35	€0.67	€0.40	€0.61	€1.27	€0.63	€0.98	€2.28
	2%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.85	€0.46	€0.70	€1.46	€0.68	€1.07	€2.49
	0%	**€0.04**	**€0.05**	€0.09	€0.36	€0.53	€1.03	€0.52	€0.80	€1.65	€0.74	€1.16	€2.70

Table 83: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Concrete strength class C40.50 instead of C30/37

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.64	€0.94	€1.73	€0.83	€1.25	€2.57	€0.97	€1.50	€3.33	€1.16	€1.85	€4.56
	2%	€0.71	€1.04	€1.91	€0.90	€1.36	€2.78	€1.04	€1.61	€3.55	€1.22	€1.94	€4.80
	0%	€0.78	€1.14	€2.09	€0.97	€1.46	€2.99	€1.10	€1.71	€3.78	€1.28	€2.04	€5.04
9 storeys	4%	**€0.04**	**€0.06**	€0.10	€0.39	€0.58	€1.09	€0.52	€0.78	€1.55	€0.73	€1.13	€2.50
	2%	€0.11	€0.15	€0.25	€0.46	€0.67	€1.27	€0.58	€0.87	€1.74	€0.79	€1.22	€2.71
	0%	€0.17	€0.24	€0.40	€0.52	€0.76	€1.44	€0.64	€0.97	€1.93	€0.85	€1.32	€2.91
5 storeys	4%	€-0.12	€-0.16	€-0.26	€0.22	€0.32	€0.57	€0.41	€0.61	€1.17	€0.57	€0.87	€1.80
	2%	€-0.06	€-0.08	€-0.13	€0.28	€0.41	€0.73	€0.47	€0.70	€1.34	€0.63	€0.96	€1.98
	0%	€0.00	€0.00	€0.00	€0.34	€0.49	€0.88	€0.53	€0.78	€1.50	€0.69	€1.04	€2.16
3 storeys	4%	€-0.08	€-0.11	€-0.17	€0.22	€0.31	€0.54	€0.37	€0.54	€1.01	€0.58	€0.88	€1.79
	2%	€-0.02	€-0.03	€-0.05	€0.27	€0.39	€0.69	€0.43	€0.63	€1.17	€0.64	€0.96	€1.96
	0%	**€0.03**	**€0.05**	**€0.08**	€0.33	€0.47	€0.83	€0.49	€0.71	€1.32	€0.69	€1.04	€2.13

Table 84: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Reduce foundation timber variant with 100% of the load difference

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.67	€1.01	€2.07	€0.87	€1.37	€3.19	€1.02	€1.64	€4.22	€1.21	€2.01	€5.94
	2%	€0.74	€1.12	€2.30	€0.94	€1.48	€3.46	€1.09	€1.75	€4.51	€1.28	€2.12	€6.27
	0%	€0.82	€1.23	€2.52	€1.01	€1.60	€3.73	€1.16	€1.86	€4.80	€1.34	€2.23	€6.59
9 storeys	4%	**€0.02**	**€0.02**	**€0.04**	€0.39	€0.59	€1.24	€0.52	€0.81	€1.82	€0.75	€1.20	€3.04
	2%	**€0.08**	€0.12	€0.22	€0.46	€0.70	€1.45	€0.59	€0.92	€2.05	€0.81	€1.30	€3.30
	0%	€0.15	€0.22	€0.40	€0.52	€0.80	€1.67	€0.66	€1.02	€2.29	€0.88	€1.41	€3.55
5 storeys	4%	€-0.17	€-0.24	€-0.42	€0.19	€0.29	€0.56	€0.40	€0.60	€1.28	€0.57	€0.89	€2.08
	2%	€-0.11	€-0.15	€-0.26	€0.26	€0.38	€0.75	€0.46	€0.70	€1.49	€0.63	€0.99	€2.30
	0%	€-0.04	€-0.06	€-0.11	€0.32	€0.48	€0.93	€0.52	€0.80	€1.69	€0.69	€1.08	€2.52
3 storeys	4%	€-0.15	€-0.21	€-0.35	€0.18	€0.26	€0.49	€0.34	€0.52	€1.07	€0.57	€0.90	€2.06
	2%	€-0.08	€-0.12	€-0.20	€0.24	€0.35	€0.67	€0.41	€0.61	€1.26	€0.63	€0.99	€2.26
	0%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.85	€0.47	€0.71	€1.45	€0.69	€1.08	€2.47

Table 85: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, Prefab core instead of in situ core

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.70	€1.06	€2.18	€0.90	€1.41	€3.33	€1.04	€1.69	€4.38	€1.24	€2.06	€6.15
	2%	€0.77	€1.17	€2.41	€0.97	€1.53	€3.60	€1.11	€1.80	€4.68	€1.30	€2.17	€6.48
	0%	€0.84	€1.28	€2.64	€1.04	€1.64	€3.87	€1.18	€1.91	€4.97	€1.37	€2.28	€6.81
9 storeys	4%	**€0.05**	**€0.07**	€0.13	€0.42	€0.65	€1.36	€0.56	€0.87	€1.97	€0.78	€1.26	€3.23
	2%	€0.12	€0.17	€0.31	€0.49	€0.75	€1.58	€0.62	€0.97	€2.21	€0.85	€1.36	€3.49
	0%	€0.19	€0.27	€0.49	€0.56	€0.85	€1.80	€0.69	€1.08	€2.45	€0.91	€1.47	€3.76
5 storeys	4%	€-0.13	€-0.18	€-0.32	€0.24	€0.36	€0.71	€0.44	€0.68	€1.47	€0.62	€0.97	€2.30
	2%	€-0.06	€-0.09	€-0.16	€0.31	€0.46	€0.90	€0.51	€0.78	€1.68	€0.68	€1.07	€2.53
	0%	€0.00	€0.00	€0.00	€0.37	€0.55	€1.10	€0.57	€0.88	€1.89	€0.74	€1.16	€2.76
3 storeys	4%	€-0.09	€-0.12	€-0.21	€0.24	€0.35	€0.68	€0.40	€0.61	€1.29	€0.63	€0.99	€2.33
	2%	€-0.02	€-0.03	€-0.06	€0.30	€0.44	€0.87	€0.47	€0.71	€1.49	€0.69	€1.08	€2.54
	0%	**€0.04**	**€0.05**	€0.09	€0.36	€0.54	€1.05	€0.53	€0.80	€1.69	€0.75	€1.17	€2.76

Table 86: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, All EPD's low value

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.81	€1.35	€4.01	€1.01	€1.73	€6.04	€1.16	€2.02	€7.86	€1.35	€2.40	€10.88
	2%	€0.90	€1.49	€4.43	€1.10	€1.88	€6.53	€1.24	€2.16	€8.39	€1.42	€2.52	€11.46
	0%	€0.98	€1.64	€4.86	€1.18	€2.02	€7.02	€1.31	€2.29	€8.91	€1.49	€2.65	€12.04
9 storeys	4%	**€0.06**	€0.09	€0.24	€0.49	€0.82	€2.51	€0.63	€1.08	€3.59	€0.87	€1.52	€5.84
	2%	€0.14	€0.23	€0.58	€0.57	€0.95	€2.92	€0.71	€1.21	€4.03	€0.94	€1.64	€6.32
	0%	€0.22	€0.36	€0.92	€0.65	€1.08	€3.32	€0.79	€1.34	€4.47	€1.01	€1.76	€6.79
5 storeys	4%	€-0.16	€-0.25	€-0.59	€0.28	€0.47	€1.31	€0.51	€0.86	€2.69	€0.69	€1.19	€4.17
	2%	€-0.08	€-0.12	€-0.30	€0.36	€0.59	€1.67	€0.58	€0.98	€3.07	€0.76	€1.31	€4.58
	0%	€0.00	€0.00	€0.00	€0.44	€0.72	€2.02	€0.66	€1.10	€3.46	€0.83	€1.43	€5.00
3 storeys	4%	€-0.11	€-0.17	€-0.39	€0.28	€0.45	€1.24	€0.47	€0.78	€2.33	€0.71	€1.21	€4.16
	2%	€-0.03	€-0.05	€-0.11	€0.35	€0.57	€1.58	€0.54	€0.90	€2.69	€0.77	€1.32	€4.55
	0%	**€0.05**	**€0.07**	€0.17	€0.42	€0.69	€1.91	€0.61	€1.01	€3.05	€0.84	€1.44	€4.93

Table 87: Required CO_2 price for equal potential profit of a timber and a concrete structure in the parameter study, All EPD's high value

	Additional revenue	**3.6 m span**			**4.8 m span**			**5.4 m span**			**6.0 m span**		
		Carbon storage			Carbon storage			Carbon storage			Carbon storage		
		100%	50%	0%	100%	50%	0%	100%	50%	0%	100%	50%	0%
20 storeys	4%	€0.56	€0.80	€1.44	€0.73	€1.10	€2.22	€0.86	€1.34	€3.00	€1.04	€1.67	€4.33
	2%	€0.61	€0.89	€1.60	€0.79	€1.19	€2.41	€0.92	€1.43	€3.20	€1.09	€1.76	€4.56
	0%	€0.67	€0.97	€1.75	€0.85	€1.28	€2.59	€0.97	€1.51	€3.40	€1.15	€1.85	€4.79
9 storeys	4%	**€0.04**	**€0.05**	€0.09	€0.34	€0.50	€0.93	€0.45	€0.68	€1.36	€0.65	€1.01	€2.29
	2%	€0.09	€0.13	€0.21	€0.40	€0.58	€1.08	€0.51	€0.76	€1.52	€0.70	€1.09	€2.48
	0%	€0.15	€0.20	€0.33	€0.45	€0.66	€1.24	€0.56	€0.85	€1.69	€0.76	€1.18	€2.66
5 storeys	4%	€-0.10	€-0.14	€-0.22	€0.19	€0.28	€0.49	€0.36	€0.53	€1.02	€0.51	€0.77	€1.62
	2%	€-0.05	€-0.07	€-0.11	€0.25	€0.35	€0.62	€0.41	€0.61	€1.16	€0.56	€0.85	€1.78
	0%	€0.00	€0.00	€0.00	€0.30	€0.43	€0.75	€0.46	€0.68	€1.31	€0.61	€0.93	€1.94
3 storeys	4%	€-0.07	€-0.09	€-0.14	€0.19	€0.27	€0.46	€0.32	€0.47	€0.88	€0.52	€0.78	€1.62
	2%	€-0.02	€-0.03	€-0.04	€0.24	€0.34	€0.59	€0.37	€0.55	€1.02	€0.56	€0.86	€1.77
	0%	**€0.03**	**€0.04**	**€0.06**	€0.29	€0.41	€0.71	€0.42	€0.62	€1.15	€0.61	€0.93	€1.92

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