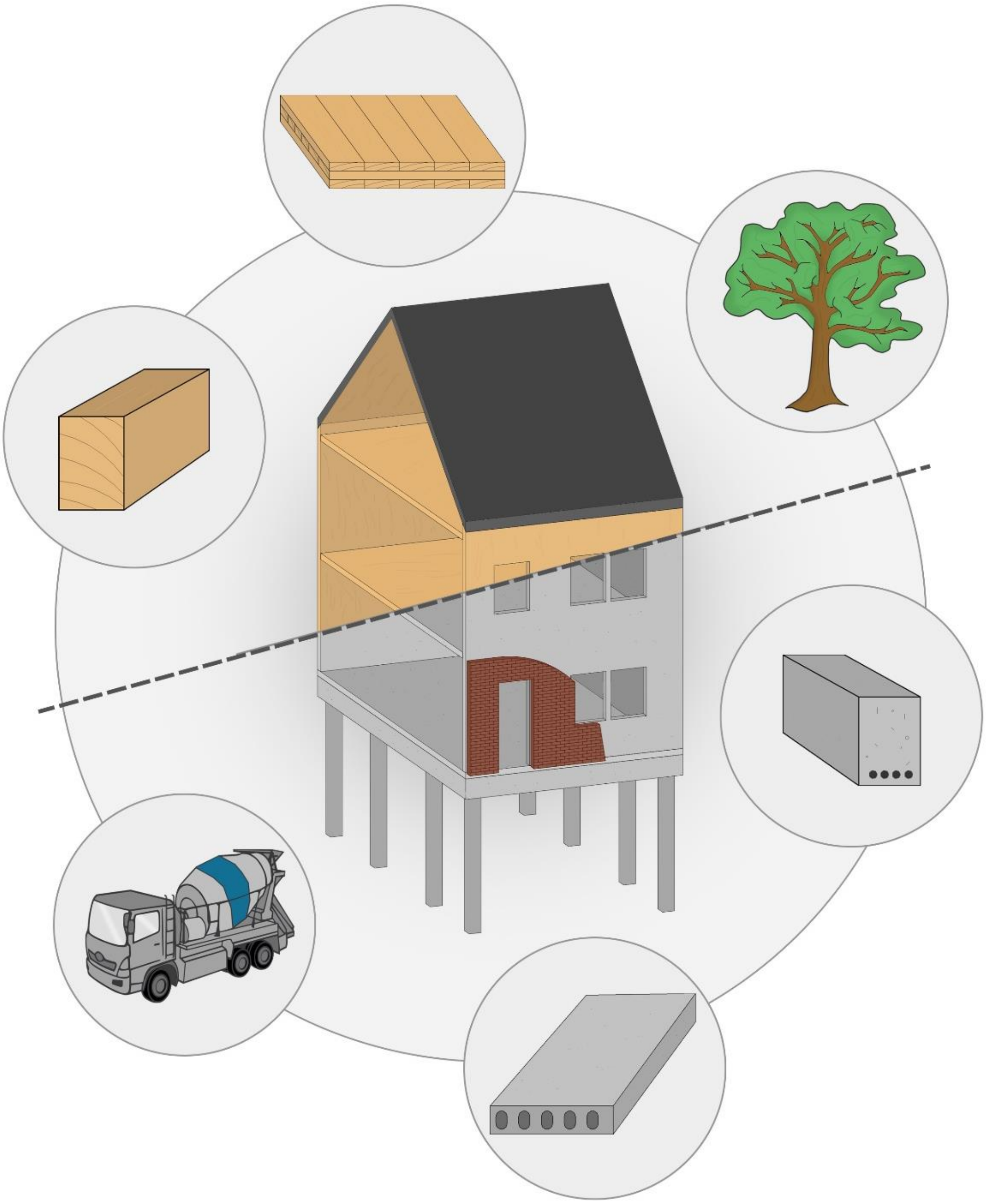
THE ENVIRONMENTAL IMPACT OF STRUCTURAL ELEMENTS MADE OF CONCRETE COMPARED TO TIMBER

A case study of terraced housing in the Netherlands



MSC THESIS

TU Delft, MSc Civil Engineering, track Building Engineering

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THE ENVIRONMENTAL IMPACT OF STRUCTURAL ELEMENTS MADE OF CONCRETE COMPARED TO TIMBER

A case study of terraced housing in the Netherlands

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PREFACE

This is the Master Thesis that is made as the last project before obtaining a Master's degree of Civil Engineering at the Delft University of Technology in Building Engineering within the Structural Design track.

I started my study at the TU Delft as an Architecture student. After I received my Bachelor's degree in Architecture, I decided that I wanted to take the engineering route and switched to Civil Engineering. Here I started the Master Building Engineering. I focused less on the architectural design and more on the structural aspects of a building. In my opinion, Architecture and Structural Engineering go hand in hand when it comes to an efficient building. You need both, even though the fields might be contradicting at times. I am very happy I got to experience both perspectives in my studies.

At both Architecture and Civil Engineering, we have learned that it is important to build environmentally friendly, making sustainable homes or other sustainable buildings, which do not need much energy during the building process, or when it is in use. How can this be achieved? We were taught some useful tips and tricks about insulation, green energy, flexible layouts and so on. What we did not learn was how to decide which construction material to use. I remember one of my teachers saying: "just pick one". Other teachers said that timber was a more sustainable option then concrete or steel, but why was never elaborated. It was implied to be general knowledge. The first time this issue was fully elaborated, was in the course Materials and Ecological Engineering. Here, we learned that determining the best construction material is not easily done. There are a lot of factors that will influence the outcome. We learned about shadow costs and the Life Cycle Analysis.

As engineers we are taught to not blindly follow rules or trends. This is exactly what I plan on doing. Is the current timber trend justifiable?

I would like to thank my committee: Roel Schipper, Chris Noteboom, Henk Jonkers and Wolfgang Gard, for giving me guidance, especially in these digital times of Covid-19. I also want to thank contractor Kroon en de Koning for helping to find a suitable case study and providing the needed documents to use. Especially, Ivo Zweekhorst, the director, and Loek Vriends, the project manager of The Laantjes in Hendrik-Ido-Ambacht. I would also like to thank Cassey, Lindy, Nina and Floor for correcting my spelling and grammar and lastly, my friends and family for their opinions and support.

I enjoyed expanding my knowledge of life cycle assessments and sustainability concepts in the construction sector. This knowledge will be very useful, as there is increased awareness for sustainability in the construction sector. This topic interests me because it is a very relevant problem in the market nowadays. It seems to me that there are few people who have the required knowledge to be able to give a good answer to this issue. As a structural engineer to be, I therefore think it is very important to delve into this topic. This knowledge will contribute to my expertise in a positive way.

- Marit Nijman, Zwijndrecht, 14-12-21

SUMMARY

This research tries to answer the question which construction material, concrete or timber, is best to use during the construction of terraced housing in the Netherlands, based on the environmental performance. Existing studies often do not take all aspects of a design for the comparison into account, or have a bias toward one material. In order to investigate the main research question, a literature study has been executed together with a practical case study.

The environmental performance can be determined with the Life Cycle Assessment (LCA) method. The LCA divides the life of a building, product or half-product, into stages A to D. With the LCA method, the shadow costs of a product can be determined. The shadow costs are the costs that would be needed to undo the environmental damage. In order to compare two different materials, it is important to make sure that the basis of the comparison is equal.

Five similar studies have been investigated, which compare concrete and timber as a construction material, based on the environmental impact:

- Study 1 – A Swedish study executed by the SP technical research institute in 2018. Hypothetical designs for an apartment complex in both concrete and timber are evaluated over LCA stages A-C. The designs include durability, loadbearing capacity and energy usage during utilization. The researchers concluded that there are no significant differences between the construction materials. It is good to note that during this research both the concrete and timber industry were consulted, resulting in an optimal LCA for both materials. CO_2 storage was not included in this study.
- Study 2 – A Dutch study executed by NIBE in 2019. A concrete corner house was redesigned with timber. The MPG was determined, this includes stages A-D, with the addition of carbon storage. The timber variant preformed 20% better. However, the calculations were not transparent.
- Study 3 – Another Dutch study, this one executed by W/E adviseurs on behalf of NBvT (timber industry) in 2016. Several standard residence typologies were designed with traditional or timber building materials. The MPG was used, so stages A-D were compared. It was not mentioned if stored CO_2 was included. The timber variant preformed 24% better. However, the calculations were not transparent.
- Study 4 – An English study by A. Zeitz et al in 2019. They compared existing parking garages over stages A1-A3. Even though the calculations show that the timer variant performed 29% better, the conclusion was that there were too many variables to determine which is better. CO_2 storage was presumably not included.
- Study 5 – An Australian study executed by D. Thomas et al in 2018. Several brick residences were redesigned with timber and compared over stages A-C. The redesign included the thermal comfort especially. The researchers concluded that there was no significant difference. CO_2 storage was presumably not included.

These studies show that there are several ways to execute an LCA comparison. Three aspects about the executions are notable, that influence the outcome of the comparisons. The first aspect is the model that is used: are the compared models real or hypothetical and do they fulfil the same requirements. The next aspect is the system boundaries of the LCA. It is safe to say that the more stages are added in the comparison, the more the conclusion is meaningful. However, adding more stages also means that the end-of-life of a product has to be predicted, what can lead to inaccuracies. The last aspect is what database is used. This has a high impact on the outcome, so using a good data source is important.

For the case study in this thesis, several structural elements in project “De Laantjes” in Hendrik-Ido-Ambacht are redesigned, in both concrete and timber alternatives. A central residence of a block of

terraced houses is selected. This residence has 3 stories that are 2,9 meters high. The house has a width of 5,4 meters and depth of 9,2 meters.

The alternative designs do not just take the imposed loads into account, but multiple functional requirements. The requirements included in this study are: strength, deflection, fire resistance, thermal insulation, sound resistance and vibration resistance. To determine requirements according to the Dutch regulations, the Dutch norms and the Bouwbesluit have been consulted.

The shadow costs per alternative design are determined for three levels. Each level includes more LCA stages, becoming more complete, but also adding more uncertainties. The levels are: stage A1-A3, A-C and A-D. The costs are determined for the entire reference life of 75 years. If a part can be used for longer than 75 years, this has been included in stage D. For the end of life it is assumed that the construction materials are recycled and not re-used. These calculations follow the Dutch regulation described in the "Bepalingsmethode" which refers to NEN-EN 15804 and NEN-EN-ISO 14040. The important aspects of the approach of the comparison are listed below:

- The redesigns are made on elemental level, taking the unchanged case study as the starting point to identify spans and loads.
- The elements need to fulfill all requirements for strength, deflection, fire resistance, thermal insulation, sound resistance and vibration resistance, not just the loadbearing capacity.
- Other characteristics like costs are ignored.
- The load schemes are simplified, excluding the openings for windows, doors and stairs. Also, some requirements were tested using simplified rules, or rules of thumb.
- The LCA calculation is based on the category three data (public, non-specific data) of the Nationale Milieu Database (NMD).
- Assumptions have been made about travel distances, means of transport and building processes that might not be the same as what would actually occur.
- It is assumed that at the end-of-life the construction materials are recycled, not re-used. Used concrete becomes 40% of new concrete, used reinforcement steel becomes 75% of new steel and used timber becomes 48% of new chipboard. The benefits in stage D are calculated using these percentages and multiplying them with the A1-A3 values of the new product.
- The current Dutch code does not take stored CO_2 into account, because the timber products are currently expected to be burned at the end-of-life. However, as the elements in this study are assumed to be recycled, an estimation is given of how this storage influences the shadow costs if it were taken into account.

The lowest shadow costs, according to the current Dutch code, are highlighted per LCA level. The shadow costs including the carbon storage are given in brackets.

	Variant	Materials	Shadow costs
Intermediate Floor (L = 5,4 m)	Hollow core slab	70 mm screed 200 mm hollow core slab	A1-A3: **€4,56/m²** A-C: **€5,93/m²** A-D: **€4,05/m²**
	Cast in situ concrete	70 mm screed 170 mm cast concrete With 10Ø10 mm reinforcement	A1-A3: €7,74/m² A-C: €9,23/m² A-D: €5,79/m²
	CLT	70 mm screed 220 mm CLT	A1-A3: €8,56/m² A-C: €10,39/m² A-D: €7,88/m² (A-D*: €1,08/m²)
	LVL	70 mm screed 25 mm LVL 45x240 mm LVL 90 mm mineral wool 25 mm gypsum board	A1-A3: €6,60/m² A-C: €8,08/m² A-D: €7,50/m² (A-D*: €6,15/m²)

Façade (bxh = 5,4x2,9 m)	Precast concrete	100 mm brick 40 mm cavity 140 mm rock wool 90 mm concrete (with reinf.)	A1-A3: €8,46/m² A-C: €9,21/m² A-D: €7,30/m²
	Cast in situ concrete	100 mm brick 40 mm cavity 140 mm rock wool 90 mm concrete (with reinf.)	A1-A3: €9,16/m² A-C: €9,97/m² A-D: €8,12/m²
	CLT	100 mm brick 40 mm cavity 140 mm rock wool 80 mm CLT	A1-A3: €8,36/m² A-C: €8,71/m² A-D: €7,80/m² (A-D*: €5,56/m²)
	HSB	100 mm brick 40 mm cavity 120 mm HSB frame + rock wool	A1-A3: **€6,56/m²** A-C: **€7,26/m²** A-D: **€7,14/m²** (A-D*: €6,24/m²)
Load bearing wall (bxh = 9,2x2,9 m)	Precast concrete	100 mm concrete (with reinf.) 100 mm concrete (with reinf.)	A1-A3: **€5,00/m²** A-C: **€5,33/m²** A-D: **€1,50/m²**
	Cast in situ concrete	100 mm concrete (with reinf.) 100 mm concrete (with reinf.)	A1-A3: €6,77/m² A-C: €7,15/m² A-D: €3,28/m²
	CLT	30 mm gypsum board 100 mm CLT 40 mm rock wool 100 mm CLT 30 mm gypsum board	A1-A3: €7,59/m² A-C: €7,91/m² A-D: €5,63/m² (A-D*: €-0,57/m²)
Ground floor (L = 5,4 m)	Rib cassette floor	70 mm screed 300 mm Rib cassette floor +EPS	A1-A3: €8,67/m² A-C: €10,23/m² A-D: **€6,74/m²**
	CLT	70 mm screed 180 mm CLT 130 mm EPS	A1-A3: **€8,16/m²** A-C: **€9,93/m²** A-D: €7,88/m² (A-D*: €2,28/m²)
Foundation (Beam = 5,4 m) (Pile = 18 m)	Concrete beam	400 x 500 mm concrete 4Ø15mm reinforcement	A1-A3: €6,28/m A-C: €6,68/m A-D: €3,16/m
	Timber beam	400 x 500 mm hardwood	A1-A3: **€3,95/m** A-C: **€4,75/m** A-D: **€2,47/m** (A-D*: €-11,53/m)
	Concrete pile	Ø 320 mm concrete (with reinf.) (1 pile for N_{ed}= 479 kN)	A1-A3: €31,56/pile A-C: **€230,72/pile** A-D: **€199,16/pile**
	Timber piles (5)	Ø 210 mm (average) spruce Concrete topping (5 piles for each N_{ed}= 479/5 kN)	A1-A3: **€18,26/piles** A-C: €681,56/piles A-D: €663,30/piles (A-D*: €566,05/piles)

TABLE 1: SHADOW COSTS ALTERNATIVE ELEMENT DESIGNS FOR CASE STUDY DE LAANTJES

*Including carbon storage

As can be seen in table 1, some elements need additional materials to fulfill all mentioned requirements. The intermediate floor element has four alternatives: a hollow core slab, cast in situ concrete, cross laminated timber (CLT) and a laminated veneer lumber (LVL) floor. The designs that use the least materials: the hollow core slab and the LVL variant, score best in stages A1-A3. The hollow core slab has the lowest scores, as besides the concrete, no additional materials are needed to be produced. The stages A4-D are quite similar for all variants. This leaves the hollow core slab the most favorable with these stages added.

The façade wall is also redesigned with four alternatives: prefab concrete, cast in situ concrete, CLT and a wood frame construction (HSB). Even though the concrete variants are very similar in design, the prefab design scores better in the A1-A3 phase. The opposite was expected, since the variants have the same input materials, but the prefabricated variant has more processes in this stage. This shows how much the data can vary. The HSB wall is favorable in stages A1-A3, as it has less materials in total. The stages A4-C are quite similar for the variants, making the HSB sill favorable. Stage D changes this, as the CLT and concrete design have more material that can be used in a next cycle. However, the HSB variant remains the most favorable.

Next, the loadbearing wall. For this element three alternatives were designed: prefab concrete, cast in situ concrete and CLT. Again, the prefab concrete wall is favorable in stages A1-A3 over the cast in situ variant. The CLT design has a higher A1-A3 cost, partially because this design needs additional materials for fire protection and sound insulation. The stages A4-C are quite similar for all variants. Stage D is more favorable for the concrete designs, as all materials of the element can be re-used, which is not the case for the timber variant. This results in the prefab variant being most favorable.

The ground floor only has two variants: rib cassette floor and CLT. Both variants are insulated with EPS, as this can withstand the moisture in the crawlspace. The product stage, A1-A3, is very similar for both designs. The same holds for the staged A4-C. In stage D, the concrete has more benefits from re-use than the timber variant, making the concrete variant more favorable over all.

For the foundation, two designs have been compared: the existing concrete variant, with a cast beam and vibro piles, and a timber variant, with hardwood beams and spruce piles with a concrete topping where the groundwater varies. Starting with the beams: the differences in the product phase are caused by the materials, given timber an advantage. For stage A5, concrete only needs a pump mixer, where the timber variant needs a crane. This gives concrete a slight advantage. The benefits in stage D are similar for both materials, making the timber beam have a lower shadow cost overall.
Next, the piles: because the timber pile has a smaller surface, less ground pressure resistance can occur. Therefore, more piles are needed to carry the same load. The original designed concrete pile has an axial force of 479 kN. It is assumed that this load can be carried by five timber piles. Even though five piles are needed in the timber variant, this is still more environmentally friendly for stages A1-A3. The costs in A4 are bigger for the timber piles, because more piles are transported and concrete for the toppings needs to be transported. For the concrete piles, only one steel mold needs to be transported together with the concrete tips and reinforcement by truck. The concrete is transported with a truck mixer. The biggest difference in costs occurs in stage A5. The driving of the piles have a relatively high cost, so needing to drive five piles instead of one makes the concrete piles preferable. Even when taking into account that driving a timber pile costs less energy, because the pile has a smaller diameter.

The combination of the variable input data and the assumption made relating to the building process, make these shadow costs estimations and not precise numbers. The differences between the shadow costs of the alternative designs are not significant enough to conclude which material is best to use during the construction, based on the environmental impact for this specific terraced house. The only element that did show a significant difference, was the foundation pile: concrete piles are better to use in this case study, based on the environmental impact.

Whether or not the CO_2 storage is taken into account, has a high impact on the shadow costs. The difference in the estimated shadow costs including carbon storage for the alternative designs are significant enough to conclude that for the walls and floors the CLT variants are better to use. For the foundation beam, hard wood is better to use than concrete and the piles are still better in concrete, based on the environmental impact.

How this storage should actually be included in the Dutch regulations, is still discussed. This shows that besides the data source and the assumptions about the building process, the regulations have a high impact on the outcome of an LCA comparison.

The industry is changing rapidly. Besides the evolving regulations, new developments can change the input of the shadow cost calculation. Once these new developments can be used in practice, the environmental data has to be adjusted. For this research, this would mean that the environmental data input changes, making a totally new conclusion possible.

Even though the outcome of the LCA calculations are an estimation and not a precise number, this study still shows a valid way to compare different building materials in a relatively fair way. The basis of the comparison was equal by including various functional performance demands and comparing the fully designed elements per unit, rather than just including the construction material itself. The accuracy of the shadow costs is highly dependent on the input data and the assumptions made about the building process in the LCA calculation. These inputs of the calculation can be changed, making this study relevant for all similar cases, including future projects.

CONTENTS

1. INTRODUCTION

The impact of the construction industry on the global environment is significant. From the 1970s onwards, initially the scarcity of fossil materials became a focal point. Over the last decades, global warming has become a much larger concern. Construction is an important source of CO_2 production: "Building construction emissions – those related to the manufacturing of building materials – amounted to 11 Gt CO_2 in 2018, for a total of 39% of global energy-related emissions" (IEA, 2019).

Therefore, for students in the field of civil engineering who will be in the position to have a big impact on design and construction choices, it is important to have an unbiased perspective on the choice for construction materials.

Information on sustainability of construction materials at universities is offered in different courses, by scientists with focused specialisms. As a result it can be challenging for students to get a clear overview of the environmental impact of materials. Methods for assessment and comparison of construction materials are still under development and not widely used in legislation. Another complication is that professional trade magazines (e.g. Cement, Bouwen met Staal or Het Houtblad, three Dutch magazines for structural design in concrete, steel and timber) may not provide unbiased information, since publishers are collaborating with or are even financially supported by the industries that manufacture or process these construction materials. For students, and also people working in the construction field, it is not always clear that this bias is something to be aware of. Therefore, this MSc thesis will focus on using unbiased information and comparing building materials in a methodologically fair way.

1.1 RESEARCH OBJECTIVES

For this thesis the building material concrete will be compared with the building material timber. The comparison will include aspects like where the materials come from, how they are put together, how they function within a building and what happens when the building is demolished. Furthermore, the performance such as the fire safety, strength and vibration resistance will be addressed. Lastly, the future developments like the Smartcrusher and geopolymer concrete will be elaborated and how these might influence the comparison will be discussed.

It is important to take the environmental impact of buildings into account. The method used to do this should be objective and transparent. Also, the method should allow to compare different building materials. A lot of times the comparison is done comparing 1 kg of material with another. However, only when full structural elements are designed with the same performance, a fair environmental comparison can be made. This study is focused on making such a fair comparison for a specific case study, aiming to be objective and transparent.

The case study used for the comparison is project "De Laantjes". De Laantjes is a project undertaken by "Kroon en de Koning" in the Volgerlanden in Hendrik Ido Ambacht. The project has a wide variety of homes. For this thesis, block 1A of the project will be used. This is a terraced house block with six residences. The existing construction consists mainly of prefabricated concrete elements.

1.2 RESEARCH QUESTIONS

The main question for this thesis is as follows:

- Which construction material: concrete or timber, is more suitable to use during the construction of the following basic elements of a terraced house in the Netherlands, based on the environmental impact: ground floor, intermediate floor, façade, load baring wall and foundation?

This question will be answered by means of sub-questions:

- In what way do concrete and timber differ in structural performance?
- And in environmental performance?
- What is the LCA method and can it be used to compare concrete and timber in a fair way?
- What are the functional requirements of following elements in order to perform in case study De Laantjes: ground floor, intermediate floor, façade, load baring wall and foundation?
- Given the loads, load scheme and functional requirements of case study "De Laantjes", what dimensions should the mentioned elements have when designed with commonly used timer and concrete systems?
- What are the shadow costs of the designed elements for "De Laantjes"?
- What are the most environmental impact determining factors for the designed elements?
- Which of the designed elements are the most environmentally friendly, based on the shadow costs?
- How might several new developments in the construction industry influence the findings of this research?

1.3 RESEARCH APPROACH

To answer these questions, a literature study will be used combined with a practical case study. The LCA method and ECI calculations will be evaluated by looking at how the values are determined. During this research a distinction is made between the different building components: ground floor, intermediate floor, façade, load bearing wall, foundation beam and piles. When is which material the most suitable?

In general the report will be divided into the seven parts:

- Part 0: Introduction

The subjects is introduced and the outline of the thesis is discussed.

- Part 1: Background information

The theory of sustainability is elaborated and The LCA method and shadow cost indication are introduced.

- Part 2: Functional properties

The differences in properties of the two materials are determined

- Part 3: Environmental performance

Fist the environmental performance of concrete and timber is discusses. Next, the LCA is elaborated, focusing on the comparison of concrete and timber, looking at each stage of the LCA.

- Part 4: Case study

The case study is introduced and alternative designs are made for the mentioned elements. Next, the shadow costs are determined for the alternatives.

- Part 5: Developments

Several changes in the market will be discussed that might influence the findings of this thesis

- Part 6: Final remarks

The discussion, conclusion and the recommendations are given.

1.4 RESEARCH OUTLINE

In general, the report will look like this:

Part 0: Introduction	1. Introduction			
Part 1: Background information	2. Sustainability	3. LCA: Life cycle assessment		
Part 2: Functional properties	4. Functional properties of concrete and timber			
Part 3: Environmental performance	5. Environmental performance concrete and timber	6. LCA of concrete and timber		
Part 4: Case study	7. Case study: introduction	8. Case study: Functional requirements	9. Case study: LCA approach	10. Case study: Design
Part 5: Developments	11. Developments in sustainability			
Part 6: Final remarks	12. Discussion	13. Conclusion	14. Recommendations	

Part 1: Background Information

2. Sustainability

2.1 Demands in the building industry

A lot of regulations are created to preserve our environment. The amount of greenhouse gasses that is released into our atmosphere is one of the problems that is being restricted. In the Netherlands, with the National Climate Agreement, the government has a central goal: to reduce greenhouse gas emissions in the Netherlands by 49% compared to the amount in 1990. The government advocates a 55% reduction in greenhouse gas emissions in Europe by 2030 (Klimaatakkoord, 2019). Also, a target has been set to transfer from a linear to a circular economy by 2050 (Rijksoverheid et al., 2016). However, all this is contradicting with the current situation of housing shortage in the Netherlands. The marked has to build more, whilst at the same time reducing its environmental footprint (Van Wijnen, 2020).

In addition to this, utility and residential buildings should since 2021 be built as "Bijna Energie Neutrale gebouwen" or BENG. This is an energy performance demand that is determined by three individually achievable requirements: the maximum energy requirement, the maximum primary fossil energy use and the minimum share of renewable energy (Rijksoverheid, 2020).

Furthermore, according to the "Bouwbesluit 2012", for all houses and office buildings built after January 1st 2013 with a total user surface larger than 100 m^2, an environmental impact calculation must be made. This calculation must be done according to the procedure defined by the Stichting Bouwkwaliteit: "Estimation method for calculating environmental impact of buildings and civil engineering constructions" (Bepalingsmethode Milieuprestatie Gebouwen en GWW werken) including at least the 11 environmental impact categories related to environmental costs for involved emissions of harmful compounds and utilization of finite resources. What this is will be discussed in chapter 3.

2.2 Sustainability

In order to determine which material, concrete or timber, is more sustainable to use, sustainability must be defined. In the dictionary it states to be "something that is able to be maintained at a certain rate or level". In the building industry the definition is a bit different.

In 1987, The World Commission on Environment and Development (or the Brundtland Commission) wrote the report "Our Common Future". This formulated a long-term strategy regarding sustainability. It defined sustainable development as follows: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. " (*The World Commission on Environment and Development, Our Common Future*, 1987) It also defined four "needs" which would indicate the lever of prosperity: availability of finite resources; clean environment by minimizing harmful emissions; social fairness and economic growth. (Jonkers, 2020)

In 2020, Peters Ro et al. interpreted these definitions for structural engineers. They became: "Increase service life of buildings; limit material use; use sustainable materials; consider the environmental impact of construction and transport; and design the structure for circular use in the future." (Peters Ro et al., 2020)

2.3 Circularity

In the last 100 years the raw material extraction has increased 20 times (Partnership & Materials, 2018). This is due to the increase in world population and the developing of growing regions. The need for resources will further increase, as the population and developments are still increasing. This conflicts with the need for the sustainability of the earth. There will be environmental consequences, but also economical, as the scarcity of materials will influence the import and export of those materials. The Netherlands, for example, imports 68% of raw materials (Rijksoverheid et al., 2016). If those materials are scarce, building will become more expansive.

Within the above definition of sustainability, circularity plays an important role since it limits the use of (finite) resources. A circular economy can be interpreted in many ways. Kircherr et al. analyzed 114 different definitions to conclude the following definition: "Circular economy is an economic system that replaces the 'end-of-life' concept with reducing, alternatively re-using, recycling and recovering materials in production/distribution and consumption processes" (Kirchherr et al., 2017). The Ellen MacArthur foundation differentiates two types of circularity cycles: biological cycles and technical cycles, see figure 1 (Ellen MacArthur Foundation, 2015).

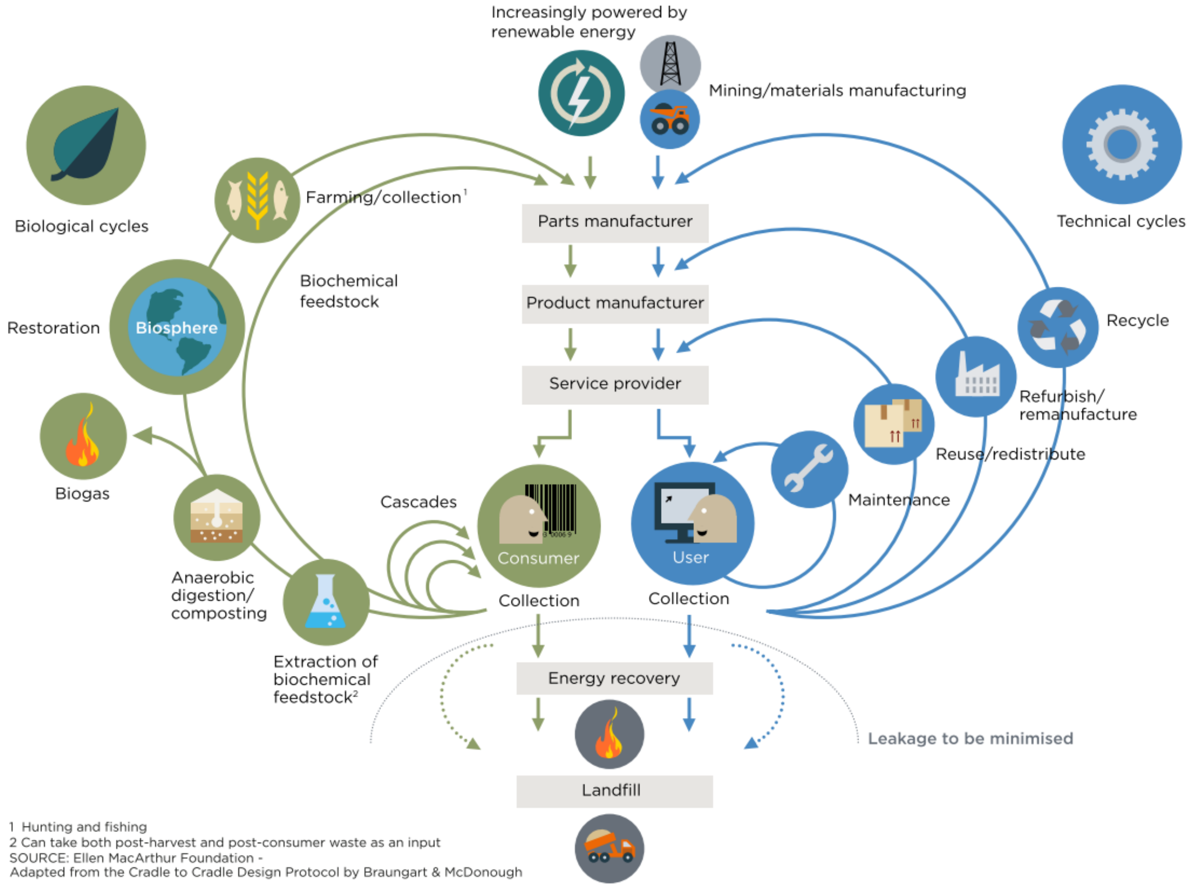


FIGURE 1: CIRCULARITY CYCLES (ELLEN MACARTHUR FOUNDATION, 2015)

The figure shows the technological and biological nutrient-based products and materials cycle through the economic system, each with their own set of characteristics. To activate the two cycles in the building industry we need to collect building materials. This is not straightforward because a building is a fixed object, consisting of a quantity of different products and materials attached to each other. In relation to a building, we need to harvest materials. If products are inextricably linked, harvesting is not possible so demolition is the only option. The more a building is detachable, the easier it is to harvest products and the more natural it is to do so. Therefore, detachability underlies the enabling of a circular building economy. This therefore shows that detachability is not an end, but a means to enable re-use (van Vliet et al., 2019).

The construction sector in the Netherlands contributes to approximately 50% to the national resource use. Currently, more than 95% of the waste produced in this sector is recycled, though not remaining the same quality (downcycling) (Rijksoverheid et al., 2016). Besides the reduction of waste, reducing material use, re-use and transformation of existing buildings and re-use of building elements, the bio based economy is part of the strategy of the government to reach the target of a circular economy in 2050 (Rijksoverheid et al., 2016).

There are various initiatives to make circularity easier to execute. A well-known one is the use of a material passports. This lists the materials used in a building, so that at the end-of-life, when the elements are used elsewhere, everything that is needed to know, is easily accessible. An example of such a passport is Madaster (materialen kadaster), the Circular Building Platform by BAM or Insert by BOOT. Also, the passports can be integrated into BIM models (Building Information Modelling), allowing for exchange between different platforms. This can be useful as a sustainable building is a cooperative effort of architects, engineers, contractors, manufacturers, governing bodies and so on.

Circular construction benefits both the party who makes an element that can be used again later, and the party who reincorporates that element into their design. This seems redundant: for reusing one element, the benefit is defined at the end-of-life of its first cycle and also at the beginning of the next, while this is in fact the same phase. However, there is a good reason for this. Namely, the design and use of circular elements should be encouraged. That encouragement should apply to both the creator and the next user(s). A circular element will not be made if the benefit can only be taken at the beginning of the next cycle. The same is true for the next user if the benefit only applies at the end of the previous cycle (Cobouw, 2021).

3. LCA: LIFE CYCLE ASSESSMENT

The climate deterioration is not something you can easily measure, since it is a non-material property. Over the years many methods have been developed to be able to quantify the environmental impact. For example, the Carbon Footprint method, which expresses the Global Warming Potential in a single number, or the Cumulative Energy Demand (CED) method, which considers the amount of primary (fossil) energy that is required (and associated Global Warming Potential) in the different stages of a product. The Life Cycle Assessment (LCA) is a 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, 2020). Each aspect can be expressed in their own number. This method will be used for this study.

The main goals for performing an LCA, according to Jonkers (2020), are as follows:

1. Identification of the life cycle stage contributing most to the total environmental impact of the product.
2. Identification of the environmental 'hot spots' over the entire life cycle of a product: which 'module' (A1-5; B1-7, C1-4) within the 3 life cycle stages of a product contributes substantially to the overall impact.
3. Collecting information required for making an Environmental Product Declaration (EPD) of a product (this will be elaborated in section 3.3). This information can also be used to compare the environmental performance of products with similar functionality.

3.1 LIFE CYCLE STAGES

The LCA divides the life of a building, product or half-product into several stages, see figure 2. Stage A1-A3 looks at the raw materials, where they come from and how these raw materials form the product. Stage A4-A5 contains the process of bringing the product to the construction site and the construction process. Next, stage B consists of all the things necessary to be able to use the product, so maintenance, operational energy etc. Stage C gives scenarios of what can happen with the product when it is no longer in use, so the detachment and processing at the end-of-life. Lastly, stage D lists potential benefits after use of product, in relation to the stage C, like reusing the product or recycling etc.

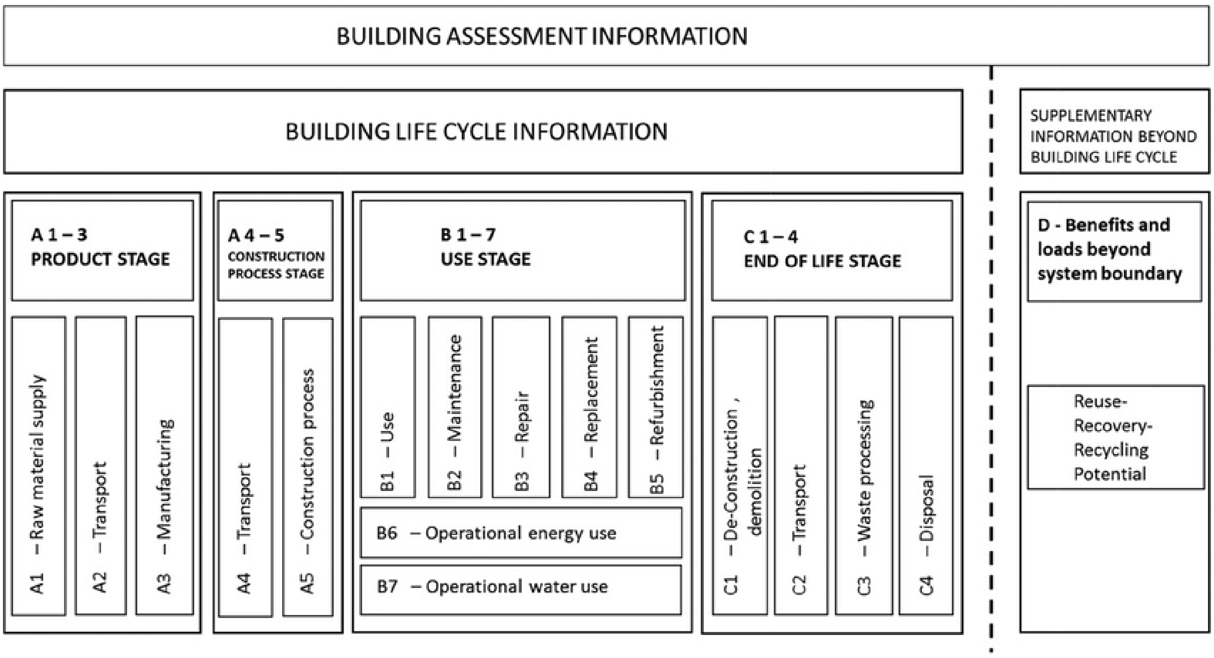


FIGURE 2: LCA (LCA SUPPORT,2O21)

For an LCA study, not all stages need to be looked at, so it is imported to establish the system boundaries of the study in advance. There are three popular boundaries for LCA studies:

- Cradle to gate: stage A1, A2 and A3, the creation of the product until it is ready to be transported
- Cradle to grave: stage A1 trough stage C4, the creation of the product up to and including the disposal.
- Cradle tot cradle: stage A1 trough stage D, the entire life of the product until the start of its new life.

Now, per stage the environmental impact can be quantified. Internationally many different LCA-based methods exist, each of these methods use specific ways in how to express the environmental impact of a product by using a specific counting or crediting system. Most of the time, the impact is divided over several impact categories. Per category the amount of harmful substances is determined.

3.2 IMPACT CATEGORIES

Various LCA methods are available, each considering different impact categories. In the Netherlands, the CML-2 baseline method is mostly used (Maastrigt, 2019). This method was developed by the Institute of Environmental Sciences (CML) at Leiden University in 2001. Other methods used in the Netherlands are TWIN2011 by the Dutch Institute for Building Biology and Ecology (NIBE) and RECIPE by a cooperation of the RIVM, CML, Radboud University Nijmegen and Pré Consultants (NIBE, n.d.) (Volksgezondheid Rijksinstituut voor en milieu, n.d.). The CML-2 baseline contains a total of eleven environmental impact categories, which are the most used in LCA. A short description is given per impact category based on the publication by Wouter van Wijnen (Van Wijnen, 2020).

GWP Global warming potential
GWP quantifies the effects of anthropogenic (human-induced) greenhouse gases. This includes carbon dioxide (CO_2), methane (CH_4), Chlorofluorocarbons (CFCs), Ozone (O_3) and Nitrous oxide (N_2O). These greenhouse gases are converted to the reference unit: kg CO2 equivalent. The effect of global warming results in the disturbance of climatic phenomena and temperature change, resulting in decrease of biodiversity.

ODP Ozone depletion potential
Contrary to the negative effect of ozone as greenhouse gas in the lower atmosphere, it prevents harmful ultraviolet radiation entering earth in the higher atmosphere. Halogenated gases cause damage to the ozone layer, resulting in negative effects for human health and ecosystem qualities. The combined effect of all contributing gases is converted to the reference unit, which is kg CFC-11 equivalent.

AP Acidification potential
Emitted acidic compounds react in the atmosphere with water, creating the phenomenon of acid rain. This effect damages ecosystems, decrease biodiversity and has a corrosive effect on structures. Examples of compounds causing acid deposition in the atmosphere are sulphur oxides (SO_x) and nitrogen oxides (NO_x). The reference unit is kg SO_2 equivalent.

EP Eutrophication potential
Eutrophication is the process of disproportional organic growth by increased available nutrients in an ecosystem. This leads to oxygen depletion in water bodies, resulting in loss of biodiversity. Nitrogen (N) and phosphorous (P) compounds induce eutrophication and its effect is expressed in kg PO_4
3-equivalent.

POCP Photochemical ozone creation potential
Next to the contribution of ozone in the lower atmosphere to global warming (see GWP), it is toxic for humans and nature at high concentrations. Combustion of fossil fuels emit carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOC_s). These elements react by photochemical oxidation to form ozone. This type of air pollution is known as smog. The reference unit is kg ethylene (C_2H_4) equivalent.

ADP Abiotic depletion potential
This environmental impact category is split into two subcategories: ADP-E and ADP-F, the first is the ADP for non-fossil resources the latter for fossil resources. These categories are measures for the scarcity of abiotic (non-living) finite resources, such as minerals, metals and fossil fuels. ADP-E has a reference unit of kg antimony (Sb) equivalent; ADP-F has either the same reference unit as ADP-E or MJ net calorific value. This can be converted by the following factor: 4.81E-4 kg antimony per MJ.

HTP Human toxicity potential
HTP measures the toxic substances affecting human health. Both the toxicity and the dose of harmful compounds determine the relative contribution to the impact category. The reference unit is kg 1,4 dichlorobenzene (DB) equivalent.

FAETP Freshwater aquatic eco-toxicity potential
This environmental impact category quantifies toxic substances, affecting organisms living in freshwater aquatic ecosystems. Examples of affecting components for this impact category are wastewater, mining of heavy metals and fossil fuel extraction. The reference unit is kg 1,4 dichlorobenzene (DB) equivalent.

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

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

The results can be expressed per impact category or added up per LCA stage. It can even be added up to a single value. This requires weighing the impact categories. This weighing is necessary because adding up the amount of for example CO_2 emissions with other emissions, is like adding apples to pears. So first both need to be expressed in the same unit before adding them up. As you can imagine, this weighing process leads to a lot of discussions, because how can one express different things in the same unit? Most of the time this weighing is done by expressing the environmental impact into hypothetical money, this is called 'monetarization'. This money should be the amount needed to make the environmental impact undone. Such costs are called the 'shadow' costs of a product. If these shadow costs are included in the sales price of a product, it could become sustainable, if the extra money is indeed used to compensate or prevent the environmental damage. Including environmental costs in the sales price is called 'internalization'. It is also possible to not include the shadow costs in the total price: 'externalization', this will still give an insight in how much a structure or process costs society non-money wise.

3.3 OUTCOMES

The LCA method is used to calculate the EPDs (environmental product declaration) of products or half products. This is a list of quantities of inputs (raw materials, energy, processes) and outputs (emissions to environment) that are involved during the respective service life stages related to the 11 impact categories. These EPDs can be used to calculate the Environmental Cost Indicators or ECIs (in Dutch: milieu kosten indicator or mki's), which express the environmental impact of a (half-)product in money. These values can be used to determine the environmental impact of an entire building. One simply adds up the ECIs of the used materials multiplied by the amount used of that material. The ECI's are collected in an environmental database of construction materials. The Dutch National Environmental Database (Nationale Milieudatabase) lists environmental costs for building products based on EPDs determined according to the method prescribed by the Dutch SBK (Stichting BouwKwaliteit). So if one wants to determine the entire environmental impact for a Dutch project, this "'Nationale Milieudatabase" is the catalogue to use.

This is, however, easier said than done. Not every material, element and (transport) process is listed in the database. This limits the estimation of the impact of constructions. In addition to that, the database divides its data in three categories. Categories 1 and 2, represent brand- or branch specific products for which the delivered data are reviewed by an independent certified consultant. The environmental profiles, but not the underlying data, of these categories can only be viewed via specific tools: not very transparent. Category 3 is not brand- or branch specific and/or is not independently reviewed, but is more transparent in showing how the underlying data is organized. These materials are a lot less favorable then the ones in category 1 and 2. Why the branch ones are so good, is not publically shared. We just have to trust that the impartial consultant approved them fairly. But, this means that no one can learn from these good, effective materials.

The National Environmental Database (NMD) has made the Bepalingsmethode, which states how the LCA should be used to determine ECIs and EPDs. It also has a database that contains environmental data on construction products and building installations: products - supplied by the industry, which is used in the calculation of the environmental performance of construction works in the calculation tools. The environmental data in the NMD includes environmental profiles: lists of environmental effects expressed in various environmental impact categories according to European Standard (EN) 15804 (Milieudata - Nationale Milieudatabase, n.d.).

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

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

EQUATION 1: MPG (VAN WIJNEN, 2020)

Currently, the MPG requirement is set at a maximum value of 0,8. Which can be achieved for all buildings without too much effort. This requirement will be increased to reach the sustainability goals set by the government, promoting circular construction further (Rijksoverheid, 2021).

3.4 Framework

Preforming an LCA requires four steps, see figure 3 (European Committee For Standardization, 2006b).

<u>Step 1:</u> First, the goal and scope of the study should be defined.

<u>Step 2:</u> Next, the Life Cycle Inventory is made. This lists all the in- and outputs of the within the system boundaries. This can be drawn in a process tree, making a clear overview.

<u>Step 3:</u> The third step translates the data from step 2 to the environmental impact. This is called the Lice Cycle Impact Assessment. The results can be expressed into one value using points or money depending on the characterization method chosen.

<u>Step 4:</u> The last step is to interpret the data of the previous steps, called the lf cycle interpretation. The findings of the assessment should be reviewed and presented.

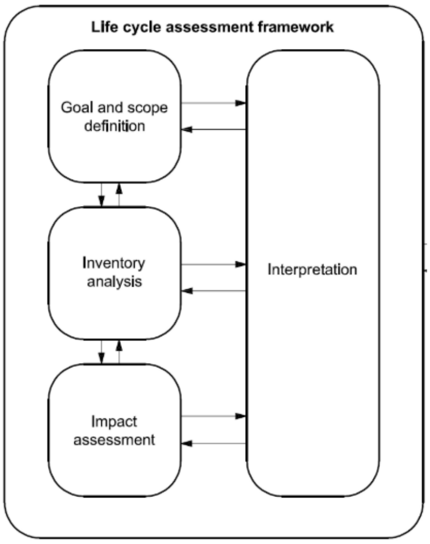


FIGURE 3: LCA FRAMEWORK (EUROPEAN COMMITTEE FOR STANDARDIZATION, 2006B)

Quantifying the environmental impact of circular products can be modelled in two ways. The first option is to extend the reference service life, representing the entire service life of the number of (re)use cycles. The effects of the re-use cycles, both positive and negative environmental contributions, are modelled in the use stage (module B). The second option is to perform a multi life cycle assessment (mLCA). In this method, each cycle is modelled as separate a LCA and are aggregated to obtain the results of the circular product. Challenges in this method arise for the allocation and use of module D (Schut & Leeuwen, 2018).

3.5 Comparing different materials with LCA

Now the question is, to what extend can the environmental impacts of two different construction materials be compared for a similar construction? In order to do that it is important to make sure that the basis for comparison is equal: is the specific function and intended service life of two constructions similar? If not, the comparison would not be relevant. Unfortunately, this is what happens in studies in the building field, resulting in false outcomes. Such false comparisons are sometimes deliberately used for 'greenwashing' of a (half)product. The comparison can, in these cases, be based on different functionalities, or with a different amount of environmental impact categories or life stages. The focus can be put on only one aspect or one impact category, ignoring all others. This can result in a much too positive outcome, whilst other impact categories would show a more negative result. These false comparisons are very commercial. People want to sell their product and show the quality of their product compared to the other options in the field. This needs to be taken into account in a fair study that uses external sources: even if a research is solidly substantiated, it does not mean it is fair.

Part 2: Functional Properties

4. Functional properties of Concrete and Timber

There are certain requirements a structure needs to fulfil in order to make a functioning building. Even though concrete and timber can be used for the same elements, they have very different characteristics that influence their performance. In this chapter some requirements will be elaborated in relation with the properties of first concrete (section 4.1) and then timber (section 4.2). The requirement that will be discussed are as follows:

- Strength: how much stresses can the material tolerate?
- Deflection: how will the material deform when it is exposed to stress?
- Fire safety: how is the material influenced by exposure the fire?
- Insulation: is the material able to block heat or cold?
- Acoustics: is the material able to block noise?
- Vibrations: how likely is the material to tremor?
- Durability: how long is the material able to perform?

Practical examples of using concrete and timber to design elements fulfilling these requirements are given in chapter 10.

4.1 Concrete

Concrete is an artificial stone-like material used in construction. Modern concrete is composed of the binder cement and one or more aggregates such as sand, gravel or crushed stone. Cement has the property of hardening when water is added. The specific recipe of concrete can vary by changing the grain size of the different types of sand and gravel, or by changing the amount of cement. Also, admixtures can be added to, for example, make the mixture cure faster or to minimize deterioration. Because of the material's relatively low price, ease of use and the broad experience, concrete is a widely used building material.

<u>Strength</u>

The strength of concrete depends on the recipe used. The more cement is added, the stronger the concrete becomes. The strength also depends on the aggregates. Concrete is divided in several strength classes. The class of a recipe is determined by measurements. The compressive strength of concrete is denoted by concrete strength classes which relate to the characteristic cylinder strength f_{ck} or the cube strength $f_{ck,cube}$, in accordance with EN 206-1. The strength classes in this code are based on the characteristic cylinder strength f_{ck} determined at 28 days (European Committee For Standardization, 2004). The strength of concrete can vary from 12 N/mm^2 to more than 150 N/mm^2 for ultra-high performance concrete (Breye & Vos, 2013).

Because concrete is very brittle in tension, reinforcement bars can be added. These bars will carry the tension load, whilst the concrete will carry the compression load in an element. The concrete and steel will work together when an element is loaded in bending (Braam & Lagendijk, 2011).

<u>Deflection</u>

The elastic deformations of concrete largely depend on its composition (especially the aggregates). The values given in the standards should be regarded as indicative for general applications. However, they should be specifically assessed if the structure is likely to be sensitive to deviations from these general values (European Committee For Standardization, 2004).

Creep and shrinkage of the concrete depend on the ambient humidity, the dimensions of the element and the composition of the concrete. Creep is also influenced by the maturity of the concrete when the load is first applied and depends on the duration and magnitude of the loading. The creep coefficient, $\varphi(t,t_o)$ is related to E_e, the tangent modulus, which may be taken as 1,05 E_{cm}.

Cracking is normal in reinforced concrete structures subject to bending, shear, torsion or tension resulting from either direct loading or restraint or imposed deformations. Cracks may also arise from other causes such as plastic shrinkage or expansive chemical reactions within the hardened concrete (European Committee For Standardization, 2004).

Fire resistance

The temperature of a fire raises the surface temperature of the concrete. The center of the element remains relatively cool. This difference in temperature causes strains, stresses and even cracks due to thermal expansion. Inside the concrete the free water starts to expand causing more pressure. Also, the physically bound water will evaporate resulting in the dehydration of the cement. These three phenomena cause the concrete to start spalling. During spalling, parts of the concrete break off under (high) pressure. This phenomenon can be very violent, even causing an explosion of the entire cross-section. To avoid spalling, several precautions can be taken (Breunese & Meljaars, 2015):

- Adding an insulation layer.
- Adding PP fibers to the concrete mix, this will release the water expansion pressure.
- Using smaller aggregates with less thermal expansion.
- Not using fine fillers, as these reduce the permeability, trapping the free water inside the element.
- Using a higher water/cement ratio. This may seem contradicting, since adding more water increases the amount of free water in the concrete, but this also insures a higher permeability, which allows the expanded water to release.

Usually concrete elements will have enough resistance without additional materials. This is especially the case for low rise buildings, as the requirements are lower (Bouwbesluit, 2012).

Insulation

The thermal conductivity of concrete decreases when temperature rises. The amount of decrease is dependent on the concrete mix properties, especially the moisture content and permeability. The decrease of thermal conductivity is caused by moisture loss and dissociation of small amounts of physically bound water present in concrete, due to the increased temperature. The lambda value, indicating the thermal capacity, is $\lambda_{concrete} \approx 1{,}7$ [W/mK](Shahedan et al., 2017). Additional material needs to be added to fulfil the insulation requirement in the Netherlands. There are options for adding air gaps in the concrete, making it act as an insulator (Viveen, 2021). This added insulation is usually not enough to meet the requirements, or results in an element with an extreme thickness.

Acoustics

Concrete elements have a great mass, making them good air sound insulators. Usually, there is no need to add sound insulation to fulfil the requirements in the BouwBesluit for solid slabs. Mass also plays a part in contact sounds absorption, making concrete preform relatively well compared to lightweight materials (van der Linden et al., 2011).

Vibrations

Whether a floor vibrates depends on the mass and the natural frequency of the floor, see figure 5. The figure shows these two properties plotted against each other. Class D or better is acceptable for residences. These properties depend on the modulus of elasticity, the moment of inertia, the mass and the static scheme, see figure 4. Concrete has a large self-weight, making the module mass bigger. In combination with a large modulus of elasticity and moment of inertia, making the natural frequency bigger, there are little to no vibrations in the elements. For terraced houses the span l is relatively small, making this requirement easy to suffice.

E Elasticiteitsmodulus [N/m²]
I Traagheidsmoment [m^4]
μ verdeelde massa [kg/m]
ℓ Lenge van de balk

Tabel 4: Eerste eigenfrequentie en modale massa voor balken

Oplegcondities	Natuurlijke Frequentie	Modale massa
ℓ	$f = \frac{4}{\pi}\sqrt{\frac{3EI}{0.37\mu l^4}}$	$M_{mod} = 0{,}41\ \mu\ l$
ℓ	$f = \frac{2}{\pi}\sqrt{\frac{3EI}{0.2\mu l^4}}$	$M_{mod} = 0{,}45\ \mu\ l$
ℓ	$f = \frac{2}{\pi}\sqrt{\frac{3EI}{0.49\ \mu l^4}}$	$M_{mod} = 0{,}5\ \mu\ l$
ℓ	$f = \frac{1}{2\pi}\sqrt{\frac{3EI}{0.24\mu l^4}}$	$M_{mod} = 0{,}64\ \mu\ l$

FIGURE 4: NATURAL FREQUENCY AND MODULE MASS (HIVOSS, 2008)

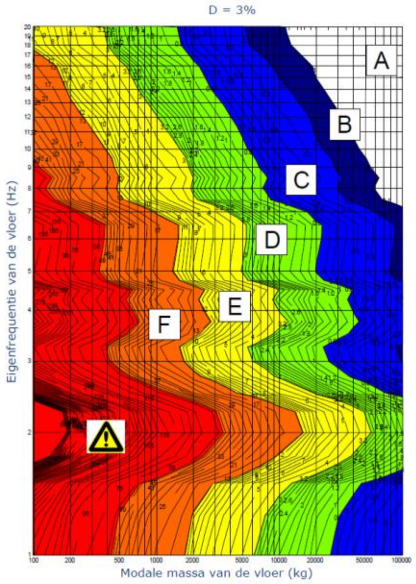


FIGURE 5: VIBRATION CLASSES (HIVOSS, 2008)

<u>Durability</u>
Even though the usual lifespan assumed at the beginning of a project ranges from 30 to 75 years, concrete can last much longer. It does not need much maintenance unless it starts to deteriorate. This can happen when the material is not used in a correct way.

Concrete carbonation can cause embedded steel reinforcements to corrode. The steel will expand, resulting in cracking and weakening the concrete. It commences as soon as concrete is exposed to the atmosphere, dependent on the concrete's porosity and permeability. Carbonation is the most common cause of reinforcement corrosion in above ground structures. The corrosion protection of the reinforcement depends on density, quality and thickness of the concrete cover. A minimum concrete cover, C_{min}, is defined in order to ensure the safe transmission of bond forces, the protection of the steel against corrosion and an adequate fire resistance. The cover density and quality is achieved by controlling the maximum water/cement ratio and minimum cement content and may be related to a minimum strength class of concrete (European Committee For Standardization, 2004).

The alkali-reaction or the alkali-granulate reaction (AGR) is a chemical reaction between reactive aggregates and the alkalis contained in the cement. This reaction produces an expansion inside the concrete which will create tensions, swelling and cracks. This can be prevented by avoiding the situation in which the three conditions necessary for the initiation of the reaction are simultaneously present: water (relative humidity condition greater than 80-85%), amount of alkaline in the large concrete and reactive silica (presence of reactive aggregates) (Jedidi & Benjeddou, 2018).

4.2 Timber

The term wood is used to describe the fibrous substance that makes up a tree. When a tree is sawn or fallen down, it can be called lumber. Lumber still has bark around it. When the wood is processed and made into construction materials, it can be called timber (Duffield timber, 2021). Wood can be sawn into all kinds of timber elements. Sawn elements can be combined into so-called composite elements, with glue and/or mechanically, like with nails and bolts. Veneer is obtained by peeling the tree. Veneer layers can be glued together to create plywood or LVL (laminated veneer lumber). Sawn timber boards can be glued together crosswise result in so-called CLT (cross laminated timber). Sawdust and woodchips can be used to manufacture materials like OSB (oriented strand board) or MDF (medium density fiber board). Some of these product are suited to be used structurally, like CLT and LVL (De Groot, 2018). The following section mainly looks into the properties if these structural timber products.

Strength

Wood is a material with a high natural variability. The characteristic strength value depends on the wood species and the wood quality. Based on these two identifications the timber is classified into so-called strength classes (Sandhaas & Blass, n.d.). Strength grading is the process of sorting sawn timber into the strength classes to which the same mechanical and physical properties can be assigned. The grading can be done with visual assessments, like measuring the width of growth rings to estimate the strength or looking at knot sizes which reduce the strength. Also machines can grade the timber with x-ray scans or vibration tests. This allows a far more accurate estimation of the strength and stiffness properties (Sandhaas & Blass, n.d.). The strength of timber varies from 12 to 50 N/mm^2 for softwood and to 70 N/mm^2 for hardwood (European Committee For Standardization, 2006a).

Wood is an anisotropic material, which means it demonstrates different properties when stress is applied in different directions, e.g. parallel or perpendicular to the grain. Also, the strength value decreases when the moisture content rises or the time of loading gets longer (RISE Research Institutes of Sweden, 2019). The construction service class describes the moisture it is exposed to. The duration class described the duration of the loading, which can vary from less than a week (short term loading) to more than ten years (permanent loading). The material properties vary both within one structural element and between different elements. Because of all mentioned causes for variation in strength, there are quite a few modification factors used to design a member safely. The design value X_d of a material property with the characteristic value X_k is defined as follows (European Committee For Standardization, 2006a):

$$X_d = k_{mod} \times \frac{X_k}{\gamma_m}$$

EQUATION 2: DESIGN VALUE OF MATERIAL PROPARTY X FOR TIMBER CONSTRUCTION

Here k_{mod} is the modification factor, which takes the strength variation due to the load duration and moisture content into account. The value can be determined by selecting the service class and load-duration class of the structure. The partial factor γ_m is dependent on the type of wood. In addition to these modifications, factor k_h should be used, which takes the influence of member volume into account, for solid timber and glued laminated timber.

The structure of CLT, with its perpendicular layered boards, evens out the variations in the wood and reduces the property differences. The strength of a CLT product is determined to a large extent by the composition of the cross-section (RISE Research Institutes of Sweden, 2019).

Deflection

The mechanical wood property stiffness also responds to load duration: long term loading results in increased deformations. This phenomenon is called creep: increasing deformation under constant load. Long-term or creep deformations in wood under permanent load are significantly influenced by the surrounding climate. Changes in moisture content are one of the primary causes of major creep deformations. Therefore elements that are located outside of a building show more long-term deformations than the same element indoors. For the same reason, members with large cross-sections have fewer creep deformations than those with small cross-sections. This is because the rate of change in moisture content tends to be far lower, since the outer surface is relatively smaller. Surface treatments which prevent the exchange of moisture between wood and the surrounding air can limit creep (Sandhaas & Blass, n.d.).

For a structural component, the total deflection is determined based on the initial deflection, w_{inst}, added up with the deflection causes by creep, w_{creep}. w_{creep} can be demined using the deformation factor, k_{def}, which is dependent on the moisture content of the wood material and the variation in this moisture content, see equation 3, 4 and 5 (RISE Research Institutes of Sweden, 2019). The value of k_{def} is dependent on the wood type, so sawn timber or glued laminated timber, etc.

$$w_{\text{creep}} = k_{\text{def}} w_{\text{inst}}$$

$$w_{\text{fin,G}} = w_{\text{inst,G}} + w_{\text{creep,G}}$$

$$w_{\text{fin,Q}_i} = w_{\text{inst,Q}_i} + w_{\text{creep,Q}_i}$$

EQUATION 3&4&5: FINAL DEFORMATION FOR PERMANENT AND VARIABLE ACTIONS

Fire resistance

Timber does not conduct heat much. This can be felt by touching the wood. It does not feel cold, as it does not conduct your personal heat into the material. This means that during a fire, the heat is also not conducted towards the center of the element, where it remains relatively cool. If an exposed non-fire-retardant-treated wooden surface is exposed to the effects of fire, it will ignite. The burning then continues inwards at a largely constant speed. The cross-section of the element gets gradually smaller. The speed at which the material burns, is called the charring rate. The charring rate is slow, since the char layer that forms provides thermal insulation. In the pyrolysis zone, between the charcoal and the still in unharmed timber, flammable gases are formed. Those gasses diffuse through the char layer until they encounter the oxygen in the air and begin to burn. A clear boundary forms between the char layer and the remaining cross-section, see figure 6. In the pyrolysis zone the temperature is not high enough to char, but the properties of the wood are nevertheless affected by the heat. The charring is greater at wide splits and external corners (RISE Research Institutes of Sweden, 2019).

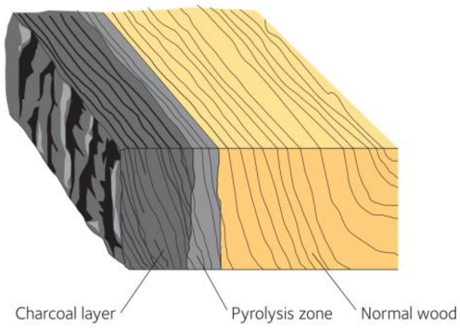


FIGURE 6 BURNED TIMBER CROSS-SECTION (RISE RESEARCH INSTITUTES OF SWEDEN, 2019)

The fire resistance of the structure can be provided using either reduced section properties or fire resistant lining, or a combination of both approaches. The reduced cross-section method uses the known charring rate. To make sure an element can withstand a fire for a certain amount of time, the remaining part of the burned up cross-section after this time is used to calculate the load bearing capacity in accordance with EN 1995. An alternative method for calculating fire resistance is given in EN 1995. This is the reduced properties method, which uses reduced material properties for the 'hot' design, however the use of this method is currently precluded by the UK National Annex (TRADA Technology, 2009).

The wood "protects itself" via the char layer, but sometimes extra layers are required to provide additional fireproofing. An element can be improved for fire by either adding protective layers, making the timber less hot, or by impregnating the wood, reducing the charring rate. Impregnation to increase fire resistance must be done at high pressure (or vacuum), rather than with a brush or roller, to sink deep into the wood. This is important so that the desired retardant effect can be achieved, even if the outer layer is burned away (Breunese & Meljaars, 2015).

Insulation

Wood has small temperature differences in one element, compared to stone like materials. This is due to the fact that wood has good thermal insulation properties. However, additional insulation is mostly still required to meet the modern standards for the building. The thermal conductivity of wood depends on the wood's density and moisture content. For dried pine and spruce with a moisture content of around 12 %, the thermal conductivity, known as the lambda value, is given to be $\lambda \approx 0.13 - 0.14$ W/m °C (RISE Research Institutes of Sweden, 2019).

Acoustics

As with other lightweight structures, low-frequency sound is difficult to insulate against in timber structures. For floor or wall panels the required level of sound reduction can mostly not be provided by just the timber itself. Additional insulation material is needed to minimize the direct sound transmission (RISE Research Institutes of Sweden, 2019).

In addition to direct sound transmission reduction, flanking sound should also be addressed. There are, in principle, two methods to reduce the flanking sound: vibration damping using flanking transmission barriers or separate inner cladding of load-bearing elements. A combination of these methods can also be used. Flanking transmission barriers are used to reduce the vibrations primarily in a vertical direction. They tend to involve elastic isolation strips that are fitted to create a separation between the floors and so reduce the transfer of sound, while still permitting the transfer of static forces (RISE Research Institutes of Sweden, 2019).

Vibrations

Since timber has less mass than other construction materials, it tends to vibrate more. This can be counterbalanced by insuring the element has a big moment of inertia, see figures 4 and 5. This enlarges the natural frequency. Vibration resistance is something that needs to be taken into account during the design of a floor element and it can even be the governing criteria. Regardless of the type of wood-based floor, it was found that the floors all have similar dynamic characteristics. A good performing wood-based floor commonly has a fundamental natural frequency above 8 Hz (Karacabeyli & Gagnon, 2019).

Durability

For timber, natural durability is the sense of resisting destructive organisms and thus the ability to guarantee the load-bearing capacity and usability throughout the service life of a product (Sandhaas & Blass, n.d.). The two main causes of damage are fungi and insect attack. The natural durability of the individual wood species against insect attack varies considerably. Hardwood tends to be more durable. However, resistance among individual wood species to termite infestations varies (Sandhaas & Blass, n.d.). Use-classes, as prescribed in EN 335 and EN 460, are used to determine if the biological durability is sufficient for the intended application of the timber product in climatic circumstances.

Fungal attacks occurs in wood with a moisture content higher than 20%. Heat tends to enlarge the change of insect attacks. Cracks and gaps, which form in treated wood, can become the basis for egg-laying or the start of infestation. Also, Radiation (UV) and polluted air (acids) can damage timber (Sandhaas & Blass, n.d.).

There are several ways the wood can be protected. Paints and coatings are used as weathering protection, since they can help mitigate precipitation, high humidity and UV rays. Chemical modification measures require impregnation, most often pressurized, followed by drying and a reaction period. However, not all wood varieties lend themselves to impregnation because of pits. For example, spruce is very difficult to impregnate, which rules out the possibility of chemical modification. Timber species open to the use of acetylation include pine, beech, maple and particularly Radiata pine, a fast-growing species with large annual ring widths. Chemical wood preservation should always be a last resort, since it means using biocides. The final modification option is thermally treated wood. The wood is heated to a temperature ranging from 150 and 240°C. This causes the –OH groups to decompose (Sandhaas & Blass, n.d.).

Part 3: Environmental Performance

5. Environmental performance of concrete and timber

Which of the materials is better environmentally, concrete or timber, is not a question with a single answer. Depending on who you ask, the reactions will vary. In this section a few popular arguments will be discussed. How these arguments relate to the LCA method, will be elaborated further in the next chapter.

5.1 Concrete

Concrete has many environmental advantages, including durability, longevity and heat storage capability. However, cement production is among the most energy intensive materials used in the construction industry and major contributor to CO_2 in the atmosphere (Babor et al., 2009). In the Netherlands the production of concrete contributes to 1,6% of the total CO_2-emissions. This includes the emissions of the reinforcement steel (Vermeulen, 2017).

Concrete is manufactured from aggregates, hydraulic cement, and water. Sand and gravel is usually mined in the rivers near the North Sea and is transported by boat (Dyckerhoff, 2021).

The hydraulic cement can be straight portland cement or a mixture of portland cement and some proportion of a supplemental cementing material, such as fly ash or slag. The use of fly ash from coal-fired power plants is beneficial in two ways: it helps with processing the coal-fired power plants waste and it reduces the energy needed to make cement. Fly ash can be used as a source of silica in cement production, or more commonly as a partial substitute for cement. Fly ash can substitute up to 35% of the portland cement in a concrete mixture (Struble & Godfrey, 2004).

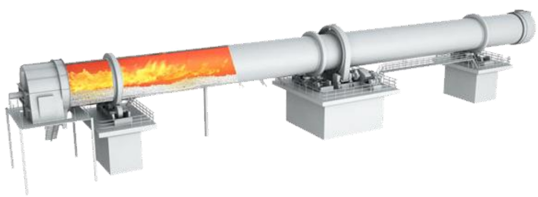


FIGURE 7 KILN (AGICO CEMENT, N.D.)

Portland cement requires a source of calcium (usually from limestone) and a source of silicon (such as clay or sand). Small amounts of bauxite and iron ore are added to provide specific properties in the final product. These raw materials are finely ground and mixed, then put into a rotary cement kiln, see figure 7. The kiln is a long, sloping cylinder with zones that get progressively hotter up to about 1450°C. The kiln rotates slowly to mix the contents moving through it. In the kiln the raw materials undergo complex chemical and physical changes required to make them able to react together through hydration (Babor et al., 2009).

There are two different sources of carbon dioxide emissions during this cement production: decomposition of $CaCO_3$ (limestone/marl) into CaO and CO_2 and the combustion of fuels to get the kiln to a temperature of 1450°C (van Gent, 2021). The very high temperatures used in a cement kiln have one advantage: the potential for burning hazardous waste as a fuel. Waste fuels that can be used include used motor oil, spent solvents, printing inks, paint residues, cleaning fluids, and scrap tires. These can be burned relatively safely because the extremely high temperatures result in very complete combustion with very low pollution emissions. For some chemicals thermal destruction in a cement kiln is the safest method of disposal (Babor et al., 2009).

The water in concrete is normally ordinary tap water or ground water, with no further processing. Thus it has very little embodied energy and no waste (Struble & Godfrey, 2004). Concrete used in structural applications normally includes some amount of reinforcing steel, and in some applications this steel is pre-stressed. The steel ads to the environmental damage of concrete products.

Concrete is usually manufactured by combining and mixing these constituents in large batches in a ready-mixed concrete plant and then hauling the mixture to the construction site in a truck. These processes (moving materials, mixing them, and hauling the concrete) require modest amounts of energy and produce small amounts of waste. Dust, unused concrete, and wash water contaminated with concrete are the principal waste, and the latter two wastes may be at least partially reclaimed and reused (Struble & Godfrey, 2004).

When a concrete element is used and exposed to the air, carbonation occurs. Carbonation is known as the chemical reaction of $Ca(OH)_2$ and calcium–silicate–hydrate (C–S–H) in concrete with CO_2 in the air to form $CaCO_3$ and water. Carbonation reduces the hydroxide concentration in the pore solution, which can cause damage of the embedded reinforcement bars (Chang & Chen, 2006). The reaction only occurs at the surface of the element, where the CO_2 is present. So, if the cover of the reinforcement is sufficient, no damage will proceed.

If this deterioration is prevented, concrete can have a very long service life. Buildings made of concrete are often repurposed, making the service life as long as possible. Concrete structures are built to withstand a variety of loads and may be exposed to many different environments such as exposure to seawater, deicing salts, sulfate bearing soils, abrasion and cyclic wetting and drying (Kosmatka & Wilson, 2011). The ingredients of the concrete mixture will depend on these loads and the environment to which it will be exposed. Properly designed and built concrete structures are strong and durable throughout their service life. After completion of proper proportioning, concrete hardens into a strong, noncombustible and watertight building material that requires little or no maintenance (Kosmatka & Wilson, 2011).

At the end of its service life, a concrete structure must be demolished and disposed. The demolition process is done by brute force, or elements are dismantled and used circular. These processes use modest amounts of energy. Concrete is mostly recycled. Waste includes unused concrete, contaminated wash water, and used formwork (Struble & Godfrey, 2004).

5.2 TIMBER

Where concrete has multiple raw ingredients, timber is much simpler: it exists out of the renewable source material wood. The manufacturing of timber products consists of the natural tree growth, tree harvesting, transport to the factory and the industrial processing to the final product.

During the production of wood, several waste streams reduce the forest product efficiency. On average, 60% of the original volume of a tree ends up in sawn timber and LVL. The remaining percentage consists of the bark, offcuts and sawdust. The bark and sawdust are used as biomass to (partially) power and heat the factory. The offcuts are processed to woodchips and used in the production stream of other wood-based products (Food and Agruculture organisation of the united nations et al., 2020).

Generally, glued timber products have a higher environmental impact then other timber products due to the manufacturing of adhesives and additional production steps. LVL has the overall highest impact per kilogram material due to the energy intensive bonding process (Van Wijnen, 2020). Besides glue, nails, crews and dowels can be used in addition to the timber. These products can be seen as raw material for the production of these timber elements.

Glulam, or GLT is a structural product composed of multiple pieces of finger-joined dimension lumber adhesively face-to-face bonded to create a desired form. A significant development in the glulam industry was the introduction of fully water-resistant phenol-resorcinol adhesives in 1942, which allowed GLT to be used in exposed exterior environments without concern of glueline degradation (Ivanova et al., 2016).

Cross-laminated timber (CLT) is a new-generation engineered large-size structural panel product, which consists of layers of sawn timber oriented at right angles to one another and then bonded using adhesives. CLT was originally invented in the 1970s in Europe and introduced as an innovative wood product in the early 1990s in Austria and Germany (Ivanova et al., 2016). The species of wood used depends on the location of a manufacturing plant. In the Netherlands spruce is usually used (Woodteq, 2021). Cold-set structural adhesives are preferred to increase the productivity of manufacturing CLT panels. These include emulsion polymer isocyanate (EPI), polyurethane (PUR), and phenol-resorcinol formaldehyde (PRF) (Ivanova et al., 2016).

The countries where most structural timber is imported from are Scandinavia, Germany, Russia and the Netherlands itself. Production forests have grown by 30% in the past 50 years in Europe. Each year they are increasing by 1.5 million soccer fields (Houtbouw holland, n.d.). The wood can either be processed into timber products near the harvesting place and then transported, or the raw wood is transported and processed in Dutch timber factories. Either way the wood is likely to have a great transport distance. It is preferable to keep distances as short as possible. The increase in production forest helps to reduce the travel distances.

Timber is part of the carbon cycle. Carbon is an essential element for all organisms. This element is stored and exchanged between the geosphere, hydrosphere, biosphere and atmosphere, see Figure 8. This process is known as the carbon cycle and contains greenhouse gases, when released to the atmosphere (Riebeek, 2011). An advantage of timber over non-biogenic building materials, is that it stores biospheric CO_2 when the product is used, potentially lowering the CO_2 levels in the atmosphere.

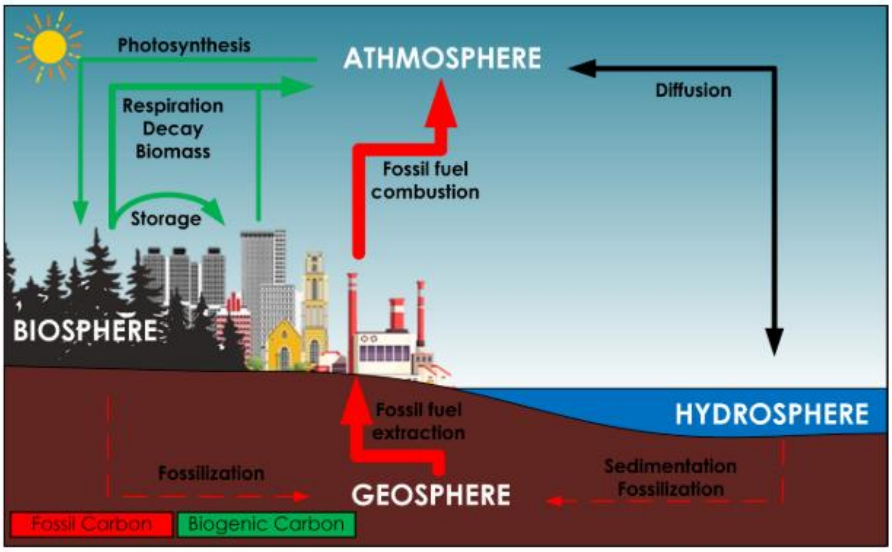


FIGURE 8: THE CARBON CYCLE (RIEBEEK, 2011)

Two types of carbon can be identified in the cycle: fossil and biogenic carbon. The first is originated from decomposed material in the geosphere, the second from biomass in the biosphere (European Committee for Standardization, Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification, 2018). A distinction can be made between fossil and biogenic carbon, based on the duration they are stored. Formation of fossil carbon takes millions of years opposed to 1 to 10000 years for biogenic carbon (Ciais et al., 2013). Therefore, fossil-based resources are classified as non-renewable, whereas biogenic based resources are classified as renewable. In recent years, combustion of fossil fuels increased the concentration of greenhouse gases in the atmosphere on top of the natural flux within the system (Riebeek, 2011).

The process of capturing and storing CO_2 is called carbon sequestration. This lowers the concentration of CO_2 in the atmosphere. This phenomena should not be confused with embodied carbon, as this is an acronym for the carbon footprint (Dulmage & Mousa, 2018). The reaction causing the carbon sequestration to store in trees is given in figure 9.

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

$$C_6H_{12}O_6 + 6\ O_2 \xrightarrow[\text{Burning}]{\substack{\text{Respiration}\\ \text{Decomposition}}} 6\ CO_2 + 6\ H_2O + \text{Heat}$$

FIGURE 9: (KYRKLUND, 1990)

The CO_2 will re-enter the atmosphere at the end-of-life gradually through natural deterioration or directly when burned, see the second equation in figure 9. If waste-to-energy is used to dispose of wood when the building is demolished, all the carbon stored in the biomass is released to the atmosphere. If energy can be produced from wood waste and then that energy is used to reduce fossil fuel use, then this represents a climate mitigation strategy (Karacabeyli & Gagnon, 2019). The Dutch LCA standards (Bepalingsmethode) do not require substitution effects that may occur at the end of life to be considered.

Besides, new timber products like CLT (cross laminated timber) and glulam (glue laminated timber) will have a long lifespan if they are used in dry surroundings. At the end-of-life, the product does not need to be burned, but can be used again. The CO_2 storage will be much longer. In a next cycle of the product the timber can be chipped to use in chip based elements. If the element is used in four cycles, and it can be used for that long, the CO_2 will be captured for more than 100 years. The norms (EN 15804) see this as permanent storage, so the advantages should be taken into account, which does not happen. In the meantime the forest can regrow, also capturing CO_2 (Cobouw, 2020).

The amount of sequestered carbon can be calculated by the formula from EN 16449 based on the biogenic carbon content, see the equation 6.

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

In which:

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

EQUATION 6: SEQUESTERED CARBON (EUROPEAN COMMITTEE FOR STANDARDIZATION, 2014)

This was formerly not taken into account for the LCA calculation, as the LCA only deals with input and output. Since 2021 it is mandatory to make biogenic CO_2 visible in LCAs, by including it as a separate environmental impact category in the Netherlands. This is based on the European standard for LCA's of building products: EN 15804+A2. This provides insight into the importance of (temporary) biogenic CO_2 sequestration, but this is not (yet) reflected in EPD, ECI and MPG (Keijzer et al., 2021).

At the end of its life, the same amount of CO_2 is released as it once captured. The sequestration during the life cycle of the product is therefore not incorporated (Vogtlander, 2012). However, as mentioned before, timber products can be used after the service life of a building. This makes the sequestration longer. There are many examples of timber building that are much older than 100 years, like the St Andrew’s church in Essex, which was built in the 7th century and is still standing (Blazeski, 2017).

Besides, by using timber, one captures CO_2 and takes it out of the atmosphere. By bringing timber to the city and maintaining the woods, twice as much CO_2 is captured with the same forest space. This only works if the forest is well cared for. Even if this is temporary, it still releases strain and gives room for improvement. The carbon sequestration in timber buildings is a short-term solution, converging to the point where everything is made out of timber and only non-re-usable timber is replaces by new timber. This would result in no additional carbon sequestration. But, as long as there is an increase in building needs, the amount of CO_2 stored can grow.

6. LCA OF CONCRETE AND TIMBER

In this chapter the materials concrete and timber are put side by side, following the format of the Life Cycle Analysis from NEN 15804, as introduced in chapter 3.

6.1 STAGES A1-A3

The first stages are A1 to A3, which make up the product stage. All LCA analyses include these stages. They provide insight in the material inputs, the transportation processes up to the factory gate, the energy used to process the materials, as well as the processing of any waste arising from those processes (European Committee for Standardization, 2013).

If the input of materials is second-hand, or the energy used is recovered from secondary fuels, the system boundary between the new system and the previous system (providing the secondary materials) is set at the output of the previous system.

Materials or energy leaving the system at the product stage must be allocated as co-products. Loads and benefits from allocated co-products are not allowed to be declared. So, as a general rule, potential loads or benefits from A1-A3 do not appear as benefits in the LCA.

A1	Raw material extraction and processing, processing of secondary material input (e.g. recycling processes)
A2	Transport to the manufacturer
A3	Manufacturing

TABLE 2: LCA STAGES A1-A3

Table 2 shows what each separate stage includes. Below a summery is given of what this implies when concrete and timber is considered:

- **A1**: The raw materials for concrete consist of sand, gravel, water, cement and optionally other additives. In the Netherlands, sand and gravel is usually mined in the rivers near the North Sea. Water is extracted from rivers nearby or from ground water. Limestone is burned to create the cement in Germany.
  Timber products consist of the trees that are harvested in Scandinavia and mid-Europe (Forest for all Forever, 2020). During the production process of timber, several wood waste streams reduce the forest product conversion efficiency. On average, 50% of the original volume of round wood can end up in sawn timber and 60% if LVL is made (Food and Agruculture organisation of the united nations et al., 2020). The remaining percentage consists of the bark, offcuts and sawdust.
- **A1**: Concrete and timber can also be re-used from a previous product system, meaning that an entire element is extracted from a previous building. Also both materials have a recycle option. In the case of concrete, this means that old concrete is crushed up and re-used as aggregates in a new recipe. Timber can be chipped and glued together, making new timber products like chipboard.
- **A1**: Stage A1 also includes the generation of electricity, steam and heat from primary energy resources. For Timber the not used parts of the tree: bark and sawdust are used as biomass to (partially) power and heat the factory. The offcuts are processed to woodchips and used in the production stream of other wood-based products (Thistleton Architects et al., 2018). This is called primary recovery. Secondary recovery is also possible. This is when a timber product form a previous cycle is partially used in the new cycle and partially used for energy.
- **A2**: For concrete the transport of the raw materials is mainly inland. Sand and gravel can be transported by ship, which is relatively environmentally friendly as a lot of material can be transported at once. The wood for timber is imported from plants in Scandinavia and mid-

Europe and is done by truck. There are also plants in the Netherlands, but those are not yet big enough to provide for the entire demand.

- **A3**: The ingredients for concrete need to be measured and are put together in a mixer. If the concrete is used for cast in situ elements, this is the end product. In case of precast elements, this is only a pre- product. The concrete then needs to be put into a mold and harden before it becomes the end product.
  Depending on what the timber end product is, the wood needs to be sawn, glued and otherwise treated.
- **A1-A3**: Finally, all waste over the entire A1-A3 stages need to be included in the product stage. For concrete this is the unused excess mixture. This can be washed out with water, making it possible to re-use the sand, gravel and water (with non-usable cement still in it). This has to be done quickly, as the cement will react and harden. When this is not possible, the hardened concrete has to be taken to the recycler.
  The excess wood can be used as an input in a different timber product like chipboard. Also the wood can be used to generate energy, as mentioned in stage A1.

6.2 Stages A4-A5

Stages A4-A5, or the construction process stage includes the information modules for the transportation from the production gate to the construction site, the storage of products, including the provision of heating, cooling, humidity control and the energy or materials to install the product into the building (European Committee for Standardization, 2013).

A4	transport to the building site
A5	installation into the building

TABLE 3: LCA STAGES A4, A5

Table 3 shows what each separate stage includes. Below a summery is given of what this implies when concrete and timber is considered:

- **A4**: Both the timber products and concrete products are usually transported with a truck. So the difference for timber and concrete for this module is highly dependent on the distance that need to be gapped. This is different for each project. There are a lot more concrete factories spread out in the Netherlands, which could lead to shorter distances. On the other hand, concrete elements are a lot heavier than timber elements, leading to more energy needed for the same distance.
- **A5**: Additional materials can be needed to install the concrete or timber elements. This can be cement or additional concrete for the concrete elements. For timber elements, glue or bolts can be needed.
- **A5**: For both concrete and timber elements, a crane can be used to get prefabricated elements to the correct position. For concrete elements this happens more, as these elements are heavier. However, concrete can also be cast in situ, for which a pump can also suffice.

6.3 Stage B

Stage B, or the use stage, includes the modules covering the period from the handover of the building or construction, to when it is deconstructed or demolished. The duration of the use stage may be different from the required service life of a building. For example, a product can be replaced during the service life, or a product can be re-used after the service life. This stage covers all planned actions during the service life to maintain the installed product such that it can perform its required function, both technical and esthetical. It also includes the operation of building related services such as heating, cooling, lighting, water and internal transport (lifts and escalators).

B1	Use or application of the installed product
B2	Maintenance
B3	Repair
B4	Replacement
B5	Refurbishment
B6	Operational energy use (e.g. operation of heating system and other building related installed services)
B7	Operational water use

TABLE 4: LCA STAGES B1-A7

Table 4 shows what each separate stage includes. Below a summery is given of what this implies when concrete and timber is considered:

- **B1**: Both concrete and timber elements do not damage the environment when they are used.
- **B2**: This stage includes painting and cleaning the elements. Concrete can be painted, but this is not required. Depending on what kind of timber is used, this does need to be painted as a protection layer against moisture and deterioration. It can be assumed that concrete and timber have to be cleaned similarly.
- **B3-B5**: It is assumed that both concrete and timber elements do not need repairs, replacements or refurbishment in the service life of the building (Van Wijnen, 2020).
- **B6-B7**: Both concrete and timber elements do not need operational energy or water.

6.4 Stage C

Stage C, or the end-of-life stage, starts when an element is replaced, dismantled or deconstructed from the building and does not provide any further functionality. This can be at the end-of-life of the building, but also before or after this time. During the end-of-life stage, all output from dismantling, deconstruction or demolition of the building, materials or construction elements, are at first considered to be waste. This output can only become not-waste when it complies with all the following criteria:

- the recovered material, product or construction element is commonly used for specific purposes;
- a market or demand exists for such a recovered material, product or construction element;
- the recovered material, product or construction element fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to those products;
- the use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.

The "specific purpose" in this context is not restricted to the function of a certain product but can also be applied to a material serving as input to the production process of another product or energy.

The criterion for "overall adverse environmental or human health impacts" refers to the regulations at the time and place of the assessment. The presence of any hazardous substances exceeding these limits in the waste prevents the waste from reaching the not-waste state. All elements that have become not-waste are excluded from module C and are assessed in module D (European Committee for Standardization, 2013).

C1	De-construction, demolition
C2	Transport to waste processing
C3	Waste processing for re-use, recovery and/or recycling
C4	Disposal

TABLE 5: LCA STAGES C1-C4

Table 5 shows what each separate stage includes. Below a summery is given of what this implies when concrete and timber is considered:

- **C1**: Whether a product can be de-constructed or has to be demolished is dependent on the design rather than the material used for the elements. When a design is circular, the elements are easy to disassemble. Cranes are needed to lift the heavy elements, especially heavy concrete parts. If the element is glued to the building with glue or cement it needs to be demolished first.
- **C2**: It is hard to predict where the deconstructed or demolished elements will go, so the code works with assumed distances from 50 to 100 km, depending on the waste processing type.
- **C3**: For timber, four types of end-of-life scenarios are common: re-use, recycling, energy & thermal recovery and landfilling. Regardless of which scenario is used, the biogenic carbon content is assumed to be emitted when following the EN 15804 framework.
  Concrete can be re-used, recycled or become landfilling. Landfilling is not common for both concrete and timber in the Netherlands.
- **C4**: For both concrete and timber, there is not a lot of material that needs to be disposed. Most, if not all, can be re-used or recycled.

6.5 Stage D

Module D consists of the environmental benefits or loads resulting from re-use, recovery or recycle. This includes all flows leaving the product system that have not been defined as co-products, see stage A1-A3 (European Committee for Standardization, 2013).

D	Re-use, recovery and/or recycling potentials, expressed as net impacts and benefits

TABLE 6: LCA STAGES D

Table 6 shows what this stage includes. Below a summery is given of what this implies when concrete and timber is considered:

- **D**: With a circular design, the element in either concrete or timber can be used in the next cycle. When this is not possible, concrete can be crushed and used as aggregates in new concrete. Timber is used to make woodchips or for the production of electricity as mentioned before.

6.6 LCA studies in practice

The LCA method can be used to compare the environmental impact of different designs. In practice, this has been done several times. However, the comparison is not always fair. Some examples are given below with the assessment of whether the study was fair.

Study 1

In this Swedish study, conducted by SP Technical Research Institute of Sweden, an apartment complex based on concrete (a cast-in-situ and precast variant) and an identical apartment complex based on CLT variant were compared. In this study, both the concrete industry and the timber industry were intensively involved, resulting in optimal LCA studies for both materials. The study compares the amount of CO_2 equivalent that is emitted for 1 m^2 living area over stages A-C with a reference life of 100 years. CO_2 storage was not included in this study. The designs of the variants include durability, bearing capacity, fire safety and energy use during the use phase. All variants have a concrete foundation. For the CLT variant, two scenarios were distinguished, one was with the given data of the producers (best case) and one based on experiences (proven case). The two scenarios differ quite a lot in the use phase, especially the replacements and maintenance, so both were included in the comparison. The results show no significant differences between concrete and timber structures for the same functions during the life cycle. One of the conclusions was that there are a lot of variables when determining the LCA. The minor differences in the results are accordingly less than the degree of uncertainty involved in the study. The results are shown in table 7.

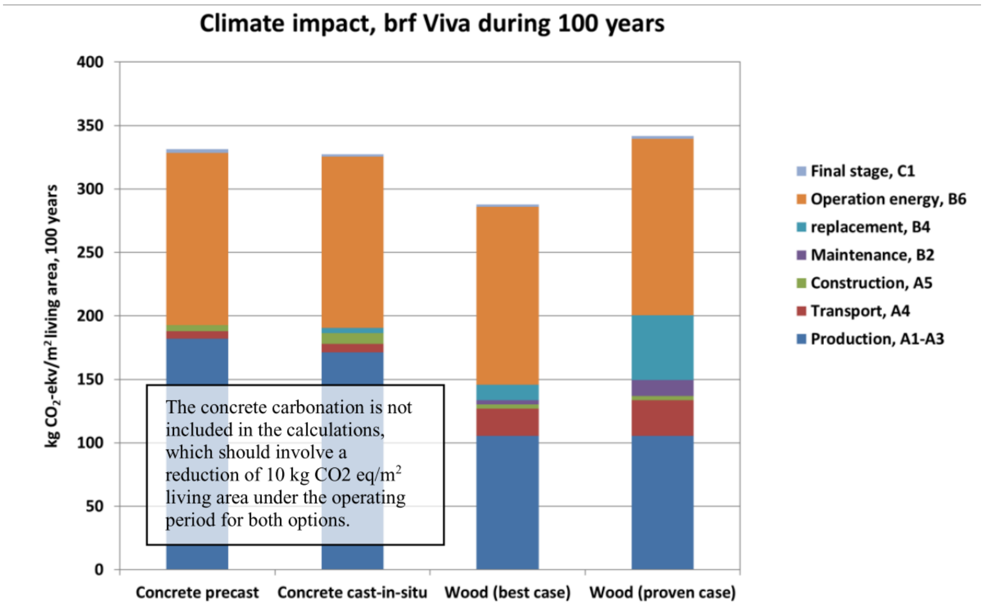


TABLE 7: CLIMATE IMPACT IN KG CO2 EQV. (KURKINEN ET AL., 2018).

It is good to note that this study does not include all functional requirements that a building has, for example the noise damping is excluded. Also, stage D of the LCA is ignored which has a great impact on the resulting CO_2 score. Furthermore, the study mentions that there are a lot of variables, that results in an inaccurate conclusion. This could have been limited by using a real case study. The downside of this is that then the study would be case specific, so both ways have potential. Lastly, there is a big difference between the CO_2 emissions of the best case and proven case CLT variants. This raises the question of whether or not this should be included in the data of the producers. Also, does concrete differ between best and actual case as well? This is not discussed in this study (Kurkinen et al., 2018).

Study 2

This next study was executed by the organization NIBE. They believe that to achieve the targeted reductions in shadow costs and CO_2 emissions, a large increase in bio-based materials is needed. A corner house case study was used by determining the MPG. Next, that house was redesigned by swapping the parts with bio based materials, see table 8. The reference case study had an MPG of 0,70 and the bio base variant had an MPG of 0,56, a 20% reduction. CO_2 storage was included in this MPG.

Onderdeel in referentie	Biobased alternatief
Betonnen heipalen	Houten heipalen
Betonnen vloeren woning Betonnen vloeren appartement	Houtskeletbouw vloeren Houten kanaalplaatvloeren (+ benodigde geluidsisolatie)
Beton en gipsblok wanden	Grenen logs wanden/HSB dragende en woningscheidende wanden
Baksteen gevel, kalkzandsteen binnenblad en glaswol isolatie	Gevelelementen van stro en hout met eikenhout bekleding
Betonnen dakpannen Bitumen dakbedekking	Rieten dakbedekking Plantaardige dakbedekking
Dakisolatie	Vlaswol isolatie
PVC dakgoot	Houten dakgoot
Baksteen straatstenen	Bamboe terreinverharding

Tabel 1: vervangen onderdelen in de MPG-berekeningen t.b.v. woningbouw.

TABLE 8: PROJECT CHANGES NIBE RESEARCH, 2019)

They state that “to estimate the impact (shadow price and CO_2 -emissions) we have made calculations. We would like to stress that these calculations are based on scenarios. Although they were drawn up with the greatest care, they remain mere predictions, based on assumptions. We therefore consider the results in outline only and not in detail” (NIBE Research, 2019). It is unfortunate that no more details are given. The rest of the report addresses how bio-based materials can be used to help to reach our climate goals, which is based on the conclusion that is not touched upon.

Study 3

This next research was executed by the company W/E adviseurs in 2016. It studied whether (and if so, how much) building with timber products would increase the climate potential, specifically for residences. Even tough W/E adviseurs is an impartial company, the study was carried out on behalf of the Dutch Timber Industry Association (NBvT).

The NBvT assumes that building with timber leads to a reduction in CO_2 emissions: “by building with a timber frame construction system more often, a contribution can be made to achieving the Dutch climate goals” (NBvT, 2016). In order to substantiate this message, NBvT commissioned W/E to carry out a quantitative study. This study would provide insight into the potential CO_2 reduction that can be achieved by using timber construction instead of the traditional 'heavy' construction methods (concrete and limestone). The study was limited to the construction of new houses with ground floor-level access.

The research started with re-calculating the environmental impact of several housing variants. These variants are taken from the sample buildings from RvO (Rijksdienst voor Ondernemend Nederland). The residential buildings in this set have been deemed representative for current residential construction. In 2014, the Ministry materialized some of the example buildings, so that they could serve as references for the environmental performance calculation (MPG). This MPG score includes all life stages from A to D, using the NMD data. It expresses the total environmental impact in kg CO_2 equivalent, see figure 10. Whether or not these MPGs include CO_2 storage was not touched upon. The ground-level residences that are considered in this study were constructed in concrete, sand-lime brick and wood-frame construction.

CO2-emissie	[kg CO2 eq./m2bvo*j]		Bouwmethode		
Woningtype	Uitvoering	Code	'Zwaar'	HSB	
Rijtussen	standaard	RIJ-stan	3,27	2,33	71%
2-1-kap	standaard	KAP-stan	3,71	2,65	72%
Vrijstaand	standaard	VRIJ-stan	4,31	3,62	84%
Gemiddeld	standaard	stan	3,76	2,87	76%
		tov 'standaard'	100%	100%	
Rijtussen	zonder hout	RIJ-geen	3,54		
2-1-kap	zonder hout	KAP-geen	3,92		
Vrijstaand	zonder hout	VRIJ-geen	4,48		
Gemiddeld	zonder hout	geen	3,98		
		tov 'standaard'	106%		
Rijtussen	maximaal hout	RIJ-max	3,54	1,98	56%
2-1-kap	maximaal hout	KAP-max	3,92	1,64	42%
Vrijstaand	maximaal hout	VRIJ-max	4,48	2,87	64%
Gemiddeld	maximaal hout	max	3,98	2,16	54%
		tov 'standaard'		75%	

FIGURE 10 CO2 RESULTS OF COMPARISON BETWEEN THE CONCRETE (ZWAAR) AND HSB BUILDING METOD (W/E ADVISEURS, 2016)

This provided insight into the CO_2 emissions that arise as a result of the materials used during the life of the home. These emissions are translated into scenarios for the annual construction of new homes in the Netherlands. The scenarios are based on assumptions, following expected new construction development. Three scenarios were considered. In "autonomous", it is assumed that the number of timber frame homes in 2017 is the same as in previous years (1,500 homes). The remainder are traditional 'heavy' construction methods. At "Goal", 10,000 timber homes have been build, a number that NBvT considers feasible. "Maximum" assumes 100% timber frame construction, which is not a realistic assumption, but gives an impression of the total potential, see table 9. The comparison of "Goal" with "autonomous" shows that with 10,000 timber frame homes, a 6% reduction in CO_2 emissions can be achieved. This means more than 106,000 tons less CO_2 annually. With a complete switch to wood frame construction, the reduction would be 24% (W/E Adviseurs, 2016).

CO2-equivalenten	2017*	houtskeletbouw		zware bouwmethoden		Scenario	Reductie	
Scenario	woningen	woningen	ton eq	woningen	ton eq	ton eq	ton eq	%
AUTONOOM	37.100	1.500	55.832	35.600	1.770.827	1.826.660	0	0%
STREEF	37.100	10.000	372.216	27.100	1.348.017	1.720.234	106.426	6%
MAXIMAAL	37.100	37.100	1.380.923	0	0	1.380.923	445.737	24%

TABLE 9: CO2 REDUCTION WHEN SING TIMBER BUILDINGS (W/E ADVISEURS, 2016)

Once the conclusion was drawn that it is better to build a house with HSB than with heavy construction materials, it is logical that the more the HSB method is used, the bigger the reduction. However, that first conclusion was drawn quite quickly. There is no transparency of the MPG calculations and which parts of the building are and are not included in the calculation. It is stated that the "bepalingsmethode" is used, so the correct rules and database are used. But, without transparency of the calculations, no real conclusion can be drawn.

Study 4
In 2019 A. Zeitz, C.T. Griffin and P. Dusicka did a study comparing different parking garages. They found four case studies, each comparable in size, but all with a different construction material, see figure 11. The materials were (from left to right) precast concrete, cellular steel, post-tensioned concrete and mass timber. They choose parking garages as their case study, as the structure has little requirements other than that it needs to be strong and stable (no sound or insulation requirements).

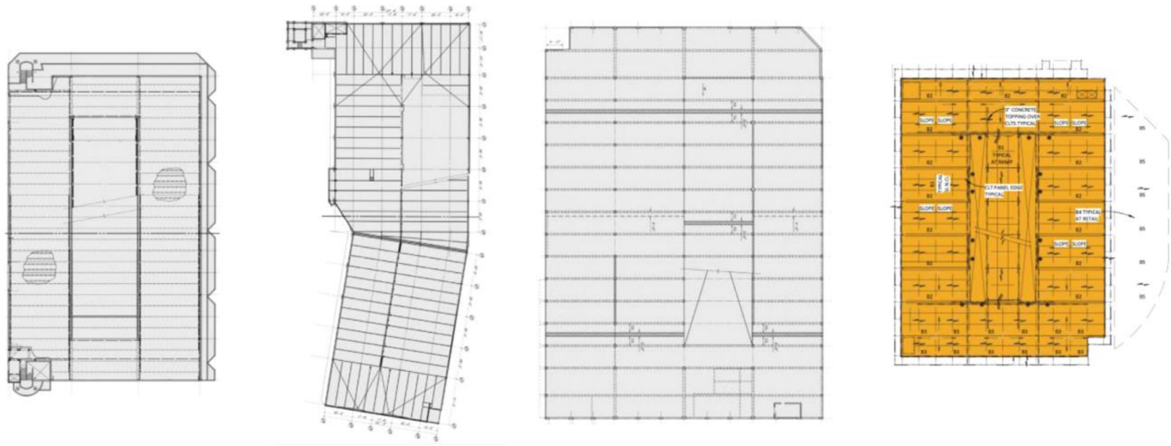


FIGURE 11: THE FOUR PARKING GARAGES WITH DIRRENT MATERIALS

They considered the cradle to gate stages of the LCA, so stage A1 trough stage A3, without taking CO_2 storage into account. For each garage they made two calculations, the first assuming the worst case scenario and the other assuming the best case scenario. They used the ECI database (The Inventory of Carbon and Energy), but since CLT was not yet in this database, the glulam data was used instead. The values found were divided by the total floorplan of each garage. Their findings are listed below in table 10. Note that the "embodied carbon" is the same as the carbon footprint.

Total "cradle-to-gate" embodied carbon divided by total parking area ($kgCO_2e/m^2$) for each case study.

Primary span	Worst practices	Best practices
Precast concrete	80	52
Cellular steel	107	41
Post-Tension conc.	80	46
Mass timber	67	37

TABLE 10: EMBODIED CARBON (ZEITZ ET AL., 2019)

They concluded that the differences were not significant. There was too much variety in the outcomes to make a solid conclusion, so the construction material does not matter for the environmental impact (Zeitz et al., 2019).

Study 5
In 2018 D. Thomas and G. Ding made a research comparing the performance of brick and timber in residential buildings. They picked out 10 reference projects in brick and designed a timber alternative, making sure the thermal performance was the same. Table 11 shows the general changes made, going from the brick to the timber design.

Building envelope materials for conventional and timber design.

Building Component	Conventional design (Brick veneer envelope)	Timber design (Timber clad envelope)
Substructure	Sand blinding, Concrete piers (in area of fill), 200um Waterproof membrane	Concrete piers, Galvanised steel piers-braced, 19 mm timber cladding wall enclosure
Structural floor	Ground floor: EPS foam, reinforced concrete floor & ribs	Ground floor: 140 mm Treated pine bearers, R3.1 insulation, 90–120 mm treated pine joists & 12 mm Ply under floor covering
	First floor: Timber I-beams & chipboard	First floor: Timber I-beams & chipboard
Floor finishes	Ground floor: Carpet with underlay or ceramic tiles	Ground floor: 19 mm Hardwood flooring or Ceramic tiles on 15 mm fibrous cement sheeting
	First floor: Carpet with underlay	First floor: Carpet with underlay
External wall	Structure: 90 mm Pine timber frame, vapour barrier &50 mm air cavity	Structure: 145 mm Treated pine framing, R3.1 insulation batts, vapour barrier & 38 mm air cavity/vertical battens
	Lining to the inside: 10 mm Plasterboard	Lining to the inside: 10 mm Plasterboard
	External cladding: Extruded clay brick	External cladding: Painted timber cladding & timber architraves
Roofing	Structure: Pine timber frame/truss, R3.5 insulation to living areas	Structure: MGP 10 Pine Timber frame/truss, R3.5 insulation to living areas
	Covering: Roof sarking & concrete tiles	Covering: Roof sarking & concrete tiles

TABLE 11: CHANGES FROM BRICK TO TIMBER DESIGN (THOMAS & DING, 2018)

Next, they made an LCA calculation looking at stage A trough C, cradle to grave (noted as LCE in the table) with a reference life of 50 years, without taking CO_2 storage into account. The environmental impact was expressed in embodied energy. This energy is defined as a sum of the energy consumed at the construction stage, the initial embodied energy in material manufacturing, the material waste during construction and the energy used in major plant and equipment for construction activities on site. The results are shown in the table below.

Project ID	GFA (m^2)	LCE (50 years) (MJ)		LCE (50 years) (MJ/m^2)	
		Brick	Timber	Brick	Timber
1	290	2,230,507	2,009,116	7,691	6,928
2	334	3,051,217	2,827,444	9,135	8,465
3	171	1,900,948	1,708,336	11,117	9,990
4	281	2,471,915	2,234,080	8,797	7,950
5	192	1,947,019	1,760,811	10,141	9,171
6	246	2,475,470	2,221,483	10,063	9,030
7	260	2,476,941	2,274,446	9,527	8,748
8	171	1,851,943	1,696,303	10,830	9,920
9	240	2,122,896	1,943,651	8,845	8,099
10	124	1,144,086	1,037,806	9,226	8,369
Mean	231	2,167,294	1,971,348	9,537	8,667

TABLE 12: RESULTS (THOMAS & DING, 2018)

The analysis revealed that a timber envelope can provide benefits over the original brick design. This benefit is less significant on a 50-year period. The results show that the LCC of the timber designs are on average 2% per m^2 less than brick design over the 50-year period, which is not significant. Also, the material and construction cost of the timber designs are 6% per m^2 less. However, the maintenance cost of the timber is 26% per m^2 greater than for the brick designs over the 50-year period (Thomas & Ding, 2018).

Remarks

These studies show that there are several ways to execute an LCA comparison. The way this comparison is executed can influence the outcome. The question is, what is the right way? Three different aspect of the methods used in these studies are highlighted. It is discussed how these aspects should be handled to make a fair comparison possible.

The first aspect is the used model. Some studies compare two (or more) similar existing structures, both with different construction materials, like studies 4 and 5. The upside to this method is that both the designs are realistic. The downside is that the designs are never exactly the same. A building could have slightly different functions, making one have an unintended advantage. Other studies compare a real design with a hypothetical redesign, executed with a different material, like studies 1, 2 and 3. The upside to this is that the situation is the same. However, since the redesign is hypothetical, not all requirements of the original design have to have been taken into account. This can be seen in the study 1: not taking sound reduction into account, making the redesigns have an advantage. Therefore, this method only works if all the functional requirements are taken into account for the redesign.

The next aspect is the system boundaries of the LCA. Studies use cradle to gate, cradle to grave or cradle to cradle. It is safe to say that the more stages are added in the comparison, the more the conclusion is meaningful. However, adding more stages also means that the end-of-life of a product has to be predicted, which can lead to inaccuracies.

The last aspect is used data. Depending on where the studies are executed, the local database is used. There are differences in these databases, as there are different rules that describe how this data should be retrieved. Also, within one database there can be several options for the same material depending on the different producer. In addition, data can be lacking as seen in study 4. The data has a high impact on the outcome, so using a good data source is important

Part 4: Case study

7. Case Study: Introduction

The requirements of a structure depend on the project. There are different rules for different situations. So, to be able to discuss the pros and cons of using either concrete or timber, a situation should be chosen.

The Netherlands plans to build 1 million houses in the upcoming 10 years (Ten Teije, 2021). Of these 1 million houses, 42% is single-family houses (eengezinswoningen). A popular typology for a single-family house in the Netherlands is the terraced house (rijtjeshuis). So, for this thesis contact has been made with construction company “Kroon en de Koning”, to request help in finding a project with a terraced house that is representative and/or similar to other projects with the same typology. In this chapter this project will be introduced: “De Laantjes” in Hendrik Ido Ambacht, see figure 12.

FIGURE 12: DE LAANTJES (DE VOLGERLANDEN HENDRIK-IDO-AMBACHT, N.D.)

De Laantjes is a project undertaken by “Kroon en de Koning” in the Volgerlanden in Hendrik Ido Ambacht. The project is implemented as the first of the 4 projects that make up the 4 Dorpjes: De Laantjes, De Straatjes, De Erfjes and De Hofjes, see figure 13. In the project there is a wide variety of homes, from detached, semi-detached to terraced houses. During the design, the future residents are involved in the manner of housing choices. This means that the fundamentals for the homes are fixed, but there are several possible variations that the residents may choose. For example, there are two different sizes for the extension of the living room, different layouts of the second floor with the choice between two or three bedrooms and much more. For this thesis, Block 1A of the project will be used. The block is situated on the Jacobuslaan, see figure 14.

FIGURE 13: DE 4 DORPJES (DE VOLGERLANDEN HENDRIK-IDO-AMBACHT, N.D.)

FIGURE 14 & 15 : LOCATION BLOCK 1A (DE LAANTJES, 2020)

The block consists of 7 houses. The two on the left and the one on the right is slightly bigger. Number 12 (as indicated in figure 15) will be the house looked at, this is one of the central houses.

The construction of the houses consists mainly of prefabricated concrete, except for the roof which consists of wooden frames. The foundation beams are cast in situ and the piles are vibro piles, which are also cast in situ. The ground floor is made up of rib cassette floor slabs. The floors above are hollow core slabs. The outer walls and the walls between the houses are prefabricated concrete. The inner walls are limestone. On top of the wooden roof frame, ceramic roof tiles are positioned. For drawing and pictures of the projects, see figures 16 to 24.

FRONT FAÇADE

CROSS-SECTION

BACK FAÇADE

FIGURE 16, 17 & 18 : FACADES & CROSS-SECTION BLOCK 1A (DE LAANTJES, 2020)

[redacted]

GROUND FLOOR **FIRST FLOOR** **SECOND FLOOR**

FIGURE 19, 20 & 21 : FLOORPLANS BLOCK 1A NUMBER 12 (DE LAANTJES, 2020)

FIGURE 22, 23 & 24 : DE LAANTJES

8. CASE STUDY: FUNCTIONAL REQUIREMENTS BUILDING ELEMENTS

In order to design different element for this case study, the approach and starting points need to be established.

8.1 APPROACH

In chapter 10, new designs for several elements in case study De Laantjes will be designed. These designs will be used to compare the concrete options with the timber options in terms of sustainability. There are several ways this comparison can be defined. One, is to select a case study with either a concrete or timber design and to redesign this case study with the other material. The two variations can be put side by side to compare the environmental impact. This approach will not be used in this thesis. Here, the comparison will be executed on element level, not on building level. This makes it possible to determine the most suiting material per element rather than for an entire building, allowing hybrid building options with perhaps a timber façade and a concrete floor. The elements that are studied have very different requirements, as will be elaborated in section 8.3, so it is plausible that for some of these elements timber will be favorable and for others concrete.

Another reason why the element level is chosen, is that this allows the elements to be more recognizable in similar situations. For example, a simply supported floor with a certain span is very similar to a simply supported floor in any other building. Rather than the entire building having to resemble another project.

The downside of studying the element level is that a lot of possible combinations emerge. On top of each element having different variations due to using different materials, there will also be different load options caused by changing the material of the surrounding elements: the loads acting on an element will be different since the surrounding elements will have a different weight when designed with a new material. For example, there are four different floor designs, each designed with different materials and thus have different weights. The load bearing wall has to carry this floor, so its dimensions depend on the weight of this floor. This results in four different variations of the load bearing wall for the four different floor types. Now, the load bearing wall has to also be redesigned with a different material, resulting in eight alternatives for the same load bearing wall. Adding even more elements to this problem will get unorganized quickly. So instead, it has been chosen to use the case study as the starting point. An element is isolated and the load scheme and loads are copied to make up the situation for which alternative designs can be created. The elements that will be redesigned are shown below: the intermediate floor, the façade wall, the loadbearing wall, the ground floor and the foundation, see figure 25.

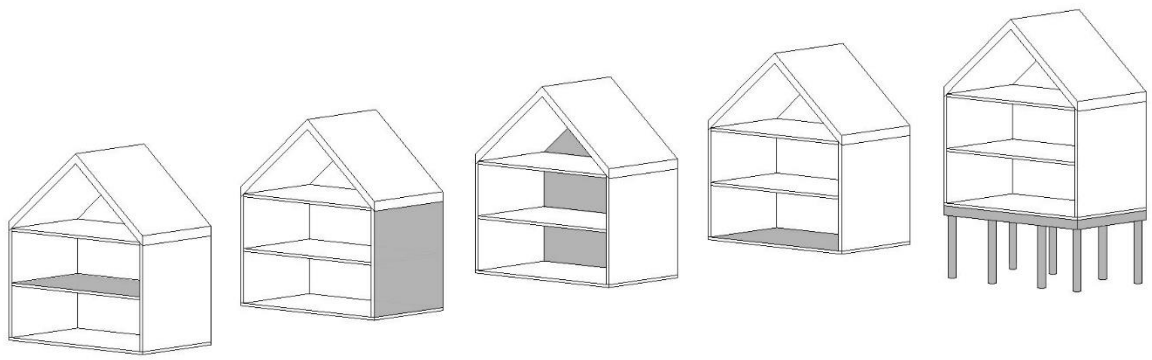


FIGURE 25: INTERMEDIATE FLOOR, FACDE WALL, LOADBEARING WALL, GROUND FLOOR AND FOUNDATION

8.2 LOAD SCHEME PER ELEMENT

The elements that will be redesigned are located in a center house. The structural principles of the original design are carried over to the alternative ones. The vertical loads are determined using the data of the project, see table 13. In the project the internal walls are modelled as variable vertical loads, as the layout of each residence can be different. The horizontal loads are determined using NEN 1991, see **appendix 2: wind calculation**.

		G [kN/m²]	Q [kN/m²]
Roof	Roof	[redacted]	
2nd Floor	Hollow core slab Screed+heating Live load Partition walls		
1st Floor	Hollow core slab Screed+heating Live load Partition walls		
Ground floor	Rib cassette Screed+heating Live load Partition walls		
Load bearing wall	Concrete wall Concrete wall		
Façade wall	Concrete wall Masonry		

TABLE 13: VERTICAL LOADS OF DE LAANTJES

The load schemes per element are determined as follows. First, the element is located and the supports are copied. Next, all vertical loads acting on this element are listed, with the exception of the own weight of the element. The same is done for the horizontal loads. This makes up the starting point for the designs of the alternatives. The own weight of the element is dependent on the design. A visual explanation for the intermediate floor is given on the next page, see figure 26.

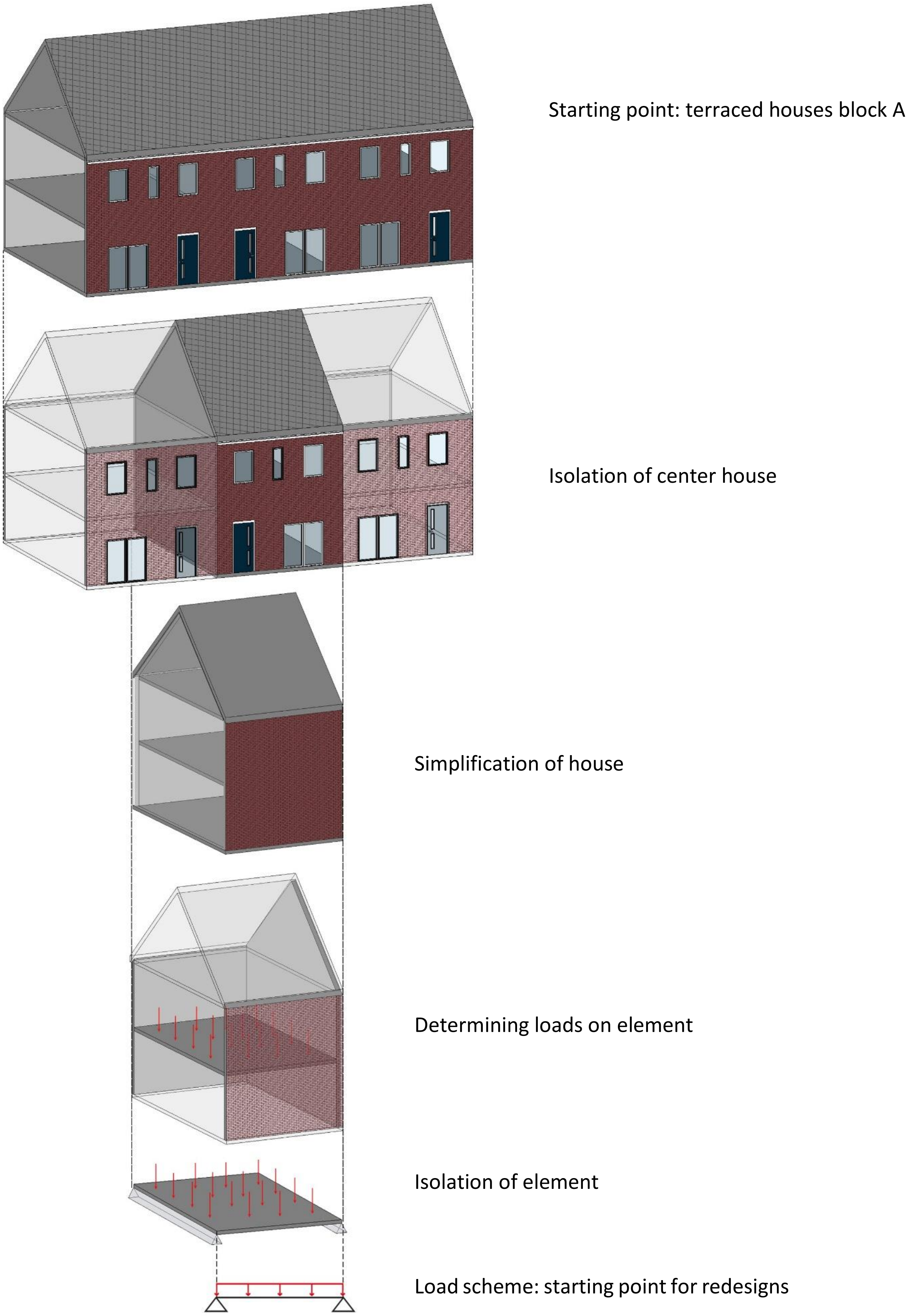


FIGURE 26: ISOLATION OF FLOOR ELEMENT

8.3 Functional requirements per element

In order to make a fair comparison, the elements need to fulfil the same requirements, making sure it is able to function within the building. To determine these requirements, the Dutch norms and the "Bouwbesluit 2012" are consulted. The requirements included in this thesis are: strength, deflection, fire resistance, thermal insulation, sound resistance and vibration resistance.

Intermediate floor

The floor needs to be strong enough to bare the loads and it should not deform too much (NEN1990). There is a fire insulation requirement as the floor has a residential function and people will sleep on this level. Since the floors are below 7 meters from the ground, the duration of fire resistance with respect to collapse is 30 minutes (BB art. 2.10). There are no thermal insulation requirement, as both above the floor and below are indoor spaces. There is a sound requirement for airborne sound and impact noise. The airborne sound difference needs to be 32 dB for spaces separated by two doors, which is the case for the living room and bedroom. The Impact noise has a maximum of 79 dB (BB art 3.17a). The floor also needs to fulfil the vibrations requirement to make it a comfortable living space. As a residence the vibration resistance needs to be class D (Hivoss, 2008).

The requirements are:

- Strength: ULS UC<1
- Deflection: SLS u< 0,004*l
- Fire safety: 30 minutes
- Airborne sound difference: 32 dB
- Impact sound: max 79 dB
- Vibrations: Class D

Façade wall

The façade of the building is not loadbearing, so there are no axial forces except for its own weight. It has to redirect the in-plane wind forces to the loadbearing walls and provides stability in the other wind direction. The deflection created by this shall be ignored, as this will not be governing. There is no fire requirement, as the element is adjacent to the outdoors (BB art 2.10). There is an insulation requirement for vertical element connected to the outdoors. The Rc- value needs to be 4,7 m^2K/W (BB art 5.3). The façade acts as an external partition wall, so the soundproofing needs to be at least 20 dB (BB art 3.2).

The requirements are:

- Strength: ULS UC<1
- Rc-value ≥ 4,7 m^2K/W
- Airborne sound difference: >20 dB

Loadbearing wall

This wall carries the vertical loads from the roof and the floors. It will also provide stability and carry the horizontal wind loads. Again, deflection not governing and ignored. The wall separates two different residences. Because each residence is its own fire compartment, the fire resistance needs to be 60 minutes (BB art 2.84). There is no insulation requirement, as both sides of the wall are a residence. There needs to be an airborne sound resistance of 52 dB and the impact sound can be a maximum of 54 dB (BB art 3.16). In the original design this is ensured by dividing the wall in two, creating an uninterrupted cavity (in dutch: ankerloze spouw).

The requirements are:

- Strength: ULS UC<1
- Fire safety: 60 minutes

- Airborne sound difference: 52 dB
- Impact sound: max 54 dB

<u>Ground floor</u>

The floor needs to be strong enough and not deflect too much, just like the intermediate floor. There are no fire requirements, as the floor is adjacent to the outdoors, or in this case the ground (BB art 2.10). The floor needs to have an RC-value of at least 4,7 m^2K/W, as it is connected to the ground (BB art 5.3). There are no acoustics requirements for the air sound resistance (BB art 3.2). The impact sound can be assumes to suffice when the floor is laid down on an insulator, like rubber, before laying it down on the foundation beam. This is the case for the existing design. The vibration resistance needs to be class D, just like the intermediate floor.

The requirements are:

- Strength: ULS UC<1
- Deflection: SLS u< 0,004*l
- Fire safety: 30 minutes
- Rc-value ≥ 4,7 m^2K/W
- Vibrations: Class D

<u>Foundation beam</u>

The beam needs to be able to transfer the vertical forces to the piles. There are no requirements for fire resistance, insulation, acoustic resistance or vibration, as the element is adjacent to the ground.

The requirements are:

- Strength: ULS UC<1

<u>Foundation pile</u>

The piles need to carry the vertical loads. Groundwater is also considered. Because of the varied groundwater level, part of the pile will be fully under water and part will be alternating between wet and dry. The top part will remain dry. The material needs to withstand this for the reference life of 75 years. This will be determined using use classes for concrete and durability classes for timber, but no quantitative test will be executed.

The requirements are:

- Strength: ULS UC<1

9. CASE STUDY: LCA APPROACH

In principle, the comparison of products based on their EPD is defined by the contribution they make to the environmental performance of the building. The comparison of the environmental performance of construction products should be based on the products use in, and its impacts on the building. In such cases the principle that the basis for comparison should be maintained by ensuring that the same functional requirements are met. Furthermore, the environmental performance and technical performance of any components, or products excluded should be the same. The information provided for such comparison should be transparent to allow the purchaser or user to understand the limitations of comparability (European Committee For Standardization, 2006b). This chapter formulates the basis of the comparison.

In chapter 3 the framework of the LCA procedure is covered. This will be used to make these LCA analyses. In this chapter the scope and definition is given.

9.1 GOAL

This study is carried out in order to compare two, three or four different construction materials for structural elements within a basic terraced house in project De Laantjes. The elements for which alternative designs are compared will be:

- The intermediate floor
- The loadbearing wall
- The façade wall
- The ground floor
- The foundation

This study is for educational purpose only.

9.2 FUNCTIONAL UNIT

The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis (European Committee For Standardization, 2006b).

In order to give a fair comparison for each of the elements, the designs should fulfil the same structural requirements. The requirements are mentioned in 8.3. Together with the load scheme, this will be the functional unit expressed in m^2 for the walls and floors, in m for the foundation beam and per piles that carry the 479 kN for the foundation piles.

The Reference Service Life (RSL) will be 75 years as this is the intended life of the building. If an element is able to have a longer life, than this will be addressed in module D. The materials are assumed to be new and not re-used from a previous cycle.

The finishing of the element will not be addressed in this study.

9.3 SYSTEM BOUNDARIES

The goal of this thesis is to perform a fair comparison. This can only be done if the entire life of a product is elaborated: stages A1-D. However, this introduces a lot of uncertainties about the different scenarios possible at the end-of-life. Information needed to make the full calculation is missing, as no one can predict the future. Also, a lot of data in the NMD is not transparent enough to use in this calculation (without a license). Because of this, it has been decided to make the environmental cost calculation on three levels. Each level adding more stages: becoming more complete, but also each level adding more uncertainties: becoming more subjective.

The three levels are:

- Stages A1-A3: This includes the production of the element.
- Stages A1-C4: This includes the production, placement, usage and demolition of the element.
- Stages A1-D: This includes what is mentioned above and also takes potential environmental gain into account.

9.4 Methodology

For this study the "Bepalingsmethode" from the Nationale Milieu Database will be used. This refers to NEN-EN 15804+A1 and NEN-EN-ISO 14040.

The data will be retrieved as follows:

A1-3	NMD category 3
A4	Estimation based on expected distances and NMD
A5	Estimation based on expected machinery and NMD
B1-7	Estimation based on service life
C1	Estimation based on expected machinery and NMD
C2	Estimation based on expected distances and NMD
C3	NMD category 3
C4	Estimation based on determined scenario and NMD
D	Estimation based on determined scenario and NMD

TABLE 14: DATA SOURCE PER STAGE

Category 3 data is non-specific public data. The data in this category is raised by 30% to accommodate the varying performance of untested environmental profiles (Stichting Nationale Milieudatabase, 2020). As both concrete and timber values will be raised, the comparison is still valid.

For some elements in the NMD, the dimensions differ from the elements designed in this study. In those cases, the shadow costs are scaled based on the weight of the element. This has only been done for data that is allowed to be scaled this way. This is indicated in the NMD per specific element.

For the end-of-life it is assumed that the elements are not re-used, but are recycled. The scenarios used to determine the end-of-life (stage C and D) are as follows:

- Concrete: 100% is recycled and the benefits are determined as 40% A1-A3 stages of new concrete.
- Reinforcement steel: 100% is recycled and the benefits are determined as 75% of the A1-A3 stages of primary reinforcement steel.
- Timber: 100% is recycled and the benefits are determined as 48% of the A1-A3 stages of timber chipboard.
- Other materials are not re-used, this includes the screed and the brickwork.

These percentages are retrieved as follows.

<u>Concrete</u>

For the used concrete it is assumed that it can replace sand, gravel and additives in a new concrete recipe. So, in order to identify the benefits at the end of life, the part of the environmental shadow costs caused by the sand, gravel and additives should be isolated. To do this, the concrete recipe in table 15 is used.

	[kg]	[%]
Cement	345	14,8%
Gravel	1028	44,0%
Sand	808	34,6%
Additives	1,6	0,1%
Water	155	6,6%
Total	**2337,6**	100%

TABLE 15: CONCRETE RECIPE (DYCKERHOFF BASAL, 2020)

The ECI of 1 kg concrete for stages A1-A3 is: €0,0075 (NMD category 3, 2021).
Of which, 14,8% is cement, or 0,1448 kg, see table 15.

The ECI of 0,1448 kg cement for stages A1-A3 is: €0,003454 (Stichting MRPI & dyckerhoff, 2019).
This is branch specific data, so this should be raised with 30% to match the proportions of the category three data of the NMD, so:
The scaled ECI of 0,1448 kg cement for stages A1-A3 is: €0,0044906.

Now, it can be concluded that of the total ECI of €0,0075 for 1 kg concrete, about €0,0044906 is caused by the cement. This is 60%. The other 40% is caused by the sand, gravel and fillers (water is neglected). So, 100% of the concrete is recycled as 40% of the A1-A3 stages of new concrete.

Steel
For the percentage of steel recycling, a rule of thumb is used. This stated that steel can be re-used as 75% of new steel (GLE Scrap Metal, 2021).

Timber
The used timber is assumed to be shredded and made into chipboard. So, the part of the environmental cost of chipboard caused by the wood should be isolated to determine the possible benefits.

The ECI of 1 kg chipboard of stages A1-A3 is: €0,0565 (NMD category 3, 2021)
Of which, 90% is wood, or 0,9 kg. The other 10% is the glue (Fritz EGGER GmbH & Co. OG Holzwerkstoffe, 2021).

The ECI of 0,9 kg spruce laths for stages A1-A3 is: €0,0301 (NMD category 3, 2021).

Now it can be concluded that of the total ECI of €0,0565 for 1 kg chipboard, about €0,0301 is caused by the timber. This is 48%. So, 100% of the timber can be recycled as 48% of the A1-A3 stages of chipboard.

10. Case study: multi-disciplinary design and environmental performance

In this chapter the alternative designs for the different elements are given. These fulfil the defined functional requirements mentioned in section 8.3. As described in chapter 4, the materials differ a lot in properties, resulting in some element needing additional materials to fulfil the same requirement. Next, the environmental shadow costs are given per alternative design in section 10.6. The alternative shadow costs, including CO_2 storage are given in section 10.7.

10.1 Intermediate floor

The first element that will be redesigned is the intermediate floor. The floor spans between the residence separating walls. The load scheme is given below, see figure 28. The element needs to fulfil the requirements for strength, stiffness, fire resistance, air sound insulation, impact sound insulation and vibrations (section 8.3). The calculations used to determine whether the element fulfils these functional requirements, can be found in **appendix 3: Intermediate floor.**

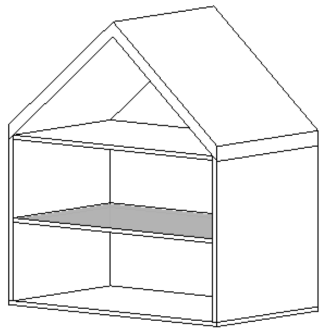


FIGURE 27: INTERMEDIATE FLOOR

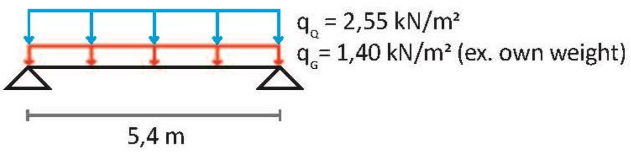


FIGURE 28: LOAD SCEME INTEREMEDIATE FLOOR

Design 1: Hollow core slab (existing)

The first design is the one that is used in the existing case study. It uses prefab concrete elements that are made by the producer Dycore. The hollow core slab floor is a pre-stressed floor system that is widely used in residential and commercial construction. The hollow cores reduce weight and material, while still retaining its strength. The slabs will be topped with a concrete screed to enclose the heating pipes and to make the floor ready for the finishing.

FIGURE 29: HOLLOW CORE SLAB (BETON LEXICON, N.D.)

Most functional requirements are tested by the producer: the strength, stiffness, fire resistance and sound insulation. All requirements are met, see the table below. A "√" means that the condition is satisfied, but no value was determined.

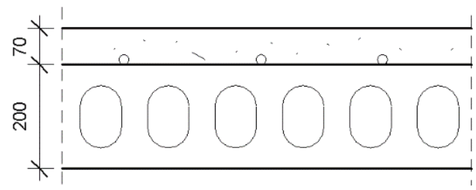


FIGURE 30: DESIGN 1 HOLLOW CORE SLAB

Strength	Stiffness	Fire resistance	Sound insulation air	Sound insulation impact	Vibrations
UC	UC	[min]	[dB]	[dB]	Class
0,22	√	90	44	√	D

TABLE 16: FUNCTIONAL REQUIREMENTS INTERMEDIATE FLOOR DESIGN 1

Design 2: In situ concrete

The next design uses cast in situ concrete. This is usually cast together with the walls, known as "gietbouw". The formwork is placed, the reinforcement is positioned inside the formwork and then the concrete is poured. When the concrete is hard enough, the formwork is slid out and then can be used for the next pour. The floor will be topped with a concrete screed to ensure a smooth finish and to enclose the heating pipes.

FIGURE 31: GIETBOUW (BETONHUIS, N.D.)

The functional requirements are tested by using the Eurocode or simplified rules of thumb

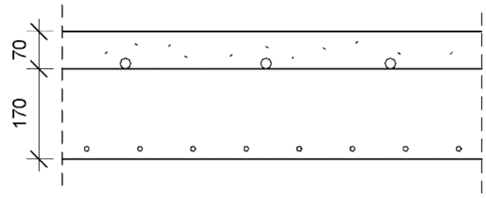


FIGURE 32: DESIGN 2 CAST IN SITU

Strength	Stiffness	Fire resistance	Sound insulation air	Sound insulation impact	Vibrations
UC	UC	[min]	[dB]	[dB]	Class
0,94	0,94	90	44	√	√

TABLE 17: FUNCTIONAL REQUIREMENTS INTERMEDIATE FLOOR DESIGN 2

Design 3: CLT

Cross Laminated Timber, or CLT, is a timber construction product. The strong, solid timber construction boards are made up of three or more layers of cross-glued pine slats. It uses the anisotropic quality of timber by crossing slabs in two directions. This insures that the slab will be strong in both directions instead of one. They can be used as floor, wall or roof elements. The CLT slats are compressed under high pressure. This increases the load capacity and makes the boards more stable and rigid. The expansion, contraction and deformation of the wood is reduced to a minimum. The floor is finished with a screed to enclose the heating pipes.

FIGURE 33: CLT (WOODYHOMES BVBA, N.D.)

The functional requirements are tested using the tool Calculatis made by a Stora Enso, a producer of bio based products like CLT, and with the Eurocode.

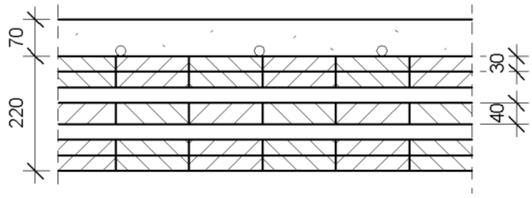


FIGURE 34: DESIGN 3 CLT

Strength	Stiffness	Fire resistance	Sound insulation air	Sound insulation impact	Vibrations
UC	UC	[min]	[dB]	[dB]	Class
0,21	0,86	30	33	65	D

TABLE 18: FUNCTIONAL REQUIREMENTS INTERMEDIATE FLOOR DESIGN 3

Design 4: LVL timber

Laminated Veneer Lumber , or LVL, is produced from approximately 3 mm thick rotary-peeled softwood veneers, that are glued together. The billet is cut and sawn into LVL beams, planks or panels. This floor uses LVL in an optimized buildup, with several beams and a panel on top. The timber parts are glued under high pressure and temperature making the elements cooperated fully. This has a positive effect on the strength, but also on the stiffness, deflection and vibration. As the floor is very thin, a gypsum board is added at the bottom to ensure fire safety. Mineral wool is added to damp sounds. The floor is finished with a screed, which makes the slab vibrate less and this encloses the heating pipes.

This floor is designed using a tool provided by the producer Kerto Ripa, ensuring it fulfils most requirements. The resulting requirements were tested using the Eurocode.

FIGURE 35: KERTO LVL FLOOR (METÄWOOD, N.D.)

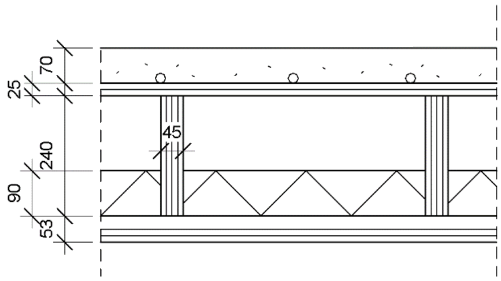


FIGURE 36: DESIGN LVL

Strength	Stiffness	Fire resistance	Sound insulation air	Sound insulation impact	Vibrations
UC	UC	[min]	[dB]	[dB]	Class
√	√	30	60	58	D

TABLE 19: FUNCTIONAL REQUIREMENTS INTERMEDIATE FLOOR DESIGN 4

10.2 FAÇADE WALL

The second element that will be redesigned is the façade wall. This wall is not load bearing and spans from floor to floor. The load scheme is given below, see figure 38, for both the total wall and the wall that spans just the ground floor to first floor. The element needs to fulfil the requirements of strength, insulation and air sound insulation (section 8.3). The calculations used to determine whether the element fulfils the functional requirements, can be found in **appendix 4: Façade wall**.

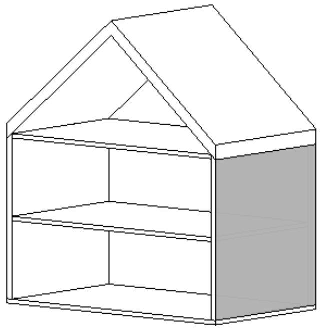


FIGURE 37: FAÇADE WALL

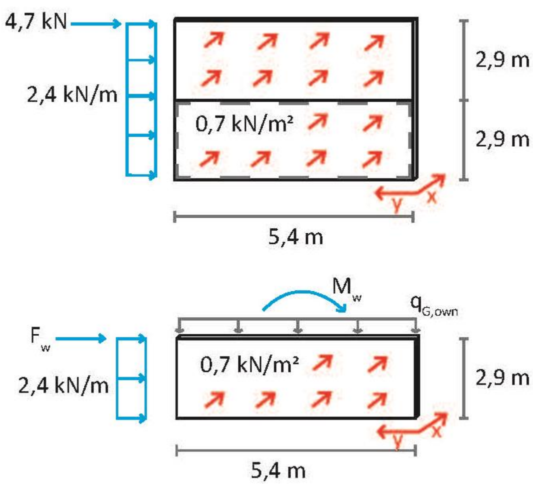


FIGURE 38: LOAD SCEME FAÇADE WALL

Design 1: prefab concrete (existing design):

The first design is the one that is used in the existing case study. It uses prefab concrete elements, such that the entire wall is made up of 1 block. Extra reinforcement is added to ensure it will not break during transportation of the product. Rockwool is used as an insulator. The wall is finished with brickwork.

The functional requirements are tested by using the Eurocode and rules of thumb.

Strength	Rc-value	Sound insulation air
UC	[m^2K/W]	[dB]
0,17	4,7	50

TABLE 20: FUNCTIONAL REQUIREMENTS FAÇADE WALL DESIGN 1

FIGURE 39: PREFAB CONCRETE WALLS (DARIA, N.D.)

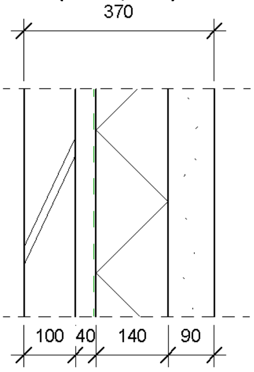


FIGURE 40: DESIGN 1 PREFAB CONCRETE

Design 2: Concrete cast in situ:

The next design uses cast in situ concrete. This is usually cast together with the floor, as mentioned before, but can also be executed separately. The formwork is positioned with the reinforcement bars and next the concrete is poured. Rockwool is added as an insulator and the wall is finished with brickwork.

The functional requirements tested by using the Eurocode and rules of thumb.

Strength	Rc-value	Sound insulation air
UC	[m^2K/W]	[dB]
0,16	4,7	50

TABLE 21: FUNCTIONAL REQUIREMENTS FAÇADE WALL DESIGN 2

FIGURE 41: CAST IN SITU WALLS (BETONHUIS, N.D.-A)

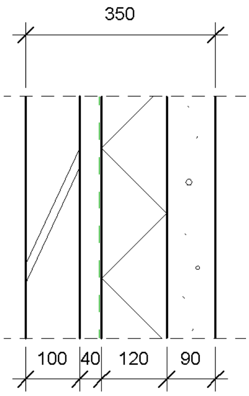


FIGURE 42: DESIGN 2 CAST IN SITU CONCRETE

Design 3: CLT

Cross laminated timber can also be used for vertical elements. The wall is insulated with rock wool and finished with brickwork.

The functional requirements are tested using the tool Calculatis made by a Stora Enso, a producer of bio based products like CLT, and with the Eurocode.

Strength	Rc-value	Sound insulation air
UC	[m^{2}K/W]	[dB]
0,67	4,7	46

TABLE 22: FUNCTIONAL REQUIREMENTS FAÇADE WALL DESIGN 3

FIGURE 43: CLT WALL (ALTER, 2019)

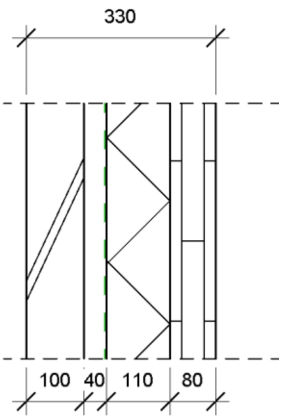


FIGURE 44: DESIGN 3 CLT

Design 4: HSB

HSB stands for “houten skelet bouw” (timber frame construction). HSB walls consist of timber columns fastened to a back plate, creating a strong, lightweight wall. The spaces between the columns are used for the insulation. The wall is finished with brickwork.

The functional requirements are tested with the Eurocode and rules of thumb.

Strength	Rc-value	Sound insulation air
UC	[m^{2}K/W]	[dB]
0,48	4,8	46

TABLE 23: FUNCTIONAL REQUIREMENTS FAÇADE WALL DESIGN 4

FIGURE 45: HSB WALL (DE KROON PREFAB, N.D.)

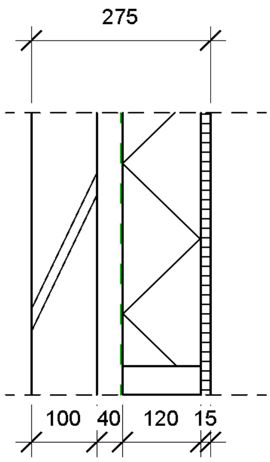


FIGURE 46: DESIGN 4 HSB

10.3 LOADBEARING WALL

The next element that will be redesigned is the loadbearing wall. The wall carries the floors and the walls above. The load scheme is given below. The element needs to fulfil the requirements of strength, fire resistance, air sound insulation and impact sound insulation (section 8.3). The calculations used to determine whether the element fulfils the functional requirement, can be found in **appendix 5: Load bearing wall**.

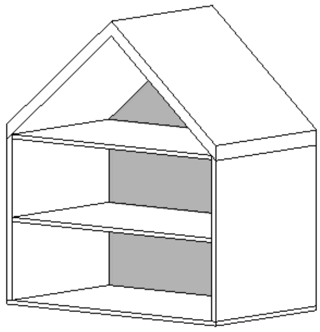


FIGURE 47: LOAD BEARING WALL

The load scheme is shown below, see figure 48. The vertical loads of the horizontal elements are carried over to the wall. The governing section of the wall is the bottom section. This section has been isolated with the accompanying loads.

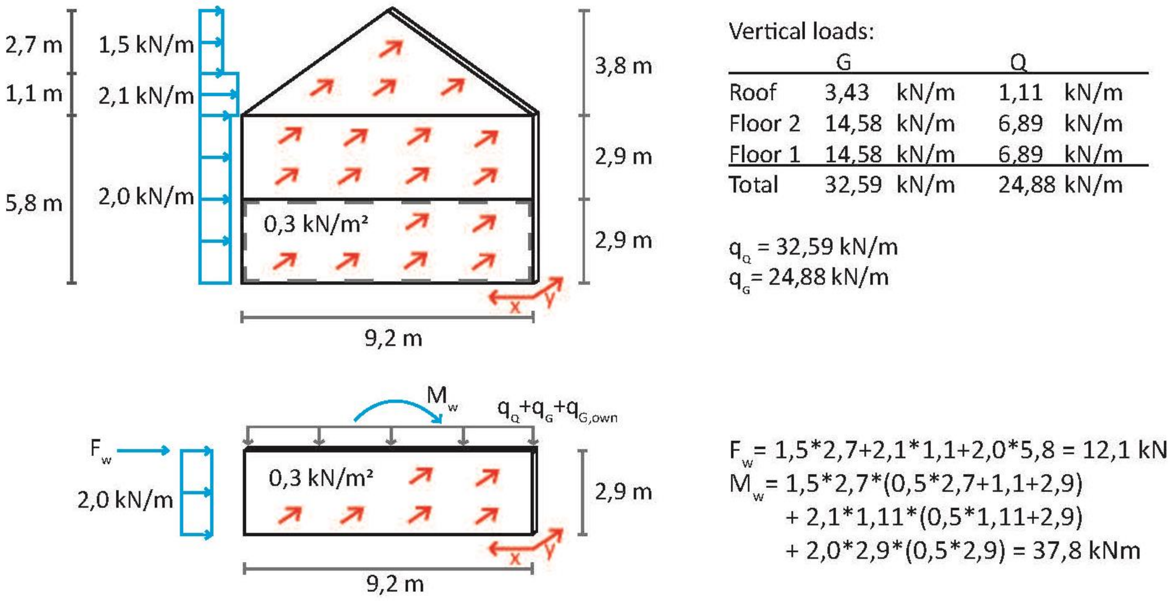


FIGURE 48: LOAD SCEME LOAD BEARING WALL

<u>Design 1: Prefab (existing)</u>

The fist design is the design used in the case stud. It consists of two separate prefab concrete walls. The walls have the width of the entire house (9,2 m) and the height of one floor (2,9 m). Two separate walls are used to ensure that no contact sound can be made between two residences.

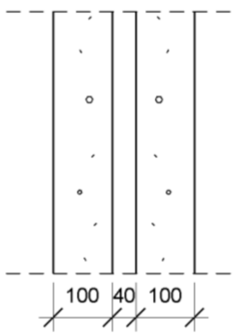


FIGURE 49 DESIGN 1 PREFAB CONCRETE

The functional requirements are tested with the Eurocode and rules of thumb.

Strength	Fire resistance	Sound insulation air	Sound insulation impact
UC	[min]	[dB]	[dB]
0,14	√	52	√

TABLE 24: FUNCTIONAL REQUIREMENTS LOAD BEARING WALL DESIGN 1

Design 2: Cast in situ concrete

This design looks a lot like the previous design. The difference is that the concrete of this design is poured on site. The advantage is that less reinforcement is needed, since the wall does not need to be transported by truck or by crane. The downside is that formwork is needed and the concrete has to harden before it can be loaded.

The functional requirements are tested with the Eurocode and rules of thumb.

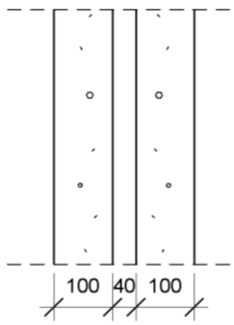


FIGURE 50 DESIGN 2 CAST IN SITU CONCRETE

Strength	Fire resistance	Sound insulation air	Sound insulation impact
UC	[min]	[dB]	[dB]
0,10	60	52	√

TABLE 25: FUNCTIONAL REQUIREMENTS FAÇADE WALL DESIGN 2

Design 3: CLT

The third design for the load bearing wall is constructed with CLT. The wall is divided into two timber sections to insure no contact sound. The cavity has to be filled with rockwool in this design to also fulfil the air sound restriction. Furthermore, gypsum board is added on both sides to suffice the fire safety requirement.

The functional requirements are tested using the tool Calculatis made by a Stora Enso, a producer of bio based products like CLT, and with the Eurocode.

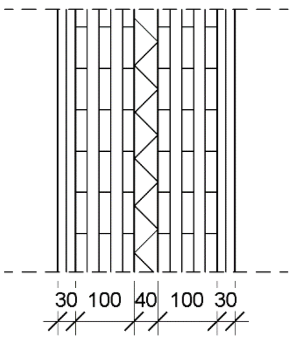


FIGURE 51 DESIGN 3 CLT

Strength	Fire resistance	Sound insulation air	Sound insulation impact
UC	[min]	[dB]	[dB]
0,78	60	52	√

TABLE 26: FUNCTIONAL REQUIREMENTS FAÇADE WALL DESIGN 1

10.4 Ground Floor

The next element that will be redesigned is the ground floor. The floor spans the foundation beams which are located below the loadbearing walls. The load scheme is given below. The element needs to fulfil the requirements of strength, stiffness, impact sound insulation and vibrations (section 8.3). The calculations used to determine whether the element fulfils the functional requirement, can be found in **appendix 6: Ground floor**. The load scheme is shown below, see figure 53.

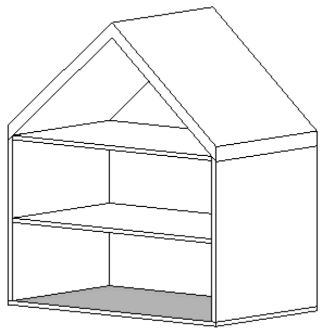


FIGURE 52: GROUND FLOOR

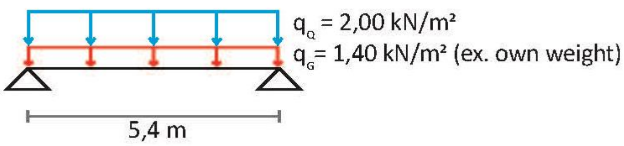


FIGURE 53: LOAD SCEME LOAD GROUND FLOOR

Design 1: Rib cassette floor (existing)

The first design is the one that is used in the existing building. The ribbed floors are a pre-stressed, insulated system floor and is mainly used in residential and light commercial buildings. The underside of the ribbed floor consists of a pre-formed EPS plate, which serves as an insulation material and at the same time gives shape to the cross-section of the concrete ribbed floor. The floor is finished with a screed to enclose the heating pipes and to join the ribs together.

FIGURE 54: RIB CASSETTE FLOOR (BRUIL, N.D.)

Most functional requirements have been tested by the producer Dycore. Others were determined with rules of thumb.

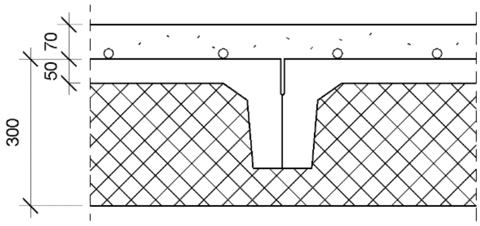


FIGURE 55: DESIGN 1 PREFAB CONCRETE

Strength	Stiffness	Rc-value	Sound insulation impact	Vibrations
UC	UC	[m².K/W]	[dB]	Class
0,50	√	5,0	√	E

TABLE 27: FUNCTIONAL REQUIREMENTS GROUND FLOOR DESIGN 1

Design 2: CLT

The CLT floor system can also be used for the ground floor. In this case, the screed is added for the heating and EPS insulation is added as an insulator. EPS is used rather than a wool, because this can resist the water in the crawlspace.

The functional requirements are tested using the tool Calculatis made by a Stora Enso, a producer of bio based products like CLT and with the Eurocode.

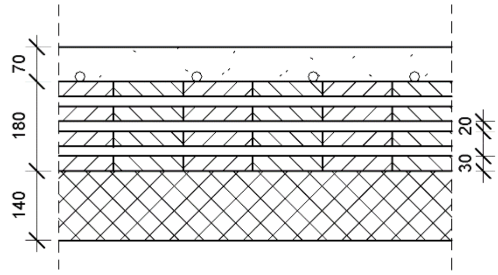


FIGURE 56: DESIGN 2 CLT

Strength	Stiffness	Rc-value	Sound insulation impact	Vibrations
UC	UC	[m².K/W]	[dB]	Class
0,23	0,32	5,2	√	D

TABLE 28: FUNCTIONAL REQUIREMENTS GROUND FLOOR DESIGN 2

10.5 FOUNDATION

The last element that will be looked at is the foundation. This element will be split up in the foundation beams and the foundation piles. The governing pile and beam in the case study are selected to design different variants for. The load schemes can be found in figure 58. The element needs to fulfil the requirement for strength (section 8.3).

The calculations used to determine whether the elements fulfils the functional requirements, can be found in **appendix 7: Foundation**.

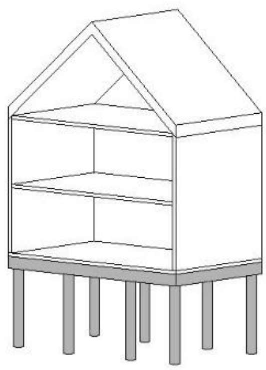


FIGURE 57 FOUNDATION

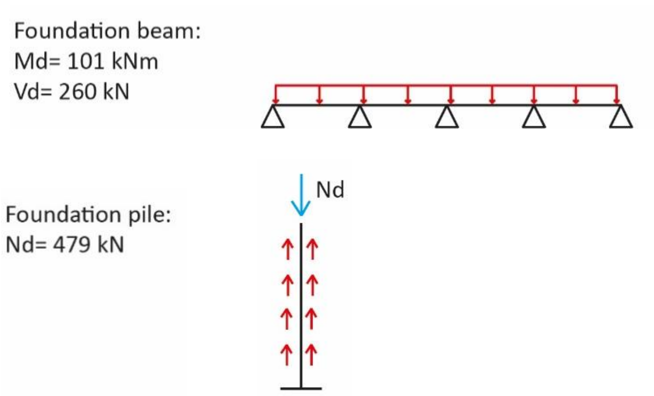


FIGURE 58: LOAD SCEMES FOUNDATION

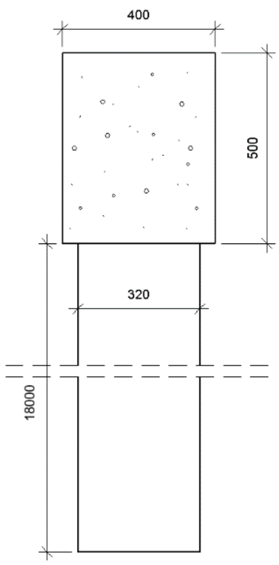


FIGURE 59 DESIGN 1 CONRETE

Design 1: Concrete beam (existing)

The concrete foundation beam that is used in the case study is made with cast in situ concrete. The formwork is placed on the ground, with a reinforcement case. Next the concrete is poured. The reinforcement was not fully designed, so this is not shown in the drawing. It is taken into account for the shadow cost: a standard value was used.

The functional requirements are tested with the Eurocode and rules of thumb.

Strength
UC
0,87

TABLE 29: FOUNDATION BEAM DESIGN 1

Design 2: Timber beam

Timber beams can also be used as foundation beams. These are prefabricated hardwood to resist ground moisture. The dimensions of the beam are kept the same. This size is bigger than standard dimensions, so either special beams should be sawn or a composite beam should be made. The first option is assumed in this study.

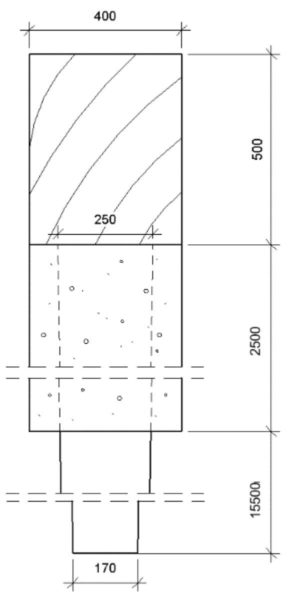


FIGURE 60 DESIGN 2 TIMBER

The functional requirements are tested with the Eurocode and rules of thumb.

Strength
UC
0,86

TABLE 30: FOUNDATION BEAM DESIGN 2

Design 1: Concrete pile (existing)

The existing foundation piles are vibro piles. When making a vibro pile, a steel formwork tube with a closed tip is first vibrated into the ground. After the tube has been brought to the right depth, a reinforcement cage is hung in the tube and it is filled with concrete. During this pouring process, the tube is pulled up, leaving the head of the tube behind. For the next pile, the same steel tube is used with a different tube head.

The functional requirements are tested with the Eurocode and rules of thumb.

Strength
UC
0,45

TABLE 31: FOUNDATION PILE DESIGN 1

Design 2: Timber pile

Sawn pine timber can be used as a foundation pile. The dimensions of a pile are limited to the dimensions of a tree trunk. Usually, this leads to thinner piles than with a concrete variant. The piles are also sloped, since the truck of a tree is sloped as well. The smaller radius leads to a smaller surface at the bottom of the pile, so there can be less opposing ground pressure per pile. This causes that more piles are needed to carry the same load compared to a wider pile, even if the timber pile itself is strong enough. The timber piles need to be protected against the fluctuating groundwater to avoid deterioration caused by fungi. Therefore, a concrete topping is added where the groundwater varies. Timber below groundwater, does not need protection as there is no oxygen there.

FIGURE 61 TIMBER PILES (SCHIPPER, 2021)

The functional requirements are tested with the Eurocode and rules of thumb.

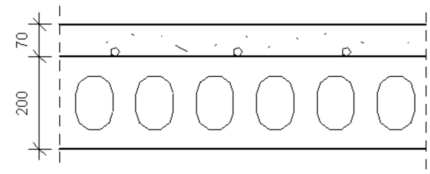
Strength
UC
0,52

TABLE 32: FOUNDATION PILE DESIGN 2

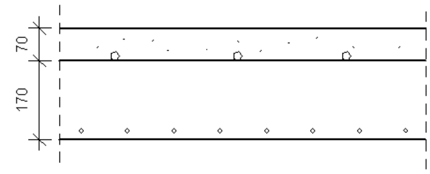
10.6 SHADOW COSTS PER ELEMENT

Below, an overview is given of the different variants per element with their matching shadow costs. The shadow costs are given on three levels as described in section 9.3. The lowest shadow cost is highlighted per level. The calculations used to determine the shadow costs, can be found in appendix 8: LCA data and calculation.

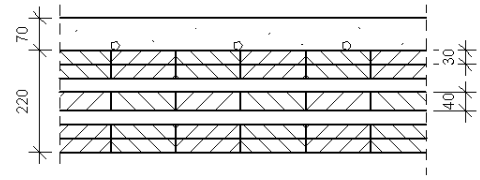
Intermediate floor



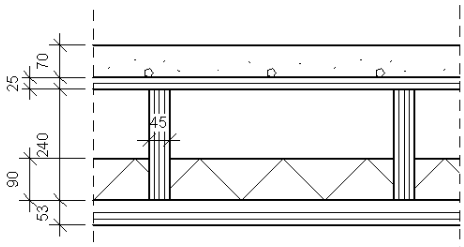
Hollow core
A1-A3: **€4,56/m²**
A-C: **€5,93/m²**
A-D: **€4,05/m²**



Cast in situ
A1-A3: €7,74/m²
A-C: €9,23/m²
A-D: €5,79/m²



CLT
A1-A3: €8,56/m²
A-C: €10,39/m²
A-D: €7,88/m²

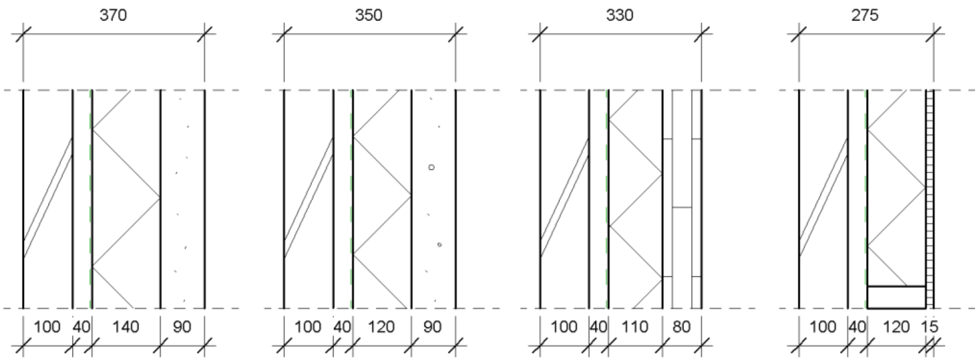


LVL
A1-A3: €6,60/m²
A-C: €8,08/m²
A-D: €7,50/m²

FIGURE 62: ALTERNATIVE DESIGNS FOR THE INTERMEDIATE FLOOR WITH CORRESPONDING SHADOW COSTS

The designs that use the least material: the hollow core slab and the LVL variant, score best in stages A1-A3, see figure 62. The hollow core slab has the lowest score, as besides the concrete, no additional materials are needed. The stages A4-D are quite similar for all variants. This leaves the hollow core slab the most favorable with these stages added.

Façade wall

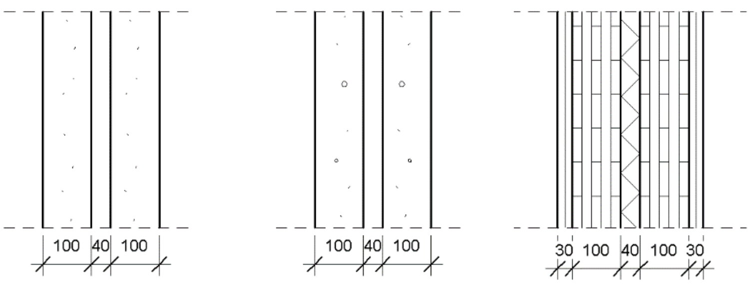


Prefab concrete		Cast in situ		CLT		HSB	
A1-A3:	€8,46/m²	A1-A3:	€9,16/m²	A1-A3:	€8,36/m²	A1-A3:	**€6,56/m²**
A-C:	€9,21/m²	A-C:	€9,97/m²	A-C:	€8,71/m²	A-C:	**€7,26/m²**
A-D:	€7,30/m²	A-D:	€8,12/m²	A-D:	€7,80/m²	A-D:	**€7,14/m²**

FIGURE 63 ALTERNATIVE DESIGNS FOR THE FAÇADE WALL WITH CORRESPONDING SHADOW COSTS

Even though the concrete variants are very similar in design, the prefab design scores better in the A1-A3 phase, see figure 63. The opposite was expected, since the variants have the same input materials, but the prefabricated variant has more processes in this stage. This shows how much the data can vary. The HSB wall is favorable in stages A1-A3, as it has less materials in total. The stages A4-C are quite similar for the variants, making the HSB sill favorable. Stage D changes this, as the CLT and concrete design are easier to use in a next cycle. However, the HSB variant remains the most favorable.

Load bearing wall

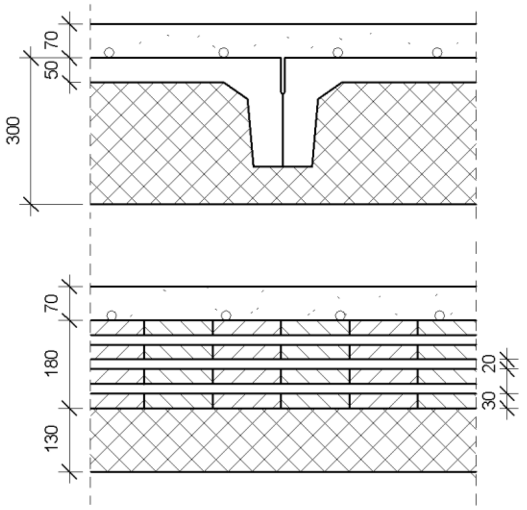


Prefab concrete		Cast in situ		CLT	
A1-A3:	**€5,00/m²**	A1-A3:	€6,77/m²	A1-A3:	€7,59/m²
A-C:	**€5,33/m²**	A-C:	€7,15/m²	A-C:	€7,91/m²
A-D:	**€1,50/m²**	A-D:	€3,28/m²	A-D:	€5,63/m²

FIGURE 64 ALTERNATIVE DESIGNS FOR THE LOADBEARING WALL WITH CORRESPONDING SHADOW COSTS

Again, the prefab concrete wall is more favorable in stages A1-A3 than the cast in situ variant, what is not expected, see figure 64. The CLT design has a higher A1-A3 cost, partially because this design needs additional materials for fire protection and sound insulation. The stages A4-C are quite similar. Stage D is more favorable for the concrete designs, as the all the materials of the element can be re-used. This results in the prefab variant being most favorable.

Ground floor



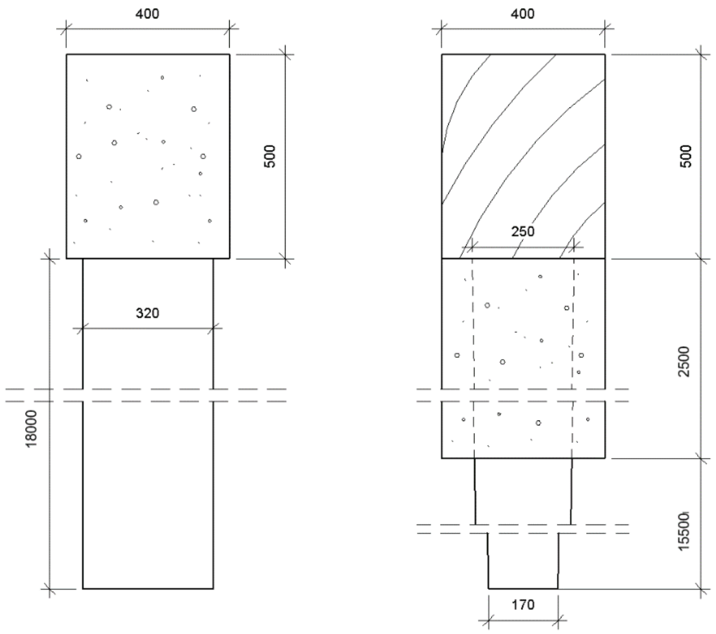
Rib cassette
A1-A3: €8,67/m^2
A-C: €10,23/m^2
A-D: **€6,74/m^2**

CLT
A1-A3: **€8,16/m^2**
A-C: **€9,93/m^2**
A-D: €7,88/m^2

FIGURE 65 ALTERNATIVE DESIGNS FOR THE GROUND FLOOR

The product stage, A1-A3, is very similar for both designs, see figure 65. The same holds for the stages A4-C. In stage D, the concrete has more benefits from re-use than the timber variant, making the concrete variant more favorable over all.

Foundation



Concrete beam
A1-A3: €6,28/m
A-C: €6,68/m
A-D: €3,16/m

Concrete pile
A1-A3: €31,56/pile
A-C: **€230,72/pile**
A-D: **€199,16/pile**

Timber beam
A1-A3**: €3,95/m**
A-C: **€4,75/m**
A-D: **€2,47/m**

5 Timber piles
A1-A3: **€18,26/piles**
A-C: €681,56/piles
A-D: €663,30/piles

FIGURE 66 ALTERNATIVE DESIGNS FOR FOUNDATION WITH CORRESPONDING SHADOW COSTS

Starting with the beam: the differences in the product phase are caused by the materials, given timber an advantage, see figure 66. For stage A5, concrete only needs a pump mixer, where the timber variant needs a crane. This gives concrete a slight advantage. The benefits in stage D are similar for both materials, making the timber beam have a lower shadow cost overall.

Next, the piles: the difference in phase A1-A3 is caused by the production, see figure 66. Even though five piles are needed for the timber variant instead of one concrete pile, this is still more environmentally friendly. The costs in A4 are bigger for the timber piles, because more piles are transported and additional concrete for the toppings needs to be transported. For the concrete piles, only one steel casing needs to be transported together with the concrete tips and reinforcement by truck. The rest of the concrete is transported with a truck mixer. The biggest difference in costs occurs in stage A5. The driving of the piles have a relatively high cost, so needing to drive five piles instead of one, makes the concrete piles preferable. Even when taking into account that driving a timber pile costs less energy, because the pile has a smaller diameter.

The LCA calculations show that the shadow costs are lower for the variants that use less material. For example, the hollow core slab performs better than the cast in situ floor. Elements should not be over dimensioned, making an element use as little as possible material.

It is better to use materials that can be used after the end-of-life- of the building. This is shown in the comparison of the façade designs: even though the HSB wall uses less material, the CLT wall is more favorable overall because of the benefits of stage D. This show that it can be better to add more re-usable construction material, rather than other additional materials like rock wool or gypsum board, which are less durable. Having little waste at the end-of-life, means that the benefit of stage D is maximized.

In almost all cases, the stages A1-A3 are the governing stages that determine the shadow cost. Process and transportation costs are very small, compared to stages A1-A3. There is one exception: the driving of the piles. This process takes a lot of time, which also costs a lot of energy. This is seen in the comparison of the piles, were the concrete piles score much better than the timber piles, because less piles need to be driven.

In the figure below, the most favorable elements are shown, based on the shadow costs for stages A-D.

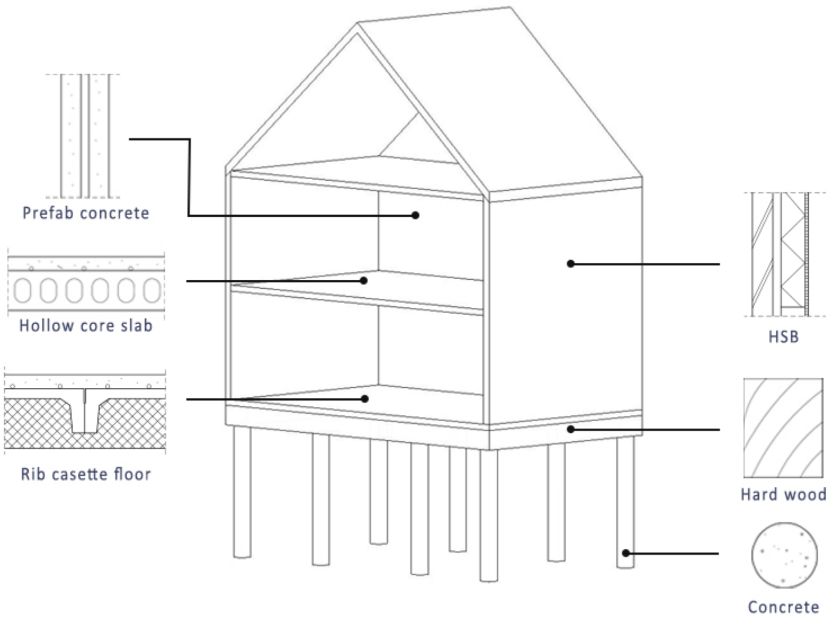


FIGURE 67 OVERVIEW OF BEST OPTIONS BASED ON THE CALCULATED SHADOW COSTS (NOT INCLUDING CARBON STORAGE)

10.7 SHADOW COSTS INCLUDING STORED CARBON

The calculations made in section 10.6 do not include the carbon storage in the timber products, as this is not stated in the “Bepalingsmethode”. However, for the end-of-life of the timber products, it is assumed that the elements are recycled, not burned. The stored CO_2 does not re-enter the atmosphere (for now) and should therefore be included in the shadow cost calculation.

How this can be included in the calculation is not (yet) stated in the regulations, so an estimation is made. The amount of stored CO_2 in the timber products is determined based on the weight and species of the timber, following EN16449. Next, the CO_2 is weighed using the weighing factor of the GWP impact category, which is €0,005/kg CO_2 eq. This price is subtracted from the original shadow cost determined in section 10.6 for the total LCA stages A-D.

	CO_2 stored [kg]	**Environmental cost of stored CO_2[€]**	**Original shadow cost stages A-D [€]**	**Shadow cost incl. stored CO_2 stages A-D [€]**
CLT intermediate floor/m^2	136	-6,80	7,88	1,08
LVL intermediate floor/m^2	27	-1,35	7,50	6,15
CLT façade/m^2	49	-2,45	7,80	5,35
HSB façade/m^2	18	-0,90	7,14	6,24
CLT bearing wall/m^2	124	-6,20	5,63	-0,57
CLT ground floor/m^2	112	-5,60	7,88	2,28
Timber found. beam/m	280	-14,00	2,47	-11,53
Timber piles/5 piles	1945	-97,25	663,30	566,05

TABLE 33 SHADOW COSTS OF THE TIMBER ELMENTS INCLUDING CARBON STORAGE

This leads to new results. The CLT variant for the ground floor has a significantly lower shadow cost, compared to the other designs. For the façade wall, the difference is less, but CLT still has the lowest costs. The storage in the CLT load bearing wall even makes the element have a negative shadow cost, making it the most favorable. For the ground floor, the CLT variant also has the lowest shadow cost. For the foundation beam, the shadow costs turn negative, remaining the most favorable option. The only elements where a concrete variant is still favorable, is the foundation pile. The figure below lists the most favorable elements based on the shadow costs for stages A-D, including the carbon storage.

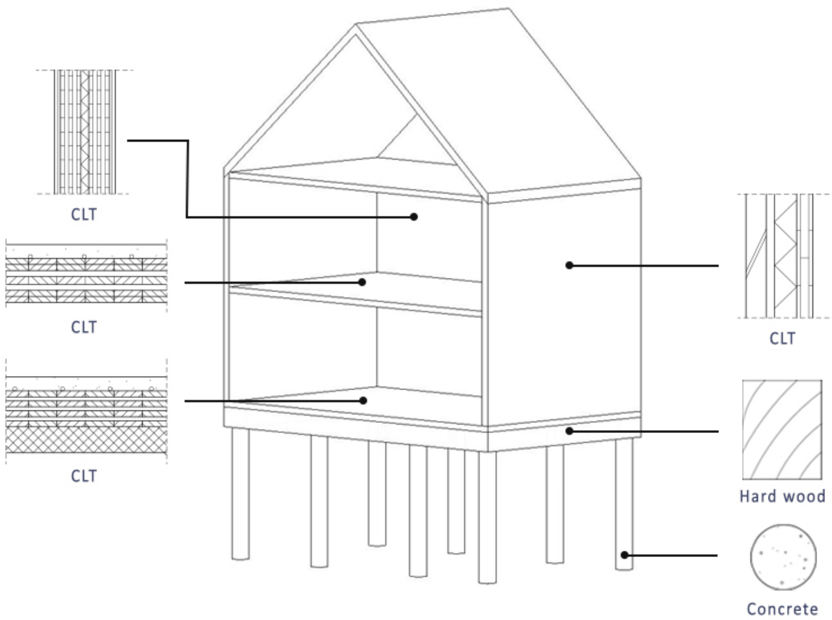


FIGURE 68 OVERVIEW OF BEST OPTIONS BASED ON THE CALCULATED SHADOW COSTS INCLUDING CARBON STORAGE

Part 5: Developments

11. Developments in the sustainability of concrete and timber

The building industry keeps developing and techniques change. Since the environment has a high priority at the moment, the new techniques are developed rapidly to minimize the environmental impact. These developments have a big influence on the comparison between concrete and timber as construction materials. In this chapter several big developments are discussed. A short description is given and a hypostasis on how this will influence the LCA.

11.1 Concrete

Alternative binder: Geopolymer concrete

The Netherlands is the world leader in the application of clinker-low cements. Geopolymers as an alternative binding agent in concrete is a logical next step. Geopolymer concrete could eventually offer an alternative to regular concrete with a more favorable environmental profile for certain applications. However, Betonhuis does not expect large-scale application of geopolymer concrete in the coming years due to technical barriers and debatable environmental advantages(Betonhuis, n.d.-b).

The usual raw materials for geopolymer concrete are blast furnace slag and fly ash, however these materials are already fully used in concrete. It replaces portland cement clinker. Large-scale application of geopolymer concrete will not be possible because of the scarcity of these alternative binders. Therefore it will have to be guaranteed that the slag and fly ash applied in geopolymer concrete come from sources which are additional to the current sources for these cement and concrete raw materials.

Also, there is still a lot of uncertainty about the constructive properties of geopolymer concrete and its development over time. The same applies to the protection of the reinforcement against corrosion in carbonated geopolymer concrete. In addition, the circular application of geopolymer concrete granulate in new concrete is problematic. The high content of alkalis can lead to ASR (alkali silica reaction) when applied in concrete based on Portland cement in combination with reactive aggregates. Geopolymer concrete can therefore only be used at the end of its service life as a foundation material or as concrete granulate in new geopolymer concrete (Vermeulen, 2018).

A hybrid version, where polymer concrete is mixed with regular concrete, has already been built in Rosmolenwijk. The result is that the concrete emitted 44% less CO_2 compared to concrete that would ordinarily be used (Betoniek, 2020). This development will influence stage A1 of the LCA.

Carbon capture

The CO_2 emissions associated with cement production are mainly caused by the clinker production. CO_2 is emitted during calcination: decomposition of $CaCO_3$ (limestone/marl) into CaO and CO_2. Also, the combustion of fuels to get the raw materials to a temperature of 1450^{o}C causes CO_2 to emit (van Gent, 2021).

Carbon Capture, Utilization and Storage (CCUS) is a technology to reduce CO_2 emissions from cement plants. In recent years, research has been undertaken to optimize reagent and membrane capture techniques. Trials are underway to find ways of concentrating the CO_2 in the gas stream to make the carbon capture more efficient and cost-effective. Captured CO_2 can then be transported to geological formations (such as empty gas fields), where it is permanently stored, see figure 69 (Cembureau, 2020).

In the period 2020-2030, several technologies will be tested through large-scale demonstration projects (in Canada, Norway, Belgium, and Germany). It is expected that in 2030-2040 the first cement plants will be equipped with Carbon Capture installations. After 2040, cement plants will start to be equipped with these types of installations as a standard (van Gent, 2021). This storage will change stage A3 of the LCA of concrete.

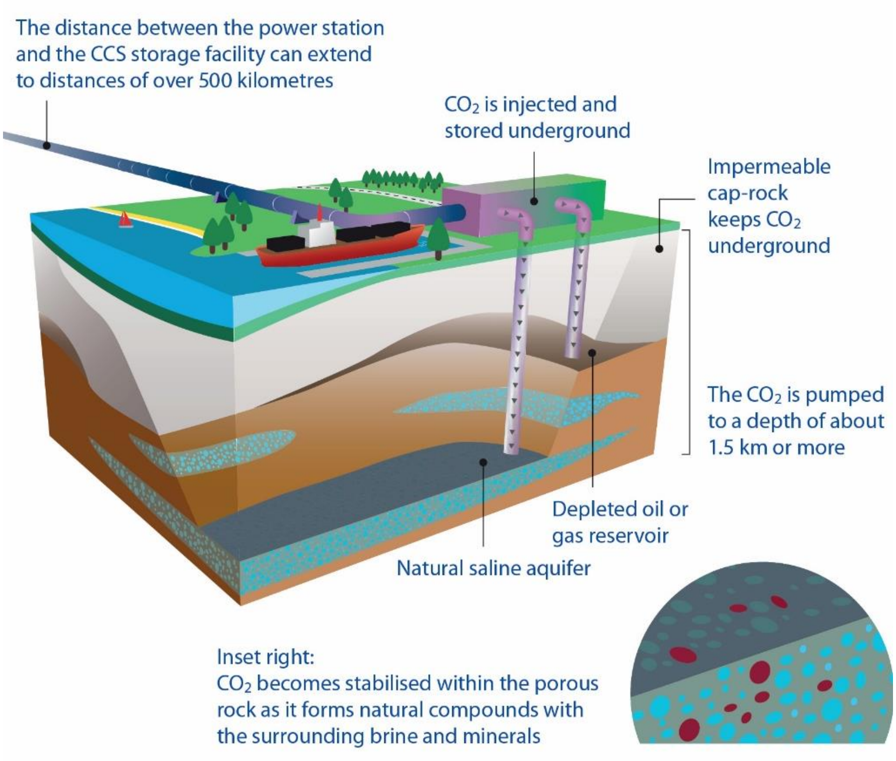


FIGURE 69 CARBON CAPTURE AND STORAGE (EUROPEAN COMISSION, N.D.)

Accelerators

Modern chloride-free accelerators promote the hydration process of cement at an early stage. Nucleation enhances the essential growth of Calcium Silicate Hydrate crystals. As a result, the curing of concrete can take place at lower temperatures, be better controlled and be demolded earlier. In addition, the application of modern accelerator technology makes it possible to use less cement or omit cement types with lower clinker content or heating (van Gent, 2021).

In practice, a reduction of 20 - 50 kg of cement per m^3 of concrete is feasible. Using CEM IIIA as a starting point, this yields 9-22,5 kg of CO_2 reduction per m^3 of concrete. With a conservative assumption of 30 kg cement savings per /m^3 concrete this means -13,5 kg CO_2/m^3 concrete. The applicability of accelerators technology is estimated at 50% of the concrete volume (van Gent, 2021). This development will change the A1 stage of the LCA of concrete.

Improved granule packing

Sand and gravel occupy the largest volume in concrete by far. The remaining space between the sand and gravel grains is filled with cement. The fewer hollow spaces in the mixture, the less cement is needed. The aim for granulate packing is to minimize the volume of hollow spaces by mixing the available aggregates in the optimum ratio. For this purpose, a sieve analyses of the individual aggregates is used, based on the optimum granulation mixture which is calculated. However, this calculation does not take into account the shape of the grains, forces on the surface and other phenomena that affect grain packing. Also, optimization of the grain packing of the applied powders (cement and fillers) is not considered. Improved granulate packing uses grain packing models that not only consider grain grading, but also other factors like the shape of the grains and surface loads. This results in a higher packing density. A higher density means that less cement adhesive is needed, leading to less environmental damage (van Gent, 2021). This development will change the A1 stage of the LCA of concrete.

Slow concrete

Slow concrete is intended to make use of the continuous strength development of concrete. After 28 days of pouring concrete, a certain strength of the concrete is required. Since concrete hardens relatively slow, the concrete has not reached its peak strength at this point. This results in unnecessarily strong concrete by adding more cement. Slow concrete is applicable in those cases where the normative loads on a construction is applied at a time later than 28 days (Loonen, 2020). It is assumed that in 10% of all applications, this can be the case. In those situations, Slow concrete can be used instead. The saves cement, which can be reduced by 10% compared to concrete that reaches its final strength after 28 days (van Gent, 2021). The concrete needing less cement will again influence stage A1 from the LCA of concrete.

Smart crusher

To decrease the environmental footprint of concrete, in which cement has the highest contribution, it would be of great importance to be able to recycle cement. The Smart Crusher is a concrete crushing and separation technology developed to optimize the separation efficiency of used concrete (Alberda van Ekenstein, 2020). If this development reaches its full potential, this influences the environmental impact of concrete massively.

In the first stages of the LCA no cement needs to be made. So this influences stage A1 and A2 of the LCA. Secondly, concrete can be used more circular, without down cycling. This influences module D in the LCA. Nowadays, all concrete is re-used by grinding it up and adding it to a new mixture, but this technology insures that one block of concrete will be able to become that same block of concrete without adding new materials.

11.2 TIMBER

Carbon storage in Timber

The temporary storage of carbon in timber products does currently not factor into the determination of the sustainability performance of buildings and structures. It is beyond the scope of the life cycle assessment that underlies the MPG, ECI and EPD. At European level it has been decided to make biogenic carbon, expressed in kg CO_2 equivalents, visible in the LCA. This year (2021) this has also been implemented in Dutch legislation. A separate environmental impact category has been made in EN 15804, the European standard for LCAs of building products to show the captured CO_2. The Netherlands is also going to use this method in the Bepalingsmethode Milieuprestatie Bouwwerken. This declaration does not yet mean that the biogenic CO_2 is included in the MKI and MPG; for that, a change in the European standard and the assessment method would be necessary (Keijzer et al., 2021). This changes the stages A1-A3 of timber products: the CO_2 reduction is added. This benefit is undone in stages C3 and C4 if the product is combusted and used for energy recovery. However, if a product is not disposed and is used again, this benefit remains.

Composite fibers from B-scrap wood

The Thermoplastic Composites Application Center (TPAC) started the project 'B-hout behoud' last year. Innodeen and Rouwmaat participate as partners. They research whether recycled scrap wood can be used for other sustainable applications. Wood has a large stream in the waste process. Every year, tons disappear into incinerators. Wood waste is divided into A-, B- and C-grade wood. A-rated wood is clean, without paint, glue, coatings or metal residues. B-grade wood may have those residues and C-grade wood is fully impregnated. The presence of those chemicals makes recycling a lot harder. However, B-wood consists largely of wood with excellent properties. Hence this research, to see if B-wood could be considered for a second life after all (Houtwereld, 2021). This development would change the LCA in stages C3 and C4, as the end-of-life scenario changes. Stage D will include the new purpose of the material.

11.3 General

Electricity

The production factories should change to a different energy source. Electricity can be extracted in an environmentally clean way, so having production processes be fueled by electricity is a big improvement. Also, the transportation of the materials and the structural elements can benefit from using a clean energy source. The first electric trucks and truck mixers are already on the road. Using electricity will influence stage A2-A5 and C1-C3.

Shadow cost tools

Several tools are in development that calculate the shadow cost of a project instantly. This makes testing multiple designs, to see which is more environmentally friendly, much easier. This also makes it easier to design with the environmental damage in mind, rather than determining the shadow cost once a design is finished. Examples of tools are form Oncra: https://oncrabio.web.app/tool, putting material options side by side. There also is One-click LCA: https://www.oneclicklca.com/, which is a plugin for Rhino & Grasshopper and Revit.

Part 6: Final Remarks

12. Discussion

Before the conclusion of this study is elaborated, a few remarks are given. To start off, the methodology together with the made assumptions are examined critically. Next, the validation of the relevance of this study is given. Lastly, some remarks are given on the relevance of this study over time.

12.1 Critical assumptions

The methodology of this thesis makes it that for the case study the elements are redesign based on elemental level. As mentioned, changing one element also changes the surrounding elements. In this study this has not been taken into account: the situation as in the case study is used as a starting point for the redesigns. In reality the other materials have a different weight, so changing an element can have a lot of influence on the loads on an element that carries the changed element. Especially when all the loads of the elements are added up to be carried by, for example, the foundation. In short, the fact that timber is a lighter building material, which would result into a structure needing a smaller load bearing capacity, is not taken into account.

To make the comparison fair, not only the loadbearing strength of an element is taken into account, but also the way it functions within the residence. Several functional requirements are defined which the element needs to suffice before it is compared with its alternative designs. There are, however, requirements which are not taken into account in this study. Requirements like air tightness, condensation and thermal conduction and more. Adding these requirements would make the comparison even more fair, but it is assumed that these requirements have little impact.

Besides functional requirements, there are other characteristics that are different for both materials, like the costs. In reality the price of a construction plays a major role in deciding what material will be used. In this study only the environmental impact is included. Also, the existing elements might be over-dimensioned to create a more pleasant indoor climate. This is not taken into account for the alternative designs.

The load schemes of the elements are simplified, excluding the openings for windows and the stairs. By excluding these, the calculations are more simple and transparent, but less complete. As this simplification is done for both the timber and concrete variants, the comparison is still likely to be fair. However, including these more complex situations could lead to interesting changes. For example, for making a window opening in a concrete wall, less concrete is needed than for a wall without an opening. For an HSB-element, this is the opposite: an opening is left out in the plating material, but two extra horizontal beams are added, making the element need more timber in total. These situations are ignored in this study. Also, some requirements were tested using simplified rules, or rules of thumb.

The ducts and pipes are ignored in this study with the exception of the heating pipes, as these influence the entire floor. In the first floor there is supposed to be a ventilation duct, which is not taken into account. For some elements this addition is easier to include than others. Also, the connections of the different elements are not considered. Although all connections of different elements should be possible, some are easier than others.

During the LCA calculation the current Dutch code is used. This results in the CO_2 storage of timber not being taken into account. It is mentioned in this thesis that this should be considered if the end-of-life scenario allows the timber to be reused, extending the CO_2 storage. Therefore an estimation is made of the shadow costs including the CO_2 storage. How and if this should actually be determined is still unknown.

The selection of environmental data sources can have a significant impact on the results of a life cycle assessment. In this thesis the NMD data form category three is used. In practice this is known as “worst case scenario” data, as this data is always allowed to be used instead of the more case specific data in categories one and two. The data in this category is raised by 30% to accommodate the varying performance of untested environmental profiles. Since this category three data is used for both the concrete and timber variants, it is likely to still be fair. However, there could be big differences between the "worst case data" and data that is more specific to the case study.

The outcome of the LCA calculation is not only dependent on the database, but also on the assumptions made during the calculation. For the transport stages, assumptions have been made about how certain elements are transported and from where these elements are send. In reality, this transportation can be a lot different. Also, other companies might be involved, changing the travel distances in the calculation. All assumptions have been made carefully, trying to keep the comparison fair, but in order to make the correct calculations, the involved companies should be known with their specific data. Even if this were possible to do for this study, no one can predict what will happen to the elements at the end-of-life. So, several important assumption were made for the end-of-life stages.

12.2 RELEVANCE OF THIS STUDY

This research is made in a time when the environment is studied massively. That is because a lot of this topic is still unexplored. This research gives a small insight in the matter related to the building industry. The laws are getting more strict. This makes change in de market not only necessary but also mandatory. This research elaborates on some of these possible changes.

The LCA method is a method to get more insight in the whole life of a material, not just the production. This method is explored and used in a practical example in this research. When the LCA method is used to compare two different materials, it is imported to be unbiased. In practice a lot of LCA studies are executed by branch associations, lacking this unbias. This study intends to be unbiased and tries to give both materials a fair chance in the comparison. Not only are the materials compared, but they are compared within the same context. The comparison is not made based on weight, but on a realistic situation. Within this situation, the elements do not only need to withstand the same load, but multiple functional requirements.

In this research it is not assumed that either concrete or timber is the best to use for all elements in a building: not all elements have the same functional requirements in a building. The different elements of the terraced house in this study are therefore treated individually.

This research hopefully shows a good example of how the LCA method can be used to compare different building materials in a fair way. The inputs of the LCA calculation can be changed according to different assumptions and/or a different data source input, making this study relevant for all similar cases.

12.3 INFLUENCE OF DEVELOPMENTS ON THE FINDINGS OF THIS THESIS

Several current development in concrete have been discussed in section 11.1. A lot of these changes are small and influence just a portion of the concrete production process. Concrete is recipe based, so it has a lot of components that can be changed. Small changes are therefore made easily. More extensive changes are also in development. The concrete industry is very big, so a lot of time and money can be put in the research of how to become more environmentally friendly. Once a development can be used in practice, the new EPD has to be determined. This new EPD can be used to calculate the environmental impact. For this thesis this would mean that the environmental data has to change, making a totally new conclusion possible.

The current timber developments, section 11.2, are less material based. The changes that are made are more regulation founded. For example, the addition of CO_2 storage in the LCA calculation of the shadow costs of timber products. Also, the end-of-life of timber product is changing as the quality of the product has enhanced. Having more quality creates more possibilities for using the timber at the end-of-life. It does not need to be burned, but can be used circular. Using timber is becoming more popular, so hopefully more production forests will be planted. If more forests are made, which are preferably in or close by the Netherlands, this material will become more environmentally friendly, without changing the material itself. Once these changes are made, the environmental data has to be changed as well. This could again lead to new conclusions for this thesis.

The moment this thesis is finished, it is already outdated. The industry is changing rapidly. But, that does not mean that this study is worthless. The principles of how the LCA method is used to compare different materials for the same situation, are still valid. When the industry changes, the input of the LCA calculation changes with it. This may change the outcome, but the method itself is timeless.

13. CONCLUSIONS

The research question formulated at the start of this research is as follows:

Which construction material: concrete or timber, is more suitable to use during the construction of the following basic elements of a terraced house in the Netherlands, based on the environmental impact: ground floor, intermediate floor, façade, load baring wall and foundation?

In chapter 10 of this thesis, the basic elements of case study De Laantjes have been redesigned using concrete and timber. The shadow costs were determined following the Dutch regulations. The elements with the lowest shadow costs were selected, see figure 70. These elements are:

- Intermediate floor: Hollow core slab with A-D € 4,05/m^2
- Façade wall: HSB with A-D € 7,14/m^2
- Loadbearing wall: Prefab concrete with A-D € 1,50/m^2
- Ground floor: Rib cassette floor with A-D € 6,74/m^2
- Foundation beam: Hardwood with A-D € 2,47/m
- Foundation pile: Virbo concrete pile with A-D € 119,16/pile

Stages A1-A3 have the biggest influence on the shadow costs, with stage D coming in second place. To make the shadow costs as low as possible, the design should be efficient, without needing additional materials and the materials that are used should be re-usable. Even though this case study can be similar to other projects, this does not mean that the shadow costs will be the same for all terraced houses in the Netherlands.

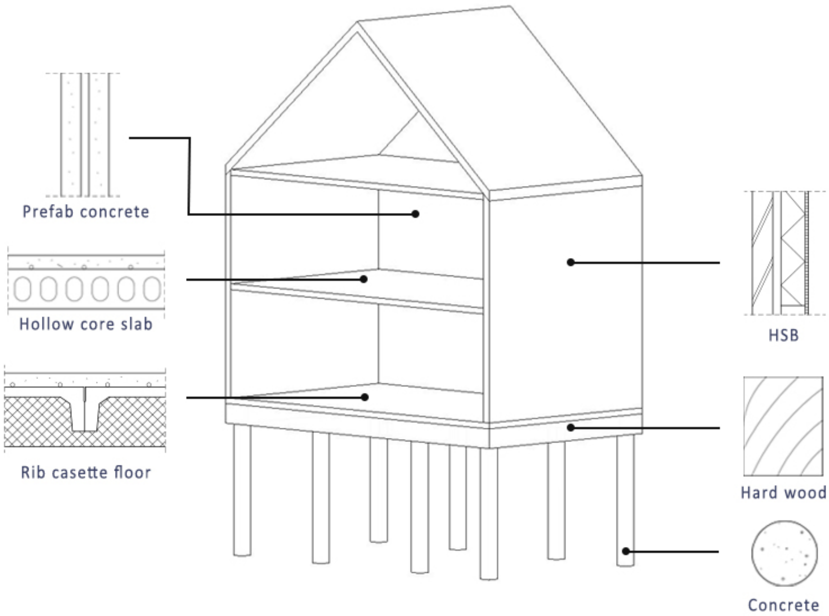


FIGURE 70 OVERVIEW OF BEST OPTIONS BASED ON THE CALCULATED SHADOW COSTS

The selection of environmental data sources has a significant impact on the results of a life cycle assessment. In this thesis the NMD data from category three is used. There are a lot of differences between data in the different categories, but also within one category, making the results of the LCA calculations less exact. The category one and two data should be more transparent to enable everyone to make a more accurate calculation.

The outcome of the LCA calculation is also based on the assumptions made during the calculation. It has been assumed how certain elements are transported and from or to where these elements are sent. In reality, this transportation can differ a lot. Also, assumptions about certain building processes can be inaccurate. All assumptions have been made with care, but in order to make the correct calculations, the involved companies should be known with their specific data. Furthermore, even if this were the case, no one can predict what will happen to the elements at the end-of-life and different end-of-life scenarios should therefore be considered.

The combination of the variable input data and the assumption made relating to the building process, make these shadow costs an estimation and not precise numbers. The differences between the shadow costs of the alternative designs are not significant enough to conclude which material is best to use during the construction, based on the environmental impact for this specific terraced house. The only element that did show a significant difference, was the foundation pile. Even though the A1-A3 shadow costs for the five timber piles were much lower than for the one concrete pile, this benefit was insignificant when the pile driving was taken into account. Because the timber piles are slimmer than the concrete piles, more piles are needed to accommodate the same load. The driving of the piles has a relatively high cost, so needing to drive five piles instead of one makes the concrete piles preferable. Even when taking into account that driving a timber pile costs less energy, because the pile has a smaller diameter. In this case study, the vibro concrete pile is better to use than the timber piles, based on the environmental impact.

The Dutch regulations state that carbon storage can be seen as permanent when it is stored for more than 100 years. However, timber products are assumed to be burned at the end-of-life, so the storage is not taken into account. In this thesis the timber is assumed to be recycled, extending the storage. Therefore, an estimation is made of the shadow costs including this storage. The elements with the lowest shadow costs including CO_2 storage were selected, see figure 71. These elements are:

- Intermediate floor: CLT with A-D € 1,08/m^2
- Façade wall: CLT with A-D € 5,35/m^2
- Loadbearing wall: CLT with A-D € -0,57/m^2
- Ground floor: CLT with A-D € 2,28/m^2
- Foundation beam: Hardwood with A-D € -11,53/m
- Foundation pile: Virbo concrete pile with A-D € 119,16/pile

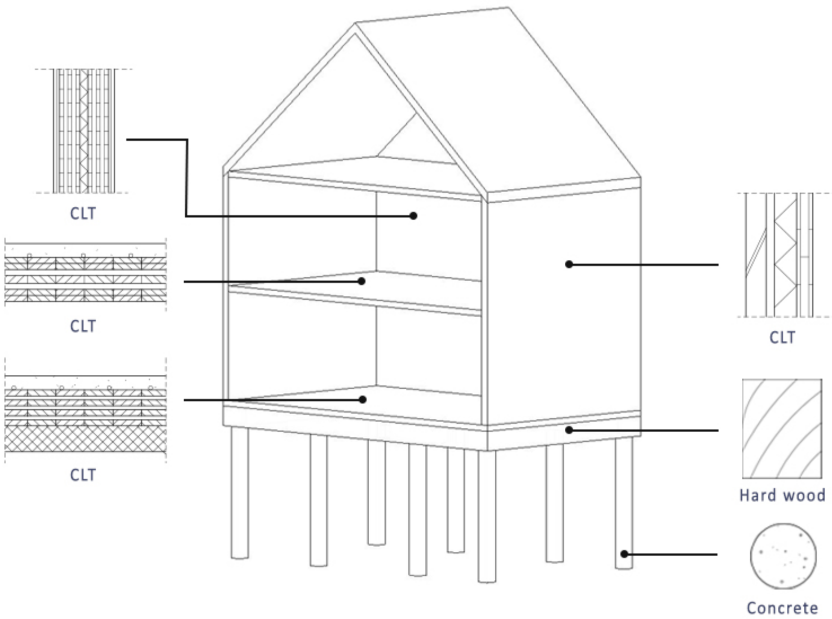


FIGURE 71 OVERVIEW OF BEST OPTIONS BASED ON THE CALCULATED SHADOW COSTS INCLUDING CARBON STORAGE

Whether or not the CO_2 storage is taken into account, has a high impact on the shadow costs. The difference in the estimated shadow costs including carbon storage for the alternative designs are significant enough to conclude that for the walls and floors the CLT variants are better to use. For the foundation beam, hard wood is better to use than concrete and the piles are still better in concrete, based on the environmental impact.

How this storage should actually be included in the Dutch regulations is still discussed. This shows that besides the data source and the assumptions about the building process, the regulations have a high impact on the outcome of an LCA comparison.

The industry is changing rapidly. Besides the evolving regulations, new developments can change the input of the shadow cost calculation. Once these new developments can be used in practice, the environmental data has to be adjusted. For this research this would mean that the environmental data input changes, making a totally new conclusion possible.

Even though the outcome of the LCA calculations are an estimation and not a precise number, this study still shows a valid way to compare different building materials in a relatively fair way. The basis of the comparison was equal by including various functional performance demands and comparing the fully designed elements per unit, rather than just including the construction material itself. The inputs of the LCA calculation can be changed according to different assumptions and/or a different data source input, making this study relevant for all similar cases.

14. RECOMMENDATIONS

The study does not end here. Several big steps can still be made within this topic. Some recommendations are listed below. They are divided into three sections, starting with the building industry, then the case study and lastly future research for master students who want to expand on this topic with their thesis.

14.1 BUILDING INDUSTRY

Within the industry a lot is still unknown. This makes it hard to come to a solid conclusion. Especially the relatively new timber products need more research. A decision has to be made on how the stored CO_2 in products can be included in the LCA computation rules. Also, the new developments that improve the environmental performance for either concrete or timber, should be included in the NMD. This way these improved products can be used in practice.

More transparency is needed in the LCA calculations. This holds for the EPDs of products and also the NMD data. The NMD holds data in three categories, of which only the third is (partially) open to the public. For the categories one and two only the final shadow cost is given, without even mentioning which stages this includes, making this data useless. A license can be bought to excess this data, but this is too expensive to use, especially for students (€ 15.762,- plus € 2.589,- per month). In other countries the local database is open to the public, making it more accessible and easy to include the environmental properties into a design. This transparency will also make it possible to learn from products with a low shadow cost. This way an improvement does not need to be invented twice.

The LCA method is slowly becoming the new standard. In order to give this trend a boost, more education is needed. This holds for both students and people who are already active in the field. For education this can mean, not just offering the knowledge in an elective, but introducing the method in mandatory subjects. Employed people can expand their knowledge by following trainings.

Architects and constructors need to not fall back on methods that are known to them. In practice this happens a lot, since what is known is easy. Other more environmentally friendly options already exist and these are not necessarily more expansive or more complex to use. Every project is different and should therefore not be treated the same. Architects and constructors should decide which materials are best to use, within the context of the project. They can ask help from producers of these materials to get an overview of the best options.

14.2 CASE STUDY

The case study De Laantjes, undertaken by Kroon en de Koning, is mainly designed with prefabricated concrete. It is important to not assume that this is the best option, based on the environment. Of course, other factors play a role, like costs and efficiency. But, as mentioned in the previous section, they should not fall back on this method, simply because it is what is known to them.

In future project, clients can be more interested in the environmental performance of a project. It should be discussed whether the project is allowed to be more expansive, if this results in a more environmentally friendly result.

14.3 FUTURE RESEARCH

Several aspects have not been taken into account in this research, see section 12.1. To get a more complete picture, one or more of these aspects should be added to future research. For example, the building cost can be compared of the different materials in relation with the environmental costs. The two costs can be added up to compare the total cost. This might show one material being way cheaper, even if the shadow costs were paid to make the environmental damage undone.

This research focusses on the terraced housing typology. Other typologies, such as high rise, will introduce different requirements for the elements and could therefore be investigated in the future.

During the LCA calculation of the case study, the NMD data is used. As mentioned before, there are a lot of varying values for the same material in de NMD. Also, some of the rules used to create the NMD data are questioned in this thesis. For example, whether the CO_2 storage in timber product should be included in these values. This data could be studied in more depth, researching how the NMD system might be improved.

The LCA calculation in this thesis makes certain assumptions related to the end-of-life scenario. A lot more different scenarios are possible. Especially when taking new developments into account. Several end-of-life scenarios could be studied to see how this influenced the LCA and what scenarios are most likely to actually happen. As mentioned in section 12.3, this study has already started to be outdated. The same comparison can be made, including new developments; keeping this research up to date.

The climate goal for 2050 is that all buildings should be environmentally neutral. How this goal can be reached and what influence this has on the concrete and timber industries, could be studied. Perhaps there is no way to make either concrete or timber environmentally neutral. This could be researched by means of the LCA, or more material orientated.

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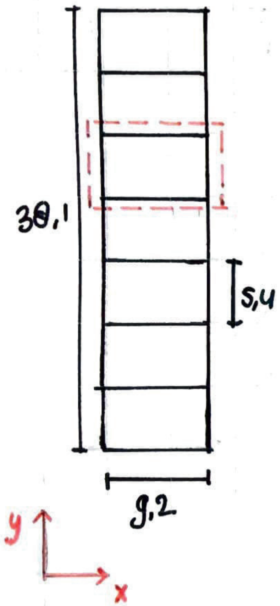
APPENDIX

Windberekening (volgens NEN- 1991-1-4)

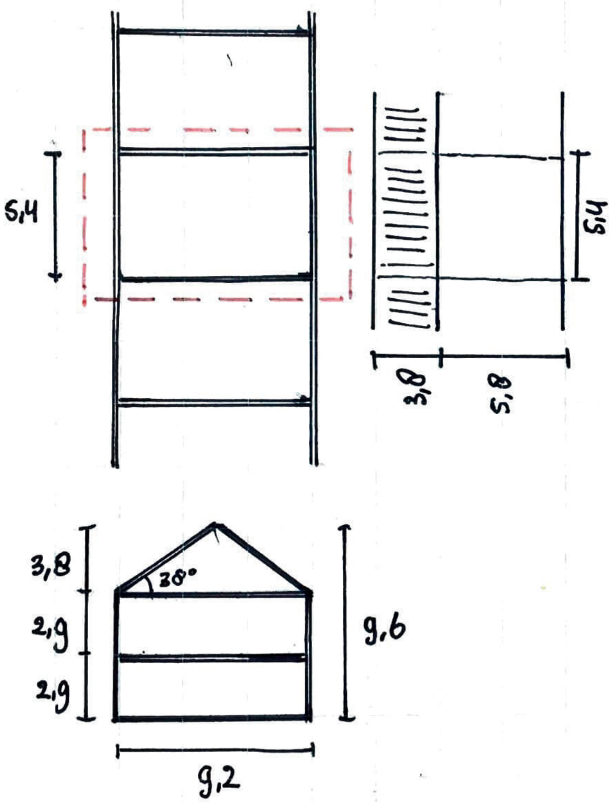
gebied II, bebouwd, h ≈ 10 m $C_sC_d = 1$

→ $q_w = 0{,}68\ kN/m^2$

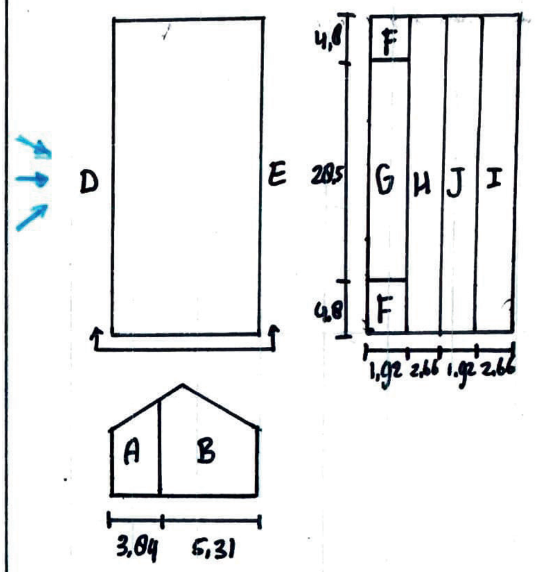
Woonblok:



Betreffende woning:



Wind zones:



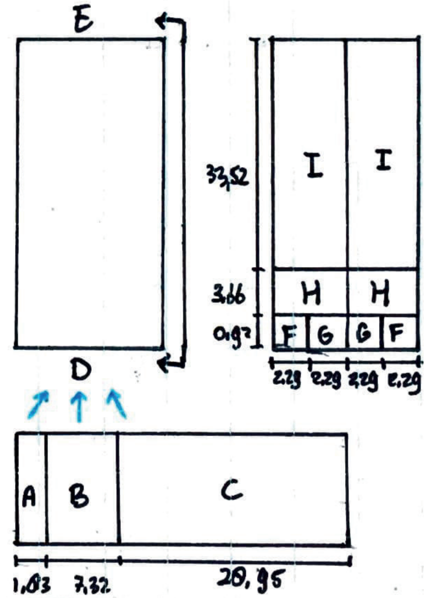
d = 9,15

b = 38,1

e = 2h = 19,10

e > d

A > 10 → $C_{pe,10}$ voor alle berekeningen



d = 38,1

b = 9,15

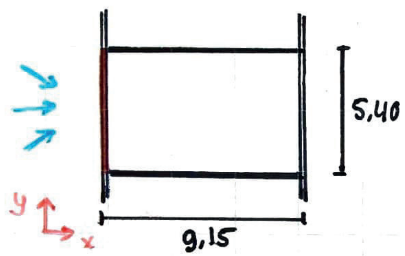
e = b = 9,15

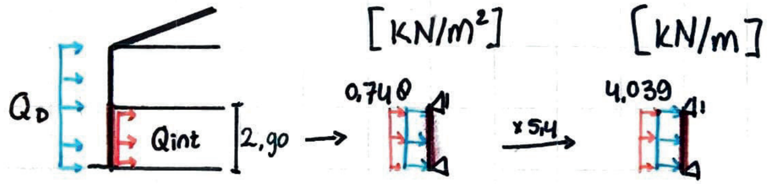
e < d

A > 10 → $C_{pe,10}$ voor alle berekeningen

Gevel:

wind in x-richting





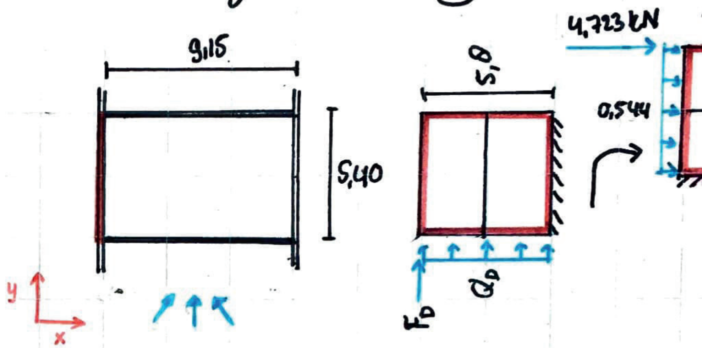
$Q_D = 0{,}8 \cdot 0{,}68 = 0{,}544$ kN/m²

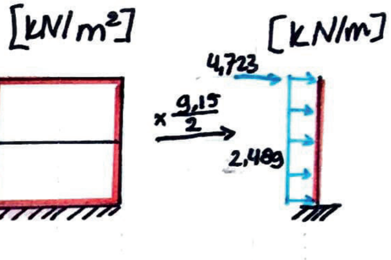
$Q_{int} = 0{,}3 \cdot 0{,}68 = 0{,}204$ kN/m² +

$0{,}748$ kN/m²

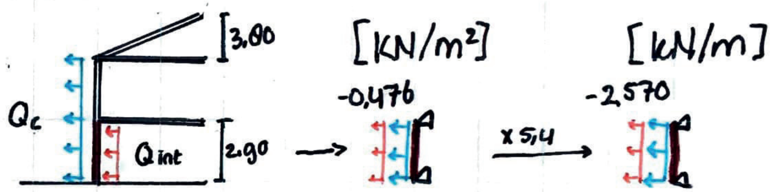
$M_{wind_x} = \frac{1}{8} \cdot 4{,}039 \cdot 2{,}90^2 = 4{,}25$ kNm

wind in y-richting





had ik hier ook Q_E moeten gebruiken?



$Q_c = -0{,}5 \cdot 0{,}68 = -0{,}340$ kN/m²

$Q_{int} = -0{,}2 \cdot 0{,}68 = -0{,}136$ kN/m² +

$-0{,}476$ kN/m²

$M_{wind_x} = \frac{1}{8} \cdot -2{,}570 \cdot 2{,}90^2 = -2{,}702$ kNm

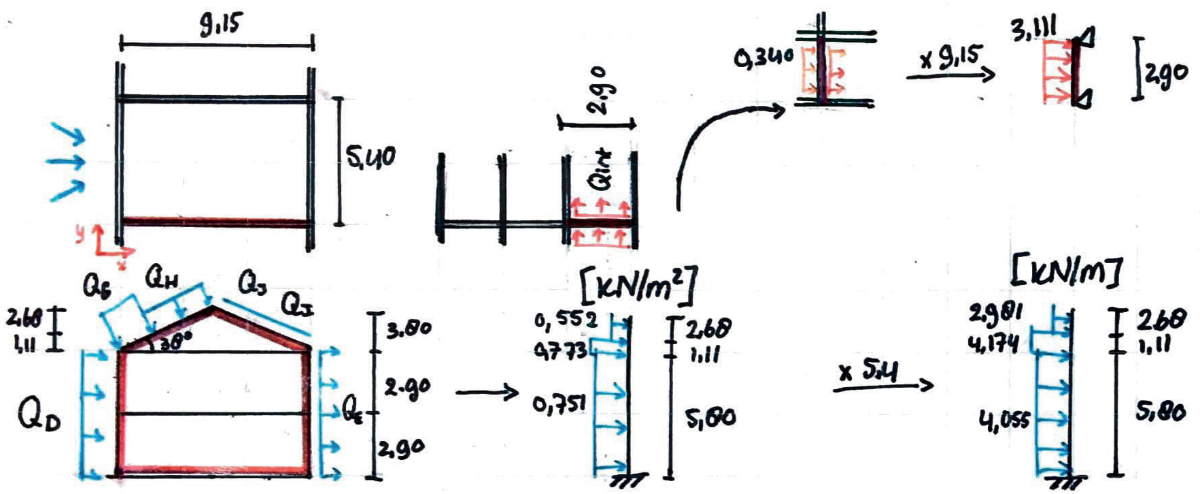
$Q_D = 0{,}8 \cdot 0{,}68 = 0{,}544$ kN/m²

$F_D = (\frac{1}{2} \cdot 9{,}15 \cdot 3{,}8) \cdot 0{,}544 \cdot \frac{1}{2} = 4{,}723$ kN

$M_{wind_y} = 4{,}723 \cdot 5{,}8 + \frac{1}{2} \cdot 4{,}723 \cdot 5{,}8^2 = 69{,}258$ kNm

Draagmuur

wind in x-richting



$Q_{int} = (0{,}2+0{,}3) \cdot 0{,}68 = 0{,}340 \ kN/m^2$

$M_{wind_y} = \frac{1}{8} \cdot 3{,}111 \cdot 2{,}90^2 = 3{,}270 \ kNm$

$Q_D = 0{,}8 \cdot 0{,}68 = 0{,}544 \ kN/m^2$

$Q_G = 0{,}7 \cdot 0{,}68 = 0{,}476 \ kN/m^2$

$Q_H = 0{,}5 \cdot 0{,}68 = 0{,}340 \ kN/m^2$

$Q_J = 0 \cdot 0{,}68 = 0 \ kN/m^2$

$Q_I = 0 \cdot 0{,}68 = 0 \ kN/m^2$

$Q_E = -0{,}5 \cdot 0{,}68 = 0{,}340 \ kN/m^2$

$Q_{H,nor} = 0{,}340 / \sin 30 = 0{,}552 \ kN/m^2$

$Q_{G,nor} = 0{,}476 / \sin 30 = 0{,}773 \ kN/m^2$

$Q_{D+E} = 0{,}85\,(0{,}544 + 0{,}340) = 0{,}751 \ kN/m^2$

$M_{wind_x} = 2{,}981 \cdot 2{,}68 \cdot 8{,}25 + 4{,}174 \cdot 1{,}11 \cdot 6{,}36$
$+ 4{,}055 \cdot 5{,}8 \cdot 2{,}9 = 163{,}58 \ kNm$

APPENDIX 3: INTERMEDIATE FLOOR

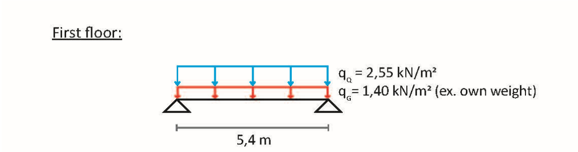
Intermediate floor design 1: Hollow Core Slab

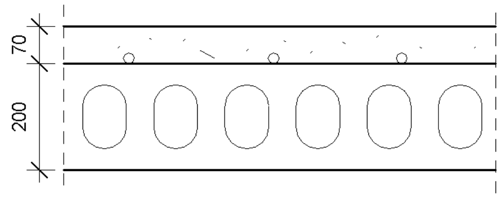
Situation

L	5,4 m	b	1200 mm
ρ	283 kg/m2	h	200 mm
Q	2,55 kN/m2	C53/65	
G	2,4 kN/m2	Mrd	119 kNm
Env. Class	XC1		

(Dycore: https://www.dycore.nl/producten/kanaalplaatvloeren/technische-productinformatie-kanaalplaatvloer)

qed=	(1,35*G+1,5*Q*)1=	7,065 kN/m	(NEN1990)
Med=	(1/8)*qed*L^2=	25,75193 KNm	
Ved=	(1/2)*qed*L=	19,0755 kN	
Ned=		0 kN	





Strength

UC= Med/Mrd= 0,216403

Defection

u≤ 0,004*L (Dycore, n.d.)

Fire safety

90 minutes (Dycore, n.d.)

Acoustics

Air

For residential, no additional materials needed (Dycore)

Ra≈ 44 dB (NPR 5272)

Impact

For residential, no additional materials needed (Dycore)

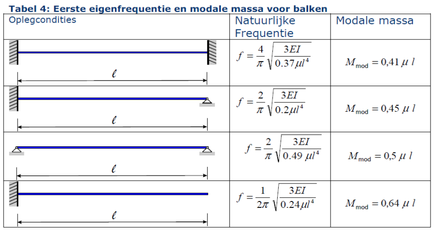
Vibrations

Woonfunctie: Class D (Hivoss, 2008)

E=	3,70E+10 N/m2	(Estimation based on stength)
I=	0,0006 m4	
μ=	605,5 kg/m	
L=	5,4 m	

Demping=	D1+D2+D3=	3 %
f=	(2/pi)*√((3EI)/(0,49μL^4))=	10,71 Hz
Mmod=	0,5μl=	1634,862 kg

See graph: Class D, satisfies



A.2. Natuurlijke frequentie en modale massa voor balken

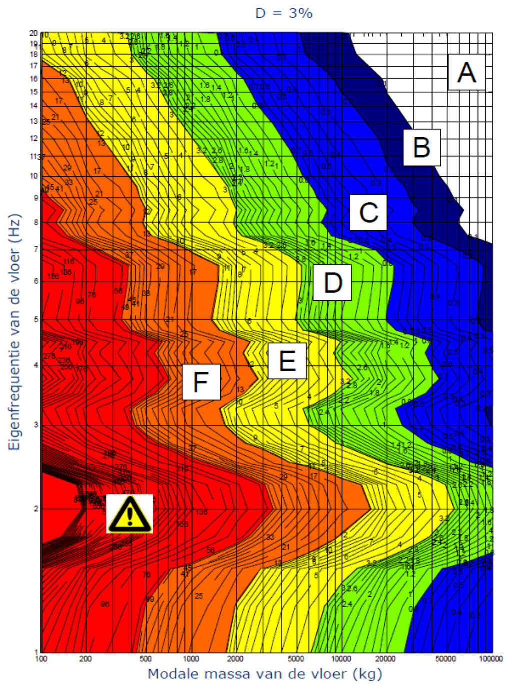
De eerste eigenfrequentie van een balk voor verschillende oplegcondities kan bepaald worden met de formules in Tabel 4 met:

E Elasticiteitsmodulus [N/m²]
I Traagheidsmoment [m⁴]
μ verdeelde massa [kg/m]
ℓ Lenge van de balk

Tabel 4: Eerste eigenfrequentie en modale massa voor balken

Oplegcondities	Natuurlijke Frequentie	Modale massa
	$f = \frac{4}{\pi}\sqrt{\frac{3EI}{0.37\mu l^4}}$	$M_{mod} = 0{,}41\,\mu\,l$
	$f = \frac{2}{\pi}\sqrt{\frac{3EI}{0.2\mu l^4}}$	$M_{mod} = 0{,}45\,\mu\,l$
	$f = \frac{2}{\pi}\sqrt{\frac{3EI}{0.49\mu l^4}}$	$M_{mod} = 0{,}5\,\mu\,l$
	$f = \frac{1}{2\pi}\sqrt{\frac{3EI}{0.24\mu l^4}}$	$M_{mod} = 0{,}64\,\mu\,l$

(Hivoss, 2008)

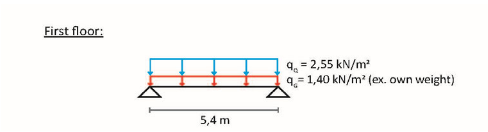


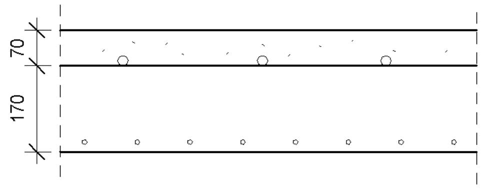
(Hivoss, 2008)

Intermediate floor design 2: InSitu Floor

Situation

L	5,4	m	b	1000	mm
ρ	2500	kg/m3	h	170	mm
Q	2,55	kN/m2	c	15	mm
G	5,65	kN/m2	Øhfd	10	mm
Class	C30/37		Ecm	33000	N/mm2
fck	30	N/mm2			
fcd	20	N/mm3			
fyk	500	N/mm4			
fyd	434,8	N/mm5			





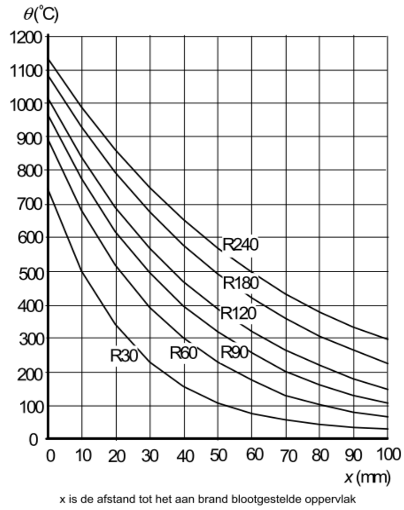
qed=	(1,35*G+1,5*Q*)1=	11,45	kN/m	(NEN1990)
Med=	(1/8)*qed*L^2=	41,74	KNm	
Ved=	(1/2)*qed*L=	30,92	kN	
Ned=		0	kN	

Resistance

d=	h-c-0,5Øhfd=	150	mm	

Reinforcement estimation:

As=	Med/(0,75*h*fyd)=	753,04	mm2	(10 bars with d=10 mm per meter floor)
Mrd=	As*fyd*0,9d=	44,20	kNm	
UC=	Med/Mrd=	0,94		
ρl=	As/(b*d)=	0,01	%	
k=	1+√(200/d)=	2,15	≤2	
Vrd=	b*d*0,12*k(100*ρl*fck)^(1/3)=	88903,25	kN	
UC=	Ved/Vrd=	0,35		



Figuur A.2 — Temperatuurverdeling in platen (hoogte *h* = 200) voor R 60 – R 240

(NEN-EN-1992-1-2)

Defection

umax=	0,004L=	21,6	mm	(NEN1990)
qek=	G+Q=	8,2	kN/m	
Eeff=	0,33Ecm=	10890	N/mm2	
I=	(1/12)*b*h^3=	4,09E+08	mm4	
utot=	(5*q*l^4)/(384*E*I)=	20,4	mm	(NEN1990)
UC=	utot/umax=	0,94		

Fire safety

Θcr=	500	°C	(NEN-EN-1992-1-2)
See table A.2			
c≥	10	mm	Sufficent

Acoustics

For residential, no additional materials needed

Ra≈	44	dB	(NPR 5272, 2005)

Impact

For residential, no additional materials needed (estimation)

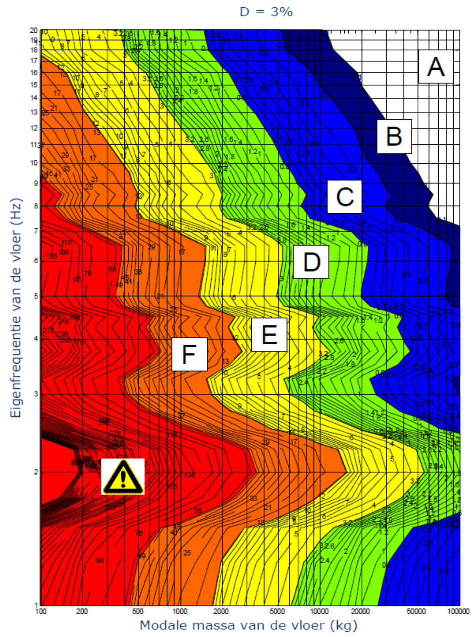
Vibrations

Woonfunctie: Class D (Hivoss, 2008)

(See floor as beam with a width of 8,59 meters)

E=	3,30E+10	N/m2
I=	3,52E-03	m4
μ=	7180,2	kg/m
L=	5,4	m

Demping= D=	D1+D2+D3=	3	%
f=	(2/pi)*√((3EI)/(0,49μL^4))=	6,87	Hz
Mmod=	0,5μl=	19386,61	kg



(Hivoss, 2008)

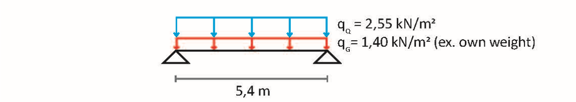
See graph: Class C, even better than the required class D

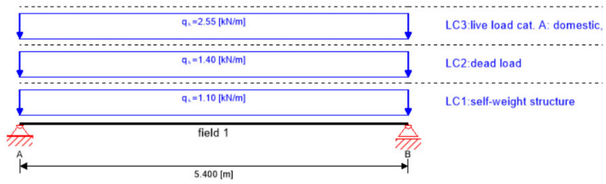
Intermediate floor design 3: CLT Floor

Situation

L	5,4 m	b	2935 mm	(Floor devided in to 3 parts of 2935 mm)
ρmean	420 kg/m3	h	220 mm	
Q	2,55 kN/m2	kmod	0,6	
G	2,324 kN/m2	kh	1,00	(Sawn timber)
Class	C24	γm	1,2	

First floor:





(Calculatis)

fmk	24,0 N/mm2
fmd	12,0 N/mm3
E0mean	11000 N/mm2

qed=	(1,35*G+1,5*Q)*2,935=	20,43 kN/m	(NEN1990)
Med=	(1/8)*qed*L^2=	74,48 KNm	
Ved=	(1/2)*qed*L=	55,17 kN	
Ned=		0 kN	

Strength

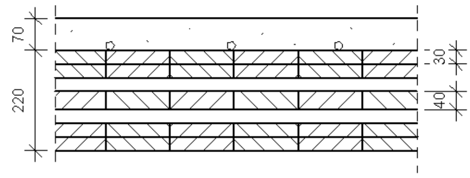
W=	(1/6)*b*h^2-(1/6)*b*h^2=	2,05E+07 mm3
σ=	Med/W=	3,63 N/mm2
UC=	σ/fmd=	0,30
	(Volgens producent=)	0,21 (Calculatis: https://calculatis.storaenso.com/)

Deflection

UC= 0,86 (Calculatis)

Fire resistance

30 minutes (Calculatis)



layer	thickness	type	material
1	30.0 mm	L	C24 spruce ETA (2019)
2	30.0 mm	L	C24 spruce ETA (2019)
3	30.0 mm	C	C24 spruce ETA (2019)
4	40.0 mm	L	C24 spruce ETA (2019)
5	30.0 mm	C	C24 spruce ETA (2019)
6	30.0 mm	L	C24 spruce ETA (2019)
7	30.0 mm	L	C24 spruce ETA (2019)

(Calculatis)

Acoustics

Air

m= 92,4 kg/m2

Ra≈ 33 dB (NPR 5272)

Impact

La≈ 65 dB (Dataholz.eu)

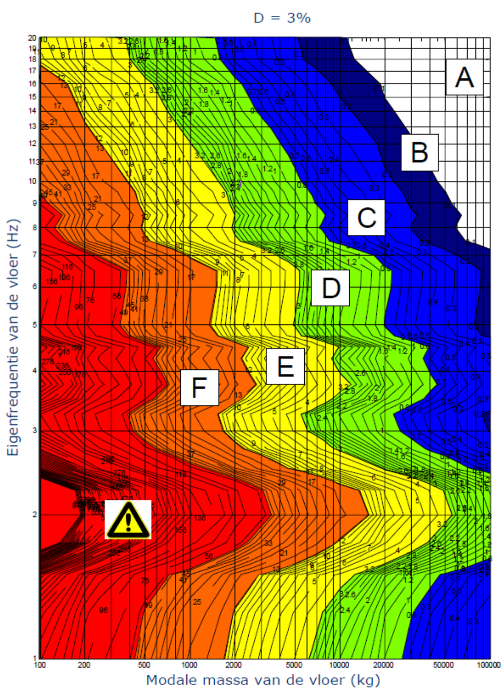
Woonfunctie: Class D

(See floor as beam with a width of 2,935 meters)

E=	1,10E+10 N/m2
I=	5,97E-03 m4
μ=	1458,2 kg/m
L=	5,4 m

Demping= D=	D1+D2+D3=	3 %
f=	(2/pi)*√((3EI)/(0,49μL^4))=	11,46 Hz
Mmod=	0,5μl=	3937,2 kg

See graph: Class D



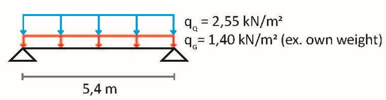
(Hivoss, 2008)

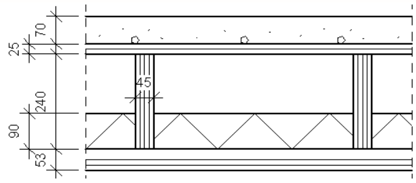
Intermediate floor design 4: Kerto Ripa

Situation

L	5,4 m		b	2400 mm
ρ	35,5 kg/m2		h	265 mm
Q	2,55 kN/m2			
G	1,75 kN/m2			

First floor:



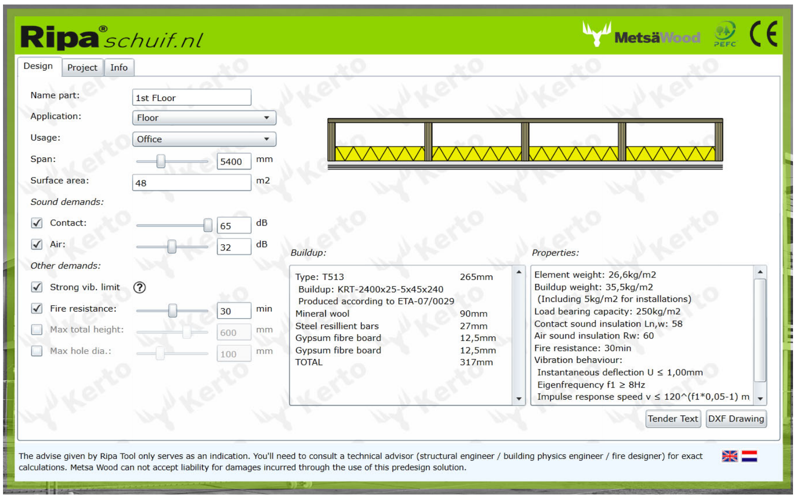


qed=	(1,35*G+1,5*Q*)1=	6,185144 kN/m	(NEN1990)
Med=	(1/8)*qed*L^2=	22,54485 KNm	
Ved=	(1/2)*qed*L=	16,69989 kN	
Ned=		0 kN	

Resistance

Max load 250 kg/m2 (Ripa: http://www.ripaschuif.nl/indexRf.html)

Load 259,9 kg/m2



Does not satisfy, but is assumed to be sufficient

Defection

Assume sufficient uinst= 1 (Ripa)

Fire safety

30 minutes

Acoustics

Air

Requirement=	32 dB		
Resistance=	60 dB	Sufficent	(Ripa)

Impact

Requirement=	65 dB		
Resistance=	58 dB	Sufficent	(Ripa)

Vibrations

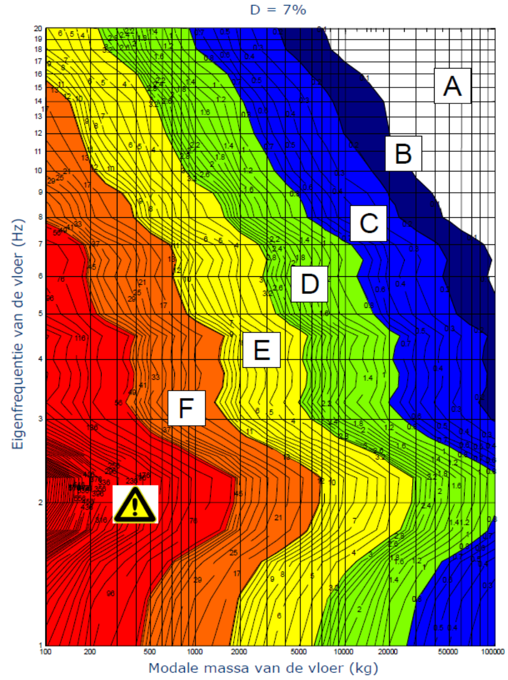
Woonfunctie: Class D Sufficent (Ripa)

μ= 3943,4 kg/m

L= 5,4 m

Demping=	D1+D2+D3=	7 %	
f=		8 Hz	(Ripa)
Mmod=	0,5μl=	10647,05 kg	

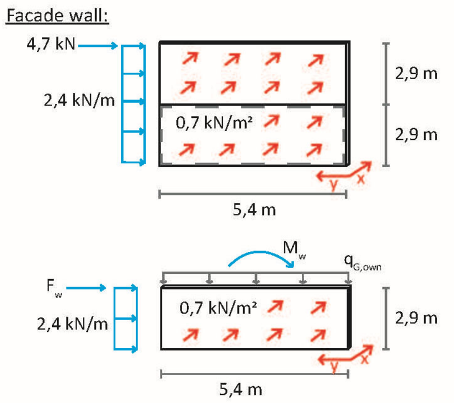
See graph: Class D



(Hivoss, 2008)

APPENDIX 4: FAÇADE

Design 1: Prefab facade



F_w = 4,7 + 2,4*2,9 = 11,7 kN
M_w = 4,7*2,9 + 2,4*2,9*(0,5*2,9) = 23,7 kNm

Situation

h	2900 mm		FG(ex. on	35,24 kN
b	5400 mm		FQ	0,00 kN
d	90 mm		FGown	35,24 kN
ρ	2,25 kN/m2		Mx	3,97 kNm
			My	68,79 kNm

C20/25

fck	20 N/mm2
fcd	13,3 N/mm2

Resistance

<u>Normal force</u>

Fed=	1,2*(FG+FGown)+1,5*FQ=	84,57 kN	
A=	b*d	4,86E+05 mm2	
σn=	Fed/A	1,74E-01 N/mm2	(NEN1990)

<u>Moment x direction (out of plane)</u>

Mxed=	Mx*1,5=	5,96 kNm	
Wx=	(1/6)*b*d^2=	3,92E+06 mm3	
σmx=	Mxed/Wx=	1,52 N/mm2	(NEN1990)

<u>Moment y direction (in plane)</u>

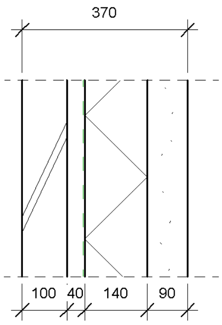
Myed=	My*1,5/7	14,74 kNm	
Wy=	(1/6)*d*b^2=	4,37E+08 mm3	
σmy=	Myed/Wy=	0,03 N/mm2	(NEN1990)

<u>Total</u>

σmax=	σn+σmx+σmy=	1,73 N/mm2	(Soons, F.A.M.& Raaij van, B.P.M. (2014) Quick reference)

ωbuc=	0,75 Prefab	
ωbuc=	1 Insitu	(Quick reference)

UC=	σmax/fcd*ωbuc=	0,17 Satisfies	(Quick reference)



Insulation

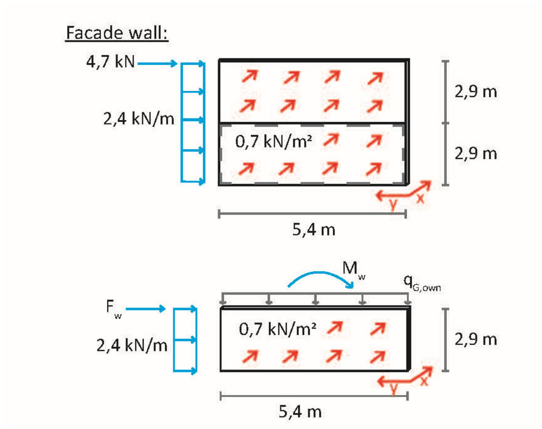
Rcmin=	4,7 m2K/W	(Bouwbesluit)

	d [m]	λ [W/mK]	R [m2K/W]	
Concrete	0,09	1,7	0,1	
Insulation	0,12	0,041	2,9	(Linden van der, A.C. et al (2015) Bouwfysica)
Air	0,04	0,025	1,6	
Manonary	0,1	1,4	0,1	
		Rc=	4,7 m2K/W	

Acoustics

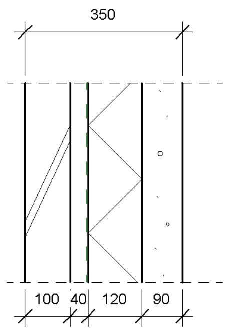
Ra≈	50 dB	(NPR 5272, 2005)

Design 2: Cast insitu facade



$F_w = 4,7 + 2,4*2,9 = 11,7$ kN

$M_w = 4,7*2,9 + 2,4*2,9*(0,5*2,9) = 23,7$ kNm



Situation

h	2900	mm	FG(ex. onv	35,24	kN
b	5400	mm	FQ	0,00	kN
d	80	mm	FGown	35,24	kN
ρ	2,25	kN/m2	Mx	3,97	kNm
			My	68,788	kNm

C20/25		
fck	20	N/mm2
fcd	13,3	N/mm2

Resistance

Normal force

Fed=	1,2*(FG+FGown)+1,5*FQ=	84,57	kN	
A=	b*d	4,32E+05	mm2	
σn=	Fed/A	0,20	N/mm2	(NEN1990)

Moment x direction (out of plane)

Mxed=	Mx*1,5=	5,96	kNm	
Wx=	(1/6)*b*d^2=	3,09E+06	mm3	
σmx=	Mxed/Wx=	1,93	N/mm2	(NEN1990)

Moment y direction (in plane)

Myed=	My*1,5/7	14,74	kNm	
Wy=	(1/6)*d*b^2=	3,89E+08	mm3	
σmy=	Myed/Wy=	0,04	N/mm2	(NEN1990)

Total

σmax=	σn+σmx+σmy=	2,16	N/mm2	(Soons, F.A.M.& Raaij van, B.P.M. (2014) Quick reference)

ωbuc=	0,75	Prefab	
ωbuc=	1	Insitu	(Quick reference)

UC=	σmax/fcd*ωbuc=	0,16	Satisfies	(Quick reference)

Insulation

Rcmin= 4,7 m2K/W

	d [m]	λ [W/mK]	R [m2K/W]	
Concrete	0,08	1,7	0,0	
Insulation	0,12	0,041	2,9	(Linden van der, A.C. et al (2015) Bouwfysica)
Air	0,04	0,025	1,6	
Manonary	0,1	1,4	0,1	
		Rc=	4,6	m2K/W

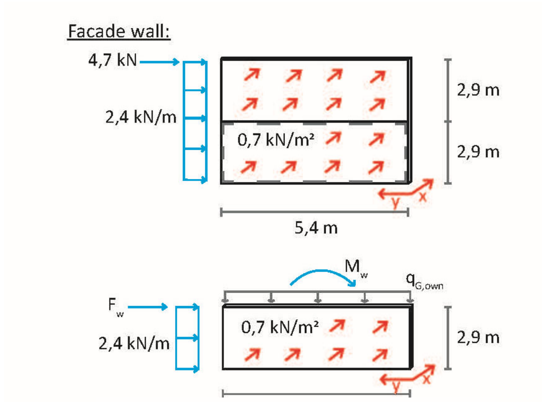
Acoustics

Ra≈ 50 dB (NPR 5272, 2005)

Design 3: CLT Facade

Situation

h	2900 mm		FG(ex. onw w.)	5,16 kN
b	5400 mm		FQ	0,00 kN
d	80 mm		FGown	5,16 kN
ρ	420,00 kg/m3		Mx	3,97 kNm
			My	67,63 kNm
C24				
fmk	24 N/mm2		kmod	0,6
fmdx	13,6 N/mm2		khx	1,13
fmdy	12,0 N/mm2		khy	1,00
			γm	1,2



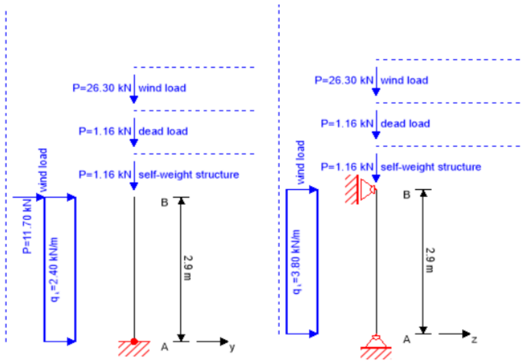
$F_w = 4{,}7 + 2{,}4*2{,}9 = 11{,}7$ kN
$M_w = 4{,}7*2{,}9 + 2{,}4*2{,}9*(0{,}5*2{,}9) = 23{,}7$ kNm

Resistance

Replace Mx with pointload, to create the same compression force in calculatis:

σ= M/W F= M/W*A
σ= F/A F=M/(1/6*t*b^2)*(b*t)
F=M/(1/6*b)= 26,3 kN

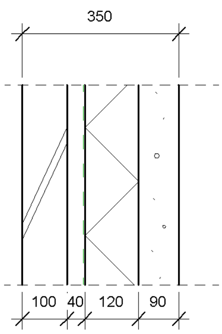
UC= 0,67 (calculatis:https://calculatis.storaenso.com/)



(calculatis)

Rc-value

	d [m]	λ [W/mK]	R [m2K/W]	
Timber	0,08	0,14	0,6	
Insulation	0,1	0,041	2,4	(Linden van der, A.C. et al
Air	0,04	0,025	1,6	(2015) Bouwfysica)
Manonary	0,1	1,4	0,1	
		Rc=	4,7 m2K/W	



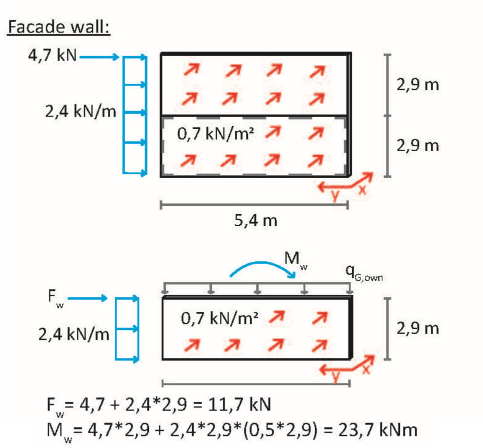
Acoustics

Ra≈ 46 dB (NPR 5272, 2005)

layer	thickness	type	material
1	20.0 mm	C	C24 spruce ETA (2019)
2	40.0 mm	L	C24 spruce ETA (2019)
3	20.0 mm	C	C24 spruce ETA (2019)

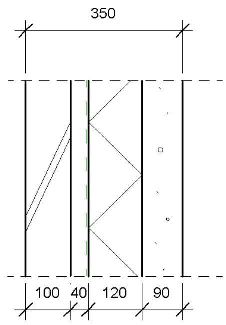
(calculatis)

Design 3: HSB facade



Situation

htot	2900	mm	<u>Vertical loads</u>		
btot	5400	mm	FG(element above)	15,36	kN
ρ	0,98	kN/m2 (average)	FQ	0,00	kN
			FGown	15,36	kN
<u>Posts:</u>					
b	45	mm	<u>Governing wind moments</u>		
h	120	mm	Mx (per post)	0,44	kNm
h.o.h.	600	mm, so 10 posts	My	9,66	kNm
C18					
E	6000	N/mm2	<u>Backboard:</u>		
fc0k	18	N/mm2	t(backboard)	15	mm
fmk	18	N/mm2	OSB board		
kmodc	0,6		fmk	20	N/mm2 (Joost de Vree)
kmodmx	0,9		kmodmy	0,9	
khx	1,05		khy	1,00	
γm	1,3		γm	1,2	
fc0d	8,69	N/mm2	fmyd	15,00	N/mm2
fmxd	13,03	N/mm2			



Resistance

<u>Normal force per post</u>

Fed=	(1,2*(FG+FGown)+1,5*FQ)/10=	3,69	kN	
Fed=	(1,35*(FG+FGown)+ψ0*1,5*FQ)	<u>4,15</u>	kN	(NEN1990)
A=	b*d	5400	mm2	
σc0d=	Fed/A	0,77	N/mm2	(NEN1990)

<u>Moment x direction (out of plane) per post</u>

Mxed=	Mx*1,5=	0,66	kNm	
Wx=	(1/6)*b*h^2=	1,08E+05	mm3	
σmxd=	Mxed/Wx=	6,13	N/mm2	(NEN1990)

<u>Strength verification of combined bending and compression</u>

UC=	(σc0d/fc0d)^2+(σmxd/fmxd)+km*(σmyd/fmyd)=	<u>0,48</u> Satisfies	
and			(NEN1995-1-1)
UC=	(σc0d/fc0d)^2+km(σmxd/fmxd)+(σmyd/fmyd)=	0,34	

with:
km= 0,7
σmyd= 0 kN (taken by backboard)

<u>Moment y direction (in plane) taken by the backboard</u>

Myed=	My*1,5=	14,49	kNm
Wy=	(1/6)*t*b^2=	7,29E+07	mm3
σmy=	Myed/Wy=	0,20	N/mm2

UC=	σmyd/fmyd+km(σmxd/fmxd)=	<u>0,01</u> Satisfies	(NEN1995-1-1)
	km(σmyd/fmyd)+σmxd/fmxd=	0,01	

With:
km= 0,7
σmx= 0 kN(taken by posts)

Insulation

Rcmin= 4,7 m2K/W

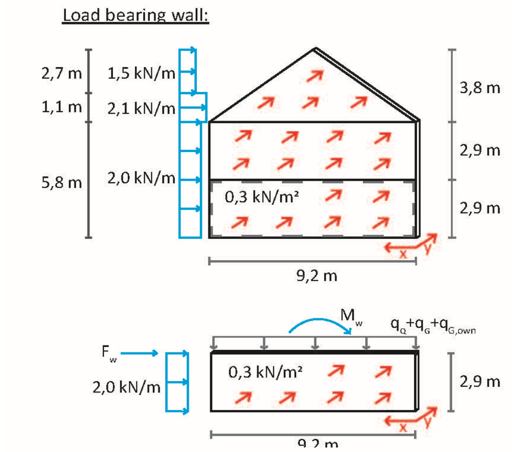
	d [m]	λ [W/mK]	R [m2K/W]	
Insulation	0,13	0,041	3,2	
Air	0,04	0,025	1,6	(Linden van der, A.C. et al (2015) Bouwfysica)
Manonary	0,1	1,4	0,1	
		Rc=	4,8	m2K/W

Acoustics

Ra≈ 46 dB (NPR 5272, 2005)

APPENDIX 5: LOAD BEARING WALL

Load bearing wall design 1: Prefab concrete



Vertical loads:

	G		Q	
Roof	3,43	kN/m	1,11	kN/m
Floor 2	14,58	kN/m	6,89	kN/m
Floor 1	14,58	kN/m	6,89	kN/m
Total	32,59	kN/m	24,88	kN/m

q_Q = 32,59 kN/m
q_G = 24,88 kN/m

F_w= 1,5*2,7+2,1*1,1+2,0*5,8 = 12,1 kN
M_w= 1,5*2,7*(0,5*2,7+1,1+2,9)
+ 2,1*1,11*(0,5*1,11+2,9)
+ 2,0*2,9*(0,5*2,9) = 37,8 kNm

Situation

h	2900 mm	FG(ex. onw w.	410,23	kN
b	9150 mm	FQ	228,90	kN
d	100 mm	FGown	66,34	kN
ρ	5,00 kN/m2	Mx	81,3	kNm
		My	2,90	kNm

C20/25
fck 20 N/mm
fcd 13,3 N/mm

Resistance

Normal force

Fed=	1,2*(FG+Fgown)+1,5*FQ=	915,22 kN	
A=	b*d	9,15E+05 mm	
σn=	Fed/A	1,00 N/mm2	(NEN1990)

Moment x direction

Mxed=	Mx*1,5=	121,95 kNm	
Wx=	(1/6)*d*b^2=	1,40E+09 mm3	
σmx=	Mxed/Wx=	0,09 N/mm2	(NEN1990)

Moment y direction

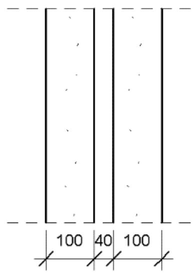
Myed=	My*1,5	4,35 kNm	
Wy=	(1/6)*b*d^2=	1,53E+07 mm3	
σmy=	Myed/Wy=	0,29 N/mm2	(NEN1990)

Total

σmax= σn+σmx+σmy= 1,37 N/mm2 (Soons, F.A.M.& Raaij van, B.P.M. (2014) Quick reference)

ωbuc= 0,75 Prefab
ωbuc= 1 Insitu (Quick reference)

UC= σmax/fcd*ωbuc= 0,14 Satisfies (Quick reference)



Fire resistance
Sufficient

Acousic inulation

Air
Ra≈ 52 dB (NPR 5272, 2005)

Contact
No contact

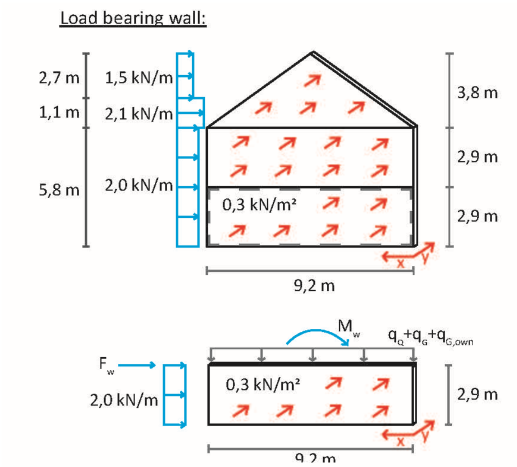
Design 2: InSitu

Situation

h	2900 mm		FG(ex. onw	410,23 kN
b	9150 mm		FQ	228,90 kN
d	100 mm		FGown	66,34 kN
ρ	5,00 kN/m2		Mx	81,3 kNm
			My	2,90 kNm

C20/25

fck	20 N/mm
fcd	13,3 N/mm



Vertical loads:

	G		Q	
Roof	3,43	kN/m	1,11	kN/m
Floor 2	14,58	kN/m	6,89	kN/m
Floor 1	14,58	kN/m	6,89	kN/m
Total	32,59	kN/m	24,88	kN/m

q_Q = 32,59 kN/m
q_G = 24,88 kN/m

F_w = 1,5*2,7+2,1*1,1+2,0*5,8 = 12,1 kN
M_w = 1,5*2,7*(0,5*2,7+1,1+2,9)
+ 2,1*1,11*(0,5*1,11+2,9)
+ 2,0*2,9*(0,5*2,9) = 37,8 kNm

Resistance

Normal force

Fed=	1,2*(FG+Fgown)+1,5*FQ=	915,22 kN	
A=	b*d	9,15E+05 mm	
σn=	Fed/A	1,00 N/mm2	(NEN1990)

Moment x direction

Mxed=	Mx*1,5=	121,95 kNm	
Wx=	(1/6)*d*b^2=	1,40E+09 mm3	
σmx=	Mxed/Wx=	0,09 N/mm2	(NEN1990)

Moment y direction

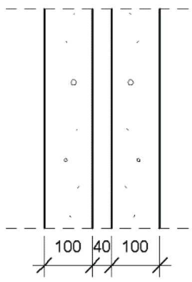
Myed=	My*1,5	4,35 kNm	
Wy=	(1/6)*b*d^2=	1,53E+07 mm3	
σmy=	Myed/Wy=	0,29 N/mm2	(NEN1990)

Total

σmax=	σn+σmx+σmy=	1,37 N/mm2	(Soons, F.A.M.& Raaij van, B.P.M. (2014) Quick reference)

ωbuc=	0,75 Prefab	
ωbuc=	1 Insitu	(Quick reference)

UC=	σmax/fcd*ωbuc=	0,10 Satisfies	(Quick reference)



Fire resistance

Θcr=	500 °C	(NEN-EN-1992-1-2)
R60		

See table A.2

c≥	21 mm	Sufficent

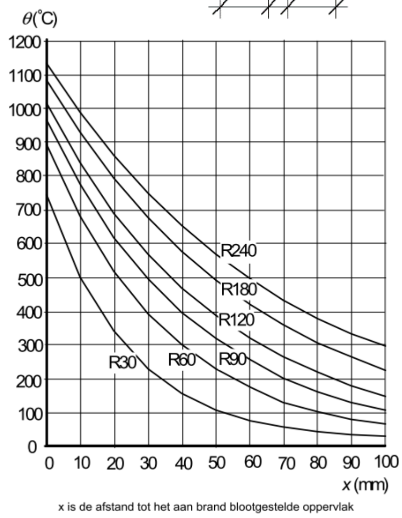
Acousic inulation

Air

Ra≈	52 dB	(NPR 5272, 2005)

Contact

No contact



Figuur A.2 — Temperatuurverdeling in platen (hoogte h = 200) voor R 60 – R 240

(NEN-EN-1992-1-2)

Load bearing wall design 3: CLT

Situation

h	2900 mm	FG(ex. onw	318,02 kN
b	9150 mm	FQ	228,90 kN
d	100 mm	FGown	10,93 kN
ρ	4,12 kN/m3	Mx	81,3 kNm
		My	2,90 kNm

C24
fmk 20 N/mm2

Resistance

Normal force

Fed=	1,2*(FG+Fgown)+1,5*FQ=	738,09 kN	
A=	b*d	9,15E+05 mm	
σn=	Fed/A	0,806657 N/mm2	(NEN1990)

Moment x direction

Mxed=	Mx*1,5=	121,95 kNm	
Wx=	(1/6)*d*b^2=	1,40E+09 mm3	
σmx=	Mxed/Wx=	0,09 N/mm2	(NEN1990)

Moment y direction

Myed=	My*1,5	4,35 kNm	
Wy=	(1/6)*b*d^2=	1,53E+07 mm3	
σmy=	Myed/Wy=	0,29 N/mm2	(NEN1990)

Total

σmax= σn+σmx+σmy= 1,18 N/mm2

UC= 0,78 Satisfies (calculatis:https://calculatis.storaenso.com/)

Fire resistance

Sufficient
UC= 0,73 (Calcualtis)
gypsum plasterboard 12,5 mm

Acousic inulation

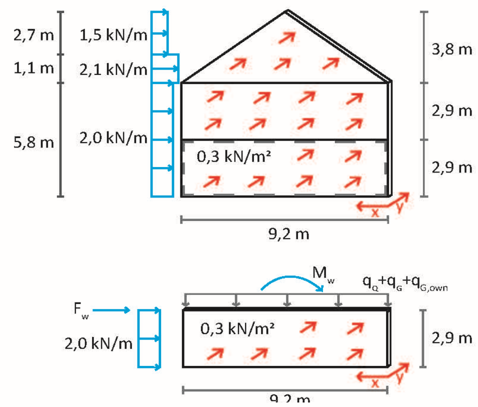
Air

Ra≈ 52 dB (NPR 5272, 2005)

Contact

No contact

Load bearing wall:

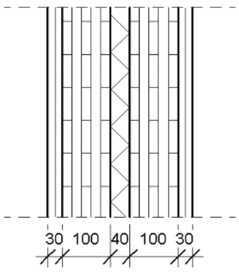


Vertical loads:

	G		Q	
Roof	3,43	kN/m	1,11	kN/m
Floor 2	14,58	kN/m	6,89	kN/m
Floor 1	14,58	kN/m	6,89	kN/m
Total	32,59	kN/m	24,88	kN/m

q_Q = 32,59 kN/m
q_G = 24,88 kN/m

F_w= 1,5*2,7+2,1*1,1+2,0*5,8 = 12,1 kN
M_w= 1,5*2,7*(0,5*2,7+1,1+2,9)
+ 2,1*1,11*(0,5*1,11+2,9)
+ 2,0*2,9*(0,5*2,9) = 37,8 kNm



layer	thickness	type	material
1	30.0 mm	C	C24 spruce ETA (2019)
2	40.0 mm	L	C24 spruce ETA (2019)
3	30.0 mm	C	C24 spruce ETA (2019)

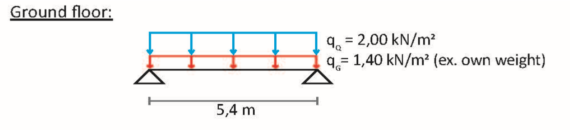
(Calculatis)

Appendix 6: Ground Floor

Groundfloor design 1: Rib cassette

Situation

L	5,4 m	b	1200 mm
ρ	210 kg/m2	h	350 mm
Q	2,00 kN/m2	C50/60	
G	3,46 kN/m2		



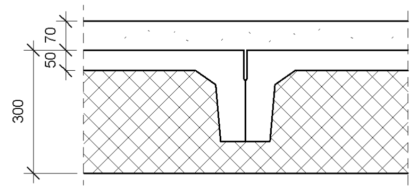
qed= (1,35*G+1,5*Q*)= 7,67 kN/m2

Resistance

q_{maxQ}= 4 kN/m2 (Dycore: https://www.dycore.nl/producten/ribbenvloeren/ontwerp-ribbenvloer)

q_Q= 2 kN/m2

UC= 0,5



Defection

u≤ 0,004L (Dycore)

Isulation

Rc-value 5 m²K/W (Dycore)

Sound insulation

Contact

Ground floors span from foundation beam to foundation beam.

Rubbers are used to damp the contact sounds (Dycore)

Vibrations

Woonfunctie: Class D

E=	3,70E+10 N/m2	
I=	0,0001 m4	(Estimation based on crossection)
μ=	667,9 kg/m	
L=	5,4 m	

Demping=	D1+D2+D3=	3 %
f=	(2/pi)*√((3EI)/(0,49μL^4))=	4,28 Hz
Mmod=	0,5μl=	1803,34 kg

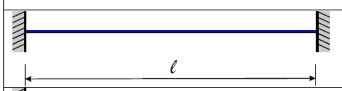
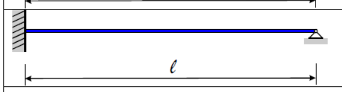
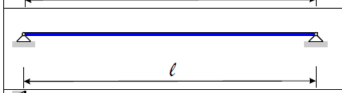
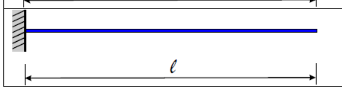
See graph: Class E Producer claims to be sufficient (Dycore)

A.2. Natuurlijke frequentie en modale massa voor balken

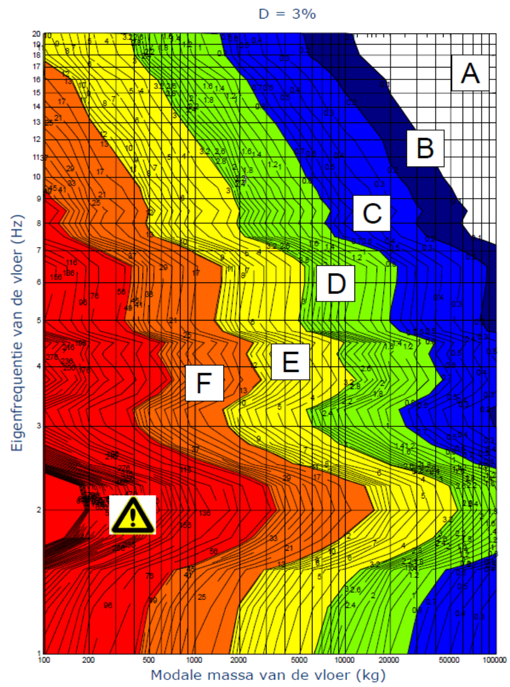
De eerste eigenfrequentie van een balk voor verschillende oplegcondities kan bepaald worden met de formules in Tabel 4 met:

- E Elasticiteitsmodulus [N/m²]
- I Traagheidsmoment [m⁴]
- μ verdeelde massa [kg/m]
- ℓ Lenge van de balk

Tabel 4: Eerste eigenfrequentie en modale massa voor balken

Oplegcondities	Natuurlijke Frequentie	Modale massa
	$f = \frac{4}{\pi}\sqrt{\frac{3EI}{0.37\mu l^4}}$	$M_{mod} = 0{,}41\,\mu\,l$
	$f = \frac{2}{\pi}\sqrt{\frac{3EI}{0.2\mu l^4}}$	$M_{mod} = 0{,}45\,\mu\,l$
	$f = \frac{2}{\pi}\sqrt{\frac{3EI}{0.49\mu l^4}}$	$M_{mod} = 0{,}5\,\mu\,l$
	$f = \frac{1}{2\pi}\sqrt{\frac{3EI}{0.24\mu l^4}}$	$M_{mod} = 0{,}64\,\mu\,l$

(Hivoss, 2008)



(Hivoss, 2008)

Groundfloor design 2: CLT

Situation

L	5,4 m	h	180 mm
ρ	420 kg/m3	E	11000 N/mm2
Q	2,00 kN/m2		
G	2,21 kN/m2		
Class	C24		

qed=	(1,35*G+1,5*Q*)1=	5,99 kN/m	(NEN1990)
Med=	(1/8)*qed*L^2=	21,82 KNm	
Ved=	(1/2)*qed*L=	16,17 kN	
Ned=		0 kN	

Strength
UC= 0,23 (Calculatis: https://calculatis.storaenso.com/)

Deflection
UC= 0,32 (Calculatis)

Insulation

	d [m]	λ [W/mK]	R [m2K/W]	
Concrete	0,07	1,7	0,0	
CLT	0,2	0,14	1,4	(Soons, F.A.M.& Raaij van,
Insulation	0,14	0,038	3,7	B.P.M. (2014) Quick reference)
		Rc=	5,2 m2K/W	

Sound insulation
Contact
Rubber added on foundation beam

Vibration
UC= 0,98 (Calculatis)

Woonfunctie: Class D

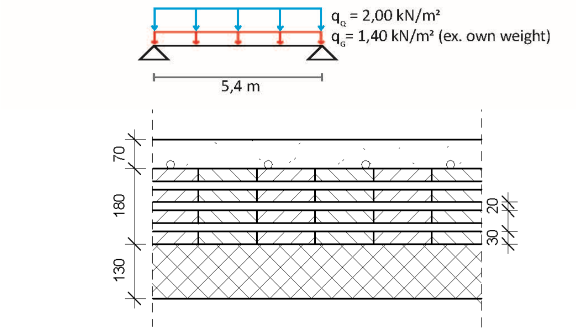
(See floor as beam with a width of 8,59 meters)

E=	1,10E+10 N/m2
I=	1,40E-03 m4
μ=	3689,1 kg/m
L=	5,4 m

Demping= D=	D1+D2+D3=	3 %
f=	(2/pi)*√((3EI)/(0,49μL^4))=	3,50 Hz
Mmod=	0,5μl=	9960,46 kg

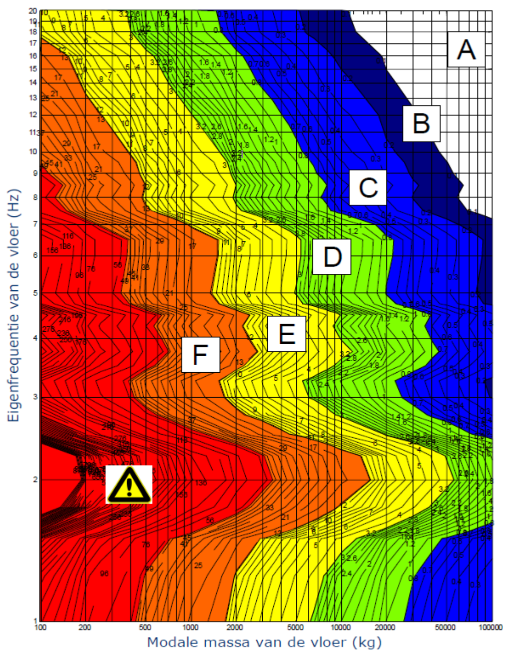
See graph: Class D, satisfies

Ground floor:



layer	thickness	type	material
1	30.0 mm	L	C24 spruce ETA (2019)
2	20.0 mm	C	C24 spruce ETA (2019)
3	30.0 mm	L	C24 spruce ETA (2019)
4	20.0 mm	C	C24 spruce ETA (2019)
5	30.0 mm	L	C24 spruce ETA (2019)
6	20.0 mm	C	C24 spruce ETA (2019)
7	30.0 mm	L	C24 spruce ETA (2019)

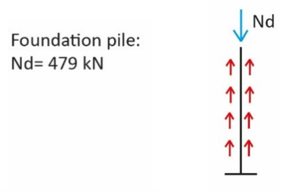
(Calculatis)

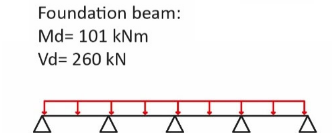


(Hivoss, 2008)

APPENDIX 7: FOUNDATION

Design 1: Concrete





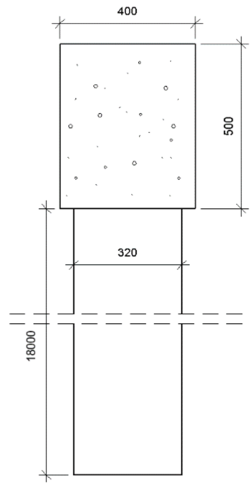
Pile

l		18	m	
d		320	mm	
C20/25				
fk		20	N/mm2	
fd		13,33	N/mm2	
Fed=		479,00	kN	(Governing load)
A=	1/4*pi*d^2	80425	mm2	
σd=	Fed/A	5,96	N/mm2	(Soons, F.A.M.& Raaij van, B.P.M. (2014) Quick reference)
UC=	σd/fd=	0,45		

Beam

b	400	mm	c	15	mm
h	500	mm	Øhfd	15	mm
Med	101	kNm			
Ved	206	kN			
C20/25					
fck	20	N/mm2	fyk	500	N/mm4
fcd	13,3	N/mm2	fyd	434,8	N/mm5

d=	h-c-0,5Øhfd=	477,5	mm	
Reinforcement estimation:				(Quick reference)
As=	Med/(0,75*h*fyd)=	619,47	mm2	(4 bars of 15 mm)
Mrd=	As*fyd*0,9d=	115,75	kNm	
UC=	Med/Mrd=	0,87		
ρl=	As/(b*d)=	0,003	%	(Quick reference)
k=	1+√(200/d)=	1,65	≤2	
Vrd=	b*d*0,12*k(100*ρl*fck)^(1/3)=	70409,05	N	
UC=	Ved/Vrd=	2,93		Additional transverse force reinforcement is needed



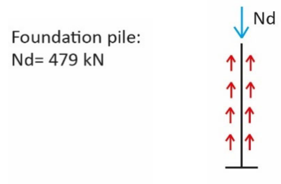
Design 2: Timber

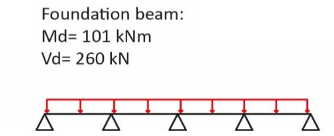
Piles					
			Crossection is smaller -> less ground pressure -> more piles		
l		18	m	Estimation: max 100 kN per pile	
d		170	mm		
C24				γm	1,3
fc0k		21	N/mm2	kmod	0,5
fc0d		8,08	N/mm2	kh	1,00

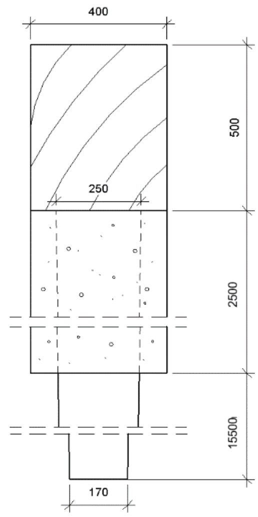
Fed=		95,80	kN	(Governing load devided over 5 piles)
A=	1/4*pi*d^2	22698	mm2	
σd=	Fed/A	4,22	N/mm2	(Soons, F.A.M.& Raaij van, B.P.M. (2014) Quick reference)
UC=	σd/fd=	0,52		

Beam				
b	400	mm		
h	500	mm		
Med	101	kNm		
Ved	206	kN		
D18			γm	1,3
fmk	18,0	N/mm2	kmod	0,5 (NEN1995)
fmd	7,1	N/mm3	kh	1,02

W=	(1/6)*b*h^2=	1,67E+07	mm3	
σed=	Med/W=	6,06	N/mm2	(Quick reference)
UC=	σed/fmd=	0,86		







APPENDIX 8: LCA DATA AND CALCULATION

NMD Data

Materials per unit:	A1-3 [€]	A4 [€]	A5 [€]	B [€]	C1 [€]	C2[€]	C3 [€]	C4 [€]	D [€]	Source
Hollow core slab 200 mm [kg]	1,02E-02						2,58E-05	6,28E-06	7,75E-05	NMD, sep 2021
Screed [kg]	1,17E-02						3,34E-04	6,20E-03		NMD, sep 2021
Concrete C30/37 [kg]	7,50E-03						3,34E-04	6,40E-06		NMD, sep 2021
Concrete C20/25 [kg]	6,80E-03	2,80E-04				1,56E-05	3,34E-04	6,40E-06		NMD, okt 2021
Cross laminated timber [kg]	5,84E-02							-2,72E-02		NMD, sep 2021
Cross laminated timber [201 mm]	6,29E+00		2,13E-01			2,12E-01	3,71E-01	2,32E-02	-1,73E+00	NMD, sep 2021
Laminated pine [kg]	5,84E-02	2,40E-03						-2,72E-02		NMD, sep 2021
Stone wool [kg]	9,82E-02	2,40E-03						3,30E-03		NMD, sep 2021
Steel frame [kg]	1,68E-01	2,30E-03					6,21E-04	6,40E-06	-1,34E-02	NMD, sep 2021
Gypsem board [12,5 mm]	1,80E-01	9,60E-03	5,90E-03			6,30E-03	3,50E-05	2,90E-03	-1,13E-04	NMD, sep 2021
Inverted U-slab with EPS [kg]	3,33E-02	2,47E-03					2,91E-05	9,61E-04	7,86E+05	NMD, sep 2021
EPS [kg]	4,06E-01	2,50E-03					2,94E-04	9,39E-02	8,81E-04	NMD, sep 2021
Chipboard [kg]	5,65E-02	2,40E-03						-2,72E-02		NMD, sep 2021
Reinforcement steel [kg]	4,59E-01	2,80E-04					-4,40E-03	3,67E-04	-1,41E-02	NMD, sep 2021
Brickwork (incl. morter) [m2]	4,56E+00		2,68E-01			1,08E-01	3,63E-01	1,50E-03	-7,32E-02	NMD, sep 2021
Prefab concrete C20/25 [kg]	1,00E-02	2,50E-03					2,63E-05	6,40E-06	7,90E-05	NMD, sep 2021
HSB frame [kg]	3,01E-02	2,50E-03						-2,46E-02		NMD, okt 2021
OSB timber plate [kg]	5,50E-02	2,40E-03						-2,72E-02		NMD, okt 2021
Virbopaal (incl. steel) [m]	1,75E+00	7,33E-03					-3,22E-03	1,22E-03	-7,81E-03	NMD, okt 2021
Timber foundation pile [280 mm ,m]	2,95E-02	2,40E-03						-2,42E-02		NMD, okt 2021
Tropical hardwood [0,06 m3]	1,19E+00					7,42E-02	1,27E-01	9,00E-03	-7,74E-01	NMD, okt 2021

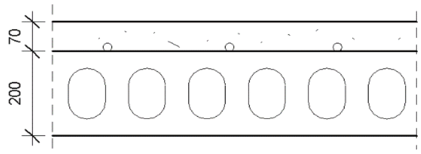
Construction machanery per unit:	[€]	Source
Crane [hour]	12,4293	NMD, sep 2021
Pump mixer [hour]	5,80030	NMD, sep 2021
Demolisher [hour]	12,972	NMD, sep 2021
Pile driver [hour]	6,6289	NMD, okt 2021

Transport per unit:	[€]	Source
Lorry truck max capacity 60 ton [t/km]	0,01543	CIE4100
Truck mixer 10m3 [m3/km]	0,02511	CIE4100

(t = teu = 1 container van 30 000 kg)
(6,10x2,44x2,59m of 38,5m3)

Intermediate Floor design 1: Prefab

		mm	kg/m2
	NeMO sand cement screed C12	70	143
	Hollow core slab Dycore (approx. 3,0 kg reinforcement)	200	283



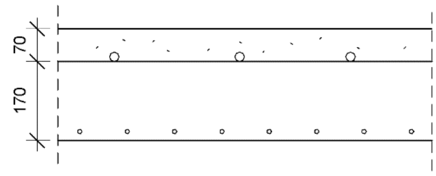
LCA for 1m2 of floor

		[€/m^2]	Total [€/m^2]
A1-A3	Production of screed	1,6731	
	Production of hollow core slab	2,8866	4,5597
A4	Transportation of screed: truck mixer 10 m3 for 10 km (Megamix)	0,0176	
	Transportation of hollow core slab: lorry truck for approx. 70 m2 floor for 35 km (Dycore)	0,0077	0,0253
A5	People	PM	
	Building crane: approx. 5 minutes per 1 hollow core slab, so for 1 m^2 hollow core slab it is 1 minute work	0,2072	
	Pump mixer: approx. 10 m^3 in 30 minutes, so 0,07 m^3 in 0,21 minutes	0,0203	0,2275
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel and concrete	0,0073	0,0073
C4	Screet waste: 100%	0,8866	0,8866
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-0,8490	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-1,0321	-1,8811

A1-A3	4,5597
A-C	5,9296
A-D	4,0485

Intermediate Floor design 2: Cast insitu

		mm	kg/m2
	NeMO sand cement screed C12	70	143
	Concrete C30/37	170	425
	Reinforcement steel	10	6,28



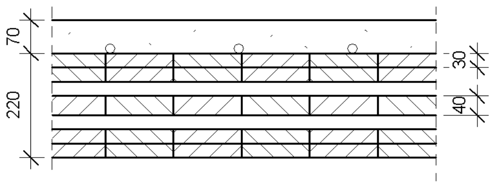
LCA for 1m2 of floor

		[€/m^2]	Total [€/m^2]
A1-A3	Production of screed	1,6731	
	Production of reinforcement steel	2,8806	
	Production of concrete	3,1875	7,7412
A4	Transportation of screed: truck mixer 10 m3 for 10 km (Megamix)	0,0176	
	Transportation of reinforcement: Lorry truck 1 tue (30 ton) for approx. 3,6 kg for 20 km (Betonstaal)	0,0000	
	Transportation of concrete: truckmixeer for 10 m3 for 8 km (Dyckerhoff Basal Betonmortel)	0,0342	0,0518
A5	People	PM	
	Placement and detachment of formwork: crane approx 30 minutes per 2 walls, so 0,56 minutes per m2 wall	0,1160	
	Pump mixer: approx. 10 m^3 in 30 minutes, so 0,07 m^3 screed in 0,21 minutes and 0,17 m3 concrete in 0,51 minutes	0,0696	0,1856
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel and concrete	0,1418	0,1418
C4	Screet waste: 100%	0,8866	0,8866
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-1,2750	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-2,1605	-3,4355

A1-A3	7,7412
A-C	9,2302
A-D	5,7948

Intermediate Floor design 3: CLT

		mm	kg/m2
	NeMO sand cement screed C12	70	143
	CLT spruce C24	220	92,4



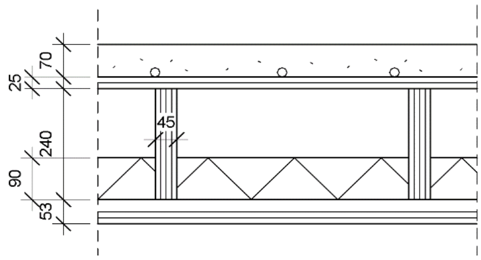
LCA for 1m2 of floor

		[€/m^2]	Total [€/m^2]
A1-A3	Production of screed	1,6731	
	Production CLT slab	6,8837	8,5568
A4	Transportation of screed: truck mixer 10 m3 for 10 km (Megamix)	0,0176	
	Transportation of CLT slab: lorry truck for approx. 70 m2 floor for 97 km (BDUvakmedia – Timmerfabrikant)	0,0214	0,0390
A5	People	PM	
	Building crane: approx. 5 minutes per 1 slab, so for 1 m^2 hollow core slab it is 1 minute work	0,2072	
	Pump mixer: approx. 10 m^3 in 30 minutes, so 0,07 m^3 in 0,21 minutes	0,0203	0,2275
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing	0,4533	0,4533
C4	Screet waste: 100%	0,8866	0,8866
D	Reuse timber: 100% as 48% of A1-A3 of new chipboard	-2,5059	-2,5059

A1-A3	8,5568
A-C	10,3864
A-D	7,8805

Intermediate Floor design 4: Kerto

		mm	kg/m2
	NeMO sand cement screed C12	70	143
	Spruce veneer	25	12
	Spruce veneer (average)	22,5	10,8
	Mineral wool	90	10,8
	Steel bars (estimation)	27	13
	Gypsum board	25	-



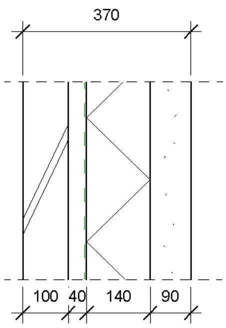
LCA for 1m2 of floor

		[€/m^2]	Total [€/m^2]
A1-A3	Production floor panel	6,6017	6,6017
A4	Transportation of screed: truck mixer 10 m3 for 10 km (Megamix)	0,0176	
	Transportation of slab: lorry truck for approx. 70 m2 floor for 96 km (Metsä Wood)	0,0212	0,0387
A5	People	PM	
	Building crane: approx. 5 minutes per 1 slab, so for 1 m^2 slab it is 1 minute work	0,2072	
	Pump mixer: approx. 10 m^3 in 30 minutes, so 0,07 m^3 in 0,21 minutes	0,0203	0,2275
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing	0,0558	0,0558
C4	Screet waste 100%	0,8866	
	Other waste 100%	0,0415	0,9281
D	Reuse timber: 100% as 48% of A1-A3 of new chipboard	-0,6183	-0,5768

A1-A3	6,6017
A-C	8,0751
A-D	7,4983

Facade design 1: Prefab

		mm	kg/m2
	Brickwork (morter is approx. 29%)	100	180
	Rockwool	140	16,8
	Prefab concrete (reinforcement is approx 3,6 kg/m2)	90	225



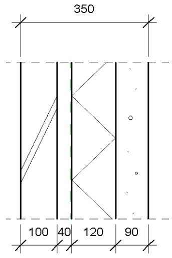
LCA for 1m2 of wall

		[€/m^2]	Total [€/m^2]
A1-A3	Prodcuction of brickwork	4,5633	
	Prodcution of rockwool	1,6498	
	Production of prefab concrete elements	2,2500	8,4631
A4	Transportation of bricks: Lorry truck 1 tue for approx. 128 kg for 18 km (Keramia BV)	0,0012	
	Transportation of morter: truck mixer 10 m3 for 10 km (Megamix) 0,04 m3 morter per m2 wall	0,0100	
	Transportation of rockwool: lorry truck for approx. 70 m2 for 10 km (Jongeneel)	0,0022	
	Transportation of prefab wall: lorry truck for approx. 70 m2 wall for 160 km (Building supply Genemuiden)	0,0353	0,0353
A5	People	PM	
	Building crane: approx. 5 minutes per wall, so for 1 m^2 facade it is 0,3 minutes work	0,0621	0,0621
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel, concrete, bricks and rockwool	0,3685	0,3685
C4	Brick waste: 100%	0,0015	
	Rockwool waste: 100%	0,0554	0,0569
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-0,6750	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-1,2385	-1,9135

A1-A3:	8,4631
A-C:	9,2092
A-D:	7,2957

Facade design 2: Cast in situ

		mm	kg/m2
	Brickwork (morter is approx. 29%)	100	180
	Rockwool	120	14,4
	Concrete C20/25	90	225
	Reinforcement	10	3,6



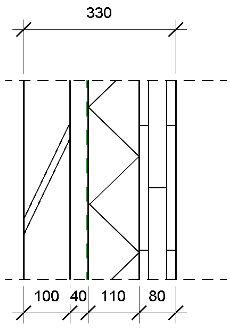
LCA for 1m2 of wall

		[€/m^2]	Total [€/m^2]
A1-A3	Prodcuction of brickwork	4,5633	
	Prodcution of rockwool	1,4141	
	Prodcution of concrete	1,5300	
	Production of reinfocement	1,6513	9,1587
A4	Transportation of bricks: Lorry truck 1 tue for approx. 128 kg for 18 km (Keramia BV)	0,0012	
	Transportation of morter: truck mixer 10 m3 for 10 km (Megamix) 0,04 m3 morter per m2 wall	0,0100	
	Transportation of rockwool: lorry truck 38,5 m3 for approx. 0,140 m3 for 10 km (Jongeneel)	0,0006	
	Transportation of concrete truck mixer 10 m3 for 8 km (Dyckerhoff Basal) 0,09 m3 morter per m2 wall	0,0181	
	Transportation of reinforcement: Lorry truck 1 tue (30 ton) for approx. 3,6 kg for 20 km (Betonstaal)	0,0000	0,0000
A5	People	PM	
	Placement and detachment of formwork: crane approx 30 minutes per 2 walls, so 0,56 minutes per m2 wall	0,1160	0,1160
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel, concrete, bricks and rockwool	0,4218	0,4218
C4	Brick waste: 100%	0,0015	
	Rockwool waste: 100%	0,0475	0,0490
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-0,6120	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-1,2385	-1,8505

A1-A3:	9,1587
A-C:	9,9688
A-D:	8,1183

Facade design 3: CLT

		mm	kg/m2
	Brickwork (morter is approx. 29%)	100	180
	Rockwool	110	13,2
	CLT	80	33,6



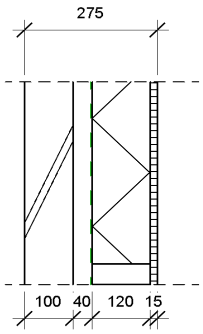
LCA for 1m2 of wall

		[€/m^2]	Total [€/m^2]
A1-A3	Prodcuction of brickwork	4,5633	
	Prodcution of rockwool	1,2962	
	Production of CLT slab	2,5032	8,3627
A4	Transportation of bricks: Lorry truck 1 tue for approx. 128 kg for 18 km (Keramia BV)	0,0012	
	Transportation of morter: truck mixer 10 m3 for 10 km (Megamix) 0,04 m3 morter per m2 wall	0,0100	
	Transportation of rockwool: lorry truck for approx. 70 m2 for 10 km (Jongeneel)	0,0022	
	Transportation of prefab CLT: lorry truck for approx. 70 m2 wall for 97 km (BDUvakmedia – Timmerfabrikant)	0,0214	0,0214
A5	People	PM	
	Building crane: approx. 5 minutes per wall, so for 1 m^2 facade it is 0,3 minutes work	0,0000	0,0000
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the timber, bricks and rockwool	0,0543	0,0543
C4	Brick waste: 100%	0,0015	
	Rockwool waste: 100%	0,0436	0,0451
D	Reuse timber: 100% as 48% of A1-A3 of chipboard	-0,9112	-0,9112

A1-A3:	8,3627
A-C:	8,7067
A-D:	7,7955

Facade design 4: HSB

		mm	kg/m2
	Brickwork (morter is approx. 29%)	100	180
	HSB frame 120x45 600 hoh	120	4,2
	HSB rock wool insulation	120	14,4
	HSB backboard OSB	15	8,25



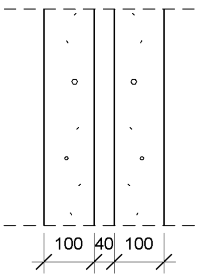
LCA for 1m2 of wall

		[€/m^2]	Total [€/m^2]
A1-A3	Prodcuction of brickwork	4,5633	
	Production of HSB element	1,9943	6,5576
A4	Transportation of bricks: Lorry truck 1 tue for approx. 128 kg for 18 km (Keramia BV)	0,0012	
	Transportation of morter: truck mixer 10 m3 for 10 km (Megamix) 0,04 m3 morter per m2 wall	0,0100	
	Transportation of HSB element: Lorry truck for approx.70 m2 for 10 km (Jongeneel)	0,0022	0,0022
A5	People	PM	
	Building crane: approx. 5 minutes per wall, so for 1 m^2 facade it is 0,3 minutes work	0,0621	0,0621
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the HSB element and brick	0,3626	0,3626
C4	Brick waste: 100%	0,0015	
	Rockwool waste: 100%	0,0475	0,0490
D	Reuse timber: 100% as 48% of A1-A3 of chipboard	-0,1139	-0,1139

A1-A3:	6,5576
A-C:	7,2568
A-D:	7,1429

Load bearing wall design 1: Prefab

		mm	kg/m2
	Prefab concrete (reinforcement is approx 3,6 kg/m2)	100	250
	Prefab concrete (reinforcement is approx 3,6 kg/m2)	100	250



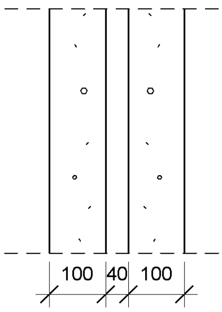
LCA for 1m2 of wall

		[€/m^2]	**Total [€/m^2]**
A1-A3	Production of prefab concrete elements	5,0000	5,0000
A4	Transportation of prefab wall: lorry truck for approx. 70 m2 wall for 160 km (Building supply Genemuiden)	0,0353	0,0353
A5	People	PM	
	Building crane: approx. 5 minutes per wall, so for 1 m^2 facade it is 0,3 minutes work	0,0621	0,0621
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel and concrete	0,0132	0,0132
C4	No waste	0,0000	0,0000
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-1,3600	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-2,4770	-3,8370

A1-A3:	5,0000
A-C:	5,3338
A-D:	1,4969

Load bearing wall design 2: Cast insitu

		mm	kg/m2
	Concrete C20/25 (reinforcement is approx 3,6 kg/m2)	100	255
	Concrete C20/25 (reinforcement is approx 3,6 kg/m2)	100	255



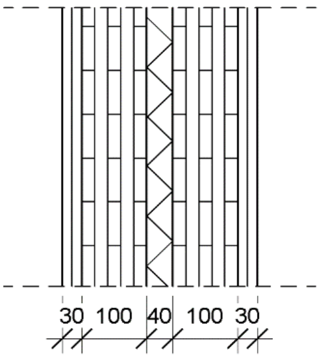
LCA for 1m2 of wall

		[€/m²]	Total [€/m²]
A1-A3	Production of concrete	3,4659	
	Production of reinforcement steel	3,3026	6,7685
A4	Transportation of concrete truck mixer 10 m3 for 8 km (Dyckerhoff Basal) 0,09 m3 morter per m2 wall	0,0402	
	Transportation of reinforcement: Lorry truck 1 tue (30 ton) for approx. 3,6 kg for 20 km (Betonstaal)	0,0000	0,0402
A5	People	PM	
	Placement and detachment of formwork: crane approx 30 minutes per 2 walls, so 0,56 minutes per m2 wall	0,1160	0,1160
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel amd concrete,	0,0000	0,0000
C4	No waste	0,0000	0,0000
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-1,3863	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-2,4770	-3,8633

A1-A3:	6,7685
A-C:	7,1480
A-D:	3,2846

Load bearing wall design 1: Prefab

		mm	kg/m2
	Gypsem board	30	-
	CLT wall	100	42
	Rockwool	40	4,8
	CLT wall	100	42
	Gypsem board	30	-



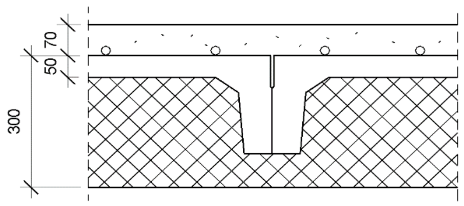
LCA for 1m2 of wall

		[€/m²]	Total [€/m²]
A1-A3	Production of CLT	6,2579	
	Production gypsemboard	0,8616	
	Production of Rockwool	0,4714	7,5909
A4	Transportation of prefab CLT: lorry truck for approx. 70 m2 wall for 97 km (BDUvakmedia – Timmerfabrikant)	0,0214	
A5	People	PM	
	Building crane: approx. 5 minutes per wall, so for 1 m^2 facade it is 0,3 minutes work	0,0621	0,0621
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m^2	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the element	0,3689	
C4	Gypsem waste: 100%	0,0139	
	Rockwool waste: 100%	0,0158	0,0298
D	Reuse timber: 100% as 48% of A1-A3 of new chipboard	-2,2781	-2,2781

A1-A3:	7,5909
A-C:	7,9060
A-D:	5,6280

Ground Floor design 1: Prefab

		mm	kg/m2
	NeMO sand cement screed C12	70	143
	Rib casette floor +EPS insulation	300	210



NMD:	kg/m2
Concrete	95%
steel	4%
EPS	1%

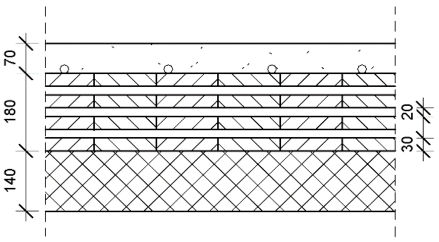
LCA for 1m2 of floor

		[€/m²]	Total [€/m²]
A1-A3	Production of screed	1,6731	
	Production of inverted U slab	6,9930	8,6661
A4	Transportation of screed: truck mixer 10 m3 for 10 km (Megamix)	0,0176	
	Transportation of hollow core slab: lorry truck for approx. 70 m2 floor for 35 km (Dycore)	0,0077	0,0253
A5	People	PM	
	Building crane: approx. 5 minutes per 1 hollow core slab, so for 1 m² hollow core slab it is 1 minute work	0,2072	
	Pump mixer: approx. 10 m³ in 30 minutes, so 0,07 m³ in 0,21 minutes	0,0203	0,2275
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m²	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel and concrete	0,0061	0,0061
C4	Screet waste: 100%	0,8866	
	EPS waste: 100%	0,1972	1,0838
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-0,5985	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-2,8898	-3,4883

A1-A3:	8,6661
A-C:	10,2320
A-D:	6,7437

Ground Floor design 2: CLT

		mm	kg/m2
	NeMO sand cement screed C12	70	143
	CLT	180	75,6
	EPS	140	2,1



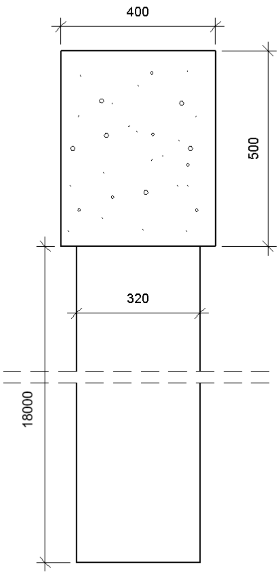
LCA for 1m2 of floor

		[€/m²]	Total [€/m²]
A1-A3	Production of screed	1,6731	
	Production of CLT slab	5,6321	
	Production of EPS	0,8520	8,1572
A4	Transportation of screed: truck mixer 10 m3 for 10 km (Megamix)	0,0176	
	Transportation of CLT slab: lorry truck for approx. 70 m2 floor for 97 km (BDUvakmedia – Timmerfabrikant)	0,0214	0,0390
A5	People	PM	
	Building crane: approx. 5 minutes per 1 slab, so for 1 m² hollow core slab it is 1 minute work	0,2072	
	Pump mixer: approx. 10 m³ in 30 minutes, so 0,07 m³ in 0,21 minutes	0,0203	0,2275
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m²	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing of screet, CLT and EPS	0,3964	0,3964
C4	EPS waste: 100%	0,0019	
	Screet waste: 100%	0,89	0,8885
D	Reuse timber: 100% as 48% of A1-A3 of new chipboard	-2,0503	-2,0503

A1-A3	8,1572
A-C	9,9317
A-D	7,8814

Foundation beam design 1: Concrete

		m2	kg/m
	Cast concrete (reinforcement is approx kg/m)	0,2	500
	Reinforcement	10	6,28



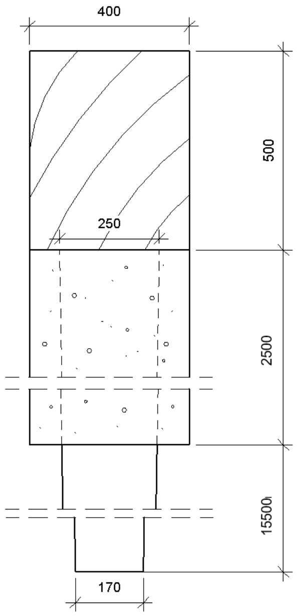
LCA for 1 m beam

		[€/m^2]	Total [€/m^2]
A1-A3	Production of concrete	3,4000	
	Production of reinforcement	2,8806	6,2806
A4	Transportation of concrete truck mixer 10 m3 for 8 km (Dyckerhoff Basal) 0,02 m3 morter per m	0,0040	
	Transportation of reinforcement: Lorry truck 1 tue (30 ton) for approx. 3,6 kg for 20 km (Betonstaal)	0,0001	0,0041
A5	People	PM	
	Pump mixer: approx. 10 m^3 in 30 minutes, so 0,02 m^3 in 0,06 minutes	0,0058	0,0058
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m beam	0,2162	
	People	PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing the steel and concrete	0,1668	0,1668
C4	No waste	0,0000	
D	Reuse concrete: 100% as 40% of A1-A3 of new concrete	-1,3600	
	Reuse steel: 100% as 75% of A1-A3 of new steel	-2,1605	-3,5205

A1-A3:	6,2806
A-C:	6,6806
A-D:	3,1601

Foundation beam design 2: Timber

		m2	kg/m
	Timber beam	0,2	84



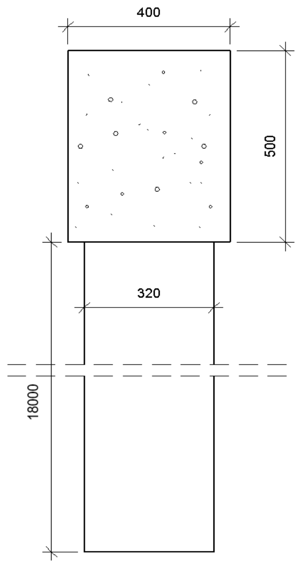
LCA for 1m beam

		[€/m^2]	Total [€/m^2]
A1-A3	Production of timber	3,9547	3,9547
A4	Transportation of timer: lorry truck for 30 ton for 97 km (BDUvakmedia – Timmerfabrikant)	0,0214	0,0214
A5	People Building crane: approx. 5 minutes per beam, so for 1 m it is 0,6 minutes work	PM 0,1243	0,1243
B	Maintenance	0,0000	0,0000
C1	Demolishing crane: approx. 1 minute work per m People	0,2162 PM	0,2162
C2	Transportation of scrap: lorry truck 1 tue for approx. 32 km (Schotte recycling)	0,0071	0,0071
C3	Processing	0,4220	0,4220
C4	No waste	0,0000	0,0000
D	Reuse timber: 100% as 48% of A1-A3 of new chipboard	-2,2781	-2,2781

A1-A3:	3,9547
A-C:	4,7456
A-D:	2,4675

Foundation pile design 1: Concrete

		mm	kg
	Vibro pile	320	3619



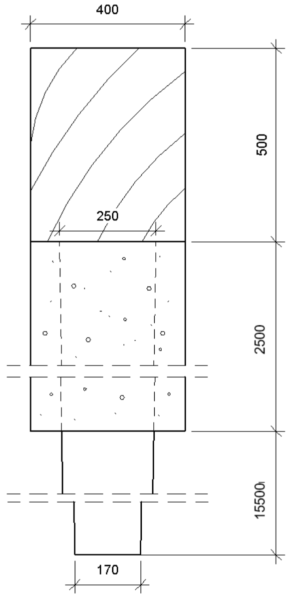
LCA for 1 pile

		[€/m²]	Total [€/m²]
A1-A3	Production of vibro pile	31,5601	31,5601
A4	Transportation of concrete truck mixer 10 m3 for 8 km (Dyckerhoff Basal) 1,45 m3 morter per pile	0,2913	0,2913
A5	People	PM	
	Pile driving: approx. 30 minutes per pile	198,8670	198,8670
B	Maintenance	0,0000	0,0000
C1	The foundation is left in the ground	0,0000	0,0000
C2	No transportation	0,0000	0,0000
C3	No processing	0,0000	0,0000
C4	No waste	0,0000	0,0000
D	Can be reused for new building	-31,5601	-31,5601

A1-A3:	31,5601
A-C:	230,7184
A-D:	199,1583

Foundation pile design 2: Timber

		mm (av)	kg
	Concrete topping	400	479
	Timber pile	210	262



LCA for 5 piles

		[€/m^2]	Total [€/m^2]
A1-A3	Production of concrete	16,2690	
	Production of Timber	1,9913	18,2603
A4	Transportation of concrete truck mixer 10 m3 for 8 km (Dyckerhoff Basal) 0,19 m3 morter per m pile	0,0382	
	Transportation of timer: lorry truck for approx. 20 piles for 97 km (BDUvakmedia – Timmerfabrikant)	0,374202	0,4124
A5	People	PM	
	Pile driving: approx. 20 minutes per pile	662,8900	662,8900
B	Maintenance	0,0000	0,0000
C1	The foundation is left in the ground	0,0000	0,0000
C2	No transportation	0,0000	0,0000
C3	No processing	0,0000	0,0000
C4	No waste	0,0000	0,0000
D	Can be reused for new building	-18,2603	-18,2603

A1-A3:	18,2603
A-C:	681,5626
A-D:	663,3024