# Circularity in the structural design

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The implementation of circular design alternatives for the load-bearing structure in the preliminary design phase

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# Preface

This report presents the last step of my Master Building Engineering at Delft University of Technology. In a master thesis all your obtained knowledge and experience will be combined and formed into your own research. For my thesis topic I wanted to find the interface between my Bachelor Architecture and Master Building Engineering and apply this on a current challenge in the building sector. Besides, both of my parents work on topics to improve our living environment, so I wanted my research to contribute as well. Maybe this has been subconsciously suggested all along?

The process of finding a thesis topic led to the Circular Economy. This system stimulates the reduction of the environmental impact in various ways. Improving the environmental impact of a building has gained popularity, but the actual implementation is limited. Therefore, I aimed for a collaboration with a party that stands in the middle of the transition in the building sector. This resulted in a conversation with Tom Blankendaal of BAM Advies & Engineering, a progressive circularity professional in the building sector. He gave me even more motivation to start investigating the possibilities to reduce the environmental impact of a building. An expert in the field of environmental impact assessments of buildings and their construction materials, is Henk Jonkers. He became the chair of my graduation committee. After the first discussions with Tom and Henk and the literature study, the need for a tool that helps to make environmentally friendly design choices became clear. Therefore, Sander van Nederveen joined the committee with an expertise in integrated design and information systems. This thesis is my first individual scientific research, so guidance in how to conduct this type of research was required. Therefore, a fellow graduating student recommended Hoessein Alkisaei and he joined as the last member of my graduation committee.
I would like to thank all of you for the guidance during the past months. I really appreciated the supportive, yet critical, approach from all of you. Luckily, during my final presentation we have the opportunity to meet each other in person.

First, I want to thank Henk. You were always available and open to discuss my progress, giving me clear and insightful feedback. Even more, your drive and curiosity in the field of environmental impact was inspiring to experience. Sander, I want to thank you for the feedback on the development of my design tool. You asked the right questions, that forced me to critically review the functionalities of the tool. Hoessein, I want to thank you for stimulating me to make choices and be confident about them. Your insight on performing a scientific research helped me to structure my progress. Lastly, I want to thank Tom. In our meetings you helped me to break down my challenges into manageable steps. The discussions about the implementation of the design tool motivated me even more. You introduced me to various people within BAM and above all, made me feel welcome in the team.

Next, I would like to thank my fellow Building Engineering students for the many collaborations and making studying more fun. Many thanks to my friends and roommates, who reviewed parts of my thesis, but moreover kept me motivated and put things into perspective now and then. Lastly, I would like to thank my parents, brother and Marc, for always being available to discuss my doubts and the sometimes required confidence boost.
To the readers of this thesis; enjoy!

# Executive summary

Politicians, scientific researchers and companies all know; the transition to a Circular Economy [CE] should start now, or actually should have started yesterday. The CE is an economic system that replaces the current take-make-waste linear system and replaces this with the reduction, reuse and recovering of resources. The building industry worldwide consumes 40% of materials and energy and is responsible for 33% of the $CO_2$ emissions (Hollberg & Ruth, 2016; WRI, 2016). The challenge is to build with limited emissions, depletion and pollution of the living environment. In order to achieve this, more guidance is needed as the implementation of the CE principles requires a new approach for designing. The influential design choices in the preliminary phases should consider circularity and the environmental impact as a key design parameter. However, insight in these design parameters is currently lacking in the building industry (Potting et al., 2017; Bocken et al., 2016; Ellen MacArthur Foundation, 2017). The aim of the research is to support the usage of strategies to reduce the environmental impact. Therefore, three circular design strategies are presented that can be followed to stimulate the development of a circular building project. Specifically, the impact of three circular design strategies, Design for Adaptability [DfA], Design for Disassembly [DfD] and Design for Material Efficiency [DfME] on the environmental impact of the load-bearing structure of a building is investigated. The materials applied in the load-bearing structure are responsible for 30%-60% of the environmental impact (Westenbrugge-Bilardie & Peters, 2013). In this research a design tool is developed that makes the practitioners in the building sector aware of the environmental impact of the design choices for the load-bearing structure.

The DfA strategy focusses on extending the lifespan by allowing a shift in functioning. This means the design of the load-bearing structure is robust and can host multiple functions. The second circular design strategy DfD aims to prolong the lifespan of the structural components in a building. The load-bearing structure is designed for deconstruction which allows the released components to be reused. The last strategy DfME stimulates to efficiently design with materials with a low environmental impact to reduce the impact and required amount of resources.

Which circular design strategy is most beneficial for the project depends on the requirements and ambition of the project. This should be investigated in the preliminary phases of the design process. In this phase, the most impact can be made on the design. Therefore, the difference in environmental impact of several structural design variants caused by the design choices should be illustrated. Unfortunately, the current determination methods for the environmental impact require a lot of detailed information of the design and thus performed at the end of the design process. Once the design is final, adjustment to improve the environmental impact are too difficult. Also, these current determination methods do not include the principles of the circular designs strategies.
In order to turn this around, the following question is answered in this research;

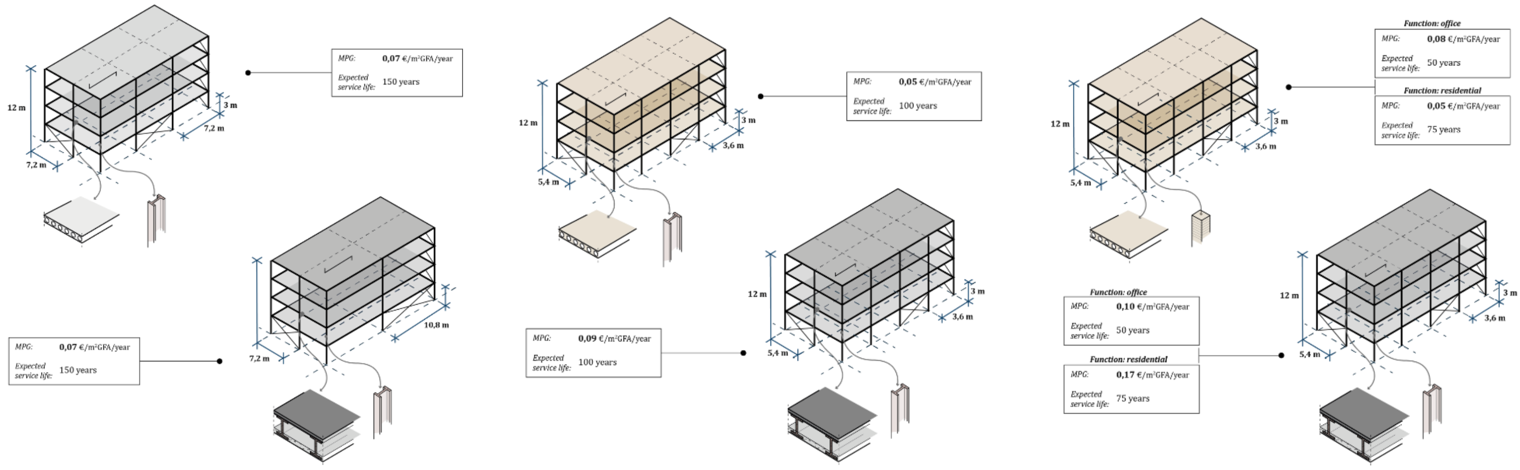
*''How can the design variant for the load-bearing structure with the most advantageous environmental impact be implemented in the preliminary design phase, considering the circular design strategies for a building?''*

To answer the main research question the following process steps are applied in this research;

- A method is developed to include the design principles of each circular design strategy affecting the design of the load-bearing structure and the environmental impact calculations. The circular design strategies lead to additional functional and related technical requirements for the load-bearing structure. By analysing the characteristics of structural building components and expert judgement of structural engineers, the structural building components are matched with the circular design strategies. This means the selected components in the developed design tool, explained in the next step, can be used to compose a structural design variant that safeguards the principles of the chosen circular design strategy.
  In addition, the circular design strategies also influence the environmental impact calculation. This calculations consists of a Life Cycle Assessment [LCA] of which the outcome is divided over the expected service life of the project. For each circular design strategy a personalised environmental impact calculation is developed, that includes the principles of the strategy.

- A step-by-step design tool is developed in Excel. This tool performs structural and environmental impact calculations based on information that is available in the preliminary design phase. The abovementioned additional requirements for the structural and environmental calculations are added to the model to safeguard the implementation of the circular design principles. The tool creates a Bill of Materials [BoM] that is used for the calculation of the environmental impact. Multiple structural design variants can be compared on their environmental impact expressed in five indicators: the MPG, the environmental performance value (in Dutch: *Milieu Prestatie Gebouwen)*, the produced amount of $CO_2$ emission, material usage, expected service life and building costs.

For each of the three circular design strategies, the design tool is used to find a structural design variant that leads to the lowest MPG. In the Dutch building sector the MPG is currently the leading means to investigate the environmental performance. In order to able to compare the results, the general geometry of a fictive case (length, width and height of the building) has been assumed the same for all strategies. The structural design variants for each circular design strategy are presented in figure 0.1.
From figure 0.1, it can be concluded that for this fictive reference project, the structural design variant of DfME with timber hollow core slab floors and timber frame and the structural design variant of DfD with timber hollow core slab floors and a steel frame both lead to the lowest MPG. Furthermore, to test and validate the design tool, two actual projects of BAM are evaluated with the tool. The first case study, Accelerator, showed that both circular design strategy DfA and DfD were interesting for the project. The most beneficial structural design variant belonged to the strategy DfA and the MPG was 42% to 56% lower compared to the other structural design variants. For the second case study, Ambachtslaan, the circular design strategy DfME led to the structural design variant with the lowest MPG. The MPG of this variant differed 20% to 50% with the other composed structural design variants. These results illustrate that the most interesting circular design strategy is different for each project.




*Design for Adaptability* *Design for Disassembly* *Design for Material Efficiency*

**Figure 0.1** Structural design variants including the MPG and expected service life (**left:** DfA, **middle:** DfD, **right:** DfME) (own figure)

The analysis of the structural design variants and the projects of BAM revealed three major impact elements in the process;

1. Firstly, the importance of exploiting the expected service life belonging to the chosen circular design strategy. In the environmental impact calculations based on the circular design strategy, the expected lifespan of the project is used to spread the environmental impact. The design tool highlights the effect of adjusting this estimated lifespan. By changing this expected service life, other structural design variants become more beneficial and lead to the lowest MPG. Including design principles that can extend the lifespan of a building can have a significant positive effect on the environmental impact. For instance a flexible load-bearing structure that allows changes in function or can be fully disassembled. Thus, the design tool stimulates the client to more carefully consider the estimation for the expected service life.

2. Secondly, the material of the chosen structural building component impacts the environmental impact due to the required quantity of the material and the environmental profile of the material. The amount of material needed for the design depends on the strength and specific weight, with concrete and steel being stronger materials than timber while timber is significantly lighter. The environmental profile of a material is based on the environmental database. In this research the Nationale Milieu Database [NMD] has been used. This database has been compared with another environmental database, NIBE.INFO. The two databases showed significant difference for the timber and concrete components. However, without the substantiation of the made assumptions of both databases, the clarification for the deviation remains uncertain. The quality and transparency of the environmental data used is influential for the outcome of the environmental calculations.

3. Lastly, the grid size defines the span in x-and y-direction of the floors and beams. The results of the design tool showed that the contribution of the floors in the total environmental impact is leading. By reducing the span of the floors, the total environmental impact decreases. Even while the number of columns and beams increases, this effect is less influential on the final outcome.

So the outcome of this research highlights three main influential aspects for the determination of the MPG; **(1)** the expected lifespan of the design assumed in the calculation method, **(2)** the quality of the environmental database of materials and **(3)** the total applied materials in the load-bearing structure. These three aspects are linked to each other. For the practitioners of the design process it is extremely important to be aware of the effect of changing the expected lifespan and thus the determination method for the environmental impact and the quality of the environmental database used.

The research shows that based on literature review, expert judgement and open databases a design tool can be built, which gives insight in the environmental impact and more design parameters to support the implementation of circular solutions in the preliminary design phase. To meet the unique project specifications different solutions are required. Therefore, the design tool supports the design process with a uniform approach.

It is recommended to enrich the design tool with more building layers and building components. In practice the tool should be evaluated on the timing in the design process and if the provided substantiation is sufficient. Science should further investigate methods and models to include the design principles of circular design strategies in the environmental impact calculations. Additionally, policy makers can use the feedback and practical knowledge collected with the tool to update current policies to stimulate the transition towards the circular building sector. This research and the developed design tool support the first steps towards the implementation of circular design solutions for the load-bearing structure as the standard.

# Content

## Part IV | Appendices

# List of figures

# List of tables

# Acronyms

**CE** Circular Economy

**LE** Lineair Economy

**BHH** Bepaling Hoeveelheden Hoofddraagconstructie

**MPG** Milieu Prestatie Gebouwen

**EPD** Environmental Product Declaration

**PCR** Product Category Rules

**LCA** Life Cycle Assessment

**NMD** Nationale Milieu Database

**BoM** Bill of Materials

**GFA** Gross Floor Area

**DfA** Design for Adaptability

**DfD** Design for Disassembly

**DfME** Design for Material Efficiency

**SBK** Stichting Bouwkwaliteit

**LCIA** Life Cycle Inventory Assessment

# Part I | Research framework

# Chapter 1

# Introduction

## 1. 1 Problem context

### 1.1.1 Transforming the construction

The current economy, which is based on exploiting non-renewable energy sources and a linear way in consuming materials, has a detrimental effect on our environment. The growing pace of urbanisation leads to increasing demand on the infrastructure and buildings, and growing consumption of products and services. This makes urban areas one of the most critical intervention points for reducing the impact on the environment. The massive usage of resources cannot be sustained any longer, and the Linear Economy [LE] should come to an end (Kubbinga et al., 2018). As the construction industry remains a key contributor to resource depletion, climate change, pollution and related problems, there is an opportunity for turning this impact around by the implementation of new principles for the construction industry (Leising, Quist & Bocken, 2017).

**Figure 1.1** Urban areas as the critical intervention points for reducing environmental impact (Haner, 2017)

**Figure 1.2** Urbanisation goes hand in hand with the growing population (Houtteman, 2020)

Since the 1950's, conceptual frameworks have been introduced to try to slow down the exhaustion of resources, such as: Regenerative Design, Performance Economy, Cradle-to-Cradle, Industrial Ecology and Bio-Based Economy (Amory, 2019;(Loppies, 2015). Many of these ideas are included in the Circular Economy [CE], a new economy model in which the use and value of raw material flows are optimised without hindering the functioning of the biosphere and the integrity of society. The aim is to protect biological and technical material stocks, avoid environmental impact and preserve existing value (Platform CB23, 2019). CE moves away from the current linear system (take, make, use, waste). It replaces it with a circular system (reduce, reuse, and recover).

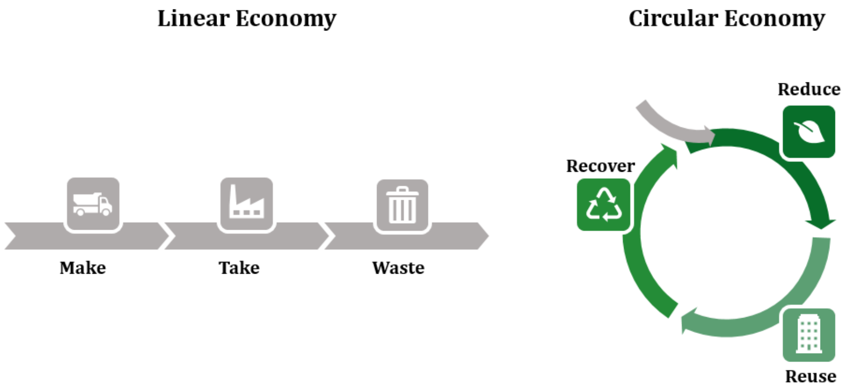



**Figure 1.3** The Linear Economy [LE] versus the Circular Economy [CE] (own figure)

The goal of the Dutch government is to achieve a Circular Economy in 2050. It is not surprising that the construction industry is one of the five industries the Dutch government lays focus on. The government states that circularity for the construction industry by smart reuse does not only mean cost reduction; there is also a demand for new products and services. New knowledge development is necessary among architects, designers, engineers, service providers, clients, implementers and producers (Rijksoverheid, 2016). Currently, urban areas often show inefficient use of resources and linear material flows (Huang & Hsu, 2003). Within this context, the construction sector has a large environmental impact, accounting for 40% of all material consumption, 33% of the CO2 emission, and around 40% of all waste (Hollberg & Ruth, 2016; WRI, 2016). In order to reduce this consumption and waste production, a logical next step would be to design with products and materials with a lower impact on the environment and keep the products and materials in use.

Within the construction sector, a division can be made between the infrastructure industry and the building industry. This research will focus on the Dutch building industry, because currently the largest impact can be achieved in this sector. Compared to the infrastructure sector in the Netherlands, the building sector is responsible for a relatively large amount of waste and has a very low recycling rate, only 3-4%. This rate is often confused with the amount of recycled materials used in the infrastructure industry, where the demolition waste of buildings is functionally used to strengthen the foundation (Rijkswaterstaat, 2015).

Circular design strategies can provide support to form a design considering two principles, a lower environmental impact and a lifetime extension of the products and materials. The early design phase of a building project is the phases with the greatest potential for influencing the design and implement the principles (Kashreen et al., 2009; Saidani et al., 2017). A tool which can help presenting the impact of circular design strategies on the reduction of material consumption and the preservation of products and materials in use could be of great benefit in steering towards circular design.

### 1.1.2 Clearing the way for a Circular Economy in the building industry

With the current rate of consumption, the world would be consuming as if there were three earths (European Commission, 2020). The concept of CE is developed to change this pattern of consumption and production that depletes our living environment. In essence, CE is an economic system that replace the end-of-life phase with reducing, reusing, recycling or recovering of materials. It is a fundamental systematic change of the current economic system. The CE concept is gaining traction by both practitioners and scholars because it is viewed as an operationalization for businesses to implement the concept of sustainable development. Due to the increasing attention and rapid development of the concept, CE has been interpreted differently among actors. Still the underlaying concepts and ideas are similar. All definitions have in common that the CE should tackle the current linear economy mindset; 'make-take-waste' (Kirchherr et al., 2017).
One of the most employed definitions for the CE, is defined by the Ellen MacArthur Foundation (2012) and will be followed in this research;

*''A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models''* (Ellen MacArthur Foundation, 2012, p. 7).

From this definition, three main principles can be extracted (Ellen MacArthur Foundation, 2012). The first principle is that a CE focusses on reducing the waste, or even aims to remove the waste of the system. This can be achieved by designing products that are optimised for reuse or dissembling. Secondly, the CE differentiates between durable and consumable aspects of products. The consumable elements are non-toxic and can be safely let in to the biosphere. Durables consists of materials that can't be returned to the biosphere such as plastic and metal. These elements should be designed for reuse. The third and last principle concentrates on the energy needed to fuel all the cycles. The energy consumption should be renewable.


**Figure 1.4** Three main principles of the Circular Economy (own figure based on Ellen MacaArthur Foundation, 2012)

Nevertheless, more guidance is needed to achieve the CE. Implementing the CE is extremely complex. Circularity is context-dependent as trying to achieve varying goals at the nano-level compared to the micro-level while being all interrelated. Adding to this, stakeholders have divergent interests of the CE leading to additional challenges within a project and the collaboration. To facilitate the transition, it is particularly important that all project stakeholders together decide on the key circularity aspects that are specific and suitable to the project (van Oppen et al., 2018).
The Dutch government-wide Circular Economy program was published in 2016 with the title 'The Netherlands will be circular in 2050'. The report actually sets two clear goals, which are currently widely recognized by government, industry, science and education; (1) 50 % less use of primary raw materials by 2030 and (2) a fully circular economy by 2050 (Rijksoverheid, 2016).

This is certainly a major challenge for the total construction industry, as an estimated 50% of raw materials are consumed in construction. In addition, the construction sector is responsible for approximately 35% of $CO_2$ emissions (Rijkswaterstaat, 2015). Moreover, a large part of all waste in the Netherlands is related to construction and demolition waste. As described in the introduction, a large part of the waste is reused in the infrastructure projects, but this is a form of downcycling (use of the material at a lesser value than the original) (Rijksoverheid, 2016). In order to turn this around, the following vision is formulated by the Dutch government for the whole construction industry;

*"By 2050, the construction industry will be organized in such a way, with respect to the design, development, operation, management, and disassembly of buildings, as to ensure the sustainable construction, use, reuse, maintenance, and dismantling of these objects. Sustainable materials will be used in the construction process, and designs will be geared to the dynamic wishes of the users. The aim is for the built-up environment to be energy-neutral by 2050, in keeping with the European agreements. Buildings will utilize ecosystem services wherever possible (natural capital, such as the water storage capacity of the sub-soil)''* (Rijksoverheid, 2016, p.61)

The challenge is to build without emissions, depletion and pollution of the living environment. This requires a new way of thinking and acting. It makes the transition to a circular construction economy not only a technical, but also a social and economic change (RVO, 2020). Transforming the building industry into a circular industry is a joint challenge, where business, government and science should work together.

### 1.1.3 The problem statement

Politicians, scientific researchers and companies have publicly agreed with the ambitions of the CE; however, implementation is often an exception rather than a rule. Besides, when circular principles are implemented, learning and validation should be captured in order to improve the principles for the future. Moreover, the assessment of the environmental impact over the life cycle of a building or a building component is commonly performed on the existing situation, yet the future buildings and innovative technologies can highly impact the circularity of the building industry (Keijzer et al., 2017). As explained the building industry has a great potential to reduce the amount of primary materials used, reduce the carbon footprint and protect material from ending up as waste. However, since CE, gained attention only limited progress has been accomplished in the building industry (Ghisellini et al., 2016; Stahel, 2016). This is partly due to technical barriers, but mostly because of cultural, organisational and market barriers. Cultural barriers, such as the lack of incentives for actors to move towards the CE are currently slowing down the circular development. These are driven by organisational and market barriers, such as lack of circular-economy legislation, limited financial stimulation to promote CE decision-making, high upfront investment costs, and a wait-and-see attitude towards circular business models (Kircherr et al., 2018; Hart et al., 2019; Adams et al., 2017).

Common understanding of the CE concept in the social and institutional dimensions among the different stakeholders in the building industry is still missing. It can be questioned whether one clear approach is suitable for such a complex transition. Circular buildings are perceived as more challenging. Certain CE principles can fit better together with certain building types, materials and components, advocating combinations of different life cycle design and construction strategies (Eberhardt et al., 2019). The problem is that the insight in the various possibilities of CE principles is lacking. Besides, there is no uniform approach to measure the impact of circular strategies. Therefore, it is susceptible to lack understanding, misinterpretation and misuse throughout the value chain.

Practitioners are reluctant to develop circular buildings, or they do not yet give priority to circularity (Kircherr et al., 2017; Kircherr et al., 2018; Hart et al., 2019). Nevertheless, more often clients define circular ambitions in their tenders, with the remark that this fits within the desired budget. Yet, the exact requirements of these circularity goals are vague and unclear. There are frameworks that help to steer the design process via general circular principles. Unfortunately, most of these frameworks are either not specified for the building industry or not concrete enough and therefore the translation of the circular strategies into practice is missing (Potting et al., 2017; Bocken et al., 2016; Ellen MacArthur Foundation, 2017).
During the tendering process it is important to gather a team of experts from different disciplines who can share knowledge and experience about circular strategies for a design. This means that the way the building sector is collaborating currently, which is mostly in a linear form, has to change into an interdisciplinary form, where knowledge is integrated and a synthesis of approaches occurs. Collaboration has been identified as a key requirement for progressing the circular economy that should be explored during all phase of the development of a building

(Adams et al., 2017). However, cooperation is only of value if it is still impactful. The possibilities of influencing project success are found to be the best during the early project stages, because decisions made together early reduce unnecessary changes during later development stages and even the total life-cycle costs (Aapaoja et al., 2013).

So, the implementation of circular design intervention should start immediately. Unveil the potential of circular design strategies by putting them into practice and validate the impact. However, the problem is that it is still unclear how to practically address this. It is of great importance to create a vision for the approach for the acceleration of the CE in the building industry. The goal of this research therefore is to develop a circular design tool for a building project which can create and compare design variants for the load-bearing structure out of circular design strategies in the early design phase. The design tool can help to substantiated the choices for structural building components and materials from a circular point of view based on the environmental impact and expected lifespan.

## 1.2 State of the Art

In this section different subjects related with the goal of this research will be shortly elaborated. A more detailed research on the analysed topics can be found in the literature study of Appendix A. Firstly, the methodology for evaluating the environmental impact is discussed. The environmental impact of a design can be expressed in the annual costs that society has to pay to prevent and repair the damage to the environment caused by the design. These environmental costs are based on two variables; (1) the Life Cycle Assessment [LCA] of the construction products and (2) the expected lifespan of the design. Then the phase during which the environmental costs should be made explicit is discussed, the preliminary design phase. Subsequently, the main circular design strategies belonging to the CE, that can possibly impact the environmental costs for a building project are shortly clarified. Lastly, a quick overview of existing tools that stimulate circular decision-making for construction products and materials is presented.

### 1.2.1 Methodology of the environmental impact

The environmental impact of a building is depended of the consumption of resources over the total lifespan. A distinction can be made in the type of resources a building consumes, either the energy or the materials used (Backx, 2020). Mostly, the environmental impact of building is dominated by the energy demand in the use phase (Heeren et al., 2015). However, the importance of the construction materials on the environmental impact will increase. Next to becoming a Circular Economy in 2050, the Dutch government strives for an Energy Neutral building sector as well (PBL, 2014). The share of the energy consumption on the environmental impact will decrease, leading to a relatively larger share of the material-related environmental impact (Heeren et al., 2015; Backx, 2020). Besides, the choice of the construction materials can also even influence the energy demand of a building, due to the physical properties, such as thermal conductivity or resistance (Heeren et al., 2015). When looking at the environmental impact of materials in more detail, it becomes clear that 30-60% of the impact is caused by the material used for the main load-bearing structure of the building design (Westenbrugge-Bilardie & Peters, 2013). For this reason, a well-considered choice for the construction materials of the load-bearing structure is important for reducing the environmental impact.

Since the implementation of the Dutch Building Regulations (Bouwbesluit) in 2012, a mandatory calculation for the material-related environmental impact should be performed for a building larger than 100 m$^2$ (Stichting Bouwkwaliteit et al., 2012). This calculation, called the Determination Method off the Environmental Performance of a Building and Civil Works, is the uniform environmental assessment method in line with the European Codes EN 15804 and EN 15978 (SBRCURnet, 2015). This determination method is also known as the environmental performance value, in Dutch; Milieu Prestatie Gebouwen [MPG]. The determination method contains rules for the calculation of the environmental performance of a complete design over the expected lifespan based on the performance of the products and elements it consists of. The outcome of the calculation is an environmental profile expressed in a price. The environmental profile consists of a number of indicators, which measure different types of effect on the environment. In section 1.2.1.1 this step of the determination method will be explained in more detail. The environmental price is also referred to as the shadow costs. The shadow costs express the costs that the society is willing to pay in order to prevent the environmental effect (de Bruyn et al., 2018). The shadow costs are expressed in euros per square meter [€/m$^2$], the lower the price the more environmental friendly the product is. The data used in order to end up with the environmental profile and shadow costs is collected in the National Environmental Database [NMD]. This database is managed by a Dutch national institute in order to ensure the quality and consistency of the environmental profiles and shadow costs.

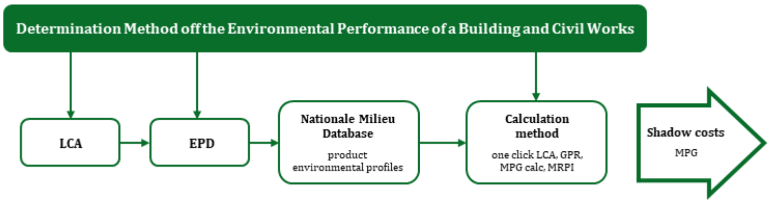



**Figure 1.5** Overview of the levels of the environmental impact calculations (own figure based on Stichting Bouwkwaliteit et al., 2012)

### 1.2.1.1 Life Cycle Assessment

The determination method is based on the environmentally oriented Life Cycle Assessment [LCA]. A LCA examines all phases in the life cycle of a product, the product and construction phase (module A), the use phase (module B), the end-of-life phase (module C) and lastly the beyond-end-of-life phase (module D). In figure 1.6 the four phases of the LCA are visible, including their sub-phases.

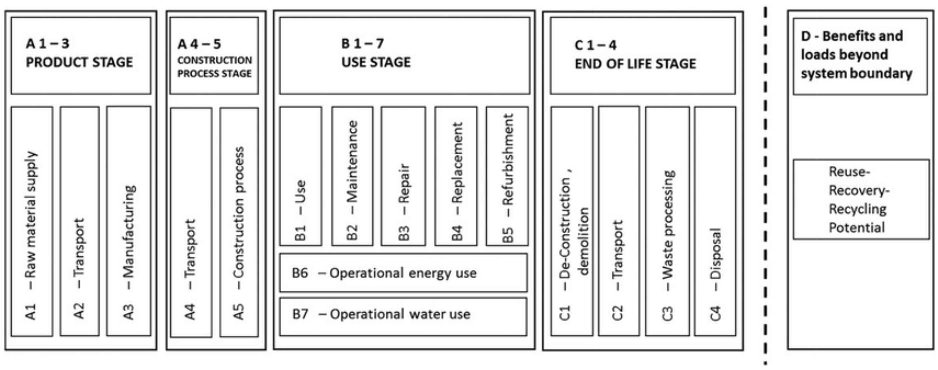



**Figure 1.6** Overview of the phases of the LCA (SBCURnet, 2015)

For each phase a set of environmental impact categories (often eleven) is analysed. The analysis creates an overview of the quantity an environmental impact indicator is produced within each life cycle phase. The result of the analysis is a product sheet of the total environmental impact of a product and is called an Environmental Product Declaration [EPD] (Backx, 2020). On this sheet the environmental impact categories are presented. These environmental impact categories are measured in equivalent units. This means the categories put various substance emissions into one group, effecting the environmental in a similar manner (Hillege, 2019; Backx, 2020). To clarify this with an example, one of the environmental impact categories

is the Ozone depletion measured in kg CFC-11-equivalent. Meaning a set of emissions that cause the destruction of the ozone layer (Hillege, 2019).
Currently, the NMD only holds the environmental impact categories related with processes in modules A (A1-A3, A4) and module C (C2-C4).

#### 1.2.1.2 Expected lifespan

The other factor influencing the environmental costs is the expected lifespan of a design. The environmental costs are calculated per square meter and can be spread over the lifespan of the building. Logically it can be stated that the longer the lifespan of the building, the lower the environmental costs. Unfortunately, this would lead to unrealistic results and cannot be accepted. In the current calculation of the Determination Method off the Environmental Performance of a Building and Civil Works the lifespan used is based on the designed function of a building (RVO, 2020). The default lifespan for residential buildings is 75 years and for office buildings 50 years (SBK, 2017).

Strikingly, despite the critical role of the lifespan in the environmental impact calculation, the effect is poorly discussed in available literature (Marsh, 2016). This is related to the complex characteristics of designing and developing a building. The building process is less standardized than industrial processes, so more assumptions are required in the environmental impact calculations. The assumptions lead to more uncertainties and will influence the credibility of the results (Blom et al., 2011; Buyle et al., 2013). Another complexity is that an individual building consists of hundreds of sperate materials, all with a different service life. The service life of a building is the period in time in which a building is in use or seen functional by its users (Rauf & Crawford, 2014). Yet, the service life of a materials is defined by the accessibility according the ISO standard 15868-1 (ISO, 2011). Materials that are inaccessible and irreplaceable, most structural materials, should intend to have the same lifespan as the service life of the building (Marsh, 2016). This gives rise to the idea of approaching a building as dynamic set of subsystems, with their own lifetime and function (Duffy, 1990; Brand, 1994). The building products should be organised based on their function and related lifespan. In this way, building products with a shorter lifespan can be removed and replaced without damaging the other layers. In the Appendix A.3.1 a more detailed explanation of this concept is discussed.

It is important to make a distinction between the lifespan of a building and the lifespan of the materials used in the building. Marsh (2016) argues that it is the lifespan of the building that becomes the determining factor in the environmental impact calculations when it is the same or less than the expected lifespan of a material. This is often the case for materials of the load-bearing structure.

Comparable with Marsh, Dias (2003) also create categories which impact the lifespan of a building. The first classification Dias (2003) makes is based on the purpose of the building: (1) monumental structures, (2) service structures and (3) sheltering structures. Materials used in monumental structures (churches and temples) are expected to have a design life of more than 300 years, while for service structures (bridges) the expected lifespan is between 100-200 years and for the sheltering structures (offices and dwellings) are rarely expected to last over 100 years (Dias, 2003). But even more factors should be included in the determination of the lifespan, such as the quality of the material, the environment in which the building is located and the quality and degree of maintenance carried out (Dias, 2003). Again, a sufficient amount of complexity. Nevertheless, the experience gained in the past can provide guidance and substantiation to express an expectation of the lifespan of structural materials (Flager, 2003). Mind that this is not directly also the lifespan of the building. The useful structural lifetime of several common materials used can be found in the table 1.1 below.

| Material description | Useful structural lifetime |
|---|---|
| Stone, brick and reinforced concrete | >75 years |
| Structural steel | 50-100 years |
| Timber | 30-300 years |

**Table 1.1** The useful structural lifetime of construction materials (Flager, 2003)

The above discussed section shows that the determination of the lifespan of a building or the separate building materials is rather complex and uncertain. Hopefully by developing the needed substantiation, in the future a more specific value can be used for the lifespan of a building instead of the default value.

### 1.2.2 Preliminary design phase

As stated in section 1.1.3 striving for a circular building project is only feasible when impact is still meaningful. By evaluating various circular design solutions in the preliminary design phase as part of the process, insight can be provided on the circular impact of these variants. In this way, the design team (i.e. architect, engineers and contractor) can play with different options and provide clarity to the client how the circular ambition can be turned into a practical design. When integration in the early design phase is not the case, implementing circular solution is often costly as most of the design already is determined. If eventually adjustments are considered, these often entail high costs. This can be represented in the ''MacLeamy Curve''. As figure 1.7 shows the design decisions that were made early in the project are more cost effective since in this stage the opportunity to influence the design is the highest and the costs for adjustments is minimal (Eberhardt et al., 2019; The American Institute of Architects, 2007). For the success of integrating circular principles is the preliminary design phase critical.

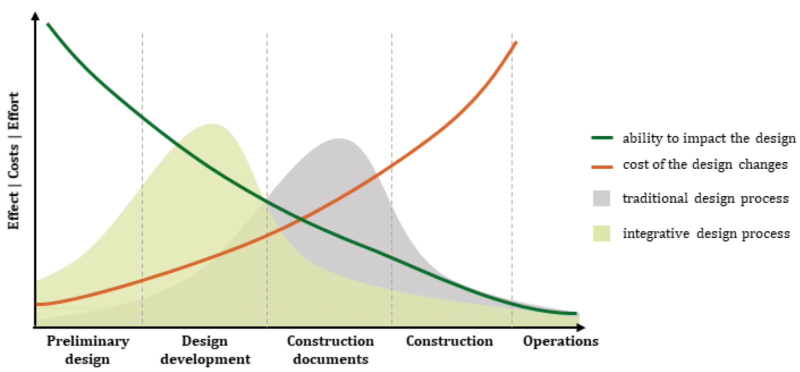



**Figure 1.7** The MacLeamy Curve (Backx, 2020)

For the design team it can be a challenge to create a good and cost-efficient design in the phase of the project where the least amount of knowledge is available. The further the project develops, the more clarity on the design problem is created (Backx, 2020).

In the preliminary phase often the structural knowledge is lacking and the choices made cannot be substantiated in argued manner. A draft version of the structural design of the project is created, including often many assumptions, which are likely to be incorrect. In the traditional design process, a structural engineer will join the design team when most of the design aspects are defined and the detailing can start. The problems identified later on in the design process are often costly and thus unfavourable. The current method for the environmental impact calculation also works in this way and is performed as a 'final assessment' instead of a mean to steer the design (Backx, 2020). In the traditional design process most environmental, social and economic cost factors have already been determined, sometimes up to 80%. The preliminary design process plays a crucial role in ensuring circularity (Eberhardt et al., 2019).

In order to include the environmental assessment in the decision-making process during the preliminary design phase, the traditional design process should shift towards the integrative design process. Meaning circular design principles can be explored and effectively implemented in a project while staying within budgetary and scheduling constraints (Busby Perkins+Will & Stantec Consulting, 2007). A multi-disciplinary and collaborative team jointly forms the design, where the diverse set of knowledge and experience of the team members is used in the decision-making (Busby Perkins+Will & Stantec Consulting, 2007).

### 1.2.3 Circular design strategies

The key-principles of the CE focus on creating an economy that decreases the resource dependencies and increase a regenerative system on all various levels. In order to make the principles more fitted for possible implementation, systemic-levels can be considered (Amory, 2019). In general, four levels for describing circularity are defined: the macro level (city, region, nation), the meso level (inter-industries), micro level (single company or consumer) and the nano level (buildings, products, components and materials) (Saidani et al, 2017). The four levels are interrelated, as the higher levels take the lower levels as the basis and the strategies defined at a higher level will influence the lower levels. Therefore, starting with the improvement in circularity at the nano level, a building, is a logical start.

In the building sector circular design can be described as: "*a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles*" (Pomponi & Moncaster, 2017, p. 711). This includes reducing the consumption of materials, optimising the useful lifetime and integrating the end-of-life phase in the design (Amory, 2019; Leising et al., 2017). Circular design is about involving all life cycle phases of a building with each a specific approach. The general principles of the CE are shortly discussed in section 1.1.2 and in the Appendix A.1 a more detailed analysis of circular frameworks and the related principles can be found. There are various circular design strategies for a building, building components and materials that can be followed. Yet, nowadays two main circular

design strategies are mentioned: Design for Adaptability [DfA] and Design for Disassembly [DfD] (Verberne, 2016).
Firstly, Design for Adaptability refers to the capacity of a design to adjust and suit new situations by being able to accommodate changing demand (Pinder et al., 2017). Designing a building that not only can host the current users, but is future proof resulting in an extension of the lifespan of a building. With this design strategy the total service life of the building can be elongated. As discussed in section 1.2.1.2 an extension of the lifespan will positively affect the environmental impact of a design. Especially, if the expected lifespan is limited based on the function of the building while the building materials can sustain a longer period. This is the case for the materials used in the load-bearing structure, as these materials are expected to be robust and therefore last long (Marsh, 2016).

The second strategy, Design for Disassembly, aims to design a building, that at the end-of-life stage is dismantlable and the released building components can be reused. In this way, valuable building components that still function can be prevented from ending up as waste and reused in other buildings (Guy & Ciarimboli, 2005). This design strategy tries to reuse the building elements as long as possible over multiple life spans (Baclx, 2020). By returning building components in their highest possible value into a new cycle, the most favourable future scenario can be achieved. The environmental impact calculations will not consider only one life cycle, but also a second cycle and even more if the building components is still suitable for reuse.

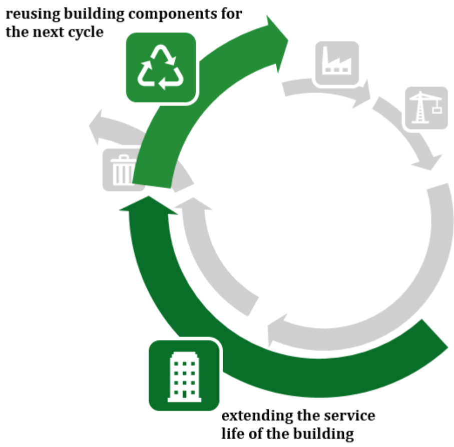



**Figure 1.8** Principle of the strategies Design for Adaptability [DfA] and Design for Disassembly [DfD] (own figure)

So, both design strategies aim to increase both resource and economic efficiency and decrease the environmental impact by extending the total lifespan of the building or the used building components (Guy, 2006). However, the exact impact of circular design strategies on the calculation method for the environmental impact is limited. Besides how circular design strategies effect the design possibilities for the load-bearing structure also remains unclear. Therefore, this research aims to include the circular design strategies in the environmental impact calculation and the structural design variants. Clarification is needed on how circular design strategies impact the choice of material components for the load-bearing structure and ultimately the effect on the environmental impact calculations. In Chapter 3 the chosen strategies for this research will be discussed in more detail. More on general circular design frameworks an strategies can be found in Appendix A.1.

## 1.3 The knowledge gap

*''A circular design tool for a building project, which both creates design variants for the load-bearing structure out of circular design strategies and compares the variants based on their environmental impact is not yet existing. Translating the circular principles into practice with the early involvement of all parties (i.e. architects, engineers and contractors) is lacking.''*

The above stated gap can be separated into two elements. Firstly, a tool that uses circular design strategies to create variants for the load-bearing structure. Various circular design strategies have arisen to serve the ambitions of the Circular Economy. Although there has been written a lot about these strategies and circularity, there is still confusion on its meaning for the building industry and implementation in actual projects. Knowledge and experience on how circular design strategies such as Design for Adaptability and Design for Disassembly affect the design of the load-bearing structure is crucial, but still unclear. Currently, calculating the environmental impact is obligatory for the development of a building. The environmental impact is calculated by performing a Life Cycle Assessment [LCA] of the given building components and estimating the expected life span of the building. The expected lifespan is based on the function of the building and a default value. The LCA methodology is made for the Linear Economy, lacking in considering the future scenarios of a building.

Secondly, the calculations for the environmental impact are made when the design is determinate. Adjustments to design to improve the environmental impact rarely occur as it is often very costly. In the preliminary design stage of a project, the design process can be stimulated by a model that evaluates structural design choices and compare the environmental impact of each design variant. These results have to be made explicit in order to create a common understanding of the impact (environmentally and economically) of the decisions for both the client and design team (i.e. architect, engineers and contractors). This is useful to support the actual implementation of circular principles in the building design during the integrative preliminary design phase.

From the aforementioned explanation of the knowledge, the following concrete point can be summed up:

- During the preliminary design phase, the environmental impact assessment of design variants for the load-bearing structure is missing.

- Lacking knowledge regarding the relation between circular design strategies and the design of the load-bearing structure of a building.

- The current calculation for the environmental impact does not consider the effect of circular design strategies principles on the Life Cycle Assessment and/or the expected lifespan.

# Chapter 2

# Research Approach

## 2.1 Research objective

The Circular Economy is currently seen as the solution to decrease the environmental impact caused by society, the Linear Economy. However, the implementation of the circular principles in the building industry is still limited. Throughout the value chain of the building industry circularity is perceived as difficult due to a lack in understanding the impact of the principles of the CE. The main objective of this research is to address and solve the aforementioned problems in section 1.1.3 and the knowledge gap in section 1.3. The goal of this research can be split in the development of a two-step tool. Generating design variants for the load-bearing structure based on a circular design strategy in the preliminary design phase is the first step of the design tool. In the second step of the tool, the user should be supported to choose the design variant with the lowest environmental impact considering the total service life of the building and its components. To sum up the above stated, the following research objective is formed:

*''Develop a design tool that can support the decision-making for the load-bearing structure conform a circular design strategy of a building based on the environmental impact during the preliminary design process.''*

## 2.2 Research questions

### 2.2.1 Main research question

The research method is based on combining the principles of circular design strategies, structural calculations and the environmental impact calculation conform the Determination Method off the Environmental Performance of a Building and Civil Works. Covering the mentioned knowledge gaps in section 1.3 form the starting point of this research. Therefore, in order to reach the research objective, the following main question should be answered:

*''How can the design variant for the load-bearing structure with the most advantageous environmental impact be implemented in the preliminary design phase, considering the circular design strategies for a building?''*

### 2.2.2 Sub-research questions

The main research question can be split into three parts. The first part of this research will focus on the influence of circular design strategies on the derivation of design variants for the load-bearing structure of a building. It should be determined which circular design strategies impact the load-bearing structure and how this effect results in actual design variants. The second part of the research examines how the environmental impact calculation including the principles of the circular design strategies can be used in the design model created with Excel. The third part of the research elaborates on how the defined relations between circular design strategies, load-bearing structure design and environmental impact calculations can be combined and become useable for the practitioners (i.e. design team) of the design process in the preliminary phases.

The main goal of this research can be split into three sub-questions;

1. **How can circular design strategies be turned into design variants for the load-bearing structure of a building?**
    - Which circular design strategies are related with the load-bearing structure of a building?
    - How are the characteristics of building components of the load-bearing structure effected by the circular design strategies?
    - How can the impact of the circular design strategies on the load-bearing structure be implemented in the model?

2. **How to assess the environmental impact of the design variants for the load-bearing structure?**
    - How can the effect of the circular design strategies on the Life Cycle Assessment included in the environmental impact calculation?
    - How can the effect of the circular design strategies on the expected lifespan included in the environmental impact calculation?
    - Which assumptions need to be made in order to be able to assess the environmental impact in preliminary design phase using an excel design tool?

3. **How can the environmental assessment be used to steer the design variants towards the most advantageous environmental impact?**
    - How can the vision of the project be matched with the circular design strategies?
    - Which information is needed of the project to form the design variants for the load-bearing structure?
    - Which insights of the environmental impact should be presented to the user of the design tool?
    - How should the user interpret the outcome of the design tool?

## 2.3 Scope

Within the master's thesis time frame, some restrictions are necessary. The aim of this research is to stimulate the implementation of circular design in the building industry. Determining the scope of the research is crucial to provide more specific knowledge in a certain domain and to indicate in which domains further research is still needed. Therefore, choices are made on the topics that are included in this research.

| Subject | Description |
|---|---|
| Building type | In this research the main building type is an utility building. The user requirements of an utility building are rapidly changing. Social developments lead to shifts in work and living preferences, requiring different type of designs to support this shift. There is no guarantee that the current designed systems will meet the future needs. Meaning every project is unique and guidance for the implementation of project specific circular principles is favourable. |
| Shape | The shape of the building is assumed rectangular. In this way only the parameters length and width influence the gross floor area. |
| Structural materials | For the design variants the main three structural materials are considered; concrete, steel and timber. For the concrete building components both prefab as in-situ concrete is included. Besides two types of mixtures for concrete are included in the design model, C30/37 and C53/65. For steel, both S235 and S355 strength types are integrated. Lastly, for the timber a separation is made between laminated softwood (GL24h, GL28h and GL30h) and sawn softwood (C24). |
| Structural design | The structural elements that can be adjusted by the users of the design tool are the floors, roof, beams, columns, walls and stability system. The design model will rule out combinations that do not fit well together (either based on material characteristics or experience in the field). Although, the foundation is often responsible for a larger amount of consumed materials, the ability to adjust the foundation type is not take into account. The design of a foundation is often highly specific to the surroundings of a project. Besides designing requires specific structural knowledge and the end-user of the design model does not necessarily have this. Additionally, the design model will be used in the preliminary design phase, meaning the design is not definite yet. Therefore, in the structural calculations assumption are required in order to create the design variants. |
| Life Cycle Analysis modules | As stated in section 1.2.1.1, the LCA consists of four modules. In this research the module B (use phase) is not considered. It is assumed that during the use phase the load-bearing structure does not cause any additional impact on the environment. Next to this, for the remaining modules the |

| | |
|---|---|
| | available data of the Nationale Milieu Database [NMD] is considered as leading. Additional sources can be the MRPI, NIBE and ABT databases for the EPD's of building components. |
| Expected lifespan | The expected lifespan can be considered from two perspectives. The first one is to design a load-bearing structure that is suitable for multiple types of usages. In this way the service life of a building in total is elongated. The second perspective is considering the lifespan of the building components of the load-bearing structure. This means extending the lifespan of the components by making them reusable. Both approaches are take into account in this research. However, this is not included in the current environmental impact calculations and assumption in this research are expected. |
| End-user of the design model | For the development of the supportive design model, having a clear idea who would be the end-user is crucial. During the preliminary design phase, the design will be constantly adjusted. The design model should be used in a quick and easy way by members of the design team. These members do not have an extensive structural knowledge. Therefore, this should be considered for which type of input can be asked to the end-users by the design model. |
| Circular design strategies | Currently, circularity is discussed more and more in literature. Thus, many types of strategies that can be followed arise. However, not all circular design strategies are applicable within the building sector and more specially on the load-bearing structure. Therefore, three different type of circular design strategies are chosen to further examine. Each of the strategies aims to focus on a specific part of the LCA. In section 1.2.3 a more detailed explanation can be found. The impact of the strategies on the environmental impact calculation can therefore be examined and compared with the each other. |

**Table 2.1** Boundaries conditions of this research

## 2.4 General approach

The objective of this research is to develop a design model that allows its users to compare various design variants for the load-bearing structure. These variants are composed conform the principles of circular design strategies and eventually evaluated on their environmental impact. In order meet the main goal of this research the following approach will be followed.

### 2.4.1 Uncovering the circular design strategies and principles impacting the load-bearing structure

Mentioned in the section 1.3 Problem Statement, the CE is a commonly discussed topic. This led to the fact that a dozen of strategies to reach the economy system emerged. Hence, two general directions in which circular design strategies can fit are defined. Subsequently the principles are of each design strategy are transformed into functional and technical requirements of the design and ended up with matching structural building product with these requirements. This is done by analysing the characteristics of each structural product and by asking expert judgement within BAM. This led to a set of structural products that fit with a certain circular design strategy.

### 2.4.2 Structural calculations

The structural calculations are necessary to create a realistic bill of material. Therefore, by using a flow diagram the sequence of calculation steps is defined and the required information is collected. The structural calculation uses a suitable load-case and defines the needed amount of material per structural product by using the rules of thumb of the Jellema and the BHH-model of IMD Raadgevend Ingenieurs (Hofkes et al., 2004; Westenbrugge-Bilbardie & Peters, 2016). Combined this resulted in a schematic structural design variant that can be assessed on the environmental impact.

### 2.4.3 Environmental impact calculations

As mentioned in section 1.2 State of the Art, the environmental impact calculation consists of two steps, defining the environmental data by means of a LCA and estimating the expected lifespan. Firstly, the effect of the chosen circular design strategies on the environmental impact calculation is derived, subsequently the effect of these strategies on the expected lifespan. The goal of this research is to support the implementation of circular design alternatives in the preliminary design phase, thus the design is still under development. So, a simplified LCA is performed including the effect of the design strategies and substantiated assumptions are made for the expected lifespan of the structural design variants.

### 2.4.4 Defining the comparing factors for the analysis of the structural design variants

The conservation between the client, architect, contractor and other parties involved in the early development of the design should be supported by the use of the developed design team. The support should be given by using the environmental impact calculations as a mean to steer direction. In the current traditional other factors are used to guide the design process, such as safety, regulations, building speed and costs. For this reason, the output of the design tool is a matrix in which in current factors and additional factors are presented. In this way the members of the design team can compare the possible structural design variants at a glance.

### 2.4.5 Design tool in Excel

As the design model is an important element of the success of this research, the following section will provide more detail on the development of the tool and the aimed functioning.

The design tool will be developed in Microsoft Excel. This program has been chosen for multiple reasons. The first reason is related with the moment of usage during the design process. The design tool should be used during the preliminary design phase. During this phase the design is continuously changed, different design options are studied and discussed with the design team. By using Excel, adjustments in the requirements, geometry or other aspects of the design can be changed in a simple and quick manner. Adding to this, Excel is a well-known program making the tool even more accessible.

Secondly, often tool in unfamiliar or scripted tools create the feeling of a 'black box' with its users. Mostly, this has to do with the fact that users cannot see or understand the reasoning behind the outcome of the tool. In Excel the users can simply use the design input and output sheets, but when more substantiation is needed, the sheets providing the data and the calculation methods can be analysed as well. Consequently, when more accurate data comes available or other assumption are necessary, the data and calculation sheets can be adjusted. The design tool should be as transparent as possible to the users.

# Part II | Research methods

# Chapter 3

# Circular design strategies

This chapter introduces the circular design strategies that are integrated in the design tool, functional and technical requirements that come along with each strategy and the effect on the possible structural products for creating the design variants.

## 3.1 Defining the circular design strategies

### 3.1.1 The hierarchy in circular design strategies

The origin of the circular design strategies can be found in the various conceptual frameworks that explain the CE. These circular frameworks are often generic but can be used as the starting point for the circular design strategies. In Appendix A.1 the circular frameworks are presented. One of the circular frameworks that is currently well-known is the 10R-model (Kircher et al., 2017). This model prioritises various circular design strategies based on their impact on reducing the consumption of resources and production of waste. Reaching a higher level of circularity means consuming less resources and producing less waste leading to a lower environmental impact (Potting et al., 2017; Kircher et al., 2017; Platform CB23, 2019).

| | | | |
|---|---|---|---|
| **Smarter product use and manufacture** | **R0** | **Refuse** | Make product redundant by abandoning its function or by offering the same function with a radically different product |
| | **R1** | **Rethink** | Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market). |
| | **R2** | **Reduce** | Increase efficiency in product manufacture or use by consuming fewer natural resources |
| **Extend lifespan of product and its parts** | **R3** | **Reuse** | Re-use by another consumer of discarded product which is still in good condition and fulfils its original function |
| | **R4** | **Repair** | Repair and maintenance of defective product so it can be used with its original function |
| | **R5** | **Refurbish** | Restore an old product and bring it up to date |
| | **R6** | **Remanufacture** | Use parts of discarded product in a new product with the same function |
| | **R7** | **Repurpose** | Use discarded products or its part in a new product with a different function |
| **Useful application of materials** | **R8** | **Recycle** | Process materials to obtain the same (high grade) or lower (low grade) quality |
| | **R9** | **Recovery** | Incineration of material with energy recovery |

**Figure 3.1** The prioritised strategies of the 10R-model (Morseletto, 2020)

In the figure 3.1 the prioritised strategies are presented. The 10R-model can be used as the basis for choosing a circular design strategy. As the stimulation of the implementation of circularity should start as soon as possible in the design process, strategies related with the design of a building are most favourable (Morseletto, 2020). The strategies R0 (refuse), R1 (rethink) and R2 (reduce) take place when products are designed and developed. Meaning these strategies can enable the implementation of circular design solutions. Additionally, Morseletto (2020) argues that these first three strategies favour all other strategies.

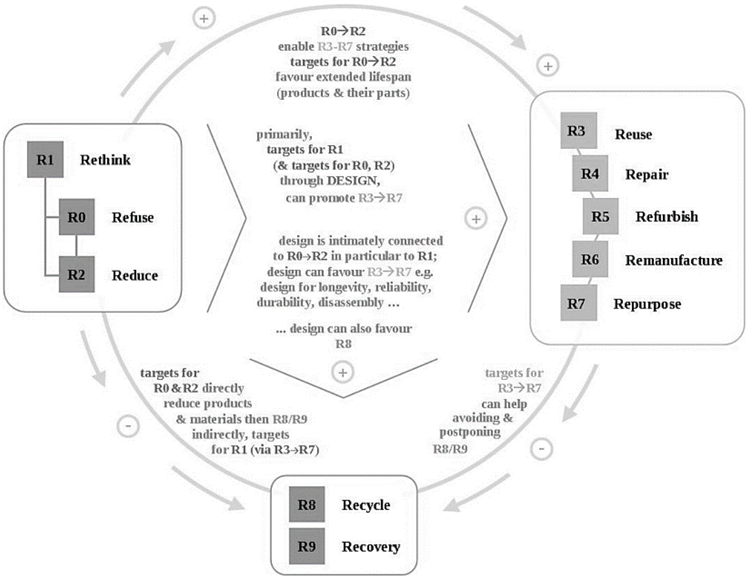



**Figure 3.2** Relation between the strategies of the 10-R model (Morseletto, 2020)

By focussing on circular design and engineering in the preliminary design phase of a building, the other strategies for the CE can be facilitated. Figure 3.2 shows that the first three strategies, R0, R1 and R2, can either promote the strategies R3-R7 by extending the lifespan of a building and its parts or enable R8-R9 by reducing the amount of materials used (Morseletto, 2020). Looking at the 10R-model, buildings can be developed smarter through an extension of lifespan or useful application of materials (Potting et al., 2017). Thus, two possible pathways can be followed in order to promote the implementation of the CE;

- *Extending the lifespan of the building and/or its components by design*
- *Efficient use of material by design*

In relation with the environmental performance of a building, both design direction can impact the determination method. An elongation of the lifespan of the total building itself, can be achieved by focussing on the use phase. Designing a building that can host multiple users and their requirements. In this manner, the flow of resources will be slowed down (Stahel, 2016; Bocken et al., 2016). Reusability extents the lifespan of the building components and therefore enables another lifecycle, closing the resource flow (Stahel, 2016). In both ways the environmental impact can be influenced and eventually reduced by the first design direction.

The second design direction influences the environmental performance by reducing the quantity of materials used and considering the environmental profile of the materials. Hereby, the flow of resources will become smaller and narrower (Stahel, 2016; Bocken et al., 2016).

In the following two sections for both design direction circular design strategies are specified. As this research focusses on the design of the load-bearing structure, the given explanation is specified on this building layer.

#### 3.1.1.1 Circular design strategies for elongating the lifespan

To achieve the optimum preservation of value through extending the lifespan, two principles characteristics of a building should be recognized. First, a building is not a static object but, can be defined as a metabolism, it is a dynamic set of subsystems (Duffy, 1990). A dynamic system is able to respond to change, so the design of a building should facilitate this dynamic behaviour. The second principles, is the realisation that a building consists of layers, each with their own lifespan (Habraken, 1961; Brand, 1994). The load-bearing structure, base building, will have a higher durability than the interior filling, the fit out. Therefore, the designed principles for the base building and the fit-out can will differ (Habraken, 1961).
For the elongation of the lifespan either the building can be considered as a whole or the building components on its own. This section will elaborate on existing circular design strategies for both ways.

As stated in section 1.2.3 and section 3.1.1 the lifespan of a total building can be extended by incorporating a certain flexibility in the design of the building. This flexibility allows changes in the building characteristics by new functional requirements of the users. This design strategy is known as Design for Adaptability [DfA]. Schmidt et al. (2010) captured the definition of adaptability after a synthesis of existing literature as follows; *'the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life'*
Furthermore, designing a durable structure refers to embedding sufficient capacity to host different users. Meaning the structure is strong enough to resist varying load scenario's and dimensions are used that can support adjustment due to a change in users (Graham, 2005). For example, the grid size of the load-bearing structure can be designed in such a way, internal walls can be easily moved around the floorplan. An adaptable building is able to easily evolve together with shifting user requirements, increasing the potential use lifecycle (Kasarda et al., 2007).

The second method to elongate the lifespan, is by securing the reusability of the building components in the design. In section 1.2.3 a design strategy that makes this possible is shortly introduced, Design for Disassembly [DfD]. Developing a design that allows deconstruction at the end-of-life stage and thus reuse of the released building components. Important factors for the success of DfD are the chosen connection type and the accessibility of the connection. The use of dry joints is desired. These types of connections such as screwed or bolted connection, can be easily assembled and disassembled, resulting in an efficient construction process. Using wet or chemical connections such as binders and glues, make it difficult to separate and reuse the building components (Guy & Ciarimboli, 2005).
Loosening building components, is not only necessary when the whole building is at the end-of-life. During the use phase, due to varying lifespan, some parts need to be replaced sooner than others (Brand, 1994). Because of this, the layers connected to the parts should be independent of each other to prevent entanglement of parts with different lifespan. The layers within the building should be organised based on either lifespan or functionality to improve the replacement of components. By making use of standardized materials and systems, the interchangeability of building components can also be stimulated (Guy & Ciarimboli, 2005).

#### 3.1.1.2 Circular design strategies for reducing the material use

The second design direction to enforce the implementation of circularity in the building sector is by reducing the material use. Throughout the lifecycles of a building a diverse set of strategies can be used in order to improve resource efficiency and reduce environmental impact (Munaro et al., 2020). At the construction and deconstruction phases, efficient building methods can be used for reducing the impacts. During the use phase, the materials must be properly maintained to preserve the value. Defining a high-quality end-of-life purpose for the released materials, reduces the inflow of new materials. However, as Morseletto (2020) argues, the implementation starts with the design. The selection of materials during the project initiative and preliminary design phase should be based on the materials' environmental impacts and efficient design. Therefore, this circular design strategy can be called Design for Material Efficiency [DfME]. Design variants following this strategy aim to reduce the amount of materials needed and the use materials that have less impact on the environment (Cordella et al., 2020).

### 3.1.2 Conclusions

Although the three design strategies, Design for Adaptability [DfA], Design for Disassembly [DfD] and Design for Material Efficiency [DfME] aim on varying aspects of circularity, the interfaces are inevitable. This can sometimes cause confusion during the design process, because the three different strategies can end up with similar design solutions. Yet it is also advantageous that the strategies can be combined. By extending the lifespan of a building, the consumption of new materials is postponed or even prevented. Similarly, by designing parts releasably, the environmental impact can be reduced due to the usage of the released secondary materials in a second cycle. In addition, disassembling and replacing building layers makes it easier to extend the lifespan and the meet the changing demands by future users. So, the strategies DfA, DfD and DfME can go hand in hand.

To conclude, during the preliminary design process it is meaningful to showcase the aim of the three design strategies separately to the involved parties, but also to underline the potential of combining design strategies.

## 3.2 The functional and technical requirements of the circular design strategies

### 3.2.1 From a circular design strategy to functional requirements and technical requirements

Three circular design strategies have been introduced in the previous sections in order to stimulate the implementation of a CE in the building sector. The goal of this research is to develop a design model that will improve the environmental performance of the load-bearing structure. In the preliminary design phase, the circular design strategies can provide guidance in order to stimulate decisions with a lower environmental impact. Nevertheless, each strategy can still lead to multiple design variants, which is complex to cover in once in the design model. Therefore, as a starting point for the development of the design model, for each circular design strategy functional requirements are defined. These functional requirements influence different aspects of the design, such as the layout of the geometry or the functioning of the building. This makes each strategy more specific as certain design variables are limited. Subsequently, the functional requirements have influence on the technical requirements of the design. When both the functional and corresponding technical requirements are defined for a circular design strategy, it can be substantiated why a specific structural design variants suits the chosen strategy. This solves one of the sub-challenges of this research, defining the impact of the circular design strategies on the load-bearing structure of a building.

Per design strategy the functional requirements are shortly mentioned. The additional functional requirements are based on the principles of each circular design strategy. Often these principles are rather general, as the scope of this research is the load-bearing structure, the principles are transformed into functional requirements for a design variant that can influence the load-bearing structure. So, it is not ruled out that in addition to the functional requirements mentioned below, more requirements belong to a design strategy.

#### 3.2.1.1 Design for Adaptability

<u>Design a building that can host multiple functions</u>

An adaptable building should be able to allow multiple type of users, meaning different functions (Kasarda et al., 2007). So, the load-bearing structure of the building, should suit a change in the building type. The shift in the building type leads also to a shift in technical requirements. The following technical requirements of the load-bearing structure are impacted:

- *Load-case*; the variable load that should be incorporated in the calculations for the design relates with the function of the building. Based on the function the variable load can differ from 1,75 kN/m$^2$ for a residential building until 5,00 kN/m$^2$ for a conference building (Westenbrugge-Bilardie & Peters, 2013).

- *Fire safety*; the fire resistance of the load-bearing structure is depending on the function and total height of the building. As the function will change, the fire safety requirements can change. The design model will be developed firstly for simple structures. Therefore, the assumed fire safety is 90 minutes. As the requirement is similar for residential and all other functions with a height of maximum 13 meters, this is included in the structural calculation.

- *Acoustics;* designing a building that should allow multiple functions during its lifespan, the number of requirements will increase. The strictest requirements will turn into the norm. In this design tool the functions can differ between office, retail, residential and more so one of these will define the requirements. For a separating floor in a residential building, the characteristic air-sound level difference must be greater than 52 dB(A). The contact noise level, directly measured below the floor, must not exceed 59 dB(A). The values for these requirements are stated in the NEN5077 standard

- *Floor to ceiling height*; the use of greater ceiling heights will provide more flexibility in the routing of services. The regulation of the indoor climate is based on the function and therefore impacted when changing this (Dodd et al., 2020). To allow adaptability, the floor to ceiling height should have a minimum of 3 meters.

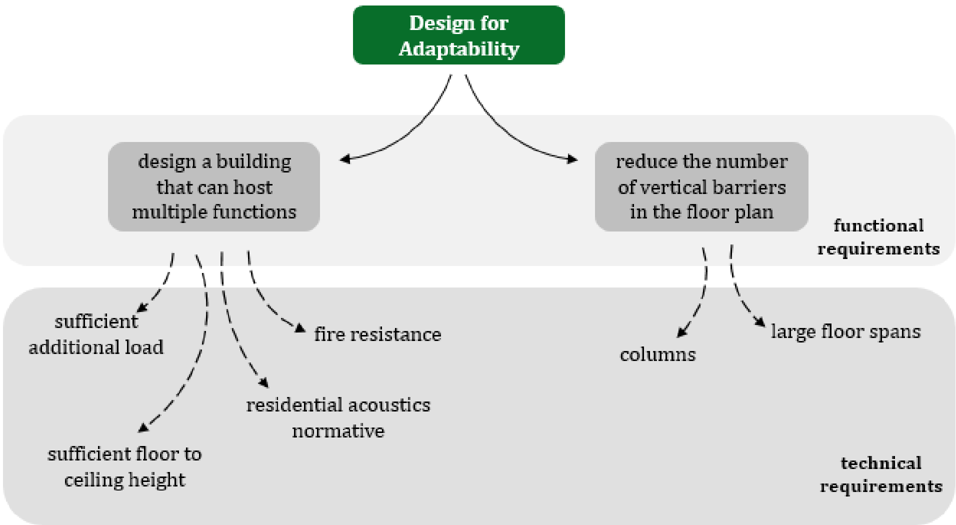



**Figure 3.3** Functional and technical requirements of circular design strategy DfA (own figure)

<u>Reduce the number of vertical barriers in the floor plan</u>
The second functional requirement is creating flexibility in the distribution of space. This means creating a floorplan where room sizes can easily change. Therefore, the interior walls should be moved around.  This means, the number of vertical barriers of the load-bearing structure, which cannot be moved, should be limited. This leads to the following technical requirements:

- *Floor span;* a wider span will allow for more flexibility the layout of the floorplan (Dodd et al., 2020). In general it can be stated the more obstacles, the less flexibility in the layout. Therefore, the floor span should be at least 7 meters and favourable even more.

- *Vertical load-bearing elements;* in line with the argument state above, choosing columns over walls as the vertical load-bearing elements will increase the flexibility in rearranging the floorplan.

In figure 3.3 an overview of the two functional requirements with the related technical requirements is presented.

**3.2.1.2 Design for Disassembly**

Use structural components that allow deconstruction
At the end-of-life stage the design allows the building to be dismantlable and the released building components can be reused (Guy & Ciarimboli, 2005). To allow this the following technical requirements are needed:

- *Bolted/screwed connections;* dry connections are key for making deconstruction possible.

- *Prefabricated components;* prefabricated components simplify the work on-site during construction and deconstruction. Adding to this, prefabricated components often have standard dimensions, which makes the reusability even more interesting (Guy & Ciarimboli, 2005).

Reduce the number of different types of structural components
The designed load-bearing structure should consider the process of constructing and deconstruction to become feasible. Therefore, reducing the different types of components used decrease the complexity. This can make the construction process more efficient and less sensitive for mistakes on-site (Guy & Ciarimboli, 2005). So the related technical requirements:

- *Minimize the varying types of components;* the same components for floor and roof system should be chosen.

- *Components that are manageable on site*; as the construction process will change due to the deconstruction requirements, components should be manageable on site. Therefore the frame system is more advantageous, meaning beams and columns instead of load-bearing walls.

The structural layer of the building should not be integrated with other building layers
Different types materials can be used, each with specific maintenance requirements and expected lifespan. In order to retain a construction component at the highest possible value, a building component should be detachable without the inclusion of other materials (Guy & Ciarimboli, 2005). Therefore the next technical requirements should be covered:

- *Create accessible connections*; without being able to reach a connection, dismantlement of the construction cannot occur (Van Vliet, 2018). Accessibility to connections refers to physically being able to access the connections between products without demolishing (parts) of the product (Durmisevic & Brouwer, 2006).

- *Separate building layers*; if a component is functional obsolete, it is possible to dismantle the component without damaging other components (Verberne, 2016). Therefore, the building layers based on the principles Brand (1994) explained in section 3.1.1.1, should remain separate.

Figure 3.4 illustrates an overview of the functional requirements and the interconnected technical requirements.

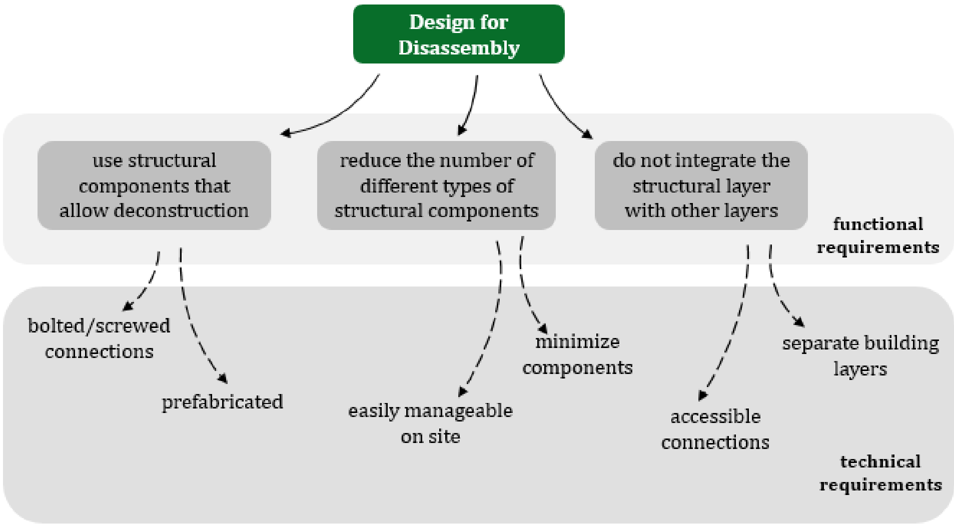



**Figure 3.4** Functional and technical requirements of circular design strategy DfD (own figure)

### 3.2.1.3 Design for Material Efficiency

<u>Optimise the design for one function</u>
To efficiently use materials, the design should be composed for one single function. Meaning the structural building components are efficiently used with a clear purpose. This will stimulate the optimisation of the load-bearing structure and the total materials needed can be reduced. The technical requirements that cover this optimisation are:

- *Minimize the materials*; by minimizing the needed components in the structural design, fewer materials are applied. For instance, the usage of columns of walls is favoured by this technical requirement.

- *Components with a relatively low self-weight compared with the possible span*; the use of structural building components that apply material on the positions needed in the structure, can reduce the total material usage. Especially, floor systems that allow larger spans, leading to a reduction of the needed vertical elements. Nevertheless, increasing the span also enlarges the thickness of a component.

Choose materials with an environmentally friendly profile

The second functional requirement is to only consider material with an environmentally friendly profile. This requirement emphasizes on the combination of both components that causes less pollution and reduce the depletion of resources. The subsequent technical requirements are in line with this functional requirement;

- *Apply light weighted materials;* the environmental impact is calculated by using the weight of materials. Therefore, materials with a light self-weight can reduce the environmental impact.

- *Prefabricated components;* the materials loss of prefabricated components can be minimised by optimised productions methods in a controlled environment.

- *Materials with low shadow costs;* the shadow costs are used to measure the created impact on the environment. Components with low shadow costs are therefore more suitable for this circular design strategy.

The functional and technical requirements are presented in figure 3.5.

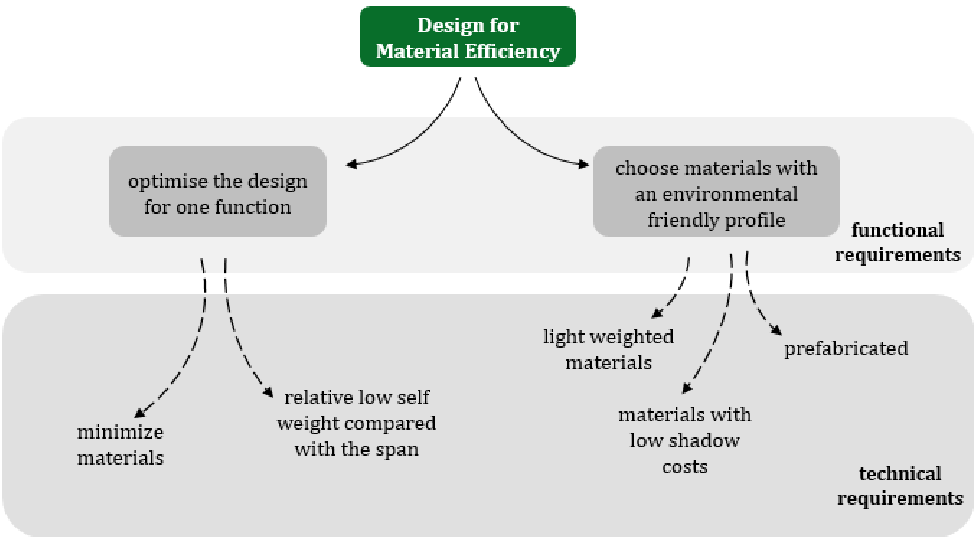



**Figure 3.5** Functional and technical requirements of circular design strategy DfME (own figure)

## 3.3 Matching structural building components with the technical requirements of the circular design strategies

As already referred, the created functional and technical requirements of the circular design strategies should be harmonised with the design options for the load-bearing structure. This will in the end lead to enhanced design considering the circular design principles aiming on a lower pressure on the environment and reduce the use of resources. In order to include the requirements of each circular design strategy into the design variants for the load-bearing structure, the following challenge should be solved. Which of the structural building components, included in this research, match with the technical requirements of the circular design strategies defined. To determine this, an overview is created of the structural building components categorised on their function and material type (i.e. floors, roofs, beams, columns, walls and stability system and concrete, steel and timber). For each component it is indicated whether the requirements are met based on the component's characteristics such as the acoustics resistance, fire safety, production method, possible span length, self-weight and connections. Additionally, expert knowledge of structural engineers within BAM is used to validate and substantiate the created distribution of structural building components per circular design strategy.

### 3.3.1 Classify the structural building components based on their characteristics

The properties of the structural building components examined are material type, service life, acoustics, fire safety, span range, production method and connection possibilities. Some of these properties of a structural component can variate and thus very dependent on the specific application. For instance, consider the fire resistance of a steel column. Various aspects in the design (cladding of the column, steel strength, column type, positioning on the floorplan and more) affect the actual fire resistance. This example illustrates that there are cases where it is difficult to describe one of the properties specifically for a structural building component. In these situations, the generic material properties of either concrete, steel or timber can be assumed. These properties are classified in an ordered relationship by applying an ordinal scale. A three-pointed scale (*poor, fair, good*) is used to rank and order the performance of the materials (Dalati, 2018). The outcome of the classification of the structural building components is presented in table 3.1.

| Structural building components | Properties structural components | | | | | |
|---|---|---|---|---|---|---|
| | *Relative weight [kg/m²]* | *Acoustics [dB]* | *Fire safety [minutes]* | *Span (general) [meter]* | *Production* | *Dry connection* |
| *Ground floor floors* | | | | | | |
| Concrete hollow core | fair | NA | NA | 7,5-17,0 | prefab | NA |
| In-situ concrete floor | poor | NA | NA | 5,0-10,0 | on-site | NA |
| Concrete wide slab | poor | NA | NA | 4,5-9,5 | comb. | NA |
| Combination floor | poor | NA | NA | <6,3 | comb. | NA |
| Ribbed floor | fair | NA | NA | <7,2 | prefab | NA |
| *Storey floors* | | | | | | |
| Concrete hollow core | fair | good | 60-120 | 7,5-17,0 | prefab | fair |
| In-situ concrete floor | poor | good | 60-120 | 5,0-10,0 | on-site | poor |
| Concrete wide slab | poor | good | 60-90 | 4,5-9,5 | comb. | poor |
| Timber hollow core | good | poor | 60-90 | 5,0-10,0 | prefab | good |
| Timber beamed floor | good | poor | 60-90 | 4,0-8,0 | prefab | good |
| Prefab shell with I-beam | fair | fair | 60-120 | 5,5-11,0 | prefab | good |
| *Beams* | | | | | | |
| Prefab concrete beam | poor | NA | good | 5,0-10,0 | prefab | poor |
| In-situ concrete beam | poor | NA | good | 5,0-7,0 | on-site | poor |
| Steel beam | good | NA | poor | 5,0-16,0 | prefab | good |
| Timber beam | good | NA | fair | 3,0-8,0 | prefab | good |
| *Columns* | | | | | | |
| Prefab concrete column | poor | NA | good | NA | prefab | poor |
| In-situ concrete column | poor | NA | good | NA | on-site | poor |
| Steel column | good | NA | poor | NA | prefab | good |
| Timber column | good | NA | fair | NA | prefab | good |
| *Walls* | | | | | | |
| Prefab concrete wall | poor | good | good | NA | prefab | poor |
| In-situ concrete wall | poor | good | good | NA | on-site | poor |
| Timber wall | good | poor | fair | NA | prefab | fair |
| *Stability* | | | | | | |
| Prefab concrete core | poor | good | good | NA | prefab | poor |
| In-situ concrete core | poor | good | good | NA | on-site | poor |
| Steel braces | good | poor | poor | NA | prefab | good |
| *Stability wall (see walls)* | | | | | | |

**Table 3.1** Classification of the structural building components based on their characteristics

### 3.3.2 Classify the structural building components based on expert judgement

The second method used to investigate how the structural building components should be distributed over the circular design strategies is by judgement of structural engineers that have an ambition with sustainable engineering. The expert knowledge and substantiation of the choices for structural building components is used to end up with a list of components matching the requirements of the circular design strategies.

In order to receive the substantiation of the design choices for the load-bearing structure, the structural engineers filled in a questionnaire individually. In the questionnaire three hypothetical design scenarios were created, one scenario for each circular design strategy. For each scenario the same general design was proposed, a simple rectangular building, 21 meters long and 12 meters wide, with 3 storeys. The primary function is an office building, but in the case multiple functions are favoured, the strategy Design for Adaptability, also a retail and residential function should be considered.

Based on the functional and technical requirements of the circular design strategies, the structural engineer was asked to compose two load-bearing structures. The list of options for structural building components contained all the components included in this research. The structural engineer could choose any structural building component from the list. After making a choice, the substantiation was requested. On the one hand, this led to a critical reflection by the structural engineer for each specific decision and on the other hand insight was received which characteristics or other factors were considered by the engineer. In the table 3.2 below, the results of the questionnaire are presented.

| Type | Component | Material | Chosen | Explanation |
|---|---|---|---|---|
| | | **Design for Adaptability** | | |
| Ground floor | | | | |
| | Hollow core slab floor | Concrete | 4 | Often applied system |
| | In-situ floor | Concrete | 2 | More design freedom |
| Storey floors | | | | |
| | Wide slab floor | Concrete | 2 | Sufficient amount of mass<br>High load-bearing capacity |
| | Slimline floor | Concrete | 2 | Accessibility of the ducts when changing function |
| | Hollow core slab floor | Concrete | 2 | Large spans<br>Efficient use of materials by pre-tensioning |
| Roof | | | | |
| | Wide slab floor | Concrete | 2 | *See storey floors* |
| | Slimline floor | Hybrid | 1 | Similar system as storey floor for vertical expansion |
| | Hollow core slab floor | Concrete | 3 | |

| | | | | |
|---|---|---|---|---|
| Beams | | | | |
| | Beams | Concrete | 3 | Durability<br>Fire resistance |
| | Beams | Steel | 3 | Combination with floor systems<br>Large spans |
| Columns/walls | | | | |
| | Columns | Concrete | 3 | Robust<br>Fire resistance |
| | Columns | Steel | 3 | Additional caution for fire safety required |
| Stability | | | | |
| | Core | Concrete | 1 | One main location for vertical transport |
| | Wind braces | Steel | 5 | Flexibility in the whole floorplan |
| **Design for Disassembly** | | | | |
| Ground floor | | | | |
| | Hollow core slab floor | Concrete | 6 | Prefabricated |
| Storey floors | | | | |
| | Hollow core slab floor | Timber | 3 | Dry connections<br>Prefabricated |
| | Hollow core slab floor | Concrete | 2 | Prefabricated<br>Often applied system |
| | Slimline | Hybrid | 1 | Dry connections<br>Prefabricated |
| Roof | | | | |
| | Hollow core slab floor | Timber | 1 | *See storey floor* |
| | Hollow core slab floor | Concrete | 2 | |
| | Slimline | Hybrid | 1 | |
| | Beamed floor | Timber | 2 | Light weighted material<br>Manageable on site |
| Beams | | | | |
| | Beams | Timber | 1 | Dry connections<br>Combination with timber floor systems |
| | Beams | Steel | 5 | Dry connections<br>Often applied system |
| Columns/walls | | | | |
| | Columns | Timber | 1 | Dry connections<br>Combination with beams |
| | Columns | Steel | 5 | Dry connections<br>Combination with beams |
| Stability | | | | |
| | Wind braces | Steel | 6 | Dry connections |

| Design for Material Efficiency | | | | |
|---|---|---|---|---|
| Ground floor | | | | |
| | Hollow core slab floor | Concrete | 5 | Efficient use of materials by pre-tensioning |
| | In-situ floor | Concrete | 1 | Ability to combine with the foundation |
| Storey floors | | | | |
| | Hollow core slab floor | Concrete | 3 | Efficient use of materials by pre-tensioning<br>Large spans |
| | Hollow core slab floor | Timber | 2 | Low self-weight |
| | Slimline floor | Hybrid | 1 | Qualities of concrete and steel combined in one |
| | Beamed floor | Timber | 1 | Low self-weight |
| Roof | | | | |
| | Hollow core slab floor | Concrete | 3 | *See storey floor* |
| | Hollow core slab floor | Timber | 2 | |
| | Slimline floor | Hybrid | 1 | |
| | Beamed floor | Timber | 1 | |
| Beams | | | | |
| | Beam | Timber | 1 | Light weighted material<br>Availability of various sizes |
| | Beam | Steel | 5 | Efficient large spans |
| Columns/walls | | | | |
| | Columns | Timber | 1 | Combination with timber beams |
| | Columns | Steel | 5 | Combination with steel beams<br>Additional caution for fire safety required |
| Stability | | | | |
| | Wind braces | Steel | 4 | Combination with frame system (beams and columns)<br>Limiting material use |
| | Core | Concrete | 2 | Stability covered in once totally covered |

**Table 3.2** Design choices of the structural engineers and the substantiation

Two aspect of the result presented in the table 3.2 stand out. In the first place, a clear resemblance can be seen in the decision-making for either columns or walls by the structural engineers. In all cases, the usage of column system was preferred over the usage of structural wall system. This can be related with the fact that the properties of a column system can be advantageous for each circular design strategy. For instance, columns allow more flexibility in the arrangement of the floorplan, so matching the strategy DfA or include fewer and less complicated joints and suit DfD. The opposite is the situation for the floor systems, here the engineers show more differences. Also, there are more options to choose from, so deviation is more likely. Especially, in the case of the strategy DfME the different points of view of the engineers become clear. It can indeed be argued that concrete hollow core slab floors are material efficient, as more material is applied on places where higher stresses occur. Even more, large spans are possible leading to the reduction of needed vertical elements. However, other engineers argue that the environmental profile of concrete does not suit the strategy DfME.

The grid size of the design also has impact on the chosen structural building components, so additionally in Appendix C.3, more detailed of the created structural design variants by the engineers can be found.

### 3.3.3 Conclusions

The structural building components are investigated on their match with the requirements of the circular design strategies. This is done by matching the specific properties of the components and the judgement of structural engineers interested in sustainable constructions. The results of both analyses represented in the table 3.3. A structural building component is included in the options of a circular design strategy when both the properties of the materials and the choices of the structural engineers' match.

| | Circular design strategies | | |
|---|---|---|---|
| Structural building components | *Design for Adaptability* | *Design for Disassembly* | *Design for Material Efficiency* |
| *Ground floor floors* | | | |
| Concrete hollow core | x | x | x |
| In-situ concrete floor | x | | |
| Concrete wide slab | | | |
| Combination floor | | | |
| Ribbed floor | | x | x |
| *Storey floors* | | | |
| Concrete hollow core | x | x | x |
| In-situ concrete floor | x | | |
| Concrete wide slab | x | | |
| Timber hollow core | | x | x |
| Timber beamed floor | | x *(roof only)* | x *(roof only)* |
| Prefab shell with I-beam | x | x | x |
| *Beams* | | | |
| Prefab concrete beam | x | | |
| In-situ concrete beam | | | |
| Steel beam | x | x | x |
| Timber beam | | x | x |
| *Columns* | | | |
| Prefab concrete column | x | | |
| In-situ concrete column | | | |
| Steel column | x | x | x |
| Timber column | | x | x |
| *Walls* | | | |
| Prefab concrete wall | | | |
| In-situ concrete wall | | | |
| Timber wall | | | |
| *Stability* | | | |
| Prefab concrete core | x | | |
| In-situ concrete core | x | | |
| Steel braces | x | x | x |
| *Stability wall (see walls)* | | | |

**Table 3.3** Structural building components assigned to the circular design strategies in case of matching requirements and properties

# Chapter 4

# Structural calculations

This chapter elaborates on the structural calculation methods and rules used in order to create structural design variants with the correct strength, stability and size. Assumptions, input for the calculations, material properties, structural principles and output of the calculations are discussed.

## 4.1 Boundary conditions and general input

The structural calculations will lead to a Bill of Materials [BoM]. This gives a representative overview of the quantity of each material used in the design, which is needed to proceed with the environmental impact calculations. The first step is to define the boundary conditions of the structural calculation implemented in the design tool, subsequently the general properties of the design that are necessary to start the calculations.

### 4.1.1 Boundary conditions of the structural calculations

By using general design guidelines, supplier information and rules of thumb the quantity of materials can be defined. The rules of thumb are mostly retrieved from Jellema (Hofkes et al., 2004) and the BHH-model (Westenbrugge-Bilbardie & Peters, 2016). The structural calculations are applicable on the common building typology in the Netherlands. Meaning standardised structures that include certain repetition. The structural building components included in the calculations are well-known in the construction industry, so innovative floor system that just entered the market are not included. Ultimately, the tool should be updated with innovations based on the feedback of the users and building industry.
As the design tool will be used during the preliminary design phase, the created structural design variants are rough and deviate from an optimised and engineered design. The created structural design variants should be used as a comparison and a mean to get a feeling about material quantities. The material quantities are expressed in the functional unit of the design tool, kg/m$^2$ GFA. The Gross Floor Area [GFA] is the sum of floor areas that can be functionally used.

### 4.1.2 General input

To start the structural calculations general properties of the design are needed. The specific entered data is used to perform the calculations. This section will shortly introduce the variables that are defined as the input for the structural calculation.

#### 4.1.2.1 Function

The building function are retrieved from the Dutch Building Regulations (Bouwbesluit, 2012). In this document each function is related with certain characteristics that impact the structural calculation; the variable load, fire safety, acoustics and floor the ceiling height. This means that based on these characteristics and the requirements of the circular design strategies certain structural building components are suitable. The building functions included in the design model are presented in the table 4.2 below. Specific requirements for the fire safety, acoustics and floor to ceiling height per function can be found in Appendix B.5.

| Function | Variable load |
|---|---|
| Residential | 1,75 kN/m$^2$ |
| Office | 2,50 kN/m$^2$ |
| Retail | 4,00 kN/m$^2$ |
| Sports | 5,00 kN/m$^2$ |
| Education | 3,00 kN/m$^2$ |
| Conference | 5,00 kN/m$^2$ |
| Industry | 5,00 kN/m$^2$ |
| Healthcare | 3,00 kN/m$^2$ |

**Table 4.1** Functions integrated in the design tool including the variable load

#### 4.1.2.2 Building size

The geometry of the building depends on the wishes of the client and design team. The building size leads to the Gross Floor Area [GFA] and this is depending on the length, width and height of the building and the number of storeys. An important note for the filling the number of storeys, is that the ground floor is not included as a storey. So, to illustrate a building with three storeys is build up as follows; the ground floor, first floor, second floor, third floor and roof. The number of storeys influence the amount of load that the load-bearing structure should transfer. Subsequently, the amount of grid lines should be entered as input. This is an important variable as this will define the span of the floor systems and therefore in the end the quantity of material needed.

| Variable | Unit | Action of the user |
|---|---|---|
| Length of the building (x-direction) | m | Input required |
| Width of the building (y-direction) | m | Input required |
| Number of storeys | - | Input required |
| Storey height | m | Input required |
| Number of grid lines (x-direction) | - | Input required |
| Number of grid lines (y-direction) | - | Input required |
| Height of the building (z-direction) | m | Automatically calculated |
| Gross Floor Area | m$^2$ | Automatically calculated |

**Table 4.2** Input parameters for the design tool

### 4.1.3 Assumptions

As most general building characteristics are depending on the function, these are automatically included in the structural calculations. Yet, to decrease the complexity of the calculation assumptions are needed.
The fire safety of a building is linked with the building height and function. Stated in the boundary conditions in section 4.1.1 the design tool focusses on common structures. Therefore a fire resistance of 90 minutes has been assumed as governing for this moment. The situation of a residential building up to 13 meters and other functionals higher than 13 meters are covered in this way.
Furthermore, the Dutch Building Regulation defines the consequence class of a construction, in this research the class CC2 has been assumed.
The function of the building leads to the variable load. Besides this load type multiple other loads should be included in the structural calculations such as the self-weight of the chosen structure and additional loads as internal walls, ducts and ceilings. The self-weight of the design depends mostly on the floor system chosen. Therefore, this load is generated when a floor system is chosen.
Lastly, for two variables of the input for the structural design variants, an extra simplification is necessary. This applied both on the chosen grid size by the amount of grid lines and the load-case. First the gird size. As mentioned before, the grid size defines the span of the floor system. The design tool will make use of simplified calculations based on Jellema (Hofkes et al., 2004) and the BHH-model (Westenbrugge-Bilbardie & Peters, 2016). Therefore, the preferred grid size based on the input of the user, is rounded to one of the chosen standard grid sizes. This approach is used in a similar way for the load-cases. By combining the different possibilities of the variable loads and permanent loads calculation values can be determined. The table 4.3 present the assumed grid sizes and the possible load-cases.

| Variable | Unit | Determinate standard situations |
|---|---|---|
| Grid size ground floor | m | 5,4 m – 7,2 m |
| Grid size storey floor | m | 3,6 m – 5,4 m – 7,2 m – 10,8 m – 12,6 m – 16 m |
| Load cases | kN/m$^2$ | 5 kN/m$^2$ – 10 kN/m$^2$ – 15 kN/m$^2$ - 20 kN/m$^2$ |

**Table 4.3** Standard grid size and load cases possibilities of the design tool

## 4.2 Structural calculation of the components

The structural design variant should be modelled step by step as certain design choices can influence the possibilities for the following structural component. This section will introduce the order of designing and which structural building components are integrated in the design tool.

### 4.2.1 Characteristics and relationships of the structural building components

Creating a structural design variant consist out of two steps. Firstly, define which structural building components should be included. Secondly, perform the structural calculation to define the thickness, weight and other characteristics of the components.

After the general input of the design is defined, the composition of the load-bearing structure can start. Indicated in section 4.1.3 the actual loads to calculate the structure are dependent of the chosen floor system. Therefore, the logical first step is to choose a floor system. A distinction is made between the ground floor floor systems, the storey floor systems and the roof. So, after the determination the ground floor, storey floor and roof the required beams to transfer the loads from the floors towards the vertical load-bearing elements can be defined. The beams are influenced by the span direction of the floors, as the primary beams should span in the opposite direction. The third step is creating the vertical load-bearing system. Two alternatives are possible, using columns or walls. In direct relation with the design choice is the stability system of the load-bearing structure. Aiming for a structure with columns other stability requirements occur than choosing load-bearing walls. All the loads are transferred to the foundation, and therefore this is the last step when designing the load-bearing structure.

#### 4.2.1.1 Floors and roof

Based on the BHH-model the four most applied ground floor floor systems are integrated in the design tool; *the combination floor, the ribbed floor, the hollow core slab floor* and *the in-situ concrete floor* (Westenbrugge-Bilbardie & Peters, 2016) . All ground floor floor systems are made out of concrete. The span of the floor is rounded to either 5,4 m or 7,2 m, explained in section 4.1.3. On the basis of the matched span and applied load the thickness and weight of the ground floor floor system can be calculated.

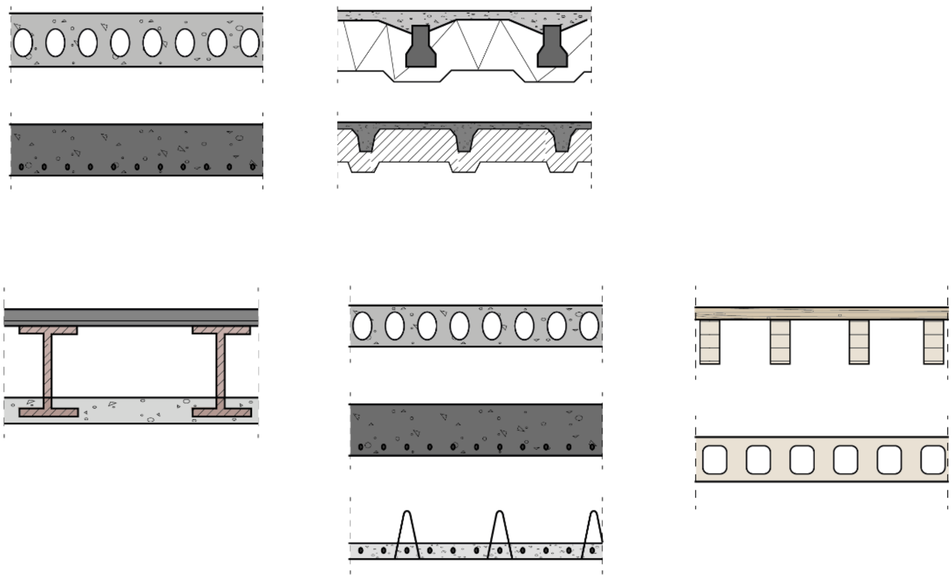


**Figure 4.1** Floor systems integrated in the design tool (own figure)

For both the storey floor system and roof similar structural products can be chosen from the following list; *concrete hollow core slab floor, in-situ concrete floor, concrete wide slab floor, timber hollow core slab floor, timber beamed floor* and *the slimline floor* (hybrid floor with steel trusses and prefab concrete slabs). This list of floor systems includes products with different materialisation and products that are common in the building industry. If a floor system is selected, based on the span and load the material quantities can be calculated. However, not all floor systems are applicable or economical for all spans. Therefore, the design tool will provide feedback to the users when a certain floor type is not suitable. The suggestion is given to change the floor system or the size of the span.

#### 4.2.1.2 Beams

Beams support the floor system and transfer the loads towards the vertical load-bearing elements, columns or walls. In this research secondary beams are not included. Based on the calculation values for the possible spans and loads the load on a beam can differ between the 18 kN/m and 320 kN/m. The dimensions of the beams are based on the maximum stresses and deformations of the beams. These stresses and deformations are related with material specific properties. The beams can be designed in *concrete*, *timber* or *steel*. For both timber and steel beams standard dimensions of suppliers are used. The product characteristics are matched with the required strength and stiffness in the design. The dimensions of the concrete beams can be defined with more design freedom, based on the design rules. Subsequently the reinforcement can be matched with the created dimensions. The specific strength classes included in the design tool can be found in Appendix B.1 – Appendix B.3.

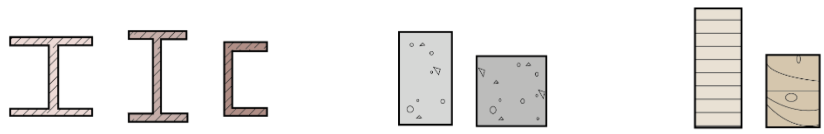


**Figure 4.2** Design options for beams in the design tool (own figure)

### 4.2.1.3 Columns and walls

Transferring the vertical loads through the load-bearing structure can either by covered by columns or walls. In section 4.2.1 the relation between the vertical load-bearing elements and stability system has been introduced.  Depending on the choice of vertical load-bearing structure the user of the design tool, certain stability systems are suitable. In the next section 4.2.1.4 this will be explained in more detail.

Columns
The possibilities of columns are similar with the given description of the beams. Thus, *timber* and *steel* columns based on profiles and sizes of supplies, while *concrete* can be designed by design rules. The required dimensions of the columns are determined from the normative situation, this means the dimensions of the columns are based on the column that must transfer the highest load. The size of the transferred load is depending on the number of columns, the span of the floor and the number of floors. The specific strength classes included in the design tool can be found in in Appendix B.1 – Appendix B.3.

Walls
In the design model three types of load-bearing walls are included; two types of *concrete mixture* and *timber softwood.* It is automatically assumed that the walls support the floors, so the walls are positioned in one direction. So the distance between the walls is the same as the span of the floors. The load transferred via the walls is as similar with the columns based on the distances between the walls and the number of floors. This will lead to the necessary amount of material.

#### 4.2.1.4 Stability

The amount of stability (i.e. stiffness) needed in a building is depending on the height of the building. Namely, this building height defines the applied horizontal wind forces. The stability system should be designed to transfer mostly the horizontal loads. In the structural calculation it is assumed that the chosen stability is similar for the x-and y-direction of the design.
Furthermore, the stability system is related with the vertical load-bearing structure. When the user of the design tool chose for columns, the stability of the design can be either braced frame or unbraced frame.

<u>Unbraced frame stability system</u>
An unbraced system is only applicable for a design consisting of a maximum of four floors (Westenbrugge-Bilbardie & Peters, 2016). If an unbraced stability system is preferred, the required quantity of material is increased.

<u>Braced frame stability system</u>
If a braced frame system is chosen, either the stability can be assured by *steel* wind braces or a *concrete* core. The dimensions and quantity of steel needed for the wind braces is related with the maximum acceptable steel stresses. For the concrete core as a stability system it is assumed that one squared core should be sufficient. The dimensions of the square can differ based on the geometry (length, width and height) of the building.

The other option for the user of the design tool is to choose load-bearing walls instead of columns. In this situation, the tool automatically indicates that the stability system is be covered with these walls an no further stability measurement are necessary.

#### 4.2.1.5 Foundation

The aimed design tool as the outcome of this research, should be suitable for users without specific structural knowledge. Currently, different types of foundation and methods are available and often very project specific. Based on the comparable BHH model and the complexity of the calculations of the foundation, this part of the load-bearing structure is not included in the research as stated in the scope in section 2.3.

### 4.2.2 General approach to the calculations of the structural design variants

The previous section, section 4.2.1, elaborated on which structural building components are included in the design tool and which principles are influencing the needed quantity of each component. For most of the components the chosen grid size, in other words the span of floors and beams, and the applied load are decisive for the required strength and thus the material quantity. The design tool consists of many structural building components that together can compose even more structural design variants. Performing the structural calculations in methodized way is key to maintain overview. Therefore this section will shortly elaborate on the structural calculation method. In the end more in depth calculations per structural building component can be found in Appendix B.

#### 4.2.2.1 Floors and roof

The design tool should be able to make quick and simple structural calculations. The input by the users can varied a lot, therefore the grid size and calculated load-case based on the self-weight of the chosen floor system are rounded to standard quantities. In table 4.3 of section 4.1.3 these quantities are introduced. Tables are created with rows presenting the standard load-cases and the columns the grid size and thus span. The tables are created for all floor systems, for both for the weight [kg/m²] as the thickness [mm]. An example is presented in table 4.4

| *Product x [kg/m²]* | ***Span of the floor system or beam*** | | | | | |
|---|---|---|---|---|---|---|
| ***Load-case*** | 16 m | 12,6 m | 10,8 m | 7,2 m | 5,4 m | 3,6 m |
| 5 kN/m² | | | | | | |
| 10 kN/m² | | | | | | |
| 15 kN/m² | | | | | | |
| 20 kN/m² | | | | | | |

**Table 4.4** Example of the tables used for the structural calculations of the floor systems

The calculation principles to fill in the tables are mostly extracted from the BHH model of Westenbrugge-Bilbardie and Peters (2016). Additionally for the timber floor systems, the hollow core slab floor and beamed floor the free software tool of Finnwood is used. It should be noted that not for all floor systems all the combination between load a span are feasible due to limitations in strength or production length.

#### 4.2.2.2 Beams, columns and walls

Similar with the calculation approach for the floor systems, the structural calculations for beams, columns, walls and stability make use of the standard load-case. However, the calculation method for the material quantity and thickness of the components deviates. The calculation uses the load-case to define the required strength of the component, the line loads on both beams and walls and the point loads on the columns, schematically illustrated in figure B.1 of Appendix B.

The calculation principles used for the dimensioning of the beams, columns and walls are elaborated in table 4.5. Additional calculations are performed to end up with both the material quantity [kg/m²] and the height or thickness [mm]. These rules present the main step of the calculation method. In general, the calculation rules define the required amount of material needed based on the applied load. Subsequently the profile that matches this material quantity is chosen from a standard list or created. The detailed calculation steps that followed the main step can be found in Appendix B.

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Concrete** | |
| Beam | $A_{b,c} = h_b \times w_b$ with $h_b = \frac{1}{10} \times L_b$ $w_b = \frac{2}{3} \times h_b$ | $A_b$: required concrete area per beam [mm$^2$] $h_b$: height of the beam [mm] $w_b$: width of the beam [mm] |
| Reinforcement | $M_r = \frac{\frac{1}{8} \times q \times l^2 \times \rho_s \times c}{0{,}9 \times d \times f_s}$ | $M_r$: mass of required reinforcement [kg/m] q: line load on the beam [N/mm] l: length of the beam [mm] $\rho_s$: specific material weight [kg/m$^3$] c: reinforcement factor; 4 d: useful beam height [mm] $f_s$: steel stresses in reinforcement [N/mm$^2$] |
| Column | $A_{needed,c} = \frac{F_{column}}{f_{concrete}}$ | $A_{needed,c}$: required concrete area per column [mm$^2$] $F_{column}$: point load on the column [N] $f_{concrete}$: admissible concrete compressive stresses [N/mm$^2$] |
| Reinforcement | $A_{needed,r} = \frac{A_{needed,c}}{p_r}$ | $A_{needed,r}$: required reinforcement area per column [mm$^2$] $p_r$: reinforcement percentage; 1% |
| Wall | $d_{needed,c} = \frac{q_{wall}}{f_{concrete}}$ | $d_{needed,c}$: required concrete thickness of the wall [mm] $q_{wall}$: point load on the column [N] $f_{concrete}$: admissible concrete compressive stresses [N/mm$^2$] |
| | **Steel** | |
| Beam | $W_{needed,s} = \frac{\frac{1}{8} \times q \times l^2}{\sigma_{s\_1}}$ | $W_{needed,s}$: required resistance moment of the beam [mm$^3$] q: line load on the beam [N/mm] l: span length of the beam [mm] $\sigma_{s\_1}$: admissible steel stresses [N/mm$^2$] |
| Column | $A_{needed,s} = \frac{F_{column}}{\sigma_{s\_2}}$ | $A_{needed,s}$: required steel area per column [mm$^2$] $F_{column}$: point load on the column [N] $\sigma_{s\_2}$: admissible steel stresses [N/mm$^2$] |
| | **Timber** | |
| Beam | $W_{needed,t} = \frac{\frac{1}{8} \times q \times l^2}{\sigma_{m\_0\_d}}$ | $W_{needed,t}$: required resistance moment of the beam [mm$^3$] q: line load on the beam [N/mm] l: span length of the beam [mm] $\sigma_{m\_0\_d}$: admissible timber bending stresses [N/mm$^2$] |

| | | |
|---|---|---|
| Column | $A_{needed,t} = \frac{F_{column}}{f_{c\_0\_d}}$ | $A_{needed,t}$: required timber area per column [mm$^2$]<br>$F_{column}$: point load on the column [N]<br>$f_{c\_0\_d}$: admissible timber compression stresses [N/mm$^2$] |

**Table 4.5** Applied structural calculation rules for defining the BoM

In the table 4.5 the timber load-bearing wall is not included. When the timber load-bearing wall is chosen in the design tool based on the line load on the wall a suitable profile is matched. The profiles are extracted from the BHH model of Westenbrugge-Bilbardie and Peters (2016).

#### 4.2.2.3 Stability

The stability of the design can be covered by steel wind braces, concrete load-bearing walls or a concrete core. Again, calculation rules from the BHH-model are used to perform the structural calculation (Westenbrugge-Bilbardie and Peters 2016). As stated in section 4.2.1.2 when load-bearing walls are applied in the design, these walls cover the stability. So the table 4.6 includes the calculation rules for the concrete core and steel wind braces.

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Concrete** | |
| Stability core | $I_c \geq \frac{125 \times q \times h^3}{E_r}$ | $I_c$: needed moment of inertia of the concrete core [mm$^4$]<br>q: horizontal line load on the core [N/mm]<br>h: height of the design<br>$E_r$: reduced elastic modules (openings/cracks) [N/mm$^2$] |
| | **Steel** | |
| Stability wind braces | $A_{needed,s} = \frac{F_d \times \sqrt{2}}{f_{y\_d}}$ | $A_{needed,s}$: required area of steel wind braces [mm$^2$]<br>$f_{y\_d}$: admissible steel stresses [N/mm$^2$] |

**Table 4.6** Applied structural calculation rules for defining the BoM for the stability system

### 4.2.3 Structural calculation in Excel design tool

The structural calculations are performed in Excel. The user of the design tool can assemble a structural design variant. The possible combinations of structural building components an user can make depends on two aspects. Firstly, the chosen design strategy by the user, as this strategy defines additional requirements that are matched with the structural building components characteristics, explained in section 3.3. Secondly, the composed structural design variant should be feasible. For instance, a timber frame system with in-situ concrete floors is not advantageous. In the design tool in Excel, these unrealistic combinations are eliminated.

The outcomes are recalled from the calculation sheets towards the overview sheet. These overview sheet presents the outcome of the structural calculation to the user of the design tool. As the user does not require specific structural knowledge, the amount of direct available information is limited. Therefore, the design tool will present per material, concrete, steel and timber the amount of material used in the assembled structural design variant, the BoM. However, if the user is interested in more detail of the calculation, additional information can be unfolded. This consists of the loads applied on the specific component [kN], the self-weight [kg/m$^2$] and the thickness or height [mm].

### 4.2.4 Conclusions

Now both the effect of the circular design strategies on the load-bearing structure and the structural calculations are set, the first sub-question can be answered;

**''How can circular design strategies be turned into design variants for the load-bearing structure of a building?''**

- Two possible pathways to stimulate the implementation of circular design alternatives:
    1. Extending the lifespan of the building and/or its components by design
    2. Efficient use of material by design

  In line with the first principle direction two circular design strategies will be integrated in the design tool; Design for Adaptability [DfA] and Design for Disassembly [DfD]. The second principle direction is covered by the circular design strategy Design for Material Efficiency [DfME].

- The load-bearing structure is affected in a different way by each of the circular design strategies. This is due to the functional and technical requirements that are related with the principles of the strategies. Because of these additional requirements, structural building components are excluded from the design process, since the requirements cannot be met.

- Whether the technical requirements of a circular design strategy are fulfilled by a structural building component, is investigated in two ways. Firstly, the technical characteristics of the components and materials is compared with the additional technical requirements and matched if possible. Characteristics that have examined are the acoustics resistance, fire safety, production method, possible span length, self-weight and connections. Secondly, structural engineers within BAM created structural design variants for each strategy and substantiated their choices for certain structural building components. The outcome of both methods is combined and per circular design strategy a list with suitable structural building components is composed.

To conclude, three circular design strategies are defined that by functional and technical requirements influence the structural design. This effect is included in the design tool by composing lists of suitable structural building components for each strategy. By making use of simplified structural calculations the BoM is created by summing up the weight per chosen structural building component.

# Chapter 5

# Environmental impact calculations

This chapter elaborates on the calculations for the environmental impact. It will answer the question which modifications in these calculations are needed to assess the structural design variants created conform the circular design strategies. In the second part of this chapter, the performed environmental impact calculations in the design tool are presented step-by-step.

## 5.1. Goal and scope definition of the environmental impact calculations

The goal of this research is to present the change in environmental impact when following the principles of the three circular design strategies. This will lead to additional insight in the preliminary design phase and a variant for the load-bearing structure can be chosen, while considering the environmental impact.
As discussed in section 1.2, the environmental impact of a building is expressed in the environmental impact costs per year, named the shadow price. This calculation is depending on the Life Cycle Assessment [LCA] and the reference service life. How these two aspects are interpreted and framed in this research, is an important step before continuing with the calculations. Therefore, the following two section will shortly discuss the defined boundary conditions of both the LCA and expected lifespan.

### 5.1.1 Boundary conditions of the Life Cycle Assessment

Initially, the LCA has been developed for the assessment of single products and materials. Since the last decade, there is an increasing demand for such assessment on a more complex level, the building level (Gervosia & Dimova, 2018). This complexity is because of the many different components and systems used in the design of a building (Escamilla, 2015). As already referred in this research, 30%-60% of the materials used in a building, belong to the load-bearing structure (Westenbrugge-Bilbardie & Peters, 2016). Consequently, the providing more insight on the environmental performance of this layer is crucial to reduce the impact.

The reports of Gervasio & Dimova (2018) and Wittstock et al. (2012) are used to create the approach for the LCA. When performing a LCA it is key to rely on a consistent methodology for collecting the environmental data. Both reports follow the principles of the EN 15978 for the analysis. The level of detail of a LCA can differ, this research aims on a quick and simple assessment, so a so called screening LCA study should be implemented. A screening LCA study serves for an initial quick overview of the environmental impacts of a building. This type of LCA study is used to make a comparison between several variants. An estimated environmental performance can be given and be used to steer the design process (Wittstock et al., 2012).

#### 5.1.1.1 Systems boundaries

The system boundaries of a screening LCA are based on the Product Category Rules following the NEN-EN 15804 (NEN, 2006). In case of the analysis of the structural building layer, the following phases form the system boundaries: the production phase (A1-A3), construction phase (A4-A5), end-of-life phase (C1-C4) and the reuse, recovery, recycling phase (D), see figure 5.1. The use phase (B) is not included as it can be assumed the structural building layer, load-bearing structure, will have little environmental impact during this phase (Trabucco et al., 2016). The Product Category Rules [PCR] define the different life cycle phases described above and presented in figure 5.1.

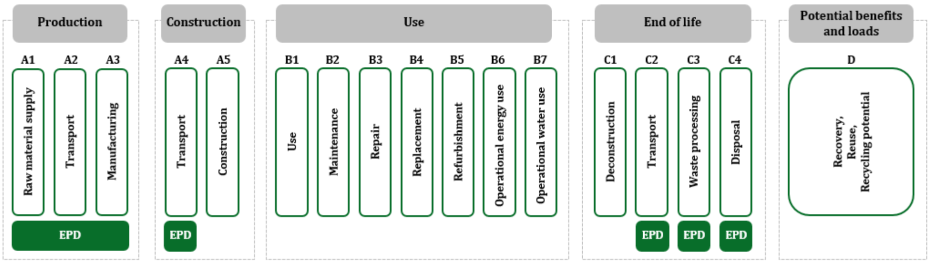



**Figure 5.1** Different phases of the LCA including an indication of the EPD availability (own figure based on NEN, 2006)

Each life cycle phase consists of different processes denoted with a letter and number. Below A1-A3, A4 and C2-C3 EPD is mentioned, this indicates that the NMD contains the environmental data of the process in the database. Therefore, these processes of the life cycle phase are included in this research.
Within these different phases the production of 11 environmental indicators are assessed. These indicators are weighted with a price, that represents the cost to eliminate one kg of its corresponding equivalent unit from the environment. The environmental indicators and their corresponding weighting factor included in this research are represented in table 4.1. These environmental indicators are chosen as the NMD includes these in the database.

| Environmental indicator | Equivalent unit | Weighted factor [€/kg eq.] |
|---|---|---|
| Global warming (GWP100) | $CO_2$ | €0,05 |
| Ozone layer depletion (ODP) | CFC-11 | €30,00 |
| Human toxicity (HTP) | 1.4-DB | €0,09 |
| Aquatic tox fresh water (sweet) (FAETP) | 1.4-DB | €0,03 |
| Aquatic tox fresh water (salt) (MAETP) | 1.4-DB | €0,0001 |
| Terrestrial toxicity (TETP) | 1.4-DB | €0,06 |
| Photochemical oxidation (POCP) | $C_2H_4$ | €2,00 |
| Acidification (AP) | $SO_2$ | €4,00 |
| Eutrophication (EP) | $PO_4$ | €9,00 |
| Abiotic resources depletion | Sb | €0,16 |
| Fossil energy carriers depletion | Sb | €0,16 |

**Table 5.1** Environmental indicators, units and weighted factor

#### 5.1.1.2 Functional unit

The functional unit of the LCA defines how the environmental performance is quantified. This can be used to compare the impact of the structural design variants. For an LCA performed in the construction sector, a functional unit of €/m$^2$/year is used.

### 5.2.1 Boundary conditions of the expected lifespan estimation

The longer this expected lifespan, the lower the environmental impact costs, as these costs are expressed per year. However, just assuming an extension of the lifespan without clear substantiation has no value for improving the environmental impact performance.
It is often not the technical lifespan of the construction materials themself that is normative, as the technical lifespan will rarely be used completely (Dias, 2003; Marsh, 2016). The eventual lifespan of a building is defined by other aspects such as the functional, economic and aesthetic value rather than the technical value (van den Dobbelsteen, 2004). This means the precise determination of the technical life span of a building component is not that relevant for the owner of the building. However, agreements are influential, in relation to the determination of the environmental impact (Hermans, 1999).

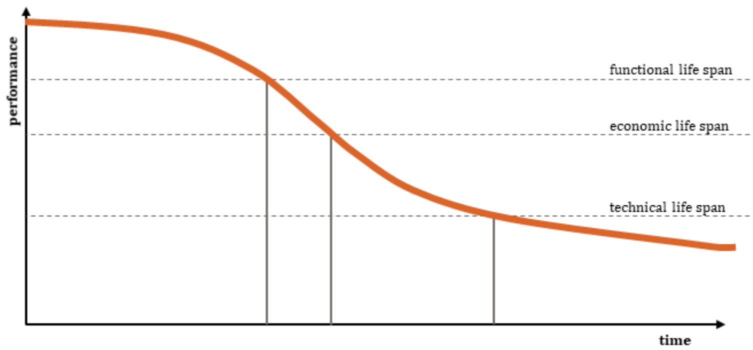



**Figure 5.2** Ratio between functional, economic and technical life span (own figure based on Nunen et al., 2003)

Currently, the values presented in table 5.2 are used for the expected lifespan when performing an environmental impact calculation based on the Dutch Building Regulations noted in the determination method (SBK, 2017).

| Function | Expected lifespan |
|---|---|
| Residential | 75 year |
| Office | 75 year |
| Retail | 50 year |
| Sports | 50 year |
| Education | 50 year |
| Conference | 50 year |
| Industry | 50 year |
| Healthcare | 50 year |

**Table 5.2** Assumed expected lifespan per function (SBK, 2017)

Strikingly, the study of van Valk and Quik (2017) showed that in principle there is no limitation on lifespan extension noted in the determination method for the environmental impact calculation. The functional life span is fully adjustable, as well as the life span of construction products, provided that it is substantiated and only applicable for new buildings. However, the determination method does not state any criteria that should be met in the substantiation. So how the extension of the service life can be proved remains a question. Therefore, resolving an extension of the reference service life is assumed as a twofold matter; firstly, how long is the designed function of the building fit-for-purpose and secondly, if the function is no longer desired, do the building components allow for reuse?

#### 5.1.2.1 Fit-for-purpose

Van den Dobbelsteen (2004) argues that flexibility can be divided into financial, functional and technical flexibility. Since technical flexibility forms a condition for functional flexibility, and functional flexibility for financial flexibility, characteristics of technical flexibility mostly suffice. The technical measures, spatial over-capacity, greater floor spans, open bearing structure, that van den Dobbelsteen (2004) names are in line with the principles of the strategy DfA. In section 5.2.2 the proposed elongation of the expected lifespan of a building when applying the strategy DfA is discussed.

#### 5.1.2.2 Allowing reuse

The figure 5.2 presents that the technical lifespan is larger than the economical lifespan of structural building components or the total load-bearing structure. Erkelens (2003) argues that in that scenario the components should be reusable or recyclable in order to prolong the lifespan of at least the used components (van den Dobbelsteen, 2004). As the design strategy DfD aims for this, effecting the reference service lifespan can be reasonable, this will be elaborated in more detail in section 5.2.2.

## 5.2 The effect of the circular design strategies on the environmental impact calculations

As the circular design strategies aim to improve the environmental performance of a structural design, this should be visible in the environmental impact calculations. In order words, by implementing the functional and technical requirements of each strategy, the calculation of the LCA and/or the expected lifespan can be adjusted. However, current systems of the LCA and expected lifespan do not consider the effects of these strategies in their determination methods. Therefore, this section will elaborate on how the environmental impact calculation is affected due to the implementation of the circular design strategies.

### 5.2.1 Modification of the Life Cycle Assessment

Circularity and thereby the circular design strategies are implemented to improve the environmental performance. A LCA is used to determine the environmental impact, integrating the measures of the design strategies into the methodology of the LCA creates the opportunity to compare the different strategies based on their environmental impact (de Valk & Quik, 2017).

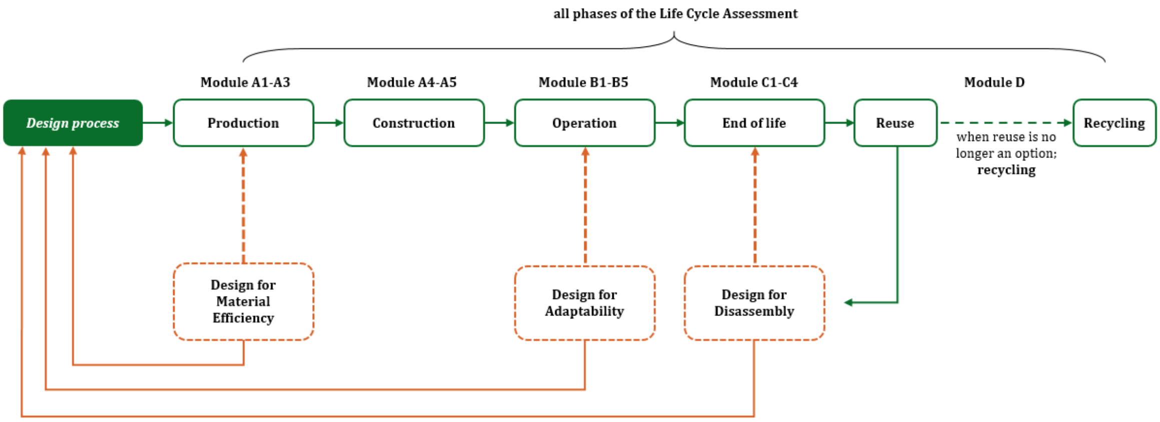



**Figure 5.3** Relation between the LCA modules and the circular design strategies (own figure)

The current methodology only aims at the current life cycle of a component or building. So, the environmental impact of the construction, including the production of the components, the use and the demolition of a building are included in this method. Therefore, the first step is to investigate the relationship between the circular design strategies and the LCA. In figure 5.3 the life cycle phases conform the PCR are presented and which phases are connected with one of the design strategies.

Firstly, the circular design strategy DfA implements additional requirements that make sure the building layout can be adjusted to the wishes of the client or due to a change in function. This means the operation/use phase of the building is prolonged, in the LCA module B1-B5. As mentioned in section 5.1.1.1 during this life cycle phase the load-bearing structure is not expected to create any significant environmental impact as the layer cannot be adjusted easily. Consequently, the LCA remains the same but the expected service life of the building will be impacted, elaborated on in section 5.2.2.

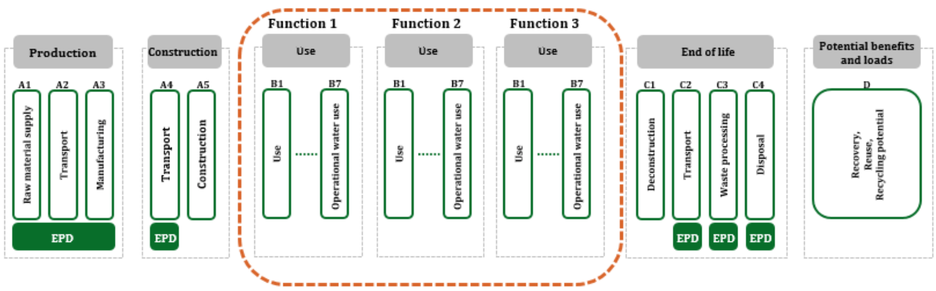



**Figure 5.4** Modification of the LCA modules due to the circular design strategy DfA (own figure)

Secondly, the investigation of the impact of the DfD circular design strategy on the LCA methodology. Figure 5.5 Illustrates that this strategy is connected with the end-of-life phase, module C1-C4. Designing a load-bearing structure that can be deconstructed, the module C3 and C4 of waste processing and disposal are extended. As the structural building components are expected to have a sufficient technical lifespan, the components can be reused and enter a new life cycle. For this second cycle, the production phase, modules A1-A3, can be skipped and thereby saving impact on the environment. So, this requires a change in the current approach of the LCA. It is chosen, to adjust the order of the modules, meaning after the use phase, module B, only the processes of C1 (deconstruction) and C2 (transport) occur, and the second use phase starts again.

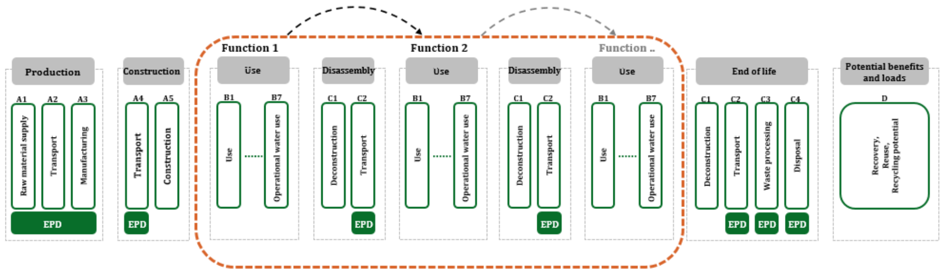



**Figure 5.5** Modification of the LCA modules due to the circular design strategy DfD (own figure)

How many times the process of deconstructing and constructing can be repeated, depends on the functional, financial and technical value of a structural building component. As the functioning and safety of a structural building components depends on the technical value, this is assumed as the covering criteria. In this research it is chosen, to assume the deconstruction process can be sustained three times. The necessary damage will occur during the assembling and disassembling process. So although it can be argued that the technical value and lifespan of structural building components is much longer, a more practical assumption has been made (Flager, 2003; Dias, 2003; Marsh, 2016).

The circular design strategy DfME is related with mainly the production phase, A1-A3. As the modules are sequential, the benefits from reducing the amount of materials or environmental profile is also visible in the other modules, however the strategy mostly impacts the production phase. Optimising the design for one function and decrease the amount of materials are the key requirements of the DfME strategy. Therefore, it is chosen no further adjustments of the LCA are required to investigate the environmental impact for this circular design strategy.

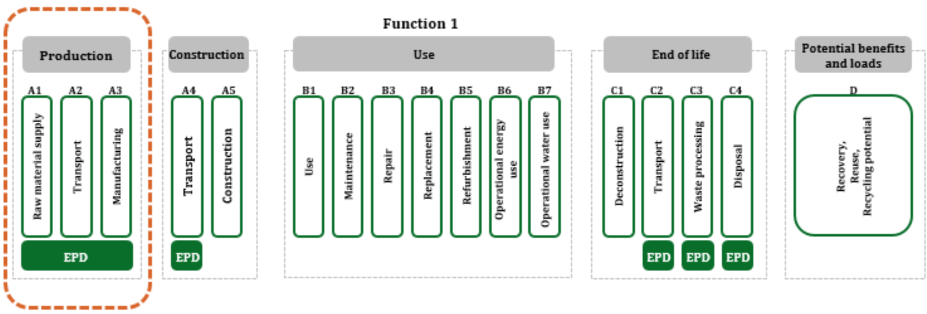



**Figure 5.6** Modification of the LCA modules due to the circular design strategy DfME (own figure)

### 5.2.2 Modification of the expected lifespan estimation

The expected lifespan defines over how many years the environmental costs for recovering the created impact can be spread. This means the longer the expected lifespan the lower the environmental impact per year. Without substantiation the generic expected lifespan is based on the function and defined by Stichting Bouwkwaliteit in the determination method for the environmental impact (SBK, 2017). This determination method also indicates that modifying the expected service life is allowed for new building project, if this can be argued (van Valk & Quik, 2017). Therefore, in this research the design principles and requirements of the circular design strategies for the load-bearing structure are used to provide the validation for extending the expected lifespan.

For the circular design strategy DfA an extension of the lifespan fits with the aim of this strategy. The added functional and technical requirements as illustrated in figure 3.3 make the load-bearing structure adaptable. These measures create the flexibility needed to extend the fit-for-purpose of the structural building layer. This is in line with the point of view that van den Dobbelsteen (2004) argues. As the created structural design variants integrate the described design principles and can suite multiple functions, an extension of the lifespan is assumed substantiated and thus can be implemented in the environmental impact calculations. It is chosen to extend the lifespan from generally 50 years towards 150 years. This assumes that the building can hosts three function and suits these functions without required adjustments of the load-bearing structure. In general, the lifespan of one function is 50 years, see table 5.2, so being able to allow three functions can results in a lifespan of 150 years, that can be assured both functional and technical.

In case of the circular design strategy DfD a modification in the expected service life is a bit subtler than the DfA strategy. The strategy DfD does not necessarily leads to a longer functional service life, but does extends the service life of the building components used in the load-bearing structure by ensuring disassembly and thus reuse. Only in the first life cycle the production phase is included, as in the second cycle the disassembled structural building components can be reused. However, if only the second or third life cycles experience profit from the reduced environmental impact, the incentive for the first cycle and its client to implement the circular design strategy DfD is low. Therefore, it is chosen to extend the expected lifespan towards 100 years. Additionally, in this lifespan the environmental impact of a maximum of three times deconstruction is included. Meaning whether the client of the first, second or third cycle differs the same environmental impact is allocated.

For the circular design strategy DfME the expected lifespan will be based on the function of the building. This strategy aims to reduce the materials and impact of the chosen materials, so no additional principles are included in this strategy to prolong the lifespan.

## 5.3 Performing the environmental impact calculations

The discussed adjustments for both the LCA and expected service life per circular design strategy form the starting point of the environmental impact calculations. In table 5.3 the adapted principles are presented that will be used for the calculations.

| Included modules of the LCA | Expected lifespan |
|---|---|
| **Design for Adaptability** | |
| • Production of virgin material (A1-A3)<br>• Transport to the site (A4)<br>*Period of use*<br>• Demolition of the building (C1)<br>• Transport to the processing site (C2)<br>• Waste processing, including recycling (C3/D)<br>• Disposal of materials (C4) | 150 years |
| **Design for Disassembly** | |
| • Production of virgin material (A1-A3)<br>• Transport to the site (A4)<br>*Period of use*<br>• Deconstruction of the building (C1)<br>• Transport to site (C2)<br>*Period of use*<br>• Deconstruction of the building (C1)<br>• Transport to site (C2)<br>*Period of use*<br>• Deconstruction of the building (C1)<br>• Transport to site (C2)<br>• Waste processing, including recycling (C3/D)<br>• Disposal of materials (C4) | 100 years |
| **Design for Material Efficiency** | |
| • Production of virgin material (A1-A3)<br>• Transport to the site (A4)<br>*Period of use*<br>• Demolition of the building (C1)<br>• Transport to the processing site (C2)<br>• Waste processing, including recycling (C3/D)<br>• Disposal of materials (C4) | 50/75 years |

**Table 5.3** Adjusted environmental impact calculation for each circular design strategy

### 5.3.1 Steps of the environmental impact calculation

Now the modifications of the calculation method per circular design strategy are performed, the actual environmental impact calculation can start. Therefore, the following steps are performed;

The **first step** is creating the BoM based on the outcome of the structural calculations. As structural building components can consist out of different construction materials, for each component the amount of concrete, steel or timber is defined in kg/m². In table 5.4 an example is illustrated.

| Type | Component | Concrete [kg/m²] | Steel [kg/m²] | Struct. steel [kg/m²] | Timber [kg/m²] |
|---|---|---|---|---|---|
| Ground floor | Hollow core slab floor with compression layer | 447 | - | 6,9 | - |
| Storey floor | Slimline floor | 168 | 1,48 | 30,08 | - |
| ... | | | | | |
| Beams | HEA S235 steel | - | - | 12,27 | - |
| ... | | | | | |

**Table 5.4** Sorting the construction materials for each structural building component

The **second step** is preparing the environmental data. This data has been retrieved from the NMD. This database consists of the main construction materials what the quantities of the raw material (input) and the emissions to the environment (output) are. However, notion should be given that this data can be limited due to lacking information and the necessity to make assumptions (Jonkers, 2020).
The environmental data is adjusted to the impact for one kg of the material per square meter. For all the materials used in the structural building components the environmental impact is calculated per life cycle process (A1-A3, A4, C2, C3 and C4). An example is presented in table 5.5. A more extensive overview of these results can be found in Appendix D.2.

| Type | Component | Shadow costs [€/m²] | | | | | |
|---|---|---|---|---|---|---|---|
| | | *A1-A3* | *A4* | *C2* | *C3* | *C4* | ***Total*** |
| Ground floor | Hollow core slab floor with compression layer | 8,75 | 0,77 | 0,36 | -0,13 | 0,00 | **9,75** |
| Storey floor | Slimline floor | 6,95 | 0,57 | 0,23 | -0,38 | -1,45 | **5,91** |
| ... | | | | | | | |
| Beams | HEA S235 steel | 0,87 | 0,03 | 0,03 | -0,38 | 0,00 | **0,55** |
| ... | | | | | | | |

**Table 5.5** Shadow costs per structural building component per LCA module (the shadow costs are calculated for the material quantities presented in table 5.4)

The negative values can be interpreted as the 'bonus' because of reuse or recycling (Jonkers, 2020). However, this also presents the inconsistencies in the data as for some of the material this 'bonus' is assigned in module C2 and for others in C3 or C4.

The **third step** is performing the environmental impact calculation conform the circular design strategy. Meaning, combining the modules of the LCA based on the defined modifications in section 5.2.1 and divide this by the matching expected service life as discussed in section 5.2.2., both are presented in table 5.3. This will lead to the environmental impact indicator, called the *Milieu Presetatie Gebouwen* [MPG] in €/m$^2$GFA/year.

### 5.3.2 Additional factors to compare the outcome of the environmental impact calculations

Besides the environmental impact calculation, other variables are often important in the creation of a design. The outcome of the environmental impact calculations should be used as a mean to steer the conversation between the design team during the preliminary phase into a more circular design. However, the environmental impact should not be interpreted as a stand-alone outcome, it should be compared with other factors. Therefore, the outcome of the environmental impact calculation, the MPG, of the created structural design variants is presented combined with the following additional factors;

- *Material usage*; by providing insight into the total amount of material applied in the design, the effect of the structural choices can become more transparent. For instance, a lot of concrete means a lot of mass while a lighter construction initiates the use of materials such as timber or hybrid floor systems.

- *$CO_2$ emissions*; currently, the $CO_2$ production is a hot topic of discussion in the building sector. This is mainly due to the possible $CO_2$ tax. To be able to facilitate this new regulation, it is decided to make this environmental impact category explicit per structural design variant. The $CO_2$ equivalent is also part of the environmental impact calculation resulting in the MPG. Thus, the $CO_2$-production is indicated to give the user of the design tool more feeling about the environmental impact of the created design variant.

- *Estimated service life*; to make it clear that the expected service life can differ per circular design strategy, the assumed expected lifespan estimation will be presented as an outcome of the design tool.

- *Building costs*; above all the realisation of a project must be economically feasible. Subsequently, based on the key figures used within BAM an estimation of the building costs will be presented per structural design variant. The key figures include material costs and the expected time/costs for the construction process.

As shortly explained for the $CO_2$-production the above stated additional factors to compare design variants are not mutually exclusive. The required material quantity in the design and the expected lifespan, service life, are both part of the environmental impact calculation resulting in the MPG.

### 5.3.3 Conclusions

After this chapter the second sub-question can be answered:

**''How to assess the environmental impact of the design variants for the load-bearing structure?''**

- By performing the environmental impact calculation, the MPG of the structural design variants can be calculated. This calculation consists of two aspects, the LCA and the estimation of the lifespan.

- Both aspects of the environmental impact calculation should be investigated on whether the design principles of the circular design strategies have effect on the determination method. From this investigation the following conclusions have been drawn:

  1. Design for Adaptability
  The LCA remains the same as the current determination method, consisting of the modules A1-A3, A4, C1, C2, C3 and C4. The expected service life is changed. Instead of defining the service life on the function of the building, the expected service life is established at 150 years. This time frame is chosen as it can be assumed that within this time frame the building can or will change, maybe even of function, and the load-bearing structure is composed based on technical measures to guarantee this flexibility.

  2. Design for Disassembly
  Both the LCA and expected service life are adjusted conform the design principles. The LCA now includes the impact of three times deconstructing and constructing the load-bearing structure. In this way the environmental impact of the production phase is equally divided over the possible life cycles. Thus, the following modules are included; A1-A3, A4, C1, C2, C1, C2, C1, C2, C3 and C4. The expected service life is assumed to be 100 years. This expected life span is assumed lower as the DfA strategy, as the process of disassembly will damage the structural building components and thereby the technical value.

  3. Design for Material Efficiency
  For DfME the two aspects will not be modified. So, this means the LCA is the same as the DfA strategy; modules A1-A3, A4, C1, C2, C3 and C4. The expected lifespan is still defined based on the function of the building, so 75 years for residential buildings and 50 years for the other functions.

- The environmental impact calculations are performed in several steps. Firstly, the outcome of the structural calculations is rearranged to a BoM sorted for concrete, steel and timber. Secondly, the environmental data is collected and prepared as the input for the calculations. Per module of the

LCA (A1-A3, A4, C2, C3, C4) per structural component the environmental data is sorted. Lastly, the adjusted calculation method for the chosen circular design strategy is performed.

- Besides the outcome of the environmental impact calculation, the MPG, four additional factors are defined to compare the results. These factors are chosen as this makes the users of the design tool aware of the relationship between the environmental impact and other important variables to steer the design. In this way, a well-considered decision can be made in line with the project specific ambition.

# Part III | Results and final remarks

# Chapter 6

# The design model

## 6.1 General results of the environmental impact calculation

As every building project is unique, the outcome of the design tool can and will differ. Ultimately, the goal of this research is to end up with the most advantageous environmental impact for a structural design variant belonging to one of the circular design strategies. The factors or design choices that have an influence on the environmental impact should be defined. Therefore this section consist of two parts. Firstly, the choices that in general have a significant influence on the environmental impact of the load-bearing structure are discussed. Secondly, for each circular design strategy, DfA, DfD and DfME, the structural design variants leading to the lowest environmental impact are presented and the choices for the design are substantiated.

### 6.1.1 Design choices that effect the environmental impact calculations

#### 6.1.1.1 Grid size

The first choice that should be made to compose two structural design variants is the size of the grid. In the design tool the grid size is used to perform the structural calculations of the load-bearing structure. Meaning when the user defines the grid size in x-direction and y-direction this will automatically turn into the span of the floors and beams.

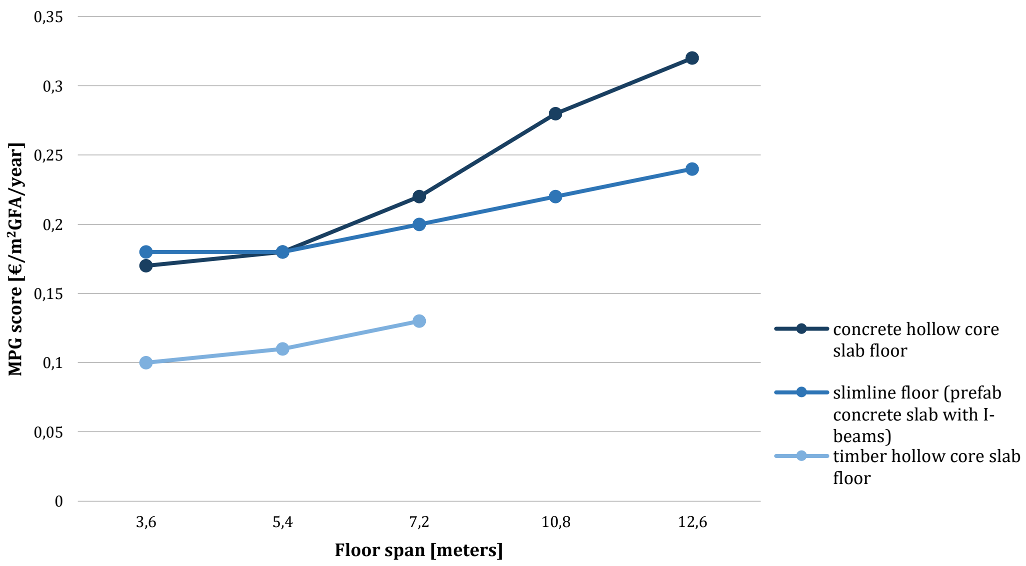



**Figure 6.1** MPG score per floor span for different structural floor systems

The graph in figure 6.1 presents that an increasement in the span of the floors, and thus the grid size, leads to an increasement in the total environmental impact calculation outcome, the MPG. Although this seems logical, it is important to emphasize that the storey floors (including the roof) determine more than half of the environmental impact. In addition, the share of environmental impact of the ground floor is also significant. This is due to the environmental profile and required material of the ground floor floor systems, more explanation can be found in the section 6.1.1.2.

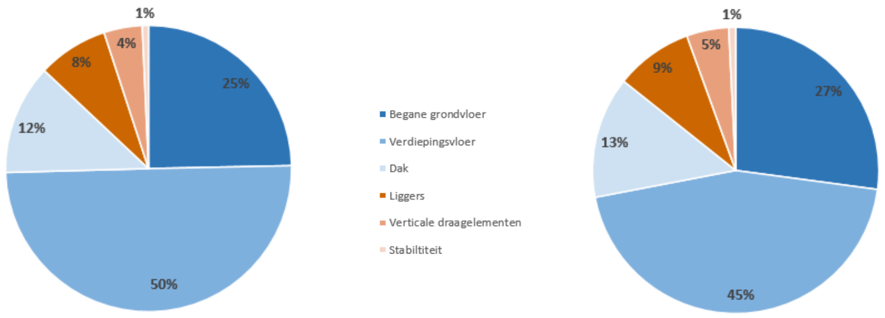



**Figure 6.2** **Left:** concrete hollow core slab floor spanning 7,2 meters with a steel frame (beams and columns S235)
**Right:** slimline floor spanning 7,2 meters with a steel frame (beams and columns S235)

The two diagrams in figure 6.2 indicate that the share of the other structural elements such as beams, columns and stability, does not influence the outcome as much as the floor span. When the floor span is decreased, the number of required columns increases. However as most of the construction materials is still in the floor systems, this effect is barely visible in the total MPG. In the situation of wooden floor systems, with a low self-weight, the share of the ground floor floor system is even more pronounced, see figure 6.3. This is because of the low environmental impact of timber structural building components, in more detail discussed in the following section 6.1.1.2.

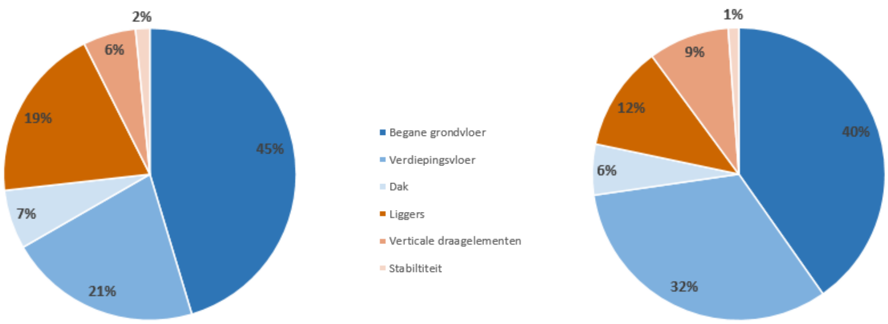



**Figure 6.3** **Left:** timber hollow core slab floor spanning 3,6 meters with a steel frame (beams and columns S235); MPG 0,10 **Right:** timber hollow core slab floor spanning 7,2 meters with a steel frame (beams and columns S235); MPG 0,13

To conclude, the larger the span of the floor systems, the higher the MPG becomes. Although with a larger span fewer vertical elements are necessary, the impact of more material needed in the floor system is significantly higher. Therefore, choosing a grid size with a floor span varying between 3,6 m until 7,2 m is recommended. However, this has effect on the functionality of the floor plan, as more vertical elements are required.

#### 6.1.1.2 Material type

The second choice that will affect the environmental impact is the type of structural building component the user will choose. More specific, the material out of which the structural building component consists, defines the environmental impact. In Appendix D the environmental data used for the calculations can be found. To illustrate the difference between materials types in the table 6.1 several floors and beams and their environmental impact are presented.

| Type | Component | Material | Shadow costs |
|---|---|---|---|
| Storey floor | Hollow core slab floor | Concrete | 4,12 [€/m$^2$] * |
| Storey floor | In-situ concrete floor | Concrete | 6,35 [€/m$^2$] * |
| Storey floor | Slimline | Hybrid ** | 4,79 [€/m$^2$] * |
| Storey floor | Hollow core slab floor | Timber | 1,39 [€/m$^2$] * |
| Beam | Prefab C30/37 | Concrete | 0,10 [€/kg] *** |
| Beam | HEA S235 | Steel | 0,04 [€/kg] |
| Beam | GL24h | Timber | 0,04 [€/kg] |

**Table 6.1** Environmental impact, shadow costs, for structural building components out of different materials

* In case of the floor systems, the shadow costs are presented for a span of 3,6 meters with a load of 10 kN/m$^2$

** Hybrid means the floor system includes both concrete and steel. A simplified illustration of a slimline floor can be found in figure 4.1.

*** In case of the concrete beam reinforcement is also included in the shadow costs.

The total environmental impact of a structural design variant depends on the quantities of each material type, concrete, steel and timber. The amount of material needed per structural building component depends on the strength and specific weight. In general it can be stated that concrete has a sufficient strength capacity, especially the compression strength, but is relatively heavy. Steel has a high specific weight, but is also very strong and thus less material is needed. Lastly, timber has a low self-weight and an attractive tension strength capacity.

In order to reduce the environmental impact structural building components with an environmentally friendly are preferred, which makes timber components the most attractive. Yet, the functional requirements of a project can impact the choice of structural building components as well. For instance, the acoustic performance of timber components is in general not sufficient and thus cannot always be implemented.

### 6.1.2 The specific design choices leading to the lowest environmental impact per circular design strategy

From the previous section it became clear that the choice of grid size and the type of material in the structural building components will affect the outcome of the environmental impact calculations. Still the functional requirements of each circular design strategy will influence the decisions-making process. This section will present per circular design strategy two structural design variants. One structural design variant in executed in concrete/steel and the other structural design variant in timber. The influential design choices, discussed in section 6.1.1, should lead the lowest environmental impact, meaning the lowest MPG. The considered aspects when composing the design and the matching final MPG are discussed. In all the designs a stability system of steel wind braces is applied. For each structural design variant, the general geometry, length, width and height, and function of the building are similar and assumed. In table 6.2 the input parameters are presented.

| Variable | Input | Unit |
|---|---|---|
| Length of the building (x-direction) | 26 | m |
| Width of the building (y-direction) | 16 | m |
| Number of storeys | 3 | - |
| Storey height | 3 | m |
| Height of the building (z-direction) | 12 | m |
| Gross Floor Area | 1664 | $m^2$ |

**Table 6.2** General input parameters for the design tool

#### 6.1.2.1 Design for Adaptability design choices leading to the lowest MPG

The circular design strategy DfA stands for creating flexibility in the overall design that allows the building to change in function and layout of the floorplan. This means if there is a reasonable change of a functional change in the future of the building, the client should consider this circular design strategy. The strategy DfA includes measures that support the functional change and extend the lifespan. For the load-bearing structure of the building this means floor spans starting from 7 meter as a minimum, a floor to ceiling height of at least 3 meters and the use of columns to reduce the vertical barriers.

The first design choice that should be made is the grid size. Explained in section 6.1.1.1. the larger the floor span the higher the environmental impact as most of the material used is part of the floors. The first design variant consists of both the floors and beams 7,2 meters and the second design variant has a floor span of 10,8 meters and the beams span 7,2 meters. The choice to increase the floor span is related with the chosen floor system.

The second design choice is to choose the materials of the design. In the first design variant concrete hollow core slab floors with a steel frame are included. A steel frame, including beams and columns, will lead to a lower environmental impact than the concrete frame. The second design variant is composed of slimline floors (prefabricated concrete slab with integrated steel beams) with a steel frame. The difference in MPG between a floor span of 7,2 meters and 10,8 meters turned out to be minimal. The larger floor span will increase the flexibility of the building layout. In the introduction of this section, it stated a concrete/steel and timber variant would be composed for each circular design strategy. However, in the situation of the DfA strategy, timber is not a suitable material due to the varying requirements related with the possible shift in building function. In general this is due to the acoustic performance of timber components. In section 3.3 this is elaborated in more detail.

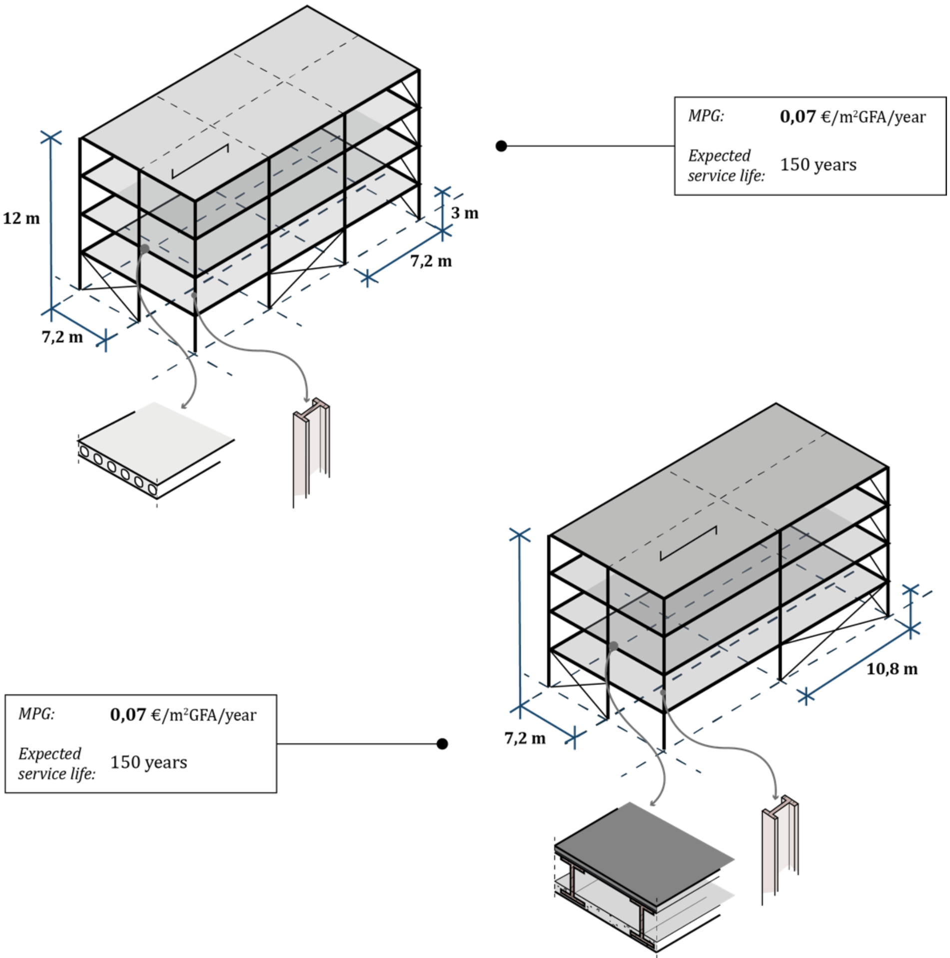



**Figure 6.4 Left:** Structural design variant 1 concrete hollow core slab floors with a steel frame **Right:** Structural design variant 2 slimline floors with a steel frame (own figure)

### 6.1.2.2 Design for Disassembly design choices leading to the lowest MPG

The key design principle of the DfD strategy is that the building allows deconstruction and thereby the reuse of the used components. This means the load-bearing structure should consists of structural building components that can be connected and disconnected, such as screwed, nailed or bolted connections. For a client the strategy DfD is interesting when the project and the function are not specifically linked to one location and can suit other places as well. A building can be used for a shorter period than initially planned for, then be deconstructed and constructed elsewhere without adding new materials.

For both design variants the most beneficial grid includes a floor span of 3,6 meters and the beams span 5,4 meters. This will decrease the material needed in the floor systems that contribute the most to the MPG outcome. The consequence of the chosen grid size is that the number of components, such as columns and beams, increases. This has an effect on the manageability of the construction and deconstruction process on site.

Thereafter, the specific structural building components should be assigned per design variant. As stated in the introduction of this section it is favoured to create a concrete and/or steel design variant and timber variant. In the first design variant a timber hollow core slab floor is chosen due to two main reasons. Firstly, the environmentally friendly profile. Secondly, the ease in handling the component on site when comparing it with a timber beamed floor system. The timber floor system is combined with a steel frame, as this suits construction and deconstruction perfectly. For the second design variant either the concrete hollow core slab floor or the slimline floor will suit best. The comparison of the MPG showed for the slimline floor an advantage of 0,01 €/m$^2$GFO/year. The concrete hollow core slab floor brings complexity to suit deconstruction due to the normally in-situ concrete compression layer and thus making dry connections more difficult. The slimline floor consists of prefabricated concrete elements and steel beams, which perfectly suit deconstruction. Yet, the integrated floor system can increase the complexity of the construction process due to more required actions on site. Yet it is chosen to apply the slimline floor in the second design variant with a steel frame system.

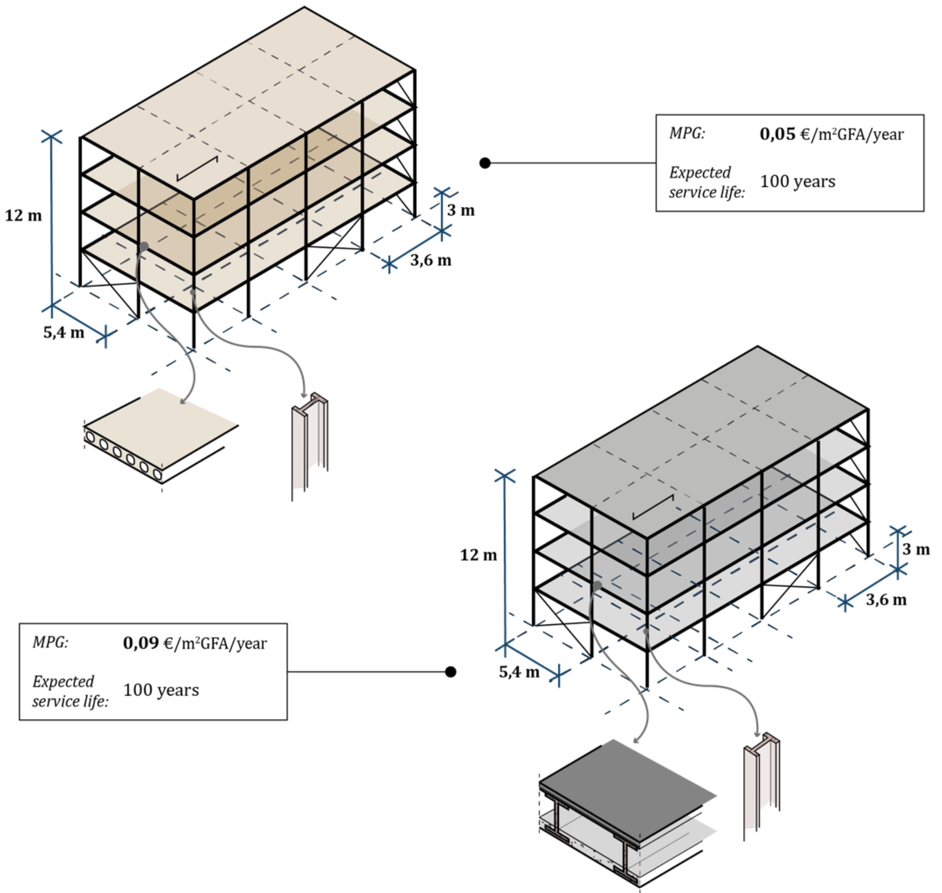



**Figure 6.5 Left:** Structural design variant 1 timber hollow core slab floors with a steel frame **Right:** Structural design variant 2 slimline floors with a steel frame (own figure)

#### 6.1.2.3 Design for Material Efficiency design choices leading to the lowest MPG

The main goal of the circular design strategy DfME is to develop a design specifically for one function in the most material efficient manner. With efficient it is meant to decrease the environmental impact. Therefore, for deciding to implement this design strategy, a client must be certain that the building will only have one function on one location.

The first design choice is chosen the same as the DfD strategy. The grid consists of floors that span 3,6 meters and the beams 5,4 meters, leading to a reduction in the amount of materials needed in the floor systems.

The second influential design choice is the type of materials. For the timber design variant, the hollow core slab floor is chosen as the storey floor and the timber beamed floor as the roof. The reason for applying the timber beamed floor not as the floor system, is due to the minimal acoustic resistance. For instance, this will not be suitable for floors that separate two different apartments. The timber floors are combined with a timber frame. For the second design variant, in concrete/steel, the most environmental efficient combination consists of the slimline floors including a steel frame.
As the expected lifespan for the circular design strategy DfME is based on the function of the building, residential or office and other functions. For each design variant a distinction between the MPG for the residential option and office option are presented.

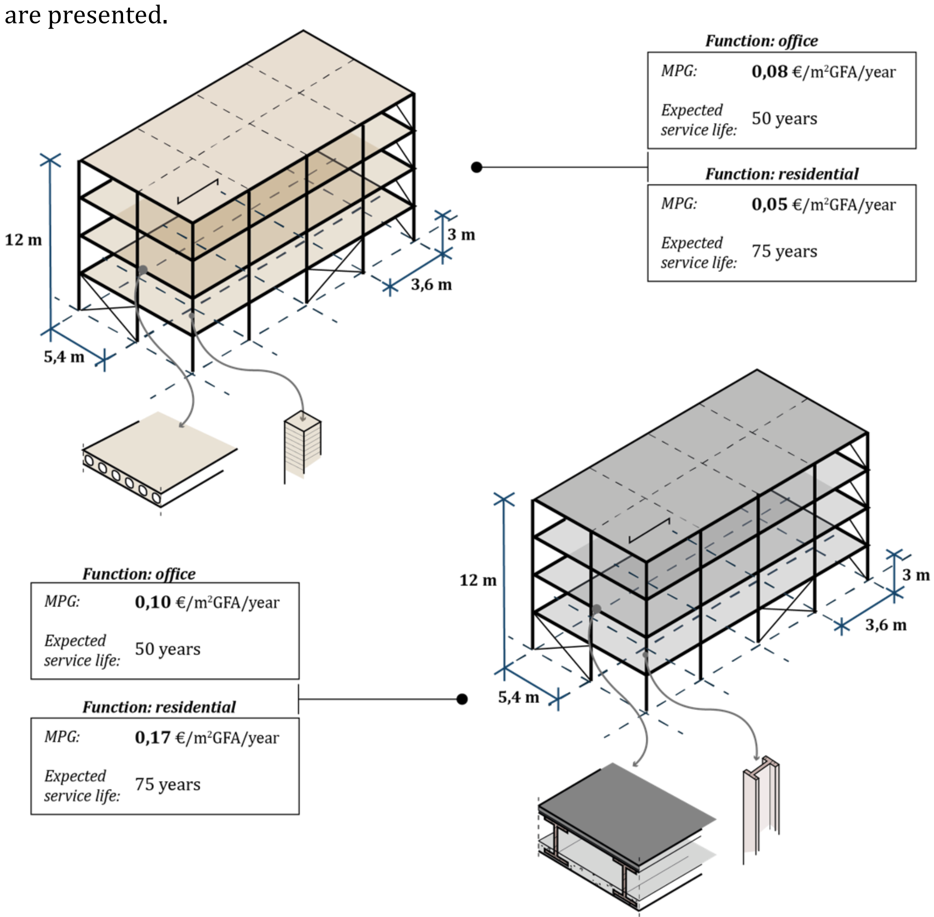



**Figure 6.6 Left:** Structural design variant 1 timber hollow core slab floors with a timber frame **Right:** Structural design variant 2 slimline floors with a steel frame (own figure)

## 6.2 The developed design model

This section will present each step of the design tool to create the load-bearing structure design variants and assess the variation in environmental impact. The design tool integrates the defined relations between circular design strategies, the load-bearing structure and the environmental impact of Chapter 3, Chapter 4 and Chapter 5. It is chosen to develop the design tool in Excel, with different tabs/sheets for a different step. In this way, the amount of information per step is balanced for the user. How the user should navigate through the design tool is explained by using the case study project Ambachtslaan Veldhoven as an example.

### 6.2.1 General description Ambachtslaan

The client of the Ambachtslaan project is the health-care organisation Lunet Zorg. This organisation supports people with intellectual disabilities by providing the needed care. In total 56 apartments should be realised and the project organisation has the aim to achieve a high level of sustainability. However, schematic architectural drawings have been set up, but the definite design for load-bearing structure has not yet been defined. Thus, the design tool will become useful to investigate the structural possibilities and the corresponding environmental performance. The following table 6.3 presents the input as a starting point for the design tool

| Variable | Input | Unit | Comment |
|---|---|---|---|
| Length of the building (x-direction) | 75 | m | Rounded value |
| Width of the building (y-direction) | 16 | m | Rounded value |
| Number of storeys | 4 | - | |
| Storey height | 2,6-3,2 | m | Rounded value |
| Height of the building (z-direction) | 17 | m | Rounded value |
| Gross Floor Area | 6000 | $m^2$ | Calculated value |

**Table 6.3** General characteristics of the case study Ambachtslaan Veldhoven

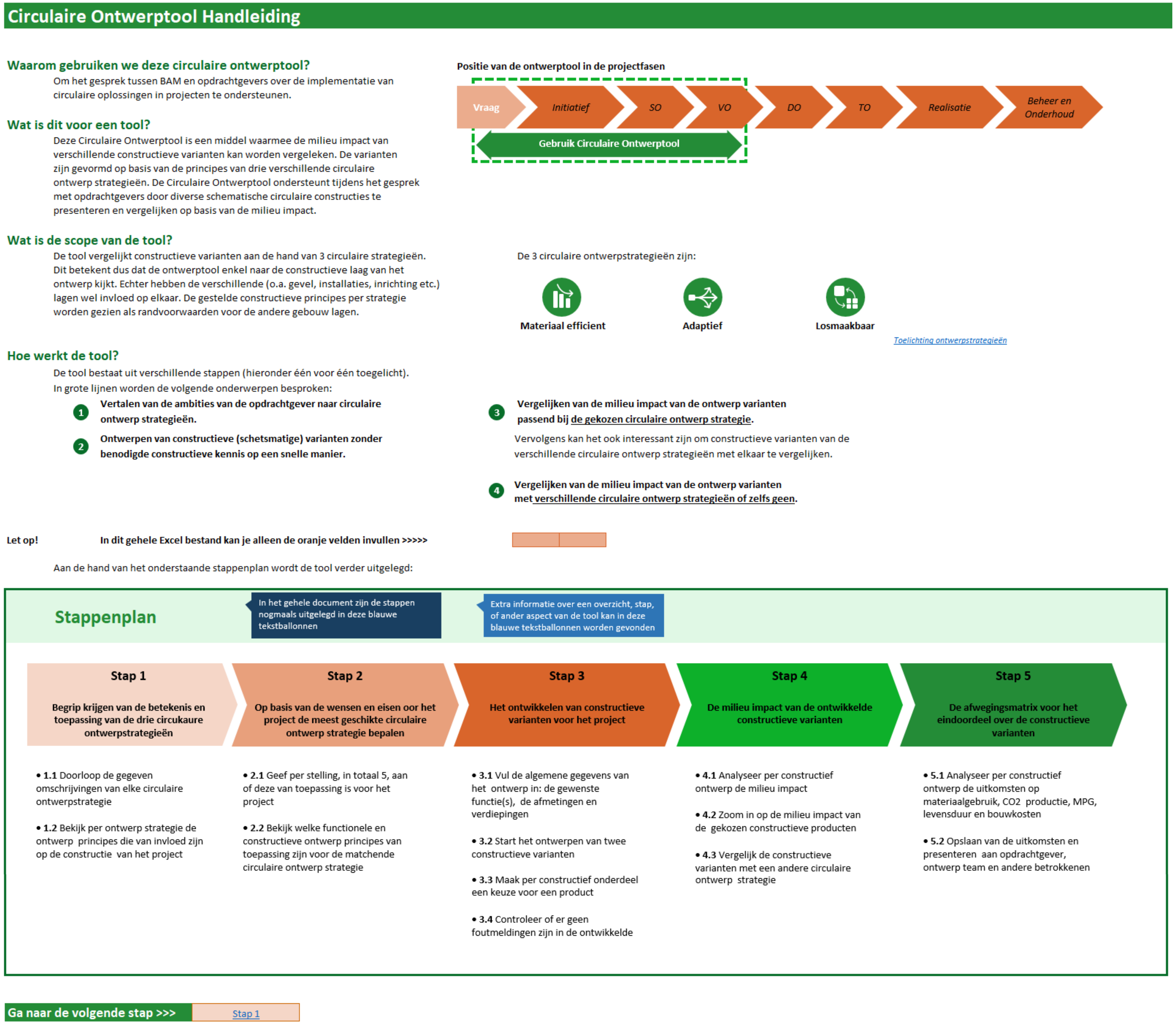
**Step 0: Overview and explanation of the design tool**

Before starting to work with the design tool, it is important to explain the user the need for a design tool that can quickly compare the environmental impact of load-bearing structure variants. In this way the environmental impact is not only used as an evaluation at the end of the design process, but used as a mean to shape the design.

Furthermore, the scope of the design tool is explained as focusses only on the structural layer of the building is considered. Adding to this, four objectives of the design tool are proposed;

1. Match the project ambition with one of the circular design strategies
2. Create design variants for the load-bearing structure that suits the defined circular strategy
3. Compare the environmental performance of two created design variants
4. Compare the environmental performance of the two created design variants with two additional design variants conform another circular design strategy

Lastly, some practicalities for the functioning of the design tool such as that orange cells should be filled in. To manage the expectations of the user, the general outline of the design tool is introduced.



**Circulaire Ontwerptool Handleiding**

**Waarom gebruiken we deze circulaire ontwerptool?**
Om het gesprek tussen BAM en opdrachtgevers over de implementatie van circulaire oplossingen in projecten te ondersteunen.

**Wat is dit voor een tool?**
Deze Circulaire Ontwerptool is een middel waarmee de milieu impact van verschillende constructieve varianten kan worden vergeleken. De varianten zijn gevormd op basis van de principes van drie verschillende circulaire ontwerp strategieën. De Circulaire Ontwerptool ondersteunt tijdens het gesprek met opdrachtgevers door diverse schematische circulaire constructies te presenteren en vergelijken op basis van de milieu impact.

Positie van de ontwerptool in de projectfasen

Vraag | Initiatief | SO | VO | DO | TO | Realisatie | Beheer en Onderhoud

Gebruik Circulaire Ontwerptool

**Wat is de scope van de tool?**
De tool vergelijkt constructieve varianten aan de hand van 3 circulaire strategieën. Dit betekent dus dat de ontwerptool enkel naar de constructieve laag van het ontwerp kijkt. Echter hebben de verschillende (o.a. gevel, installaties, inrichting etc.) lagen wel invloed op elkaar. De gestelde constructieve principes per strategie worden gezien als randvoorwaarden voor de andere gebouw lagen.

De 3 circulaire ontwerpstrategieën zijn:

Materiaal efficient | Adaptief | Losmaakbaar

Toelichting ontwerpstrategieën

**Hoe werkt de tool?**
De tool bestaat uit verschillende stappen (hieronder één voor één toegelicht).
In grote lijnen worden de volgende onderwerpen besproken:

1. **Vertalen van de ambities van de opdrachtgever naar circulaire ontwerp strategieën.**
2. **Ontwerpen van constructieve (schetsmatige) varianten zonder benodigde constructieve kennis op een snelle manier.**
3. **Vergelijken van de milieu impact van de ontwerp varianten passend bij de gekozen circulaire ontwerp strategie.**

Vervolgens kan het ook interessant zijn om constructieve varianten van de verschillende circulaire ontwerp strategieën met elkaar te vergelijken.

4. **Vergelijken van de milieu impact van de ontwerp varianten met verschillende circulaire ontwerp strategieën of zelfs geen.**

**Let op!** **In dit gehele Excel bestand kan je alleen de oranje velden invullen >>>>>**

Aan de hand van het onderstaande stappenplan wordt de tool verder uitgelegd:

**Stappenplan**

In het gehele document zijn de stappen nogmaals uitgelegd in deze blauwe tekstballonnen

Extra informatie over een overzicht, stap, of ander aspect van de tool kan in deze blauwe tekstballonnen worden gevonden

**Stap 1** – Begrip krijgen van de betekenis en toepassing van de drie circukaure ontwerpstrategieën
- **1.1** Doorloop de gegeven omschrijvingen van elke circulaire ontwerpstrategie
- **1.2** Bekijk per ontwerp strategie de ontwerp principes die van invloed zijn op de constructie van het project

**Stap 2** – Op basis van de wensen en eisen oor het project de meest geschikte circulaire ontwerp strategie bepalen
- **2.1** Geef per stelling, in totaal 5, aan of deze van toepassing is voor het project
- **2.2** Bekijk welke functionele en constructieve ontwerp principes van toepassing zijn voor de matchende circulaire ontwerp strategie

**Stap 3** – Het ontwikkelen van constructieve varianten voor het project
- **3.1** Vul de algemene gegevens van het ontwerp in: de gewenste functie(s), de afmetingen en verdiepingen
- **3.2** Start het ontwerpen van twee constructieve varianten
- **3.3** Maak per constructief onderdeel een keuze voor een product
- **3.4** Controleer of er geen foutmeldingen zijn in de ontwikkelde

**Stap 4** – De milieu impact van de ontwikkelde constructieve varianten
- **4.1** Analyseer per constructief ontwerp de milieu impact
- **4.2** Zoom in op de milieu impact van de gekozen constructieve producten
- **4.3** Vergelijk de constructieve varianten met een andere circulaire ontwerp strategie

**Stap 5** – De afwegingsmatrix voor het eindoordeel over de constructieve varianten
- **5.1** Analyseer per constructief ontwerp de uitkomsten op materiaalgebruik, $CO_2$ productie, MPG, levensduur en bouwkosten
- **5.2** Opslaan van de uitkomsten en presenteren aan opdrachtgever, ontwerp team en andere betrokkenen

**Ga naar de volgende stap >>>** Stap 1

**Step 1: Create an understanding of the three circular design strategies**

The design tool will be used in the preliminary design phase by practitioners in the tender procedure. Circularity is a relatively new topic for the building sector. This means not all users of the design tool are expected to be familiar with the three circular design strategies, Design for Material Efficiency, Design for Adaptability and Design for Disassembly. Therefore, the second step of the design tool is to create an understanding of the three circular design strategies and the relation with load-bearing structure for the users.

Per circular design strategy a description is given including the relationship with the Circular Economy and the both the functional and technical design principles that have effect on the load-bearing structure. Additionally, for each circular design strategy two example projects are given to make the strategies more tangible.

## Definities

### Circulaire ontwerp strategieën

**Stap 1.1** Doorloop de gegeven omschrijvingen van elke circulaire ontwerpstrategie

**Stap 1.2** Bekijk per ontwerp strategie de ontwerp principes die van invloed zijn op de constructie van het project

| | Circulaire ontwerpstrategie | Omschrijving | Relatie met de Circulaire Economie | Ontwerp principes | |
|---|---|---|---|---|---|
| Voorbeelden<br>Bekijk<br>**Klik hier** voor voorbeeld projecten per circulaire ontwerp strategie | Materiaal Efficient Ontwerpen | Het gebruik van materialen reduceren en kiezen voor materialen met een lagere impact op het milieu.<br>Het doel van de strategie is daarom ook om voor één functie een zo'n efficient mogelijk ontwerp te maken. Zodat de totale milieu impact kan worden gereduceerd. | Door middel van ontwerpen efficient omgaan met bouwmaterialen en daardoor de aantasting op de omgeving verminderen. | Functionele ontwerp principes<br>• Optimaliseer het ontwerp voor één functie<br>• Kies materialen met een milieu vriendelijk profiel | Constructieve ontwerp principes<br>• Minimaliseer het materiaalgebruik<br>• Toepassen van materialen met een relatief laag eigen gewicht t.o.v. de overspanning<br>• Gebruik maken van lichte materialen<br>• Toepassen van componenten met lage schaduwkosten<br>• Gebruik maken van geprefabriceerde componenten |
| Voorbeelden<br>Verberg | Adaptief Ontwerpen | De levensduur op gebouw niveau verlengen door veranderingen in het gebruik mogelijk te maken. Het gebouw wordt dan voor meerdere functies worden ontworpen. Dit geeft de klant van het project meer toekomstige gebruikers als mogelijkheid. | Door middel van ontwerpen de totale levensduur een gebouw verlengen en daardoor de aantasting op de omgeving verminderen. | Functionele ontwerp principes<br>• Het ontwerp is geschikt voor het faciliteren van meerdere functies<br>• Reduceer de hoeveelheid verticale elementen die een belemmering vormen voor de indelingsvrijheid | Constructieve ontwerp principes<br>• Pas extra draagvermogen bij de vloeren toe<br>• Zorg voor voldoende, 3 meter, vrije vloerhoogte<br>• Brandveiligheid en akoestische eisen zijn functie afhankelijk (woning maatgevend)<br>• Gebruik maken van kolommen<br>• Maak gebruik van grote vloeroverspanningen van minimaal 7 meter |

**Koning I Willem College**

**Architect**
Nieuwe Architecten

**Type gebouw**
Multifunctioneel
Onderwijsgebouw

**Omschrijving**
Nieuwe Architecten heeft een gebouw ontworpen waarin volledige indelingsvrijheid wordt gerealiseerd door de indeling in grids van acht bij acht meter. Robuuste, in het oog springende gelamineerde houten kolommen vormen samen met de gelamineerde houten liggers de hoofddraagconstructie. Vanwege de de grootte van het grid is er gekozen voor vloeren van kanaalplaten met een druklaag, zodat ook de vloer samen met de houten kruizen de stabiliteit van het gebouw verzorgt. Hierdoor ontbreekt het in het gebouw verder aan stabiliteitsvoorzieningen die het gebruik kunnen beperken.

**Superloft Toren**

**Architect**
Marc Koehler

**Type gebouw**
Woongebouw

**Omschrijving**
De Superloft Toren in Hoorn krijgt een vaste drager en flexibele invulling, zodat de lofts voortdurend kunnen worden aangepast aan veranderende behoeften en levensstijlen. De toren zal worden uitgevoerd in een prefab betonskelet. Het skelet is een CD20 systeem. Dit is een systeem met heel dunne (24 cm) in beide richtingen voorgepannen prefab betonvloeren en kolommen van prefabbeton. De overspanningen in het project zijn 8,1 meter en alle woningscheidende en binnenwanden zijn uitgevoerd in metalstud. Daarnaast blijft de dragen van beton gescheiden van de installaties en leidingen.

**Het CD20 systeem kan ook worden uitgevoerd met remontabele verbindingen**

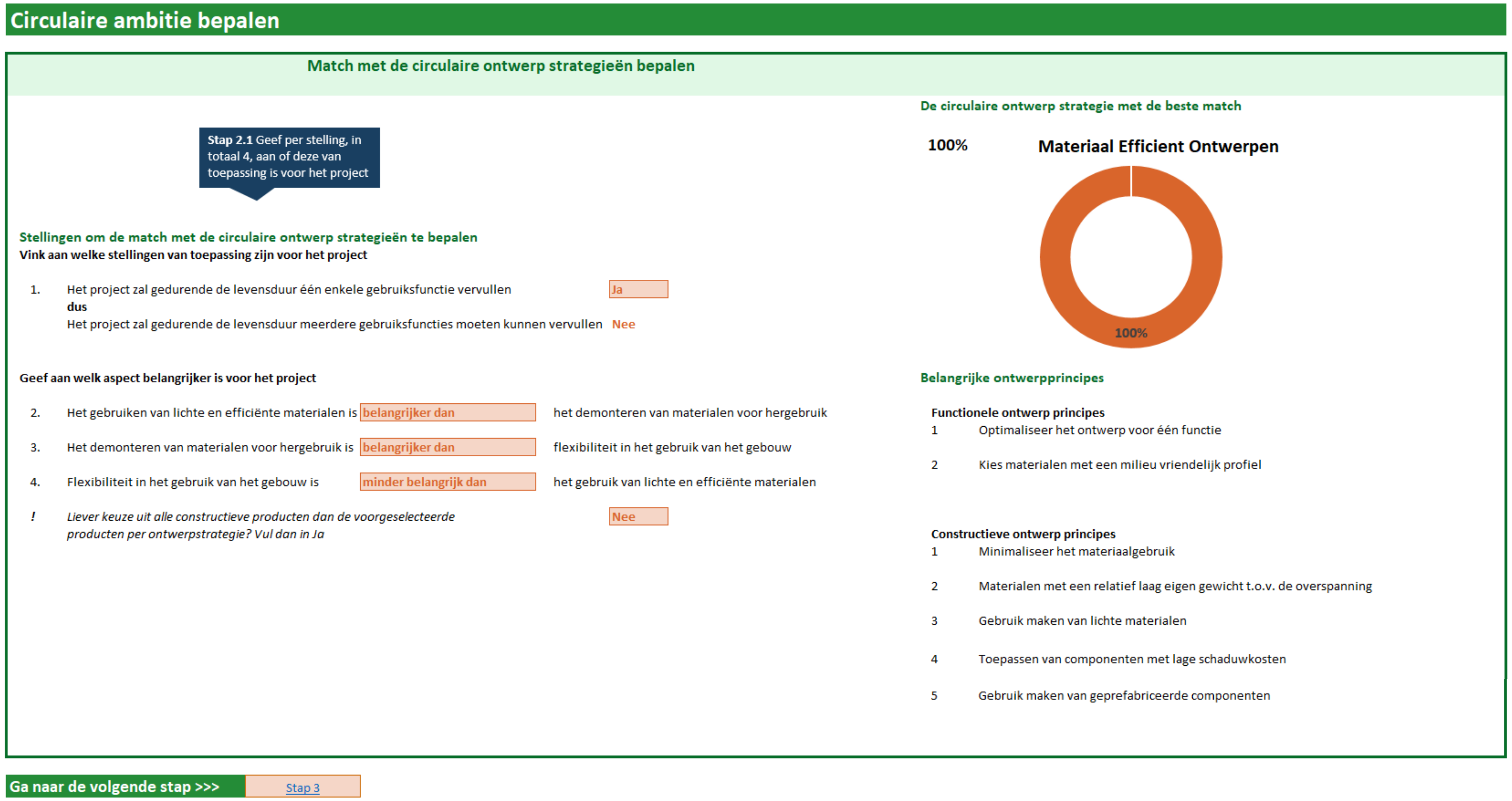
| | Circulaire ontwerpstrategie | Omschrijving | Relatie met de Circulaire Economie | Ontwerp principes | |
|---|---|---|---|---|---|
| Voorbeelden<br>Bekijk | Losmaakbaar Ontwerpen | Het ontwerpen van een demontabel gebouw, waardoor de gebruikte producten kunnen worden hergebruikt.<br>Dit betekent dat wanneer de klant de levensduur van het project wil verkorten, er geen waarde van materialen verloren gaat. Het ontwerp kan vervolgens op een andere locatie opnieuw worden opgebouwd. | Door middel van ontwerpen kan de levensduur van materialen worden verlengd Hierdoor wordt de aantasting op de omgeving verminderd omdat de materialen langer in de keten worden behouden. | Functionele ontwerp principes<br>• Kies componenten geschikt voor het losmaken van een constructie<br>• Reduceer het gebruik van verschillende type componenten<br>• Bouwlagen met een andere levensduur moeten gescheiden blijven | Constructieve ontwerp principes<br>• Droge verbindingen zoals schroef en bout verbindingen<br>• Gebruik maken van geprefabriceerde componenten<br>• Rekening houden met de toepasbaarheid op de bouwplaats<br>• Minimaliseer het gebruik van verschillende componenten<br>• Bouwlagen (constructie, installaties, afwerking etc.) gescheiden houden<br>• Toegankelijk houden van de verbindingen voor het uit elkaar halen |

**Ga naar de volgende stap >>>** Stap 2

### Step 2: Define the matching circular design strategy

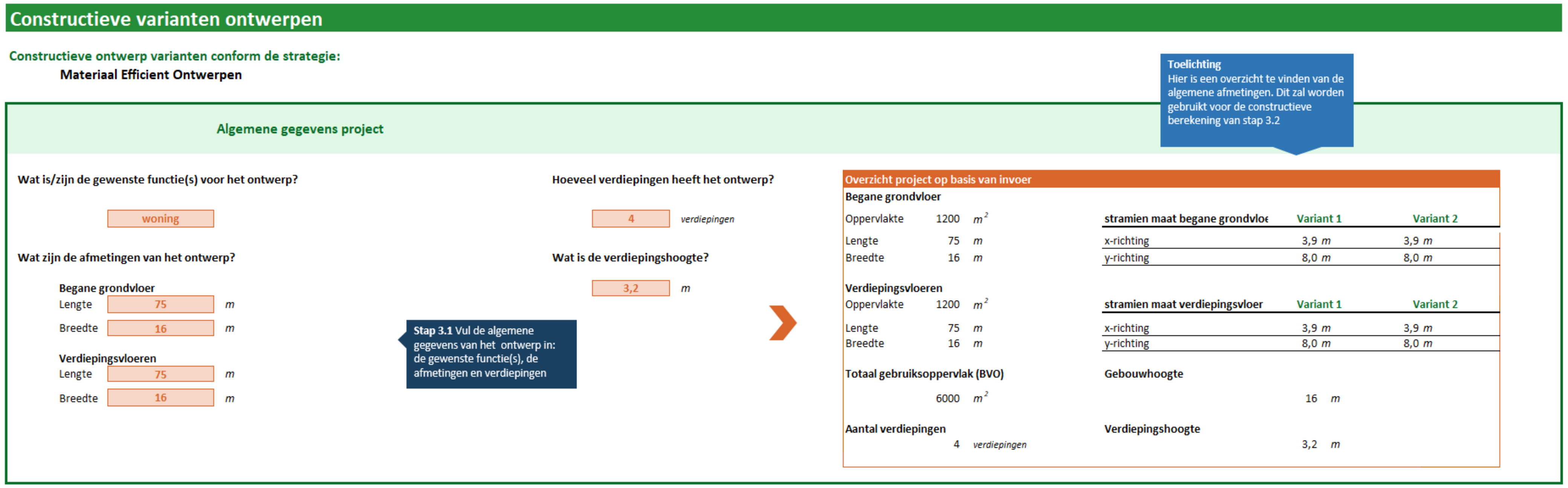
The second step of the design tool is to match one of the circular design strategies with the project. Each circular design strategy has key characteristics that define the strategy and have impact on the design of the load-bearing structure. The design tool presents four statements to investigate the preferences of the project. The user is requested to state which design principles are more important. If the four statements are filled in, on the left side the functional and technical design principles appear.

For the case study Ambachtslaan Veldhoven the client aims to develop a sustainable residential building. The project will be specifically designed for housing of people with a disability, meaning the building will serve one function. Additionally, the project aims to apply biobased materials. In the end this leads to the matching design strategy Design for Material Efficiency.




### Step 3: Create structural design variants

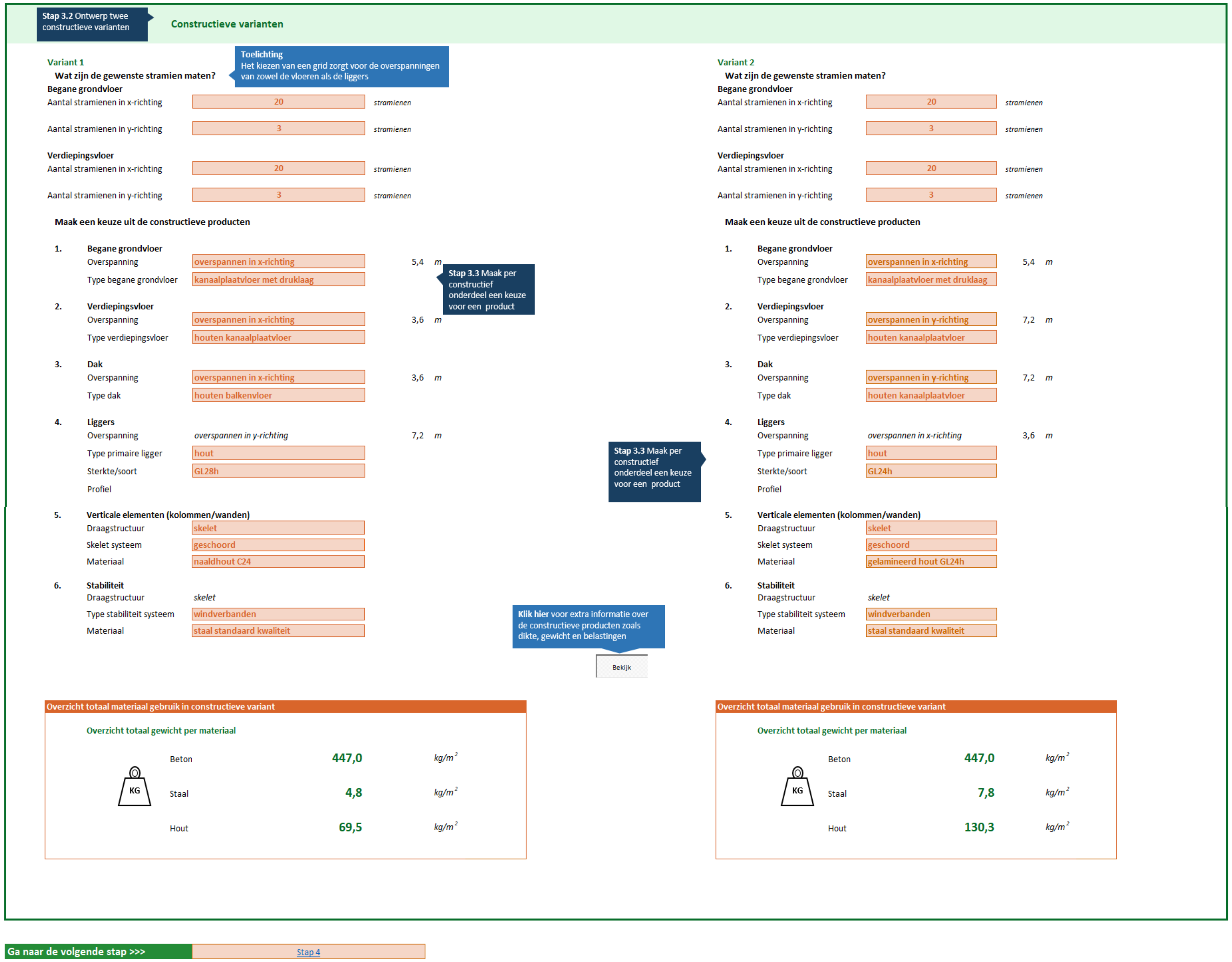
The required input before choosing the structural building components is the function and geometry of the design. By filling in the requested information on the left, at the right an overview of the project based on the input is presented. After checking the input, the creating of the structural design variants can start. To start the calculations of the chosen structural building components, the grid size should be defined. As discussed in section 6.1.1.1 the grid size influences the span of both the floors and beams.



It appeared that especially the span of the floor system has a large influence on the final environmental impact. It is favoured to decrease the span. However, the sizes should be fit the floorplan of the design, for instance columns in the middle of the living room is not desirable. For the Ambachtslaan the suitable grid is filled in the design tool. This results in a span of almost 4 meters in the x-direction and 8 meters in the y-direction. In both directions the columns can either be integrated in the partitions walls or separating walls.

The geometry and grid size are defined, so the structural building components can be selected. By creating two structural design variants, the user can compare different design options and the impact of the made choices. The vision of the client stated clearly to apply biobased materials. Therefore, for both variants the timber hollow core slab floor with a timber frame is applied. To explore the different option in design variant 1 the beams are composed out of GL28h timber and the columns out of softwood C24. The higher strength class for the beams is chosen as the span is larger (7,2 meters). For the design variant 2 for both the beams and columns GL24h is chosen. In this design variant the beams have a smaller span (3,6 meters), but the vertical loads are higher due to the floor span (7,2 meters) therefore the stronger GL24h is applied instead of the softwood. The two design variants are filled in in the design tool.

Lastly, after selecting the structural building components an overview is presented that indicates the amount of concrete, steel and timber in the design variant.



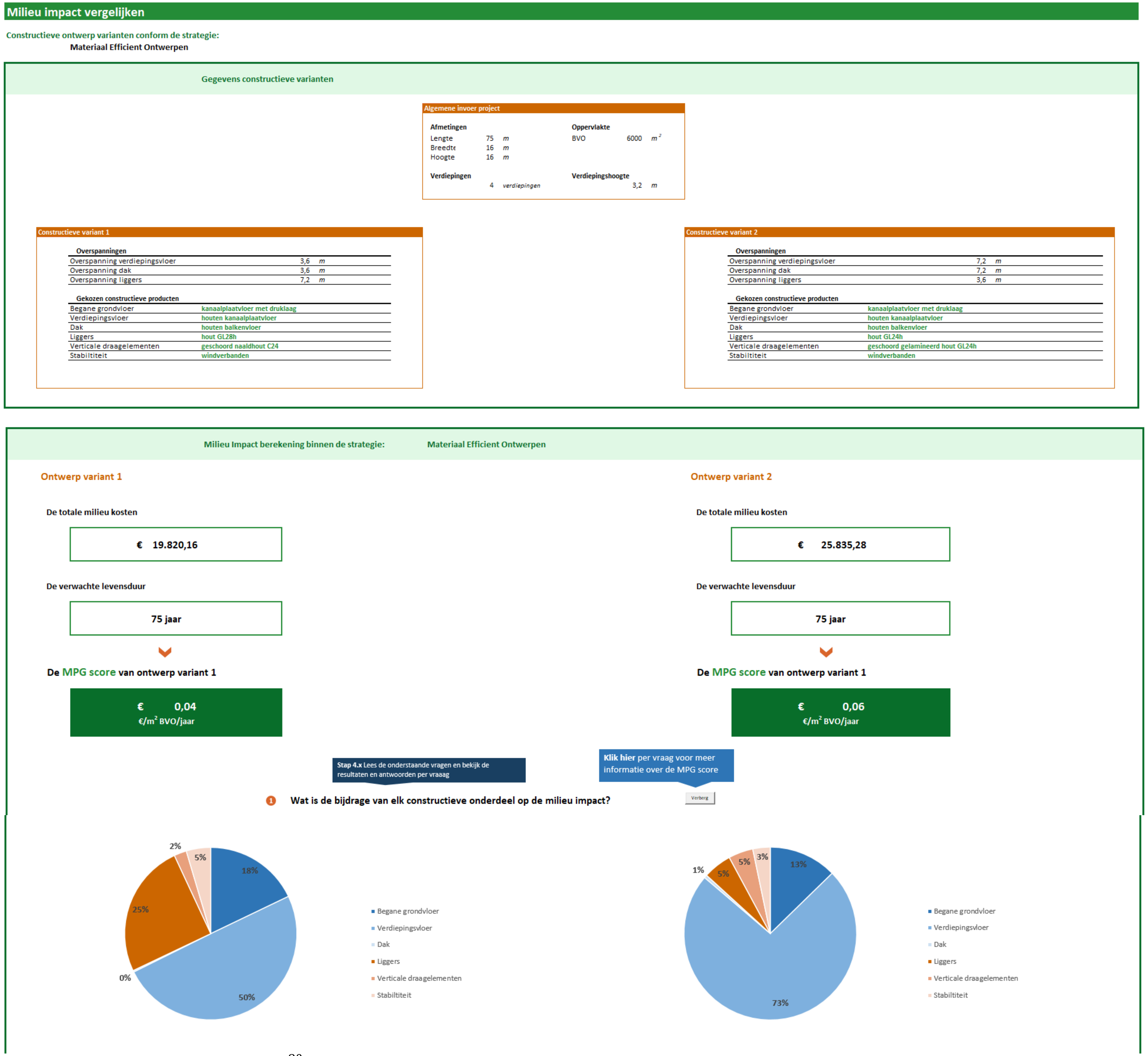
**Step 4: Compare the environmental impact**

The fourth step in the design tool is comparing the environmental impact of the choices made for the structural design variants. Stated in *step 0* the tool will first compare the two design variants of the matched circular design strategy. Nevertheless, investigating how another circular design strategy can be used to influence the environmental impact can also be valuable. Thus, the fourth step is divided into two sub-steps.

*Step 4.1: Comparison of the environmental impact of the chosen circular design strategy*

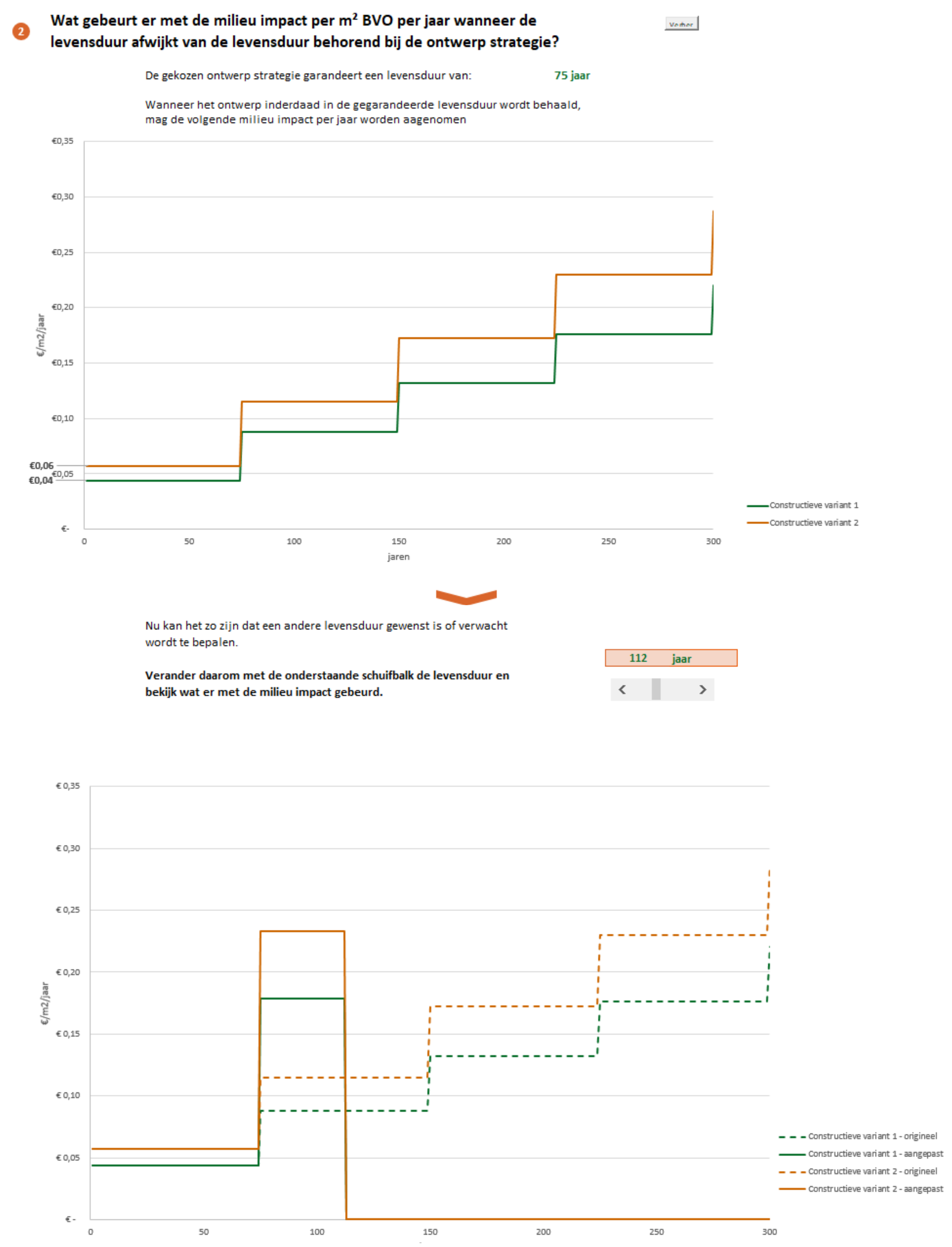
Firstly, an overview is presented of the two created structural design variants. The user can quickly check whether this is complete and continue with the assessment of the environmental impact.

For both design variants the total environmental costs, expected lifespan (based on the chosen strategy) and final MPG are showed. Subsequently, the user can gain more information about the contribution of the chosen structural building components to the total MPG, illustrated in the two circle diagrams on the right. Similar with the general results, the floor system has the largest contribution. In the design variant 2, with the floor spanning 7,2 meters, the storey floors are responsible for 73% of the MPG.



The environmental impact calculation leading to the MPG, consists of the environmental data and the expected lifespan. In section 5.2.2 the modification of the expected lifespan per circular design strategy has been introduced. The design strategy DfME chosen for the Ambachtslaan does not adjusts the expected lifespan. Thus, the used lifespan is 75 years, based on the residential function. Therefore, the graph indicates a jump after every 75 years. The environmental impact increases as if the building would be 'redeveloped' from scratch.

Though, the design tool aims to create awareness at the user by illustrating what will happen when the expected lifespan is not reached. The user can adjust the expected lifespan and experience the caused change in the MPG. An increasement in the environmental impact is visible as the expected lifespan is reduced. This is because the environmental impact will be spread over a shorter amount of time.



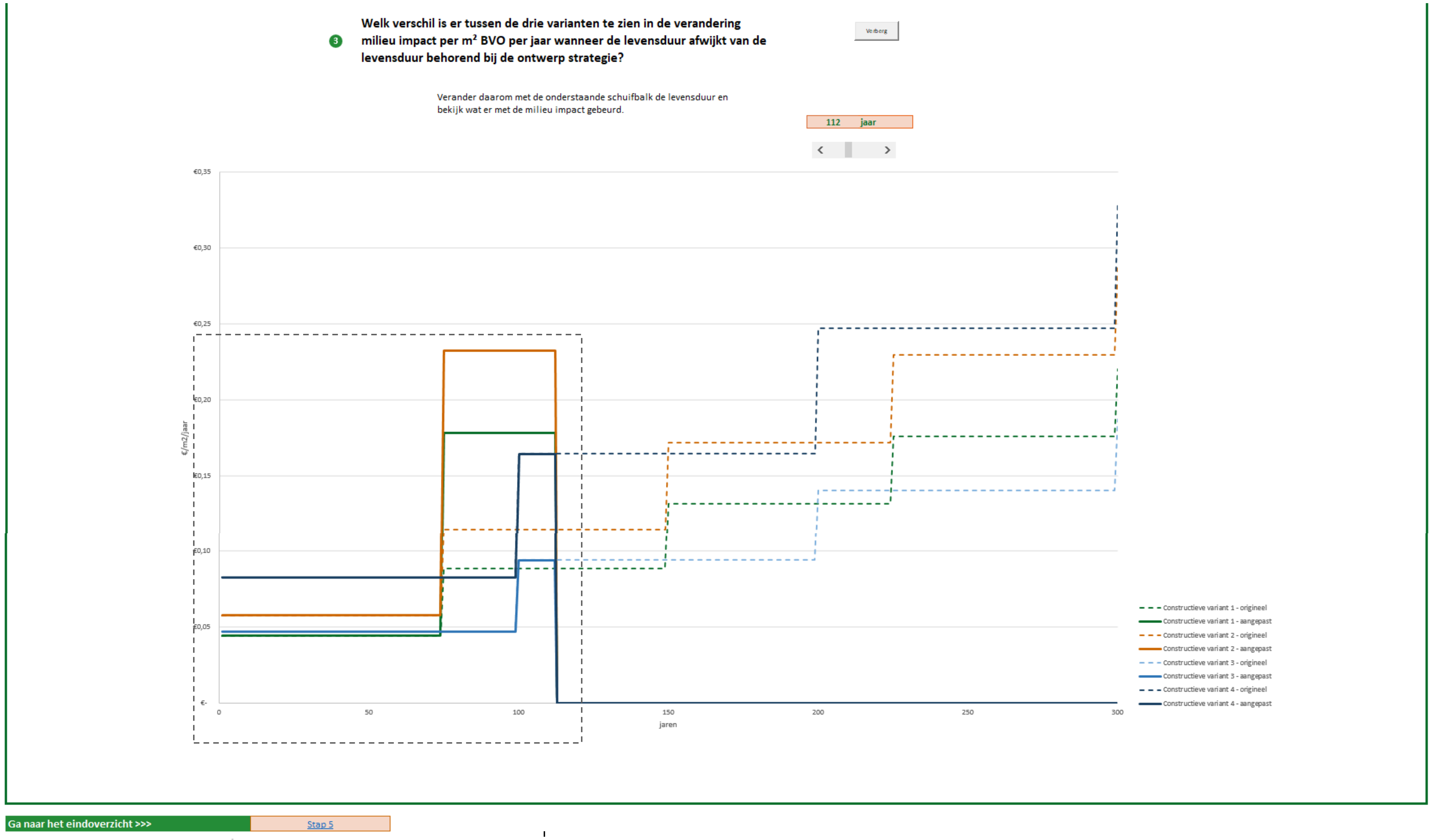
*Step 4.2: Comparison of the environmental impact of an additional circular design strategy*

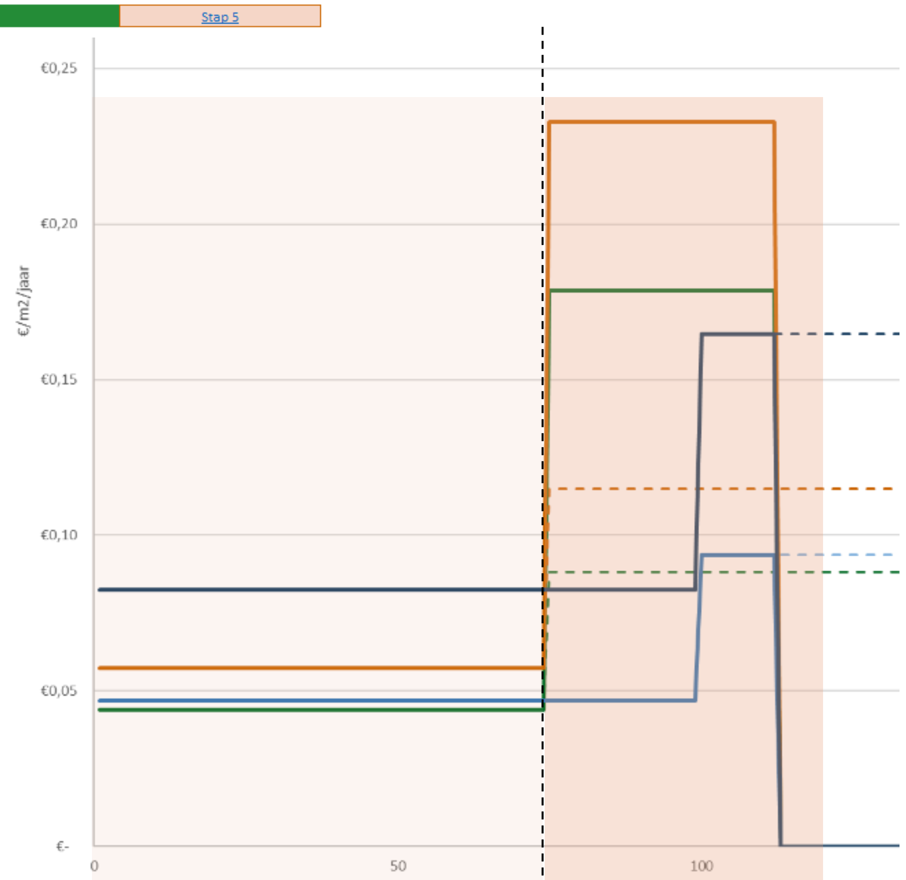
Each circular design strategy integrated in the design tool influences the design of the load-bearing structure design and environmental impact calculation in a different way. Comparing the design variants of two circular design strategies is valuable for the design process. The consequences of the design choices will become clearer. The design tool asks the user which circular design strategy is interesting for the project to compare. Next, two additional design variants are composed and the resulting environmental impact can be evaluated. For the Ambachtslaan project the circular design strategy Design for Disassembly, DfD, is chosen for the comparison. The project is designed with a standard grid and can also be hosted at another location if requested.

The design variants, in total four now, can be compared on the material usage and MPG. Subsequently, as introduced in *step 4.1*, the user can investigate the impact on the environmental impact of the design when the expected lifespan is changed.

Zooming in on the figure presented in the tool, the two blue lines, corresponding the design variants of DfD, do not deviate from the planned environmental impact when adjusting the expected lifespan. This is because due to the possibility to deconstruct the building, the valuable structural building components can be maintained. Therefore, it is not needed to compensate the environmental impact over the adjusted lifespan.

For the Ambachtslaan project during the first 75 years the structural design variant of the DfME strategy has the lowest MPG. However, after the first 75 years the environmental impact of the first two variants increases (orange and green lines dotted) and the two design options of the DfD strategy become more interesting (dark blue and light blue lines dotted and continued). This shows that after a certain period of time a tipping point can arise which design variant is the most beneficial for the environment.
The tipping point is dynamic as it depends on the project specifics (function and geometry), the chosen strategy and the created design variants.

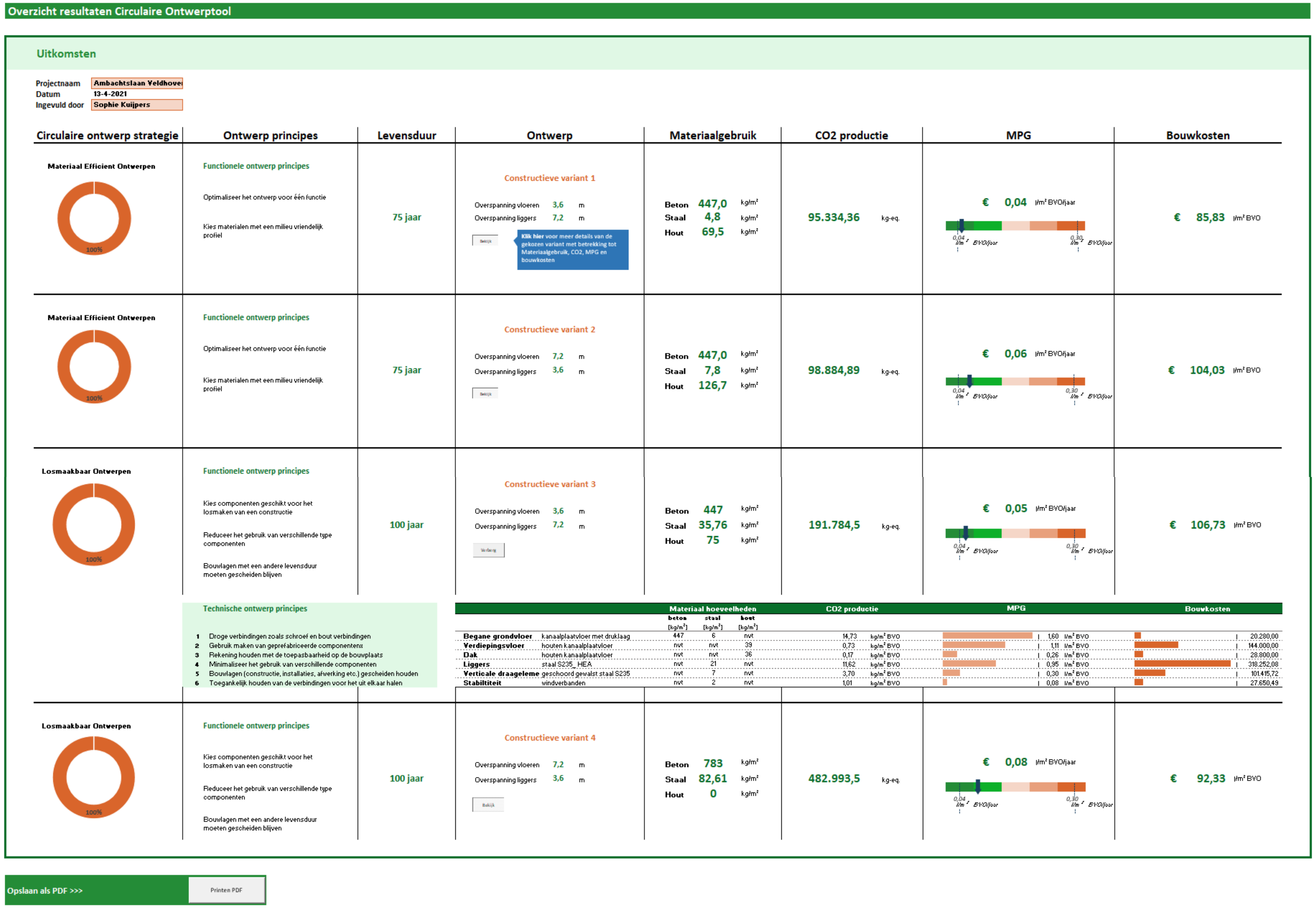


**Step 5: Summarise the outcome of the design tool**

The last step of the design tool presents the outcome. The sheet shows a matrix. In the columns of the matrix the most important factors for the environmental impact assessment of a design variants are stated. The factors material usage, $CO_2$ emissions, estimated service life and the building costs are shortly explained in section 5.4.2 and seen as influential indicators during a design process. In order to emphasize the boundaries and assumption for each design variants, the functional and technical requirements part of the chosen circular design strategy are stated. The user should be aware of the fact that the outcome of the environmental impact assumes the principles will be integrated.

The rows of the matrix present the four created structural design variants of two different circular design strategies. Additional information can be unfolded per design variant. The resulting matrix for the ccase study Ambachtslaan Veldhoven will be discussed in section 6.3.




The design tool creates step-by-step structural design variants and measure the environmental impact of each variant. The tool is an advice model to substantiated design choices during the preliminary design phase. It can help the design team of a project to find out which structural design variants are suitable and in line with one of the circular design strategies. This will contribute to the transformation towards a more circular building sector.

## 6.3 Results of the environmental impact calculations for two case studies

In this section the environmental impact for two case studies is investigated. The design tool is used to create and compare the different load-bearing structures in line with the ambitions of each project. The two case studies used to test the design tool are; (1) Ambachtslaan in Veldhoven and (2) Accelerator in Utrecht. Firstly, for each project a short description ambition and general layout of the design. Secondly, the reasoning behind the made design choices is substantiated and lastly the outcome is discussed. In section 6.2 the project Ambachtslaan in Veldhoven is used to explain the steps of the design tool, therefore only the outcome will be explained. *Remark*: the design tool is developed for the preliminary design phase to explore various design possibilities. The project Accelerator is in the construction phase. However, for the investigation of the design variants this is disregarded and the early design stage is the assumed time period.

### 6.3.1 Case study 1: Accelerator

#### 6.3.1.1 General description

The project is located on Utrecht Science Park. The desired function of the building, an office including laboratories, perfectly matches this environment. The client of the project is the development party, Kadans Science Partner. From the beginning of the project two companies had already contracted as the main tenants. Therefore, the wishes of both parties are integrated in the ambition of the project.
The vision for the project is to develop a multi-tenant building that allows interaction between the different users. The architect envisioned this as; *''the cross-fertilization between different users and disciplines leads to inspiration and innovations''*. The design team aims to create a generic building layout with large, column-free floor fields and a generous floor-to-ceiling height that facilitate various functions and tenants. The building consists of a lower part and higher part, both suitable for office space and laboratories. The structural design variants for the lower part of the building will be explored by using the design tool. In table 6.4 the input parameters are showed.

| Variable | Input | Unit | Comment |
|---|---|---|---|
| Length of the building (x-direction) | 39 | m | Rounded value |
| Width of the building (y-direction) | 42 | m | Rounded value |
| Number of storeys | 3 | - | |
| Storey height | 4,2 | m | Rounded value |
| Height of the building (z-direction) | 16,8 | m | Rounded value |
| Gross Floor Area | 6552 | $m^2$ | Calculated value |

**Table 6.4** General input parameters of Accelerator

### 6.3.1.2 Circular design strategies and design choices

The first step is to define the applicable circular design strategy. Based on the multi-tenant character and the desired flexible layout of the project, the first circular design strategy chosen is DfA. Secondly, the two structural design variants can be composed. The inputted geometry and the functional requirements lead to a floor span of 12,6 meters for both structural design variants. This is the largest possible span due to the loads on the floors. In the created design variants are presented in figure 6.7.

**Structural design variant 1**

| Span | | |
|---|---|---|
| Span of the storey floors | 12,6 | m |
| Span of the roof | 12,6 | m |
| Span of the beams | 5,4 | m |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Concrete hollow core slab floor |
| Roof | Concrete hollow core slab floor |
| Beams | Prefab concrete |
| Columns | Prefab concrete C30/37 |
| Stability | Frame with steel braces |

**Structural design variant 2**

| Span | | |
|---|---|---|
| Span of the storey floors | 12,6 | m |
| Span of the roof | 12,6 | m |
| Span of the beams | 5,4 | m |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Slimline floor |
| Roof | Slimline floor |
| Beams | Steel S235 |
| Columns | Steel S235 |
| Stability | Frame with steel braces |

**Figure 6.7** Structural design variant 1 and 2 conform the circular design strategy DfA

For the first structural design variant a well-known structural system is applied. Concrete hollow core slab floors with a concrete frame of beams and columns. The concrete frame is chosen because of multiple reasons. As the building consists of laboratories the fire resistance is critical. The material concrete has a high fire resistance. Additionally, the material is robust and easy to construct.

The second structural design variant includes relatively new floor systems, the slimline floor. Due to the possible different functions in the building, the services for the indoor climate, should be adjustable. The slimline floor allows the integration of cables and ducts in the floor system within reach. It chosen to combine the slimline floor with a steel frame, because of the connections between the steel floor beams and the beams and columns of the frame. Additional fire resistance measures are required such as wrapping the columns with gypsum.

An additional circular design strategy can be chosen to compare the outcome. The flexibility of the design is a key criterion for the client. The building layers should be accessible for future modifications. This can lead to the design solution of integrated releasable connections. Therefore, the DfD strategy is chosen for the comparison.

**Structural design variant 3**

| Span | | |
|---|---|---|
| Span of the storey floors | 12,6 | *m* |
| Span of the roof | 12,6 | *m* |
| Span of the beams | 5,4 | *m* |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Concrete hollow core slab floor |
| Roof | Concrete hollow core slab floor |
| Beams | Steel S235 |
| Columns | Steel S235 |
| Stability | Frame with steel braces |

**Structural design variant 4**

| Span | | |
|---|---|---|
| Span of the storey floors | 12,6 | *m* |
| Span of the roof | 12,6 | *m* |
| Span of the beams | 5,4 | *m* |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Slimline floor |
| Roof | Slimline floor |
| Beams | Steel S235 |
| Columns | Steel S235 |
| Stability | Frame with steel braces |

**Figure 6.8** Structural design variant 2 and 3 conform the circular design strategy DfD

For the DfD strategy two additional structural design variants are created. The only difference is the steel frame with the concrete hollow core slab floor instead of the concrete frame. The possible connection with a steel frame are more suitable for the deconstruction process compared with the prefabricated concrete frame. The combination of concrete hollow core slab floors and a steel frame is a common applied system.

### 6.3.1.3 Investigating the environmental impact of the design variants

The main goal of the design tool is to explore several structural design variants and compare their environmental impact. In table 6.5 the outcome of the four created structural design variants for Accelerator are presented. In Appendix E.1 the printout of the design tool can be found. This sheet also including the design principles that form the boundary conditions for the next steps in the development of the design.

| Design variant | Circular design strategy | Expected lifespan | Material usage [kg/m²] | $CO_2$-production [kg-eq.] | MPG [€/m²BVO/year] | Building costs [€/m²BVO] |
|---|---|---|---|---|---|---|
| Variant 1 | DfA | 150 years | Concrete: 1511,4<br>Steel: 39,40<br>Timber: 0,0 | 982.290,2 | **€0,13** | €79,13 |
| Variant 2 | DfA | 150 years | Concrete: 783,0<br>Steel: 191,0<br>Timber: 0,0 | 788.899,8 | **€0,07** | €155,05 |
| Variant 3 | DfD | 100 years | Concrete: 1438,0<br>Steel: 54,83<br>Timber: 0,0 | 880.897,6 | **€0,16** | €101,15 |
| Variant 4 | DfD | 100 years | Concrete: 783,0<br>Steel: 191,0<br>Timber: 0,0 | 788.899,8 | **€0,12** | €155,05 |

**Table 6.5** Output of the design tool for the case study Accelerator

From the table 6.5 it can be concluded that the design variant 2 of the circular design strategy DfA leads to the lowest environmental impact. The difference with the design variant 1 is caused by the chosen floor system and beams. In design variant 1 the concrete beams and floor system have a significant larger environmental impact, visible in the graphs of figure 6.9. However, the building costs of the environmental beneficial design variant 2 are almost twice as much as the design variant 1.

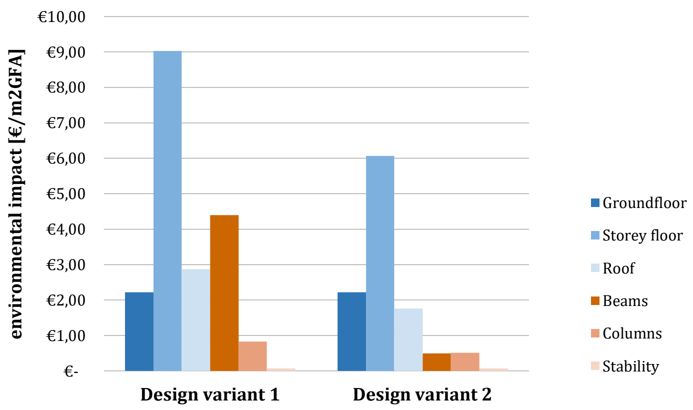



**Figure 6.9** Environmental impact per structural building component of structural design variant 1 and 2

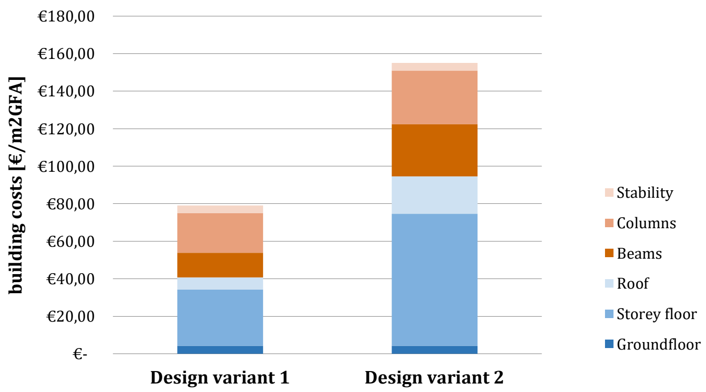



**Figure 6.10** The contribution of each structural building components to the building costs

The environmental impact, MPG, of each design variant showed in table 6.5 assumes the design will follow the expected lifespan. However, in reality it often turns out that the end of the functional lifespan is not even reached. Therefore, the design tool can provide insight in the required adjustments of the MPG if the lifespan is shortened, explained in section 6.2 in *step 4*.

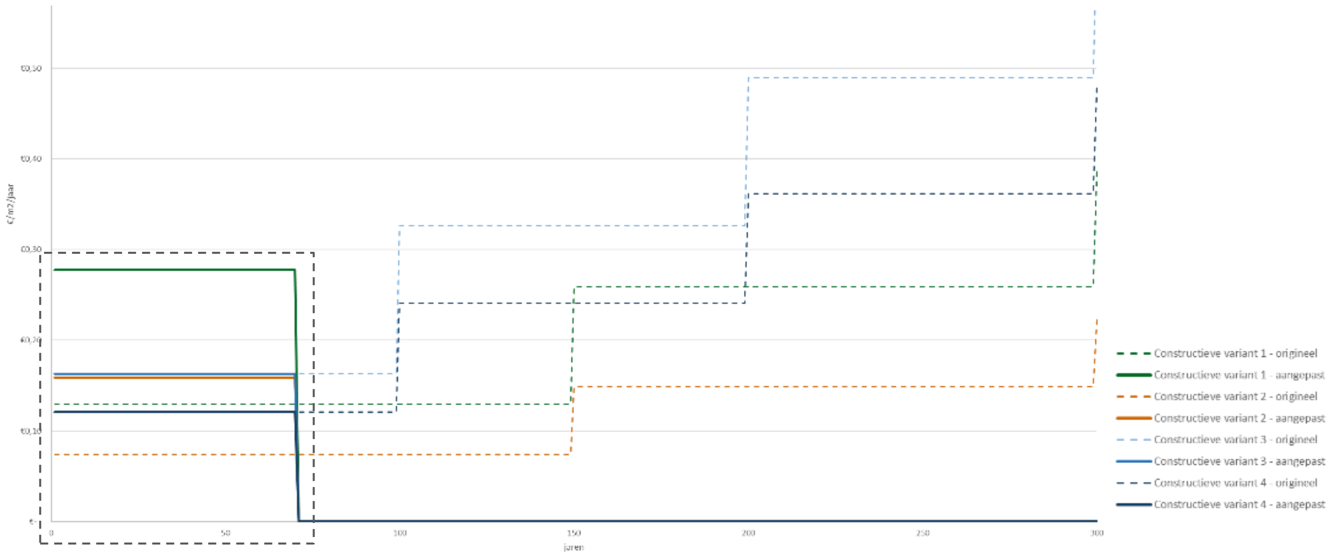



**Figure 6.11** Environmental impact of the four structural design variants over a time period of 300 years

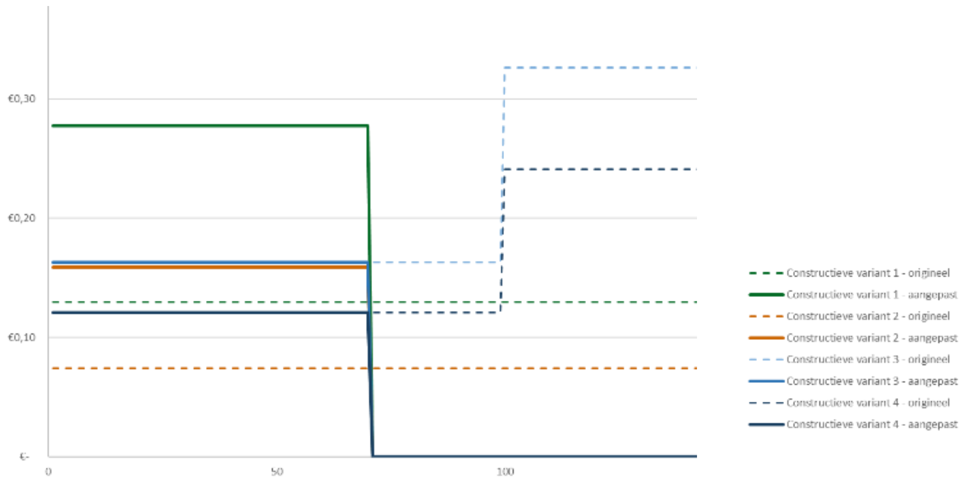



**Figure 6.12** Adjusted environmental impact due to deviating from the expected lifespan

Figure 6.11 present the situation if the lifespan is estimated at 70 years. In this new scenario the most environmental advantageous design variant is no longer design variant 2, but the design variant 4 belonging to the circular design strategy DfD. Both blue lines (light blue design variant 3 and dark blue design variant 4) do not deviate from the dotted line, due to the possibility to deconstruct, explained in section 6.2 step 4. For the strategy DfA, the environmental impact is initially spread over 150 years, but should be compensate when the lifespan is adjusted to 70 years. These graphs should make the client aware of the potential loss of value when the lifespan is shortened.

### 6.3.2 Case study 2: Ambachtslaan

#### 6.3.2.1 General description

In section 5.4.1. the general description of the Ambachtslaan is given.

#### 6.3.2.2 Circular design strategies and design choices

In section 6.2 the design tool is step-by-step illustrated, where the Ambachtslaan is used as an example to fill in the requested information. Therefore, in figure 6.13 the four created structural design variants are presented. The substantiation for the design choices can be found in section 6.2.

**Structural design variant 1**

| Span | | |
|---|---|---|
| Span of the storey floors | 3,6 | *m* |
| Span of the roof | 7,2 | *m* |
| Span of the beams | 7,2 | *m* |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Timber hollow core slab floor |
| Roof | Timber hollow core slab floor |
| Beams | Timber GL28h |
| Columns | Timber C24 |
| Stability | Frame with steel braces |

**Structural design variant 3**

| Span | | |
|---|---|---|
| Span of the storey floors | 3,6 | *m* |
| Span of the roof | 7,2 | *m* |
| Span of the beams | 7,2 | *m* |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Timber hollow core slab floor |
| Roof | Timber hollow core slab floor |
| Beams | Steel S235 |
| Columns | Steel S235 |
| Stability | Frame with steel braces |

**Structural design variant 2**

| Span | | |
|---|---|---|
| Span of the storey floors | 7,2 | *m* |
| Span of the roof | 7,2 | *m* |
| Span of the beams | 3,6 | *m* |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Timber hollow core slab floor |
| Roof | Timber hollow core slab floor |
| Beams | Timber GL24h |
| Columns | Timber GL24h |
| Stability | Frame with steel braces |

**Structural design variant 4**

| Span | | |
|---|---|---|
| Span of the storey floors | 7,2 | *m* |
| Span of the roof | 7,2 | *m* |
| Span of the beams | 3,6 | *m* |

| Chosen structural building components | |
|---|---|
| Groundfloor | Concrete hollow core slab floor incl. compression layer |
| Storey floor | Slimline floor |
| Roof | Slimline floor |
| Beams | Steel S235 |
| Columns | Steel S235 |
| Stability | Frame with steel braces |

**Figure 6.13** **Left:** the structural design variants of circular design strategy DfME **Right:** the structural design variants of circular design strategy DfME

#### 6.3.1.3 Investigating the environmental impact of the design variants

In table 6.6 the outcome of the four created structural design variants for the Ambachtslaan are presented. The printout of the design tool is illustrated in section 6.2 *step 5*.

| Design variant | Circular design strategy | Expected lifespan | Material usage [kg/m²] | $CO_2$-production [kg-eq.] | MPG [€/m²BVO/year] | Building costs [€/m²BVO] |
|---|---|---|---|---|---|---|
| Variant 1 | DfME | 75 years | Concrete: 447,0<br>Steel: 7,8<br>Timber: 94,8 | 91.606,6 | **€0,04** | €88,07 |
| Variant 2 | DfME | 75 years | Concrete: 447,0<br>Steel: 7,8<br>Timber: 130,3 | 105.824,5 | **€0,06** | €107,02 |
| Variant 3 | DfD | 100 years | Concrete: 447,0<br>Steel: 21,56<br>Timber: 123,0 | 150.030,4 | **€0,05** | €112,26 |
| Variant 4 | DfD | 100 years | Concrete: 783,0<br>Steel: 84,69<br>Timber: 0,0 | 489.798,4 | **€0,08** | €97,02 |

**Table 6.6** Output of the design tool for the case study Ambachtslaan

The two differences between structural design variant 1 and 2 are the floor span and the chosen type of timber for the beams and columns. When comparing the environmental impact per design variant, represented in figure 6.15, it is clearly visible that the environmental impact of the storey floor in design variant 2 is larger. This design variant has a floor span twice as large as design variant 1. In section 6.1 the effect of a larger floor span is discussed in more detail. The other striking element is the difference in environmental impact of the chosen beams. This is not due to the type of timber, but again the span. In design variant 1 the beams span 7,2 meters compared with the span of 3,6 meters in design variant 2. Furthermore, the building costs of design variant 1 and 2 show a difference of €18,95 per m²GFA. Again, the span of the floor has the greatest effect on this difference.

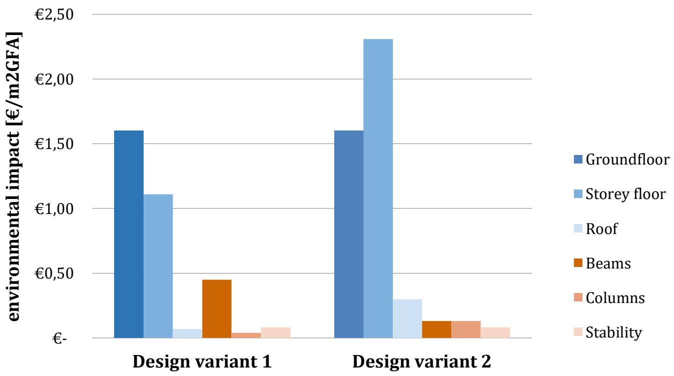



**Figure 6.14** Environmental impact per structural building component of structural design variant 1 and 2

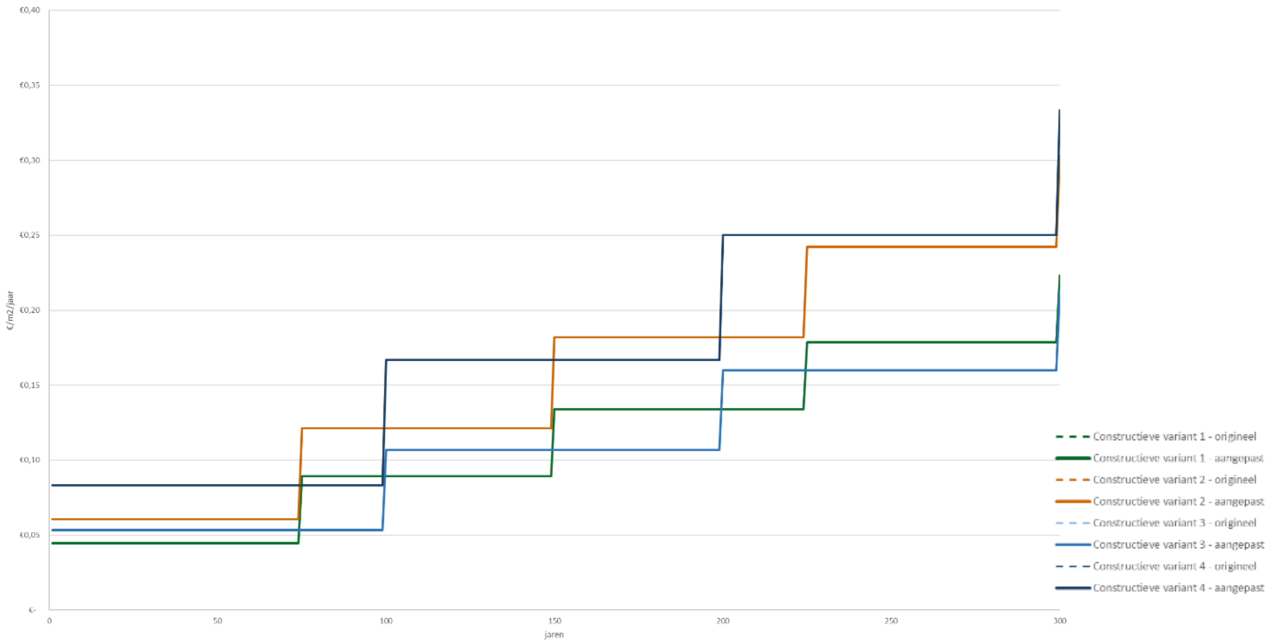



**Figure 6.15** Environmental impact of the four structural design variant over a time period of 300 years

In the case study for the Ambachtslaan the circular design strategy DfME and DfD are investigated. The DfME does not adjust the expected lifespan and is 75 years due to the residential function. After the 75 years the environmental impact grows, the jump in figure 6.15. This jump indicates the increase in environmental impact as if the building would be 'redeveloped'.

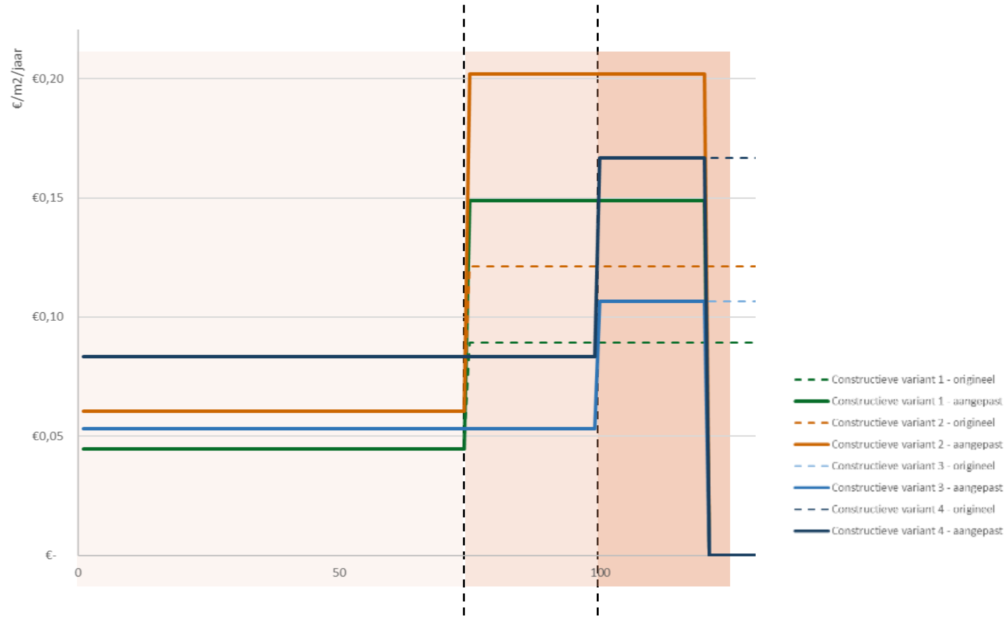



**Figure 6.16** Adjusted environmental impact due to deviating from the expected lifespan

If the expected lifespan of the project is assumed as 120 years, the scenario presented in figure 6.16 occurs. During the first 75 years the design variant 1 has the lowest environmental impact with the DfME strategy. From 75 until 100 years the design variant 1 and 2 increase significantly and the design variant 3 and 4 of the strategy DfD have the lowest environmental impact. After 100 years also the environmental impact of design variant 3 and 4 grows. From 100 until the assumed 120 years the design variant 3 has the lowest environmental impact, followed by design variant 1.

### 6.3.3 Conclusions

After this chapter the second sub-question can be answered:

**''How can the environmental assessment be used to steer the design variants towards the most advantageous environmental impact?''**

- A design tool in Excel is created to guide practitioners of the design process during the preliminary design phases towards including the environmental impact assessment as a key design criterion for the load-bearing structure. This means the user of the design tool should gather insight about design principles to include schematic structural design variants and the environmental impact of each variant. Therefore, the tool consists out of five steps that guide the user to the final outcome of the environmental assessment of four design variants:

  *Step 0*: Overview and explanation of the design tool
  Step 1: Create an understanding of the three circular design strategies
  *Step 2*: Define the matching circular design strategy
  *Step 3*: Create structural design variants
  *Step 4*: Compare the environmental impact
  *Step 5*: Summarise the outcome of the design tool

- The user can match the ambition of the project with one of the three circular design strategies. Based on this choice, the tool defines which structural building components are suitable for this strategy. Then, the user can compose the structural design variants. During this process several design choices are made and will influence the outcome of the environmental assessment. The following design choices have significant influence on the output of the design tool:

  **Grid size**
  The grid size defines the span in x-direction and y-direction of the floors and beams. The user can decide to either create large floor spans, reducing the number of required vertical elements or smaller floor spans, increasing the number of required vertical elements. The results of the design tool showed that the share of floors in the total environmental impact is leading. This means by reducing the required materials in the floor systems, thus smaller spans, the total environmental impact decreases, presented in figure 6.1. Even while the number of columns and beams increases, this effect is less influential on the final outcome.

  **Material Type**
  The second design choice that will affect the environmental impact is the type of structural building component chosen for the design variant. This is because of two reasons; (1) the environmental impact of the three main construction materials; concrete, steel and

timber and (2) the required quantity of each material. In table 6.1 the differences in shadow costs between structural building components out of concrete, steel or timber are illustrated. The amount of material needed for the design depends on the strength and specific weight of the three construction materials. Which material is the most suitable depends on the both the functional and technical requirements of the design.

- Each circular design strategy leads to a different expected lifespan. However, in reality changes can occur and the functional lifespan will not be reached. This will affect the MPG, as the environmental impact should be spread over a shorter period of time. Therefore, the design tool allows the user to gain more insight about what will happen if the expected lifespan deviates. This can create scenario's in which over a certain time period the most environmental beneficial structural design variants changes. The possible scenarios are project-specific. It is important that the user is aware of this consequence and should reflect on the assumed starting points for the project.

- The design tool presents the environmental impact of the structural design variants per circular design strategy. Each circular design strategy leads to design principles that are considered in the structural design variants. However, during the further development of the design the user should use these principles as the boundary conditions of the design. The environmental impact, MPG, of each design variant can be compared with the required amount of construction materials, the related building costs and $CO_2$ production. This outcome should form the start of the conversation between the client and design team for the exploration of the possibilities for the project.

# Chapter 7

# Discussion of the results

In this chapter the obtained results of the research are analysed. The input of the design tool was determined by performing a literature review, expert judgement and using available databases. The different steps taken in this research that led to the resulted output are investigated. First, the general ambition to tackle the stated challenges in the problem statement is discussed. Subsequently, the applied research method to define the circular design strategies, the relationship with the load-bearing structure and environmental impact calculation are reviewed. Lastly, the functionality of the created design tool in Excel, the research result, is investigated. The structure of this chapter is presented in figure 7.1.

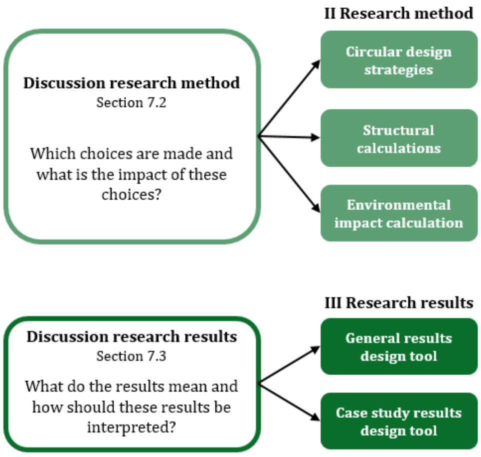



**Figure 7.1** Division in the discussion, discussing the research method and discussing the research results (own figure)

## 7.1 Research ambition

In the problem statement of this research, section 1.3, multiple challenges are stated. The rising attention for the Circular Economy [CE] created more awareness for the environmental impact of the building sector. In order to start the transition to a circular building sector, circular design strategies are introduced. Yet, the implementation of the principles of these strategies remain limited. Besides that, the circular design principles of each strategy influence the design of a project, the standard available environmental impact calculations do not consider the effect of these principles. Currently the environmental impact of a design is only assessed when the definitive design is obtained. However, the design choices that are made in the early design stages have major impact on the environmental impact of a project.

Thus, the main object of this research was to develop a design tool that can support the decision-making for the load-bearing structure design leading towards the lowest environmental impact. The design tool should make use of the design principles of circular design strategies. Additionally, the tool must be suitable for the preliminary design phases, as in this phase the decision-making is most impactful. Therefore, to reach the main objective of this research the following ambition has been developed:

1. Define a method to include the design principles of each circular design strategy that affect the load-bearing structure design and the environmental impact calculations. This research aims to combine two existing aspects in science, the design principles of circular design strategies and the structural and environmental calculations. Subsequently, the method introduces a way to connect these two aspects.

2. Develop a design tool which performs structural and environmental impact calculations in the preliminary design phase. Add the abovementioned method to the model to safeguard the implementation of circular design principles.

The result of this ambition is a design tool in Excel that creates structural design variants based on the matched circular design strategies and then assesses the environmental impact of each design variant. The user only needs to fill in the general geometry of the project and can start to explore the variation in environmental impact of the different structural design variants. This explorative character of the tool is key for the use of the tool in the preliminary design phase. The result of the design tool is an overview of the environmental impact (Milieu Prestatie Gebouwen [MPG]), material usage, $CO_2$-production and building costs per design variant. Additionally, the tool provides more insight about the influence of adjusting the expected lifespan and the most influential structural building components. This information can be used as a substantiation for design choices and strategies.

## 7.2 Research method

In this section the research method is discussed. This research method leads to the boundary conditions of the required design tool. The research method is divided into three parts, the circular design strategies, structural calculations and environmental impact calculations and will be separately analysed.

### 7.2.1. Circular design strategies

Circular design strategies transform the main principles of the CE into more specific design directions to stimulate the implementation of circular solutions. Two possible pathways are identified in this research:

1. Extending the lifespan of the building and/or its components by design
2. Efficient use of material by design

From these two pathways, the circular design strategies Design for Adaptability [DfA], Design for Disassembly [DfD] and Design for Material Efficiency [DfME] have emerged. Subsequently, for each strategy the impact on the load-bearing structure design is investigated. The functional requirements of the strategy led to more detailed technical requirements that influence the design possibility for the load-bearing structure. This resulted in specifications for the suitable structural building components, such as the usage of only prefabricated components, limitations on the minimal span for the floor and beams and more technical requirements. The additional design principles of each strategy are integrated in the design tool. Examples of the integrated principles are that certain structural building components disappear from the option list when a certain strategy is chosen, or the user is remembered to increase the floor span to the minimal span (in case of DfA).

The additional requirements form the boundary conditions of the design and are assumed to be integrated. However, the design tool does not indicate the level of integration of the design principles. Meaning a structural design variant is assumed to 'perfectly' fit the circular design strategy. Yet, for instance in practice some load-bearing structures are more adaptable, releasable or material efficient than others, but this nuance is not included in the design tool. Besides whether the advantages of a circular design strategy are actually used in practice also remains uncertain. If a load-bearing structure that can be deconstructed multiple times, ends up demolished without being deconstructed and constructed once, the value of the principles is not deployed.

Furthermore, as stated in the introduction of this research, the CE is a hot topic. This results in a lot of different points of view. This became clearer when comparing the vision of the structural engineers which structural building components suit each circular design strategy with the technical characteristics of a material. For instance, the application of concrete hollow core slab floors in the circular design strategy DfME. Due to the design of the element, the material is applied on the places where the strength is needed. In this way unnecessary material is avoided and structural engineers argued the structural building component as material efficient. However, the DfME also emphasizes the use of components with low shadow costs (i.e. environmental impact). Of all available concrete structural building components, the concrete hollow core slab floor is indeed the most environmentally friendly. Yet, compared with other available components, this environmental impact might be less advantageous and a different conclusion can be drawn.

Lastly, the research investigated the impact of the circular design strategies on the environmental impact calculations. The calculation consists of two elements, the Life Cycle Assessment [LCA] and the expected service life. How the circular design strategies impacted the outcome of the environmental impact calculations will be discussed in more detail in section 7.2.3.

### 7.2.2 Structural calculations

The structural calculations are made to create the Bill of Materials [BoM]. In this BoM the quantity of each used material is included. This information is required for the environmental impact calculations. The structural calculations that are performed conform to the BHH-model and the rules-of-thumbs (Westenbrugge-Bilbardie & Peters, 2016; Hofkes et al., 2004). The BHH-model is used as the main reference for the structural calculations. When comparing the calculated beams and columns with the rules of thumbs of Hofkes et al. (2004), the BHH-model rules lead to significantly larger dimensions for most structural building components. In the case of the beams, the outcome deviated extremely, varying between 60%-100%, from the design based on the BHH-model. For columns the difference is less extreme, 10%-30%. The BHH-model is based on the experience of structural engineers in practice, while the rules-of-thumbs are mainly based on the theory. The beams loaded on bending are most sensitive to a load iteration. Therefore, in practice the beams might be designed more conservative in order to reduce possible risks. This can clarify the differences between the rules of thumbs of Hofkes et al. (2004) and the BHH-model of Westenbrugge-Bilbardie and Peters (2016).

In the case of the two timber floor systems, timber hollow core slab floor and beamed floor, the BHH-model did consist of sufficient information. Therefore, the Finnwood software is used. However, no other calculation rules are used to compare the outcome of this tool. So, this can either result in a too low or too high material quantity.

The scope of this research is the load-bearing structure. Thus, the BoM exclusively consists of structural building components. However, each created structural design variant requires varying additional measures. For instance, a concrete structure is fire resistant, while for steel and timber additional materials are needed to ensure fire safety. The same for the acoustic requirements, timber floor systems have a very low environmental impact, however more insulation is needed to reach the same level of soundproofing compared with a concrete floor. This will increase the required amount of material thus leading to a higher environmental impact.

Due to the simplified structural calculations, complex geometries are not yet included in the design tool. The design tool suits simple rectangular shaped buildings up to 6 storeys. The tool is developed for the most common constructions. If more complex designs are desired, the structural calculation should be further developed in more detail.

### 7.2.3 Environmental impact calculations

In this research the environmental impact calculations are performed by a LCA with the use of environmental data from the Nationale Milieu Database [NMD] and spread the environmental impact over the expected service life of the design variant. Firstly, the results of the LCA will be analysed. Secondly, the effect of the adjusted expected lifespan will be discussed. Thirdly, the used environmental data of the NMD will be reflected.

#### 7.2.3.1 Effect of the adjusted LCA

Currently, the following phases form the system boundaries of the LCA for the load-bearing structure: the production phase (A1-A3), construction phase (A4-A5), end-of-life phase (C1-C4) and the reuse, recovery, recycling phase (D), presented figure 5.1. This determination method is based on the current Linear Economy [LE]. However, when a circular design strategy is followed, the determination method might not be sufficient anymore. Therefore, this research investigated how the circular design principles of the strategies modify the LCA. For both the DfA and DfME circular design strategy the LCA modules impacting the load-bearing structure are not adjusted. For the circular design strategy DfD the deconstruction module (C1) and transport to site (C2) are repeated multiple times in order to allow deconstruction during the expected service life.

| Design for Adaptability | Design for Disassembly | Design for Material Efficiency |
|---|---|---|
| • Production of virgin material (A1-A3)<br>• Transport to the site (A4)<br>*Period of use*<br>• Demolition of the building (C1)<br>• Transport to the processing site (C2)<br>• Waste processing, including recycling (C3/D)<br>• Disposal of materials (C4) | • Production of virgin material (A1-A3)<br>• Transport to the site (A4)<br>*Period of use*<br>• Deconstruction of the building (C1)<br>• Transport to the processing site (C2)<br>*Period of use*<br>• Deconstruction of the building (C1)<br>• Transport to the processing site (C2)<br>*Period of use*<br>• Deconstruction of the building (C1)<br>• Transport to the processing site (C2)<br>• Waste processing, including recycling (C3/D)<br>• Disposal of materials (C4) | • Production of virgin material (A1-A3)<br>• Transport to the site (A4)<br>*Period of use*<br>• Demolition of the building (C1)<br>• Transport to the processing site (C2)<br>• Waste processing, including recycling (C3/D)<br>• Disposal of materials (C4) |
| **Shadow costs**<br>€8,50/$m^2$GFA | **Shadow costs**<br>€9,16/$m^2$GFA | **Shadow costs**<br>€8,50/$m^2$GFA |
| -% | **+7,7%** | -% |

**Table 7.1** Included LCA modules per circular design strategy and the resulting shadow costs

In the table 7.1 the included modules are presented and the resulted shadow costs (in €/$m^2$GFA) of a design variant based on the input parameters introduced in section 6.1. The design variant is composed of slimline floors with a steel frame with both a floor and beam span of 7,2 meters. In this way this structural design variant is in line with the principles of the three circular design strategies. However, this is not the structural design variant that will lead to the lowest environmental impact.

The added modules C1 and C2 for the DfD strategy result in a small increase of the shadow costs. Compared with the other two circular design strategies of which the modules of the LCA are not adjusted, an increasement in the shadow costs of 7,7 % is noted, as stated in table 7.2.

The production modules A1-A3 are responsible for 103% of the shadow costs compared with 3,6% of the modules C1 and C2. Therefore, the impact on the total outcome is limited. Yet, the effect of the circular design strategies is not only visible in changing the order and repetition of the LCA modules, but can also adjust the processes within each module. For example, the design strategy DfME focusses on limiting the materials used in the design and thereby targets the production module A1-A3. The challenge lies in how the different circular design strategies can be compared in an equal way. Modifying the existing LCA determination method into a new determination method that includes the effect of circular design strategies can be incomplete.

#### 7.2.3.2 Effect of the adjusted expected service life

For the environmental impact calculation resulting in the MPG, the retrieved shadow costs of the LCA can be spread out over the expected lifespan of the project. Logically, the longer the lifespan the lower the MPG. However, this is not how the determination method, to derive the MPG, works. The method states that for a new building project with sufficient explanation an extension of the service life can be assumed (SBK, 2017) . Which aspects should be addressed in this explanation is not defined by any regulations. In this research based on the additional functional and technical requirements of each circular design strategy a certain extended lifespan is assumed, illustrated in figure 7.2.

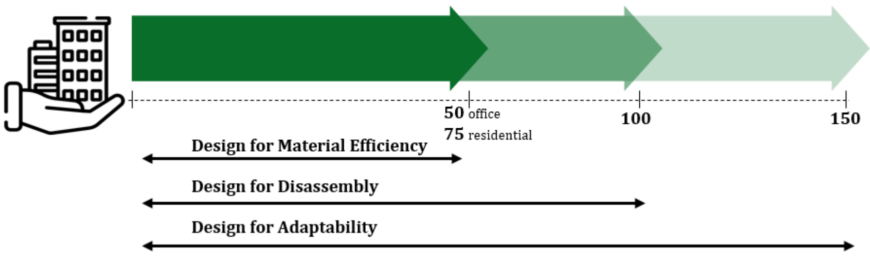



**Figure 7.2** Adjusted expected service life of the circular design strategies (own figure)

Based on the literature review and opinion of experts, it is difficult to determine whether the circular design principles provide an extension of 20, 40 or 80 years in the service life. That is why the extension has been determined in relation to the other strategies. The DfME strategy does not provide an extended lifespan, so the service life is based on the building function. The design strategy DfA ensures the longest extension and in between is the strategy DfD. The assumed extended service life is the functional lifespan of a building. Still, the technical lifespan of the used structural building components is often not reached.

In a research of W/E Adviseurs (2013) for the Nationale Milieu Database it is concluded to be careful and reserved when extending the expected service life of a building for the environmental impact calculations. Design principles that can prolong the lifespan should be quantitative substantiated. However, this validation is missing and estimations are made based on previous experiences. Working with these not quantitative substantiated estimations argues for caution, as the adjustments of the lifespan can have major impact on the MPG (W/E Adviseurs 2013). In the follow-up study of the W/E Adviseurs (2020) a qualitative calculation tool is developed to assess the allowable extension of the design. This research stated the following: *"design principles that extend the life expectancy of a building should ensure that the load-bearing structure in particular can function over a longer period, with a favourable effect on the MPG"* (W/E Adviseurs, 2020). A comparison is made between the MPG of a residential building with an expected service life of 75 years and 125 years. The MPG of the foundation and load-bearing structure is reduced with 40% and the floors with 28% when the lifespan is prolonged, see table 7.2. Thus, again the importance of a valid either qualitative or quantitative calculation method is required to determine the extension of the service life when integrated design principles that prolong the life expectancy.

| *Residential building* | **MPG** | | |
|---|---|---|---|
| *Building layer/part* | *75 years* | *125 years* | *Reduction* |
| Foundation | 0,025 | 0,015 | -40% |
| Floors | 0,084 | 0,061 | -28% |
| Load bearing structure | 0,017 | 0,010 | -40% |
| Façade | 0,070 | 0,062 | -11% |
| Roof | 0,028 | 0,027 | -4% |
| Services | 0,263 | 0,263 | 0% |
| Built-in | 0,064 | 0,063 | -1% |
| Total | 0,551 | 0,501 | -9% |

**Table 7.2** The reduction in MPG per building layer with an extension of the service life from 75 years to 125 years (W/E Adviseurs, 2020)

In section 7.3 the effect on the environmental impact when adjusting the expected life span by choosing another circular design strategy will be discussed in more detail.

### 7.2.3.3 Effect of the environmental data

For the environmental impact the Nationale Milieu Database [NMD] has been used to collect all the environmental data. It is chosen to use only one database in order to remain consistent. The advantage of the NMD is that the environmental data is presented per one kilogram of material. For instance, the global warming potential and ozone depletion of one kilogram of steel. The outcome of the structural calculations is presented in kilograms per square meter (kg/m$^2$). Thus, the database fits well with the output of the structural calculations. Nevertheless, the current NMD is not transparent or complete. The made assumptions for the LCA are presented, such as the transportation distances, the percentage of recycling, incineration or disposal, however any type of substantiation is missing. Therefore, it is difficult or even tricky to interpret the results. Besides, not all materials and processes for structural building components are included in the database (or published publicly).

Another available database for the environmental impact of structural building components is NIBE.INFO. This database holds the information of a total structural building component instead of the separate materials and processes such as the NMD. In table 7.3 the comparison between the environmental impact of structural building components from the NIBE.INFO database and the combination of the structural calculations and NMD environmental data of the design tool. The material quantities of the design tool are adjusted to the used quantities in the NIBE.INFO calculations. However, the applied load on the floor systems of the products of the NIBE.INFO database is not stated. In table 7.3, significant differences between the two environmental impact databases stand out.

| Structural building component | Shadow costs [€/m²] | |
|---|---|---|
| *Type of floor system* | *NIBE* | *NMD* |
| Timber hollow core slab floor | €4,41 | €2,27 |
| Concrete hollow core slab floor | €5,55 | €7,22 |
| Slimline floor (Steel beams with prefab concrete slabs) | €5,78 | €5,91 |
| Concrete hollow core slab floor incl. concrete topping | €7,47 | €9,18 |
| In-situ concrete floor | €8,59 | €12,04 |

**Table 7.3** Shadow costs of the database NIBE.INFO and the Nationale Milieu Database

The timber hollow core slab floor component of the NIBE.INFO database also includes insulation and the glue between the timber elements. Yet, in the description of the product it is stated that 95,2% of the environmental impact is caused by the timber. The NIBE.INFO database does not state the source of the environmental data used, however the name of the environmental profile of the timber, 077, is similar with the profile of the NMD used in the design tool. This environmental profile includes the incineration of timber at the end-of-life, which has a significant impact on the total environmental impact of the timber structural building components. For the timber hollow core slab floor this effect means a reduction of 44%, see figure 7.3. It can be questioned whether this reduction is realistic.

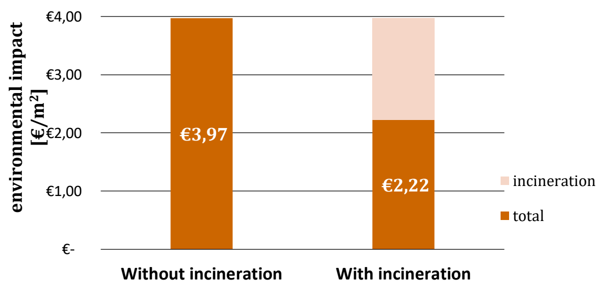



**Figure 7.3** Difference in shadow costs between timber with or without the incineration process

In table 7.2 another significant deviation is visible, the concrete hollow core slab floors. Here it appears that the NIBE.INFO database makes use of C45/55 concrete. The environmental data of the NMD applies to C30/C37 concrete. The environmental impact of concrete is dependent on the amount of cement. The higher the strength class, the more cement and thus the higher the environmental impact. However, the opposite effect appears in the analysis of both databases. Yet, it remains guesswork what causes the differences in results of the two databases. This illustrates the importance of transparency and substantiation of assumption in an environmental database.

## 7.3 Research results

This section will discuss the developed design tool. The resulting outcome and the functionality of the design tool will be discussed. The design tool is the mean to provide more insight on the environmental impact of the structural design variants. This allows the user to play with possible design choices and investigate the effect on the environmental impact.

### 7.3.1 Analysis of the results

#### 7.3.1.1 The structural design variants per circular design strategy

In section 6.1.2.1 – section 6.1.2.3 for each of the circular design strategies, DfA, DfD and DfME, two structural design variants are created that lead to the lowest environmental impact (figure 6.4 – figure 6.6). The influential design choices leading to the lowest MPG are the grid size and type of material.

In figure 6.1 it is illustrated that structural design variants with a smaller floor span lead to a lower environmental impact. This is because of the significant contribution of the floor systems to the overall environmental impact. Thus, the first impactful design choice is the grid size. The material type is the second influential design choice. The resulting environmental impact of a structural building component is dependent on the required amount of material and the environmental profile of this material. The required amount of material is based on the structural characteristics such as the applied loads and the strength of the components. The environmental profile is based on the data from the NDM. Table 6.1 emphasizes the significant differences between environmental profiles of the components, the timber hollow core slab floor leads to more than half of the shadow costs of concrete hollow core slab floor.

For each circular design strategy, a concrete/steel and timber structural design variant are composed (except for the timber design variant for DfA), in section 6.1.2.1 – section 6.1.2.3. Comparing the design variants in the same materials can provide more insight on the functioning of the three circular design strategies. In figure 7.4 the environmental impact of the concrete/steel design variants is presented and in figure 7.5 the timber design variants.

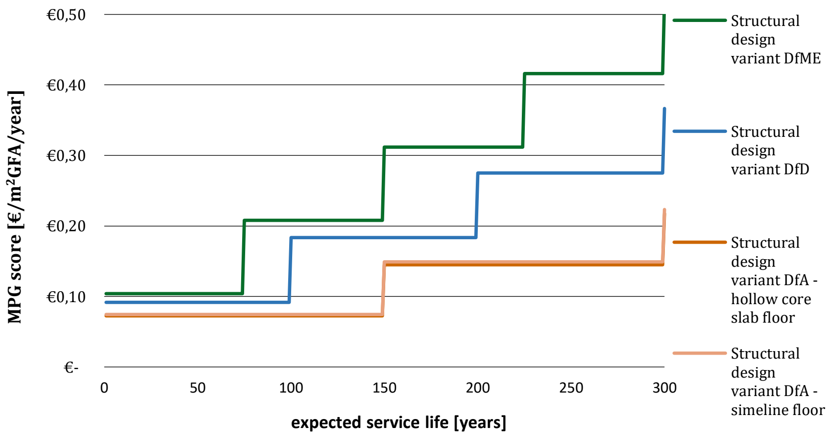



**Figure 7.4** The course of the MPG for the concrete/steel structural design variants

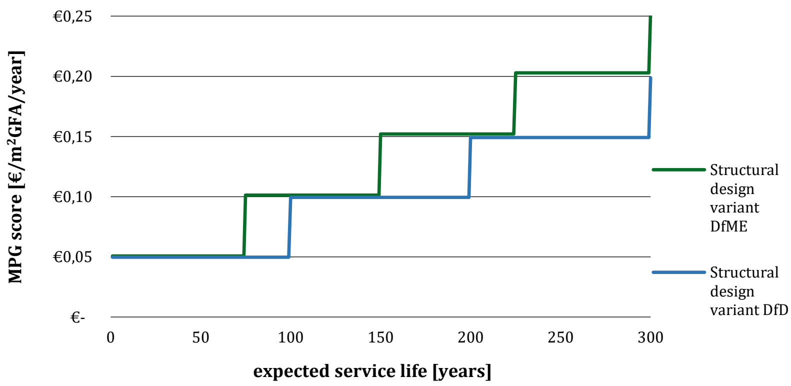



**Figure 7.5** The course of the MPG for the timber structural design variants

Both graphs in figure 7.4 and figure 7.5 present the longer the expected life span the lower the environmental impact will be. For the timber structural design variants the circular design strategy DfD leads to the lowest MPG and for the concrete/steel structural design variants the DfA circular design strategy.

However, in figure 7.6 the total kilograms of $CO_2$-equivalent show a different result. From this figure it can be concluded that the timber variant for DfME produces less $CO_2$-emissions and for the concrete/steel structural design variant instead of the design variants of DfA, the options of the DfME and DfD circular design strategies are more interesting.

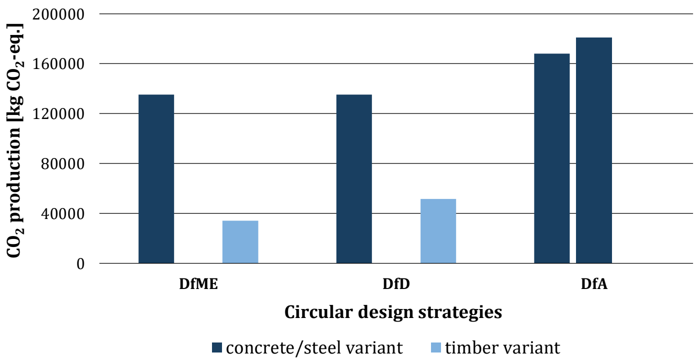



**Figure 7.6** The produced quantity of $CO_2$ emissions per structural design variant

The goal of the design tool is to increase the implementation of circular design solutions that decrease the impact on the environment. Although the structural design variants of the DfME lead to a higher MPG, the total produced $CO_2$-emissions are lower and thus have less impact on our living environment. This shows that simply looking at the lowest MPG can be insufficient. It should be noted that the produced $CO_2$-emissions are part of the MPG. However, as the introduction of this research stated, the building industry is responsible for almost 30% of the national $CO_2$ production. By making this quantity explicit with the design tool the design team becomes more aware on how to contribute to the main goal to reduce this $CO_2$ production of the building industry.

From the structural design variants, figure 6.4 – figure 6.6, the slimline floor can suit each circular design strategy. Thus, when the slimline floor system is applied in the circular design strategy with the longest expected service life, the MPG automatically returns the lowest. However, as stated in the above, only looking at the MPG does not present the whole situation. For instance, for the circular design strategy DfME and DfD the structural design variant with the slimline floors and steel frame is exactly the same. The DfD strategy leads to a lower MPG and thus this structural design variant is assumed as the most interesting. However, the design tool does not include the possible increase in building costs for the DfD structural design variant due to the need to deconstruct the structure.

#### 7.3.1.2 The case studies

In section 6.3 two case studies are presented and the environmental impact of the structural design variants are investigated. Together the case studies form a varied basis to test the design tool. The Ambachtslaan is a residential building with a sustainability vision that focuses on material usage and Accelerator is a combined office and laboratory function that aims for flexibility. Both projects have a simple geometry which fits well with the current possibilities of the tool. A big difference between the projects is that the Ambachtslaan has yet to be developed, while Accelerator is already in the construction phase. Therefore, for the Ambachtslaan the results can be used to steer the design, while the output for Accelerator can be used to reflect on the design process. This can help to define the suitable timing to introduce the design tool in the process. However, no definite conclusions can be drawn on the basis of two case studies. Testing and validating the design tool requires more case studies.

Figure 6.11 of section 6.3.1 presents the impact of adjusting the estimated service life to 70 years, instead of the original 150 years for DfA and 100 years for DfD for Accelerator (case study 1). From this change in the expected service life, the most environmentally friendly design variant changed, instead of structural design variant 2 (strategy DfA) the structural design variant 4 (strategy DfD) became the most advantageous. If the estimated service life is adjusted to for instance 125 years, again the structural design variant 2 becomes more beneficial. The turning point will be reached after approximately 93 years, see figure 7.7.

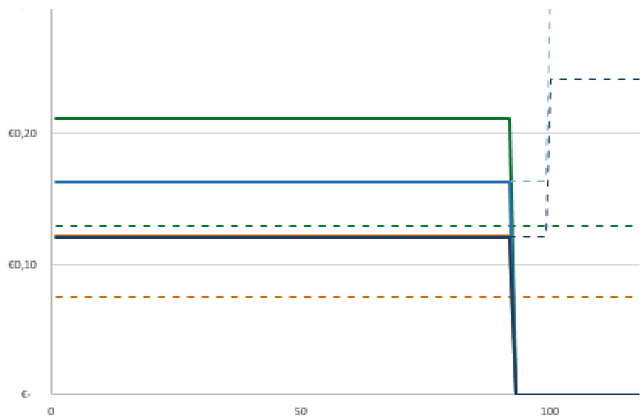



**Figure 7.7** Adjusted environmental impact due to deviating from the expected lifespan (the orange line structural represents design variant 2 and the dark blue line is the structural design variant 4)

Similarly, in figure 6.16 of section 6.3.2 the effect of changing the expected service life for the Ambachtslaan is presented. In this figure the expected service life is estimated at 120 years. This resulted in another structural design variant with the lowest environmental impact per time period. For an expected service life of 75 years, the shifting disappears and the structural design variant 1 is the most advantageous for the environmental impact, indicated in figure 7.8.

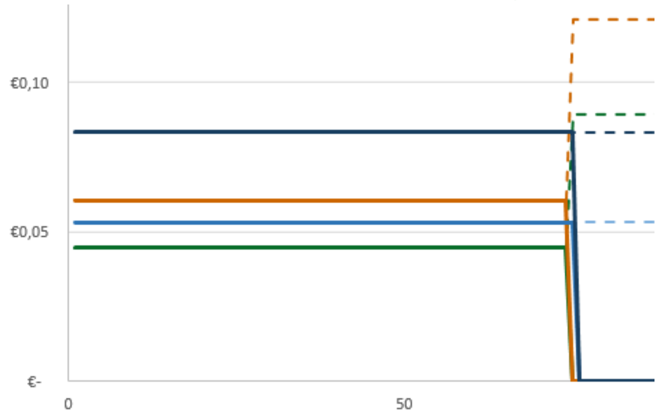



**Figure 7.8** Adjusted environmental impact due to deviating from the expected lifespan (the green line indicates the structural design variant 1)

In this case study, the tipping point appears after 75 years. However, the structural design variants will not lead to the same environmental impact at any point.

Both results of the case studies show the importance of having a clear vision of the expected service life of the project, as this can lead to significant differences in the most beneficial structural design variants.

### 7.3.2 Functionality of the design tool

The design tool should support the decision-making for the load-bearing structure conform to the circular design strategies to reduce the environmental impact. Therefore, the functionality of the tool to transfer the gained insight in this research is critical. Defining the user of the design tool will impact the required functionalities. The targeted user for the design tool is the practitioner of the design team during the preliminary design phase. This means the user is not an expert in either circularity or structural design.

One of the challenges stated in the introduction of this research is the lacking insight in both the implementation of circular design solutions and the impact of these solutions. Therefore one of the key requirements for the developed design tool is to provide the needed guidance and inform the users of the environmental impact of design choices for the load-bearing structure. Thus, the first two steps of the tool, elaborated in section 6.2, focus on creating an understanding of the circular design strategies, their additional functional and technical requirements and connecting one of the strategies with the project. Subsequently, the created structural design variants are in line with the chosen circular design strategy and their environmental impact can be investigated.

To validate the functionality and the user-friendliness, two individuals filled in the design tool. One of the test users has significant experience with circularity in the building industry and the other only with schematic design of a building. The first individual mainly focused on the explanation and substantiation of the circular design strategies and the resulting environmental impact. The other test user investigated the logic behind the steps and whether the necessary input can be filled in intuitive.

One of the recommendations after the validation was to insert 'short-cuts' for users that are more experienced with the circular design strategies. The user can skip the substantiation and directly assign the desired strategy. This will reduce the required time to achieve the output. Furthermore, it was recommended to make the effect of the chosen grid size more explicit as this is one of the influential design choices. The user should be aware when filling in the grid size, that this will define the span of the floors and beam. In the structural calculation step additional explanation is added. Lastly, both individuals recommended adding insight on the assumptions of the research. This can ensure that the output of the design tool will not be misinterpreted.

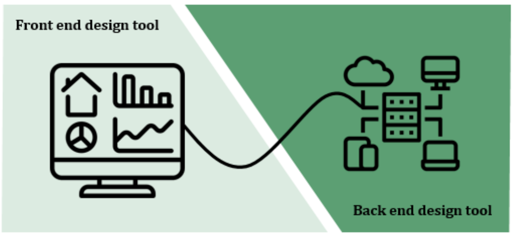



**Figure 7.9** An user side, the front end, and a database, the back end, of the design tool (own figure)

So far, the 'front-end' of the design tool is discussed. Yet, the other important factor for the success of the design tool is the 'back-end'. The back-end consists of the Excel sheets that include the structural and environmental data and perform the calculations. Comparing the design tool with structural calculation tools and software, the main difference is the level of detail. As the user has little specific structural knowledge and the diverse possibilities of structural design variants, the tool creates basic calculations in order to define the material quantities.

Furthermore, currently available tools evaluate the environmental impact when the whole design is defined and then the quantities can be extracted from extensive 3D models or software packages. The developed design tool uses quick structural calculations and directly assesses the environmental impact. An advantage of creating a design tool which has an accessible back-end, in open Excel sheets, is that the used assumptions and relationships are transparent. For instance, if the expected service life of a circular design strategy turns out to be insufficient, this can be easily adjusted. A disadvantage of the tool in Excel is the lack of a real-time connection with a database such as the NMD. If new environmental data is added to the database this should be manually added to the environmental data sheet. Subsequently, in the structural and environmental calculations this new information should be included, which is time consuming. The same actions are required to add new structural building components.

The functionality of the tool contributes to the challenge of the broader context, reducing the environmental impact of the building sector. When translating the ambition of the client to a design using the environmental impact as a means to steer the design is crucial. This should happen as early as possible in the design process, then the influence on the environmental impact is the highest, showed in figure 7.10. The blue line presents the steering on the environmental impact with the use of the design tool. This figure shows the importance of supporting environmentally friendly design choices as soon as possible in the design process.

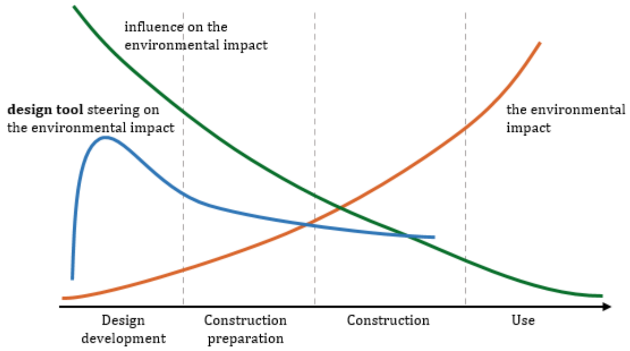



**Figure 7.10** The moment to steer the design based on the environmental impact (own figure)

The design tool facilitates the need for substantiation during the decision-making process; *'' which design choices do we make and why?''* There is not one way to implement circularity in the building sector, each circular design strategy reduces the environmental impact in another way. The design tool helps, in the early phases of the design process, to quickly investigate which strategy fits the project best and what the effect on the environmental impact is.

# Chapter 8

# Conclusions

The objective of this research is stated in section 2.1 as follows:

*''Develop a design tool that can support the decision-making for the load-bearing structure conform a circular design strategy of a building based on the environmental impact during the preliminary design process.''*

To reach this objective, the main research question is divided into three sub-research questions. In this chapter, first an answer is given to each sub-question and subsequently the main research question is answered.

## 8.1 Sub-research questions

**''How can circular design strategies be turned into design variants for the load-bearing structure of a building?''**

Circular design strategies lead to additional functional and technical requirements for the design of the load-bearing structure. If a structural building component can fulfil the additional requirements, the component can be used to create a design variant for the load-bearing structure. To conclude, this ensures that the composed design is in line with the circular design strategy.

Based on the literature study and section 3.1, a distinction between two pathways for circular design strategies is made. From these two directions, three circular design strategies are defined. A circular design strategy defines design principles that should be integrated in the design. The circular design strategies Design for Adaptability [DfA] and Design for Disassembly [DfD] extend the lifespan of the total building or building components. The third circular design strategy, Design for Material Efficiency [DfME], stimulates the effective use of building materials. The design principles in the latter strategies can be expressed in functional requirements. Subsequently, the functional requirements are transformed into technical requirements that influence the load-bearing structure. Therefore, the characteristics of the structural building components should comply with these additional requirements. The characteristics that are investigated per structural building component are the acoustic resistance, fire safety, production method, possible span length, self-weight and connection type. Subsequently, a survey is performed among structural engineers to verify the assigned structural building components per circular design strategy.

The load-bearing structure is composed by making use of simplified structural calculations. The required amount of material per structural building component is dependent on the load-case and the span. In order to simplify this, standardised load-cases and span lengths are introduced to perform quick calculations. The structural calculation led to the Bill of Materials [BoM], that is used for the environmental impact calculation.

**''How to assess the environmental impact of the design variants for the load-bearing structure?''**

The environmental impact results in the MPG, the shadow costs per square meter Gross Floor Area [GFA] per year. In order to obtain this result, before starting the calculation, the material quantities for each structural building component are required. The structural calculations lead to the amount of concrete, steel and timber in the composed design variant. Subsequently, two aspects should be defined for performing the environmental impact calculation. The first aspect is the Life Cycle Assessment [LCA] for the chosen structural building components. This aspect defines the shadow costs per square meter GFA. The second aspect is to determine the expected service life of the design. Both steps of the environmental impact calculations are influenced by the chosen circular design strategy.

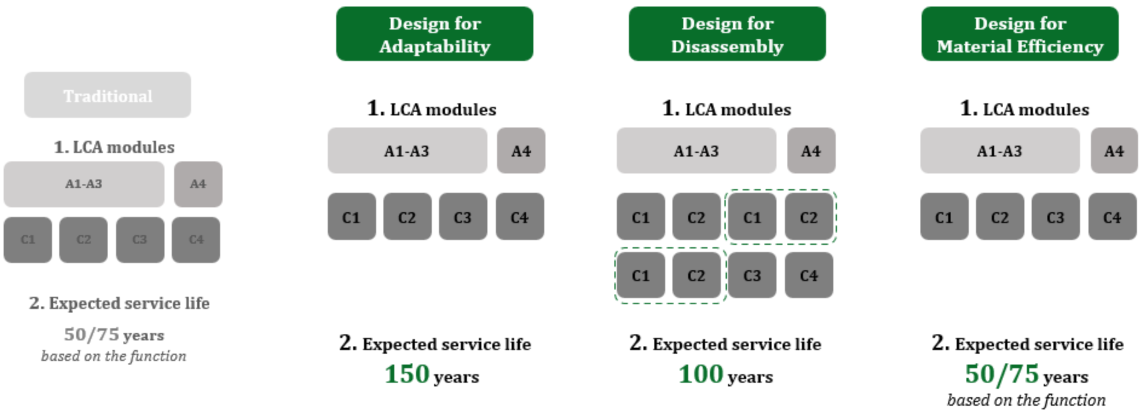



**Figure 8.1** Adjusted environmental impact calculation for each circular design strategy (own figure)

From figure 8.1 it can be concluded that the DfME design strategy used the traditional environmental impact calculation. For the DfA strategy the expected service life is no longer based on the function of the building, but assumed to be 150 years. Due to the integrated design principles of this strategy, an extension of the current assumed service life is found to be sufficiently substantiated in this research. The circular design strategy DfD changes both expected service life and the included modules of the LCA. For this design strategy the expected service life is adjusted to 100 years and the modules C1 and C2 are repeated three times, as this design strategy allows the building to be deconstructed, transported and constructed at another location.

The environmental data per LCA module is obtained of the Nationale Milieu Database [NMD]. The modules of the use phase (B1-B6) are not included, as can be seen in figure 8.1, in this phase it is assumed the load-bearing structure will not lead to any additional environmental impact. The environmental impact calculation is split into two steps:

1. The traditional LCA which uses the environmental data of the NMD and calculates the environmental impact of a life cycle phase, a module presented in figure 8.1 per kg material.

2. The adjustment of the traditional LCA and expected service life based on the chosen circular design strategy.

**''How can the environmental assessment be used to steer the design variants towards the most advantageous environmental impact?''**

A step-by-step design tool in Excel is created to stimulate the consideration of the environmental impact of design choices for the load-bearing structure in the preliminary design phase. The different steps of the tool allow the user to gain more insight on the consequences of following one of the circular design strategies. These consequences are visible in the possible structural building components, the expected lifespan and thus the resulting environmental impact.

In order to match or chose a circular design strategy, the user should understand the meaning of each circular design strategy. The first step of the tool introduces each design strategy including the additional functional and technical requirements. Example projects are illustrated to emphasize how the circular design strategy can be implemented in practice. The second step is to determine the most suitable circular design strategy for the project. This is done by filling in four simple statements that help the user to critically reflect on the main ambition of the project. In the third step the structural design variants can be composed. Design choices that have a significant impact on the outcome, the MPG, are the grid size and the material type of structural building components. It is beneficial to reduce the floor and beams span and to use mainly environmentally friendly materials such as timber. However, this should fit with the desired layout of the building and the chosen circular design strategy. The fourth step of the design tool is to investigate the environmental impact of the first two created structural design variants in step three. Furthermore, in this fourth step two additional structural design variants can be created conform another circular design strategy. This allows the user to examine the differences between the structural design variants of another strategy. Thereby, the user is stimulated to reflect whether the stated project ambition is beneficial. The last step of the design tool presents an overview of the outcome of the environmental assessment. The outcome is summarised in a matrix that, besides the MPG, indicates the expected lifespan, material usage, $CO_2$ production and building costs. The additional requirements of the circular design strategy are also included and should be interpreted as the boundary conditions of the design variant.

It can be concluded that, the outcome of the design tool can be used as a quick assessment to investigate the consequences of varying structural design variants for the environmental impact. It is a means that will substantiate the implementation of circular solutions and steer the conversation between the client and design team.

## 8.2 Main-research question

**''How can the design variant for the load-bearing structure with the most advantageous environmental impact be implemented in the preliminary design phase, considering the circular design strategies for a building?''**

In order to answer the main research question, a design tool in Excel has been developed. This tool makes it possible to determine the environmental impact of created structural design variants in the preliminary design phase. A circular design strategy is matched with the ambition of the project. Subsequently, by filling in the function and the dimensions of the schematic design, structural design variants can be composed. Then, the environmental impact of the created design variants can be investigated and even compared with design variants from another circular design strategy. The output of the design tool is a matrix in which the different design variants can be weighed against the design parameters; expected service life, material usage, $CO_2$ production, MPG and building costs. The design variant with the most advantageous environmental impact is unique and is dependent on the vision, function and more characteristics of the project. Thus, there is not 'one most environmentally friendly' structural design variant, but the design should be chosen while considering several parameters that express the effect on the environmental impact.

*The research shows that based on literature review, expert judgement and open databases a design tool can be built, which gives insight in the environmental impact and more design parameters to support the implementation of circular solutions in the preliminary design phase.*

The circular design strategies define additional functional requirements that should be included in the design. These requirements influence the load-bearing structure resulting in extra technical requirements are determined. Structural building components are assigned to the design possibilities of a circular design strategy when the technical requirements are met. In addition to the impact on the load-bearing structure, the circular design strategies also influence the environmental impact calculations. This means the LCA and expected service life can be adjusted. The results of the research present how both the design choices and the related calculation methods in the tool have significant impact on the MPG.

From the results of the generic outcome and case studies, the design tool allows the user to influence the MPG in three ways. These are the chosen circular design strategy, the material type of the structural building components and the grid size, thus the span length of the floors and beams.
Firstly, the chosen circular design strategies impact the MPG by adding additional functional requirements to both the structural and environmental calculations. The most influential is the adjustment to the expected lifespan used in the environmental impact calculations. The results of the case studies made the uniqueness of every project more explicit. A project has specific characteristics and thus other reasons why a circular design strategy is suitable. When comparing structural design variants of two circular design strategies, the estimated lifespan of the project influences which design variant leads to the lowest MPG. In other words, the

expected lifespan belonging to the chosen circular design strategy should be fully exploited otherwise the strategy is not beneficial. Therefore, the design tool allows the user to investigate this effect by visualising graphs that present the development of the environmental impact over the time period. This forces the client and design team to rethink the suitability of the starting principles of the design. Furthermore, from the results it can be concluded that the longer the expected service life used in the environmental calculations, the lower the MPG. This means most of the structural design variants from the circular design strategy DfA, with the longest expected lifespan, result in the most beneficial MPG.
Secondly, the user of the design tool can influence the resulting MPG by choosing structural building components out of environmental friendly materials. The environmental profile of a material is based on the environmental database. In this research the Nationale Milieu Database [NMD] has been used. For the structural building components, the timber components reduce the environmental impact. However, the incineration of timber is included too favourably in terms of environmental impact in the NMD. The NMD is compared with another environmental database, NIBE.INFO. When comparing the shadow costs of concrete floor systems, the environmental data of the NMD led to a higher impact than the NIBE.INFO database. Without the substantiation of the assumptions for both databases, the clarification for the deviation remains uncertain.
Lastly, the chosen grid size influences the amount of required materials in the design. The contribution of the floor systems to the total environmental impact is the largest. By reducing the span length of the floors and beams a lower MPG can be achieved. 'this is due to the fact that smaller spans of floors and beams lead to less required materials.

*In conclusion, the outcome of this research highlights three main influential aspects for the determination of the MPG;* ***(1)*** *the expected lifespan of the design assumed in the calculation method,* ***(2)*** *the quality of the environmental database of materials and* ***(3)*** *the required amount of materials. For the practitioners of the design process it is extremely important to be aware of the effects of changing the expected lifespan and thus the determination method for the environmental impact and the quality of the environmental database used.*

The goal of this research was to reduce the environmental impact of the building industry. Simply choosing the structural design variant with the lowest MPG might be insufficient. The reduction of $CO_2$ is critical for reaching the climate goals. Therefore, it is also necessary to compare the structural design variants on their $CO_2$ production. The production of kg $CO_2$ equivalent is part of the MPG, however in the resulting matrix of the design tool this is made more explicit. When this is included in the assessment of the structural design variants, a broader perspective of the environmental impact emerges. Based on the fictive case and projects of BAM, the structural design variants of the DfA strategy include large floor spans and robustness, this led to more applied material and thus more $CO_2$ emission. In contrast, the circular design strategy DfME applies materials efficiently and with a low environmental impact. This results in a significant reduction of the produced $CO_2$ emissions. Therefore, the output of the design tool is presented in a trade-off matrix to compare multiple critical parameters for the environmental impact; the amount of materials, MPG, $CO_2$ production and building costs.

This research combines the requirements of circular design strategies with the structural and environmental calculations into a design tool, that can be used in the preliminary design phase to investigate the consequences of design choices on the environmental impact. Additionally, the research emphasizes the importance of exploiting the expected service life and reflecting on the transparency and quality of the environmental database. The design tool guides the design process, but also educates the practitioners on the impact of the applied calculations and databases used.

The stated conclusions are based on the general results of the design tool and the analysis of two case studies. Therefore, the conclusions drawn are not general conclusions, but stated with the consideration of the scope of this research.

# Chapter 9

# Recommendations

This research can be used to stimulate the consideration of the environmental impact of design choices in the preliminary design phase by using a design tool. This tool and the defined relations between circular design strategies, structural design and the environmental impact can be used in a broader context. The research and tool can improve the implementation of circular design solution and thereby contribute to the goals of the CE. This chapter presents the recommendations for the further development.

- To limit the scope of this research, it is chosen to only consider the structural layer of the building. This part of the building is responsible for a significant part of the resource consumption and thus the environmental impact. Therefore, the effect of the circular design strategies is limited to this layer. Yet, the other building layers also offer opportunities to increase the circularity. In addition, the alignment between the different building layers with a varying lifespan is important for the success of circular solutions. It is recommended to further investigated the effect of the additional requirements of the circular design strategies on the remaining building layers, such as the façade and services.

- The additional requirements of the circular design strategies are matched with the characteristics of the structural building components. A structural building component either fits these requirements are not. A more detailed investigation is required to determine to what extent a structural building component suits the strategy. For instance, it is possible to design several load-bearing structures that are adaptable, however which design suits the strategy best remains unclear.

- The costs of the structural design variants are only based on the price of the materials. The additional work caused by the circular design strategies are not yet included. How the strategies affect the pricing of a building should be investigated in more detail.

- The foundation of a building is not included in this research. The foundation requires specific knowledge and many design possibilities are available. However, the foundation has a major contribution to the total environmental impact due to the large amount of material required. Based on the composed design for the load-bearing structure the most efficient foundation should be chosen. This need to be further investigated in future research.

- The structural calculations are performed by using the BHH-model and rules of thumb (Hofkes et al., 2004; Westenbrugge-Bilbardie & Peters, 2016). The extracted material quantities form the input for the environmental impact calculations and are crucial for the output of the tool. To improve the accuracy of the structural calculation multiple references cases should be investigated. Additionally, the structural calculations should be further developed to allow more complex geometries.

- Additional measures to safeguard the acoustic performance and fire resistance are not included. This means for each created design variants varying materials or coatings need to be added to the structure to ensure this. These measures will increase the environmental impact of the design.

- Further research is required to determine how the design principles of the circular design strategies can impact the Life Cycle Assessment [LCA]. The current LCA includes the module D in which beyond-end-of-life environmental impact and benefits are included. This phase has not been included in this research, but the functional and technical additional requirements of the circular design strategies will impact this module. How to integrate this in the LCA requires more detailed research.

- Currently, the functional lifespan of the project is used as the estimated service life in the environmental impact calculations. However, often the materials used in the load-bearing structure are still valuable and functional when a building is demolished. It is necessary to gain more knowledge and experience about the actual technical lifespan of building components out of concrete, steel or timber. Then, this should be integrated in the environmental impact calculations, since this will influence the results.

- The transparency of the current available environmental databases is limited. In addition, environmental impact calculation tools that make use of environmental data do not give any insight in the made assumptions and the reasoning behind it. This research included the data of the Nationale Milieu Database [NMD] in the back-end of the tool and thus it is possible to investigated the applied data. If the NMD is complete and reliable enough, it is recommended to create a real-time link between the tool and database.

- The design tool is developed to support the decision-making in the design process. The output of the design tool is analysed by using two case studies. However, it is not yet known how the model will be used in practice. Therefore, the tool should be introduced in current design processes. This leads to the validation of the developed functionalities and provides insight in the necessary improvements. Subsequently, the accuracy of the tool can be verified by comparing the stated Milieu Prestatie Gebouwen [MPG] in the tool and the actual realised MPG at the end of the design process. The captured feedback should be fed back to the structural and environmental impact calculations.

- The user-friendliness is considered in this research. It is recommended to add more visuals to the design tool. Meaning as the user is composing the structural design variants, 3D figures real-time visualise the design choices. This will improve the understanding of how design choices impact the structural design and eventually the environmental impact.

The above stated recommendations are challenges for both practice and science. To the practitioners in the building sector it is recommended to directly start using the design tool and capture the successes and improvements. Reflect on the timing of the tool and the provided substantiation for the design process. In the list of requirements for a project, the environmental impact should become equally important as the functionality and costs. For the scientists the challenges lie in further challenges are to determine the effect of circular design strategies on the determination method for the LCA and the expected service life. Methods and models should be developed and integrated in the process that proof the environmental impact stated in the list of requirements is met and which design principles are required to achieve this goal. Policy makers can use the feedback and practical knowledge collected with the tool to update current policies to stimulate the transition towards the circular building sector. These recommendations for both practice and science emphasize that the further development and implementation of the Circular Economy is a joint challenge. The experiences and results of both the practitioners and scientists should be brought together and transformed into a new way of designing that includes tuned tools and calculations to support the implementation of circular design solutions.

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# Part IV | Appendices

# Chapter A

# Literature study

## A.1 Circular frameworks

The CE concept has deep-rooted origins and cannot be traced back to one single date or author (Ellen MacArthur Foundation, 2012). In the last decades, various models have been developed to substantiate the CE. In the next section both the predecessors and the well-known models for circularity will be discussed.

### A.1.1 Regenerative Design by John T. Lyle

In the 1970s, Lyle started philosophizing about a society 'in which daily activities ware based on the value of living within the limits of available renewable resources without environmental degradation' (Lyle, 1994; Ellen MacArthur Foundation, 2012). The rapid industrial development resulted in intensive resource depletion due to the linear, one-way flows of materials. To replace this system, Lyle defined regenerative design. Regenerative design enables processes that renew or regenerate the sources of energy and material that they consume. Projecting this on the building level, regenerative building is designed and operated to reserve damage and have a net-positive impact on the environment. In order to achieve regenerative buildings less emphasis needs to be place on a single element or building and more on the whole design process and the system it is related to.

An important aspect of the regenerative design theory of Lyle (1994) is to view buildings, products or other elements as fragments of a complete system, that are interconnected (Cobbinah et al., 2020; Ellen MacArthur Foundation, 2012).

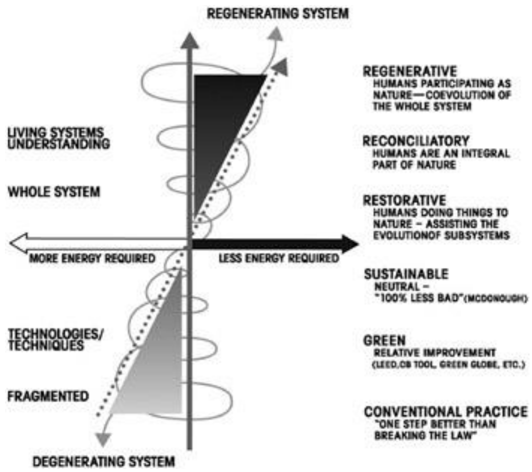



**Figure A.1** Levels of sustainability of Lyle (Reed, 2007)

The implementation of Lyle's once conceived idea is step by step. The levels in figure A.1 of the sustainability trajectory are not exclusive of one another, they are a progression, and each is nested in the next level. All levels are necessary to achieve a regenerative system (Reed, 2007).

### A.1.2 Performance Economy by Stahel

As this sub-title states, Stahel (2016) refers to the CE as the Performance Economy. His approach insists on the importance of selling services rather than products. The object of sale is not the product itself but rather the performance it provides, and the benefits offered to the user (Bocken et al., 2016). It is about an economy that aims and retain value by closing the loops. In order to achieve this, two strategies can be defined; those that foster reuse and extend service life through repair, remanufacture upgrades and retrofits, and those that recycle materials to turn old goods into as-new resources (Stahel, 2016).

The first strategy focusses on extending the utilisation phase of a product by various methods. Each method stimulates to slowdown the flow of virgin resources and maintain the products that are currently used. This strategy can also be referred to as slowing resource loops.

Through recycling, the loop between the end-of-life phase and the production of new products can be closed. This second strategy aims to close resource loops. Next to this, the consumption of virgin resources will be limited.

However, when reflecting on the definition of the CE, the main aim is to decrease the depletion of resource by intention and design. It is equally important to focus on the design of the product itself and the resource consumption. Therefore Bocken et al. (2016) added an additional strategy to create a closed loop economy (Stahel, 2016; McDonough & Braungart, 2002; Braungart et al., 2008). The last strategy is narrowing the resource loops, aiming at designing a product that uses fewer resources.

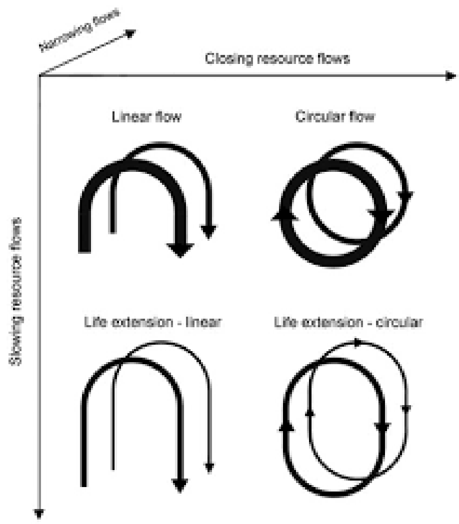



**Figure A.2** The closed loop economy systems based on Stahel (Bocken et al., 2016)

Like the theory of Lyle, Bocken et al. (2016) indicates to reach a circular or closed resource flow, a combination of the three strategies are required. In addition, different implementation methods are possible within each strategy. In which way the strategies will be executed depends on the characteristics of a project. As mentioned before in this research, a building project is often unique with diverse requirements. Thus, the question remains how can these general strategies be implemented in the development of circular utility projects.

### A.1.3 Butterfly model of the Ellen MacArthur Foundation

One of the most used frameworks in describing the CE, is the Butterfly model of the Ellen MacArthur Foundation. Building on the idea of creating a closed loop system of Stahel (1994; 2010; 2016), McDonough and Braungart (2002), the Ellen MacArthur Foundation (EMF) developed a model in order to acknowledge the need of addressing the entire life cycle of a product. In a circular economy, material cycles are closed like an ecosystem. There is no such thing as waste, because any residual flow can be used to create a new product. By considering all life cycles phases, out flow of materials can be captured and returned into the cycle at the highest possible value (Korhonen et al., 2018). Materials circulate in two separate cycles: the biological cycle (left) and technical cycle (right). The distinction between these cycles helps to understand how materials can be used in a long-lasting and high-quality way. The biological cycle includes all organic materials such as wood, food and water. These materials can be incorporated into the ecosystem and re-generated through biological processes. The technical cycle considers materials such as fossil fuels, plastics and metals. These materials limited availability and cannot easily be recreated. In the techno-cycle it is important that stocks of such finite materials are properly managed (Ellen MacArthur Foundation, 2015). The main difference between the biological cycle and technical cycle is the contribution of the ecosystem. The materials of the technical cycle cannot be consumed by the ecosystem itself and should always be actively worked in order to re-enter a new life cycle. The different reuse cycles within the technical cycle are (Potting et al. 2017; Morseletto, 2020);

- *Maintain and Repair;* aiming on extending the lifespan of a material or product. Interventions that keep the product in its current function.

- *Reuse and Redistribution;* promoting the reuse of a product at the end-of-life phase. If the product cannot be reused in the current application, the product can be redistributed in order to be reused in another situation.

- *Refurbish and Remanufacture;* upgrading the performance of an already existing product. Either without changing its function or by disassembling the product into smaller components that have value.

- *Recycle*; processing products and materials for reuse in the lowest application, recycling. This cycle is often referred to as downcycling.

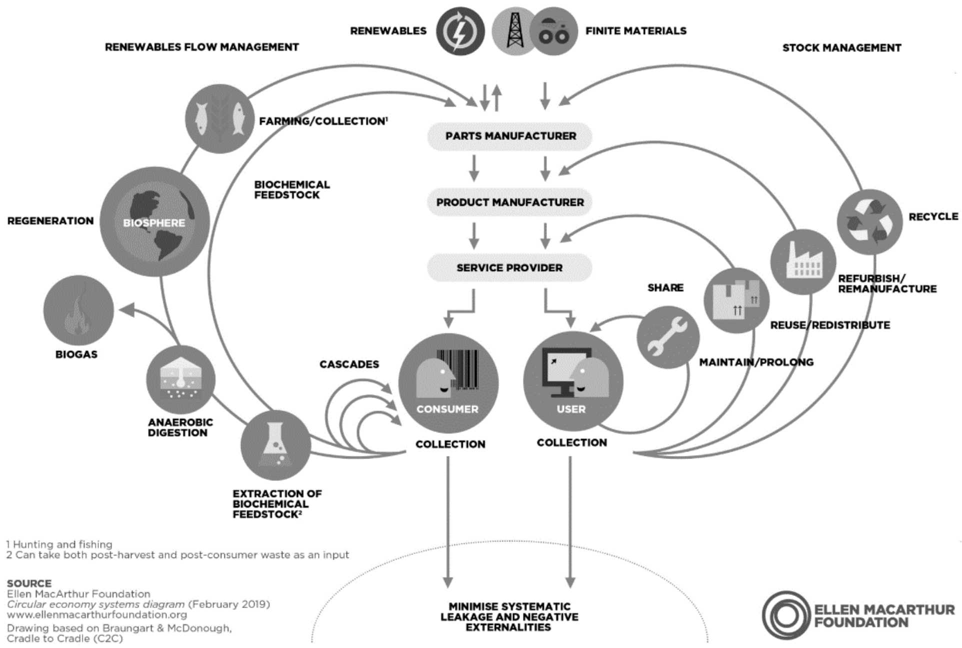



**Figure A.3** The Butterfly Model (Ellen MacArthur Foundation, 2019)

The diagram's spine, the body of the butterfly, represents the linear economic model, while the rest of the model illustrates the returning flow of technical and biological materials through 'value circles'. Within the technical cycle the smaller the cycle is, the greater the product's value that maintains (Kottaridou & Bofylatos, 2019). The cycles can be seen as different strategies already placed in a certain hierarchy. As these strategies are still applicable to various sectors, for the implementation in the building industry a more sector specific approach is favourable.

### A.1.4 The 10R framework a further development of the Ladder of Lansink

The Ladder van Lansink formed the basis of (re)thinking how to deal with waste in the Netherlands. The model is named after the Dutch politician Ad Lansink. More than 40 years ago he submitted a motion to follow a hierarchy for processing waste (Platform CB23, 2019). The aim of the model is to stimulate reusing waste within its own cycle and at the highest possible quality level (Sunnika, 2001). The higher the waste strategy can be placed on the ladder; the less raw materials are needed and the burden on the environment will be minimized. Currently the Ladder is still a common strategy framework to evaluate the circularity in the waste and environmental management sector. The levels form a hierarchy in the reuse of released 'waste' materials.

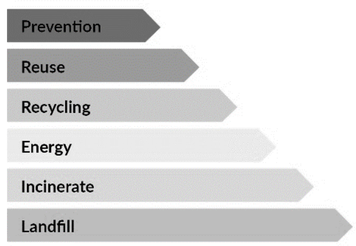



**Figure A.4** The Ladder of Lansink (Platform CB23, 2019)

By further developing on the model of Lansink, Stahel and the Ellen MacArthur Foundation the 10R model can be introduced. During the last few years, the framework evaluated from the 3R-model (refuse, reuse, recycle) into the 10R framework presented in figure A.5 (Kirchherr et al., 2017). The model uses the line of thought of the more general models and transforms them into sub-strategies. The framework exists of several strategies to reduce the consumption of resources and minimise the production of waste. The strategies are ordered on their level of circularity. The levels can be structured in three main steps. To most favourable strategies are the R0-R2 where the focus is on smarter product manufacturing and use. These strategies aim to preserve the function of product or services by circular business models and schemes promoting product redundancy and multifunctionality. The next option is the lifetime extension of the product itself with strategies such as reuse and refurbish. Lastly the recycling of materials. The strategy recover is the lowest because it means the materials can no longer be implemented in a new cycle (Potting et al., 2017).

By prioritising the strategies, creating more guidance for its user the 10R-framework separates itself from the more generic circular models of Stahel and the Ellen MacArthur Foundation. By using multiple strategies, the 10R-models provides more guidance. Still, the strategies remain applicable within various sectors and implementation in the building industry remains a challenge.

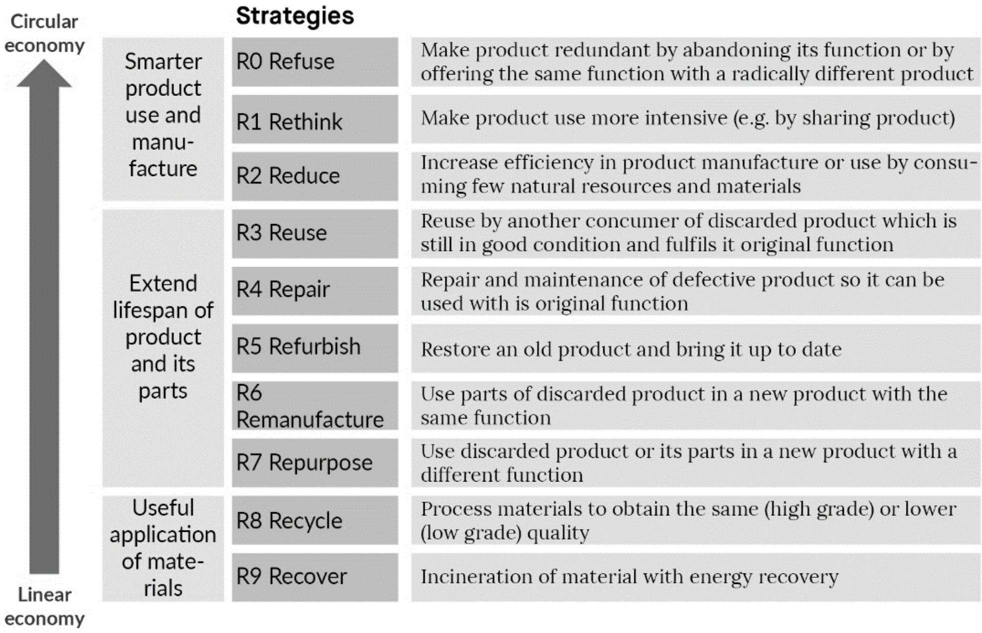



**Figure A.5** The 10R framework (Kirchherr et al., 2017)

## A.2 Tools to support the Circular Economy

Over the last couple of years, the traction of the CE led to the development of various tools in order to facilitate the implementation of circularity. This phenomenon also took place in the building industry, currently a large set of tools facilitating the circular transition is available. However, the abundance of tools makes it difficult to maintain an overview and use the tools in an effective way (Weytjens et al., 2009). The objective of this research is to create guidance by developing a support tool for the implementation of circular design alternatives for a building project in the early design stage. Although, the actual translation from a circular strategy to design solution is yet to be seen as a challenge, current available tools should be analysed in order to assess their effectiveness and limitations. The first step of the analysis is creating a non-exhaustive list with varying circularity tools derived from literature review (Cambier et al., 2020). This is followed by collecting information about the required input for the tool to function, what type of output the tool delivers and by whom it will be used. Secondly, the long list of tools is clustered and categorised based on two aspect.

A distinction has been made based on the moment of usage. As this research will focus on the early phase of the design process, the tools are assigned either to the initiating phase or design phase. In the initiation phase, the circular and sustainable ambitions for the project are defined. The tools in this phase can contribute to the decision-making on project objectives, concept design and program. During the design phase, the design is guided towards the circular ambition by supporting the proposals for structural design, outline specifications, cost information or project strategies.

The second category is based on the functioning of the tool. Meaning which aspects of the CE are covered in the tool. Based on the literature review four main categories can be extracted, tools that (1) facilitate circular design strategies, (2) measure the circularity impact, (3) stimulate the choice for a certain material or product or (4) assess the environmental impact (Cambier et al., 2020). As the last step of the analysis of the available circular guidance tools, the gaps of the existing tools can be concluded, leading to key take-aways for the development of the support tool of this research.

The following table consists of various tools, in total 41. The table presents the title of the tool, who developed it and the published year. The created longlist elaborated further on the research of Cambier et al. (2020) and focusses on support tools that are mostly available in Dutch. As the list is a non-exhaustive list, often similarities occurred in the tools. Next to this, as the circular economy is a trending topic, new tools are introduced and the features of the listed tools can evolve quickly.

| Tool | Developer | Year Published |
|---|---|---|
| 16 Design Qualities for Circular Economy (Design principles (DP)) | Vrij universiteit Brussel (VUB) Architectural Engineering | 2019 |
| 24 Design principles for Design for Change (DP) | VUB Architectural Engineering | 2016 |
| BCI<br>Building circularity index | Alba Concepts | |
| Business model innovation grid | Nancy Bocke, samual Short, Padmaskhi Rana and Steve Evans (University of Cambridge) | |
| Bouwcatalogus Veranderingsgericht Bouwen (DP) | VIBE | 2019 |
| C-calc | Cenergie | 2018 |
| CI<br>Madaster Circularity indicator | Madaster | |
| Circular Building Assessment Prototype | Building Research Establishment (BRE), VITO, University of Twente | 2018 |
| Circular Design Guide | Ellen MacArthur & Ideo | 2018 |
| Circular Transition Indicators | World Business Council For Sustainable Development | |
| Circularity calculator | IDEAL and CO Explore BV | 2017 |
| Circulator | VITO, Circular Flanders, TU Delft, Rasboud University | |
| Circulytics | Ellen MacArthur | |
| Closing the Loop by Design | Utwente | 2018 |
| DGBC Framework (strategy) | DGBC | |
| Ecolizer Ontwerptool | OVAM, VITO | 2011 |
| Green Deal Circulair Bouwen (Platform) | Circular Flanders, OVAM, Vlaamse Confederatie Bouw | 2019 |
| GaBi Circularity Toolkit (Life Cycle Assessment (LCA)) | Sphera | |
| GRO | Het Facilitair Bedrijf | 2020 |
| GPR Gebouw<br>Gemeente Praktijk Richtlijnen | | |
| Harvestmap (Reused Materials (RM)) | Superuse Studios | |
| IMPACT model | TNO | |
| IMPACT (LCA) | BRE Group | |
| Insert Marktplaats (RM) | Insert, Buro Boot | |
| Kernmeethodiek | Platform CB23 | 2020 |
| Level(s) | European Commission Joint Research Centre | 2020 |
| Madaster material pasport | Madaster | |
| MCI<br>Material circularity index | Ellen MacArthur | |
| Milieuclassificatie Bouwproducten | NIBE | 2019 |

| | | |
|---|---|---|
| MPG<br>Materiaal gevonden milieuprestatie gebouwen | Multiple | |
| Online Material Flow Analysis Tool (Material Flow Analysis (MFA)) | Team Metabolism of Cities | 2020 |
| One Click LCA (LCA) | Bionova Ltd | |
| Opalis (RM) | Rotor vzw, Atelier 4\|5 | |
| OpenLCA (LCA) | GreenDelta | |
| Platform CB23 (Platform) | 13 Companies | 2018-2023 |
| Pixii (Platform) | Pixii | |
| ReCiPe Method (LCA) | RIVM, Radboud University, Leiden Univeristy, PRé Sustainability | 2018 |
| Scenario based Life Cycle Costing (LCC) | Waldo Galle et al. | 2016 |
| SimaPro (LCA) | Pré Sustainability | |
| Totem | VITO, KU Leuven, Wetenschappelijk en Technisch Centrum voor Het Bouwbedrijf (WTCB) | 2020 |
| Werflink (RM) | Floow2 | |

**Table A.1** Overview of tools related to circularity

In order to cluster the tools based on the functioning and moment of usage, more information is gathered. For each tool a short description, the required input, the delivered output and the possible users of the tool are described. The information is used to assign the available tools to the defined categories. The objective of a support tool is based on the description and the delivered output for the suitable user. The aim of the tool led to the division into one of the four functional categories. Whether the tool is used during the initiation phase or design phase, is based on the required input for the tool. If a tool can be used without any project specific information as the input, it is often used to shape and define the project by providing guidelines or possible strategies. Most of the examined tool require input that is based on the characteristics of a project, so these tools are applicable after a preliminary design is developed. Next to this, preparing all the input by making it applicable for the support tool, can be time consuming. Tools used in the beginning of the design process will focus more on the comparison of alternatives, while support tools in the end of the design process tend to provide a 'final' review (Weytjens et al., 2009; Cambier et al., 2020).

| Functional categories | Moment of usage | | | |
|---|---|---|---|---|
| | Initiating *phase* | | *Design phase* | |
| **Circular design strategies** | 16 Design Qualities for Circular Economy (Design principles (DP)) | | | |
| | 24 Design principes for Design for Change (DP) | | | |
| | Bouwcatalogus Veranderingsgericht Bouwen (DP) | | | |
| | DGBC Framework (strategy) | | | |
| **Circularity score** | | | BCI Building circularity index | |
| | | | C-calc | |
| | | | CI Madaster Circularity indicator | |
| | | | | Circular Building Assessment Prototype |
| | | | Circularity calculator | |
| | | | Kernmeethodiek Platform CB23 Meten circulariteit | |
| | | MCI Material circularity index | | |
| **Product and material choice** | | | | Ecolizer Ontwerptool |
| | | | | Harvestmap (Reused Materials (RM)) |
| | | | | IMPACT model |
| | | | | Madaster material passport |
| | | | | Insert Marktplaats (RM) |
| | | Milieuclassificatie Bouwproducten | | |
| | | | | Opalis (RM) |
| | | | | Werflink (RM) |
| **Environmental impact** | | IMPACT (LCA) | | |
| | | | | MPG |
| | | One click LCA | | |
| | | Online Material Flow Analysis Tool (MFA) | | |
| | | OpenLCA (LCA) | | |
| | | ReCiPe Method (LCA) | | |
| | | SimaPro (LCA) | | |

**Table A.2** Tools clustered based on their function and moment of usage (own image based on Cambier et al., 2020)

### A.2.1 Gaps in the existing support tools

More and more strategy documents, frameworks and tools have been developed in literature and practice in which circular design strategies, in general and for the construction industry, are proposed and explained. What is still lacking is the translation to the actual implementation of the strategies and which steps are required for this. From a survey conducted by Weytjens et al. (2009) it could be concluded that the design practice is mostly based on experience and less on tools. This is also reinforced because many construction projects are unique in different ways (location, client preferences, etc.) and therefore require a custom-made approach, which can be hard to capture in a generic tool. Next to this, the analyses of the available tools indicated that all circular design strategies tools, do not require much input. This shows that the circular design strategies aren't translated in specific measures for the project, but kept abstract and general.
The circular impact is seen in many of the tools as an absolute outcome. This means that sufficient data is required to calculate the circularity and express this in some kind of number. The input for this tool is therefore often an extensive 3D model that contains the materials and properties used (Cambier et al., 2020). Hence, a time-consuming process is a result of this, as the whole design should be modelled in a specific program (Revit, ArchiCAD, Sketchup etc.). This can result in the situation that the design is actually already in place and no more variants can be proposed in response to the circular impact.
For both tools that support product and material choice and asses the environmental impact of product, many similarities in functioning and output are found. This means that a lot of information is available to users on these topics. However, the various tools also lead to the lack of a clear overview. Especially, when focusing on the environmental impact tools, the life cycle assessment and costing can be considered time-consuming and too complex to use as support for decision-making (Taranic, 2016; Cambier et al., 2020). In addition, for this type of calculation a lot of data is needed about the project and an LCA will not be used so quickly to do a 'fast' variant study and compare environmental impact.

Based on the outcome of the analysis of the existing tools, a number of recommendations for the development of the guidance tool within this research can be established.

Firstly, there is room for a support tool in which circular design strategies are made tangible and are realised by using the specific properties of a project. As this thesis will focus on the structure and skin layers of a building, the circular design strategies related to those layers should be included in the support tool and projected on the project. The first challenge is therefore embedding guidelines in the tool that can transform general information from the design into boundary conditions for the material choice (and components) and design strategies. In this way a study of design options can be performed based on the requirements of the specific project. It can become quite a challenge to compare variants for construction elements as early as possible in the process for which specific technical information can be required, without determining too much, because then evaluating various design scenarios no longer makes sense.

Secondly, it is important that the results of the tool can be properly understood by the stakeholders involved. The environmental impact of the various design scenarios must be presented clearly without getting overwhelmed by all possible data. This can be supported by clarifying which switches of the tool can be turned and to which consequences this leads. An example of this could be showing a clear change in environmental impact or other indicators when changing the floor type. Although the results of the tool must be accessible to various parties, it is desirable to focus on one user. This allows the user interface to be completely tailored to the user.

In summary, the guidance tool should be usable in the early stages of a design, making it possible to compare different designed construction variants. The design variants must be related to the specific project requirements and can be generated in a short amount of time. The comparison can provide insight into the environmental impact and indicators for the possible circular design strategies of the chosen structure and skin elements within the design variant, in a well-organized manner for both the user of the tool and the other parties involved in the design process.

## A.3 Circularity in the building sector

### A.3.1 The current status

The government-wide Circular Economy program was published in 2016 with the title 'The Netherlands will be circular in 2050'. The report actually sets two clear goals, which are currently widely recognized by government, industry, science and education; 1. 50 % less use of primary raw materials by 2030 and 2. a fully circular economy by 2050 (Rijksoverheid, 2016).

This is certainly a major challenge for the total construction industry, as an estimated 50% of raw materials are consumed in construction. In addition, the construction sector is responsible for approximately 35% of $CO_2$ emissions. Moreover, a large part of all waste in the Netherlands is related to construction and demolition waste. As described in the introduction, a large part of the waste is reused in the infrastructure projects, but this is a form of downcycling (use of the material at a lesser value than the original) (Rijksoverheid, 2016). In order to turn this around, the following vision is formulated by the Dutch government for the whole construction industry; *"By 2050, the construction industry will be organized in such a way, with respect to the design, development, operation, management, and disassembly of buildings, as to ensure the sustainable construction, use, reuse, maintenance, and dismantling of these objects. Sustainable materials will be used in the construction process, and designs will be geared to the dynamic wishes of the users. The aim is for the built-up environment to be energy-neutral by 2050, in keeping with the European agreements. Buildings will utilize ecosystem services wherever possible (natural capital, such as the water storage capacity of the sub-soil)''* (Rijksoverheid, 2016, p. 61)

The challenge is therefore to build without emissions, depletion and pollution of the living environment. This requires a new way of thinking and acting. It makes the transition to a circular construction economy not only a technical, but also a social and economic change (RVO, 2020). Transforming the building industry is a joint challenge, where business, government and science should work together. Therefore, also in this sector unambiguous definitions have been drawn up to prevent confusion. In this research the following definitions will be used;

- Circular construction is the development, use and reuse of buildings, areas and infrastructure, without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems by using as many renewable raw materials as possible. Building in a way that is economically, socially, culturally and ecologically responsible. Here and there, now and later (Platform CB23, 2019, p. 3)

- A circular structure is a design that has been designed and executed in accordance with circular design principles and realized with circular products, elements and materials (Platform CB23, 2019, p.3).

Since the governmental goals were composed, more steps have been taken in the building industry. The Minister of Internal Affairs, Kasja Ollongren, has announced that from January 2021 circular construction will receive extra attention in the new building regulations. Resulting in a more ambitious requirement for the calculation of the environmental impact in order to lower the depletion of natural resources (Stichting Nationale Milieudatabase, 2019).

To achieve the optimum preservation of value of the CE, two principles characteristics of a building should be recognized. First, a building is not a static object but, can be defined as a metabolism, it is a dynamic set of subsystems (Duffy, 1990). A dynamic system is able to respond to change, so the design of a building should facilitate this dynamic behaviour. The second principles, is the realisation that a building consists of layers, each with their own lifespan (Habraken, 1961; Brand, 1994). The load bearing structure, base building, will have a higher durability than the interior filling, the fit out. Therefore, the design strategies for the base building and the fit-out can will differ (Habraken, 1961).

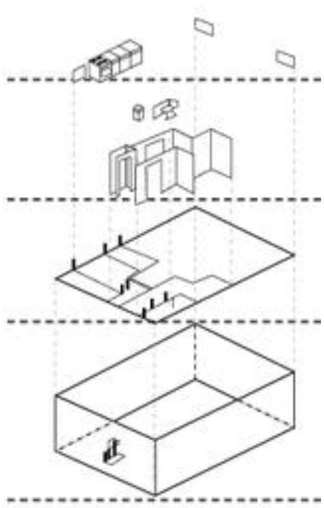


**Figure A.6** The different layers of a building (Habraken, 1961)

The structure layer, foundation and load-bearing structure, is expected to have a lifespan varying from 50-300 years, while the expected lifespan of the skin layer, the façade, is around the 20-30 years (Brand, 1994). So, a building consists of several layers, each with a layer specific expected life span. Therefore, the connection between the building layers should be releasable, in order the replace the layers with a short lifespan without damaging the layers with long lifespan (Brand, 1994; Graham, 2005).

### A.3.2 Environmental impact calculations

The necessity to include the environmental impact is gaining more traction in the Dutch building sector as stated in the section A2.1. Therefore, in this section the calculation method to achieve the environmental impact is discussed. Figure A.7 below presents an overview of the different documentation used in the Dutch building sector to perform the environmental impact calculations.

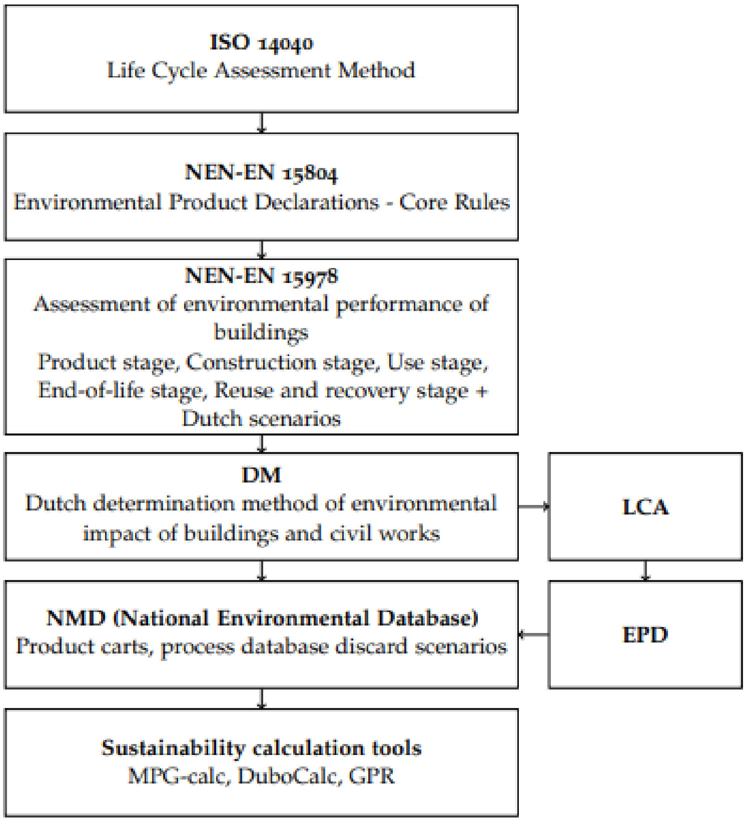



**Figure A.7** Environmental impact calculation general outline (Backx, 2020)

Since the implementation of the Dutch Building Regulations (Bouwbesluit) in 2012, a mandatory calculation for the material-related environmental impact should be performed for a building larger than 100 $m^2$ (Stichting Bouwkwaliteit et al., 2012). This calculation, called the Determination Method off the Environmental Performance of a Building and Civil Works, is the uniform environmental assessment method in line with the European Codes EN 15804 and EN 15978 (SBRCURnet, 2015). The determination method contains rules for the calculation of the environmental performance of a complete design over the expected lifespan based on the performance of the products and elements it consists of. As discussed in section 1.2, the environmental impact of a building is expressed in the environmental impact costs per year, named the shadow price. The shadow costs express the costs that the society is willing to pay in order to prevent the environmental effect (de Bruyn et al., 2018). The shadow costs are expressed in euros per square meter [€/$m^2$], the lower the price the more environmentally friendly the product is. The data used in order to end up with the environmental profile and shadow costs is collected in the National Environmental Database [NMD]. This database is managed by a Dutch national institute in order to ensure the quality and consistency of the environmental profiles and shadow costs. The environmental profile of a material is called an Environmental Product Declaration [EPD]. This is EPD includes the environmental impact divided into 11 impact categories. The environmental impact of each category is defined by performing a Life Cycle Assessment [LCA]. So, the outcome of the LCA is an EPD and this is used for the calculation of the shadow costs. The following section will discuss both the LCA and shadow costs in more detail.

#### A.3.2.1 Life Cycle Assessment

For the sustainable use of resources in the Netherlands, the LCA is an integral part of the calculation methods. In the ISO 14044 the LCA is defined as ''the compiling and evaluation of the potential environmental impacts caused by the input and output of a product systems during its lifetime''. When performing a LCA four phases are completed. Each phase will be shortly discussed in this section.

*Phase 1: Goal and scope definition*
In order to successfully perform the LCA, the analysis should be specified. This includes defining the purpose, the made assumptions, the functional unit and the system boundaries.
The level of detail of a LCA can differ depending on the goal. In this research only the load-bearing structure of a building is assessed. Thereby, this assessment will take place in the preliminary design phase. Therefore, a screening LCA is performed for a quick overview of the environmental impact (Gervasio & Dimova, 2018; Wittstock et al. 2012).
The functional unit of the LCA defines how the environmental performance is quantified. The functional unit can consists of several indicators that define its performance. The functional unit can be used to compare the impact of the load-bearing structure design variants. For an LCA performed in the construction sector, a functional unit of €/$m^2$/year is used.

After defining the objective and functional unit of the LCA, the system boundaries of the product system must be determined. The system boundaries include all possible steps between extracting the resources, the production and manufacturing, the use- and end-of-life scenarios. The following subjects are included in the system boundaries:

- *Cut off criteria;* these define which parts and materials of the product system are included. In this research only the materials of the load-bearing structure (excluding the foundation) are considered.
- *Boundary type;* The boundary type determines which phases are included. For instance, cradle to grave includes the phases from the extraction of resources up top the end-of-life of the product. Cradle to gate only considers the phases from the extraction of resources up top the manufactured product. Other possibilities are; Gate to Gate, Gate to Grave and Cradle to Cradle. In this research the phases from raw materials until the end-of-life and potential benefits and loads for the next life cycle are included, presented in figure A.8. In the use phase the load-bearing structure does not produce any additional environmental impact, so this phase is excluded.

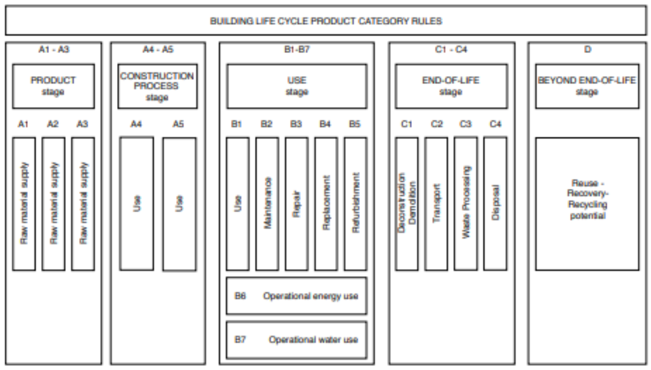



**Figure A.8** Different phases of the LCA (NEN, 2006)

- *Allocation*; It may happen that a certain product is used for multiple cycles. This can make it difficult to define how much of the environmental impact of the input is for the first life cycle or for the second life cycle. It is very important to be consistent when allocating the environmental impact over different products or cycles. In this research, the allocation of the potential benefits and loads of the environmental impact for the next cycle is not determined. Yet, the end-of-life scenario is assumed including the percentage of reuse, recycle or demolition. These percentages are based on the data of the Nationale Milieu Database [NMD].

*Phase 2: Inventory analysis*
For the defined system boundaries an inventory of the input and output data is analysed. In this research the investigated data only involves the material quantities, as LCA's also can include the use of energy and water. The database used in this research is the NMD.

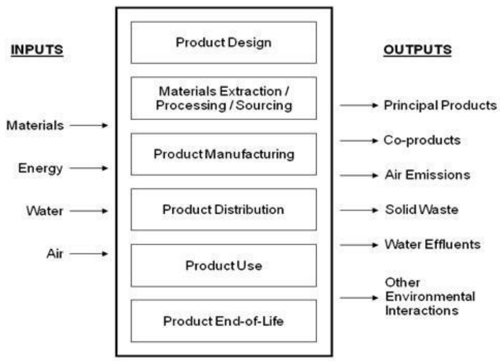



**Figure A.9** Life Cycle Inventory Analysis (SETAC, 1991)

*Phase 3: Impact assessment*
With the Life Cycle Inventory [LCI] of phase 2, the Life Cycle Impact Assessment [LCIA] can start. This assessment defines the environmental impact of the systems. The following two steps are key for the LCIA:

1. Classification; the environmental impact is divided over the impact categories. In this research the following 11 impact categories are included.

| Environmental impact categories | Equivalent unit |
|---|---|
| Global warming (GWP100) | $CO_2$ |
| Ozone layer depletion (ODP) | CFC-11 |
| Human toxicity (HTP) | 1.4-DB |
| Aquatic tox fresh water (sweet) (FAETP) | 1.4-DB |
| Aquatic tox fresh water (salt) (MAETP) | 1.4-DB |
| Terrestrial toxicity (TETP) | 1.4-DB |
| Photochemical oxidation (POCP) | $C_2H_4$ |
| Acidification (AP) | $SO_2$ |
| Eutrophication (EP) | $PO_4$ |
| Abiotic resources depletion | Sb |
| Fossil energy carriers depletion | Sb |

**Table A.3** Environmental impact categories

2. Characterisation; as the table A.3 indicates the impact categories are in equivalent unit. This means the categories put various substance emissions into one group, effecting the environmental in a similar manner (Hillege, 2019; Backx, 2020). To clarify this with an example, one of the environmental impact categories is the Ozone depletion measured in kg CFC-11-equivalent. Meaning a set of emissions that cause the destruction of the ozone layer (Hillege, 2019).

*Phase 4: Interpretation*
The last phase is investigating the results retrieved from the impact assessment. In the following section, the shadow costs are explained. These costs are used to finalise the assessment of the environmental impact.

### A.3.2.2 Shadow costs

The LCA determines per module, building phase, the environmental impact per impact category. The environmental impact of each category will be multiplied with a relevant weighting factor. These weighting factors convert the environmental impact in kg ($CO_2$ equivalent, $SO_2$ equivalent etc.) into a shadow price (de Bruyn et al., 2018).

$$\text{Shadow costs}_{\text{per impact category}}\ \textit{[€/unit material per impact category]} = \text{environmental impact}\ \textit{[kg eq./unit material]} \cdot \text{weighting factor}\ \textit{[€/kg eq.]}$$

$$\text{Sum shadow costs}_{\text{per unit material}}\ \textit{[€/unit material]} = \sum \text{Shadow costs}_{\text{per impact category}}\ \textit{[€/unit material per impact category]}$$

$$\text{Total shadow costs}\ \textit{[€]} = \text{mass material}\ \textit{[kg]} \cdot \text{Sum shadow costs}_{\text{per unit material}}\ \textit{[€/unit material]}$$

# Chapter B

# Structural calculations

This Appendix will present the applied structural calculations, used structural characterises per construction material and the outcome for each structural building component. Figure B.1 illustrates how the loads are applied on the structural building components.

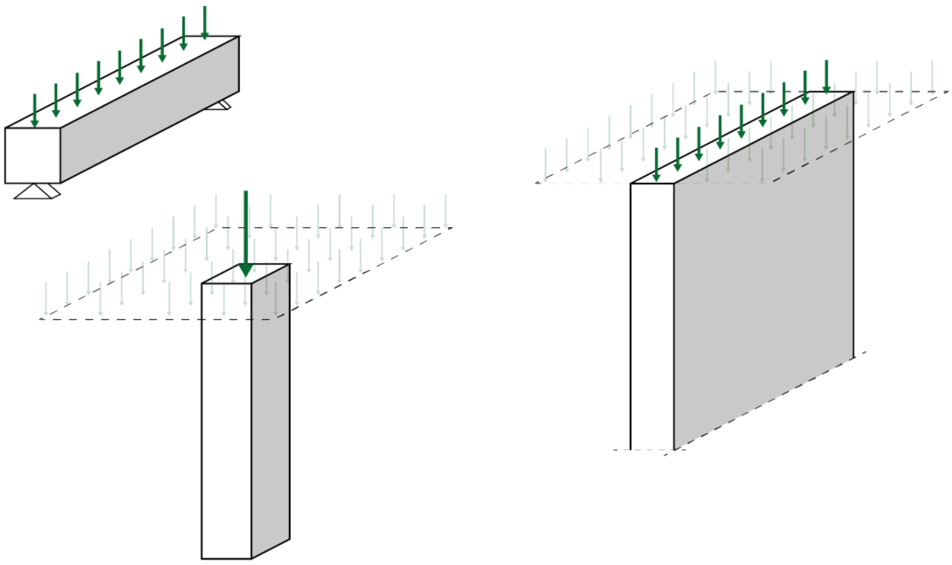


**Figure B.1** Applied loads on the structural building components (own figure)

## B.1 Concrete structural building components

### B.1.1 Concrete structural characteristics

| Strength class | Building part | Specific weight | Calculation value stresses |
|---|---|---|---|
| C30/37 | Floors, beams and columns | 2400 kg/m³ | *Compression stresses*<br>$\sigma_{C30/37prefab}$: 18 N/mm²<br>$\sigma_{C30/37in-situ}$: 15 N/mm² |
| C53/65 | Columns | 2400 kg/m³ | *Compression stresses*<br>$\sigma_{C53/65prefab}$: 32 N/mm²<br>$\sigma_{C53/65in-situ}$: 20 N/mm² |

**Table B.1** Concrete structural characteristics based on the BHH-model

### B.1.2 Concrete floor systems

#### B.1.2.1 Concrete hollow core slab floor

| Thickness of the floor [mm] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 260 | 260 | 200 | 150 | 150 |
| **10** | 320 | 320 | 200 | 200 | 150 |
| **15** | 400 | 320 | 260 | 200 | 150 |
| **20** | not possible | 400 | 260 | 200 | 150 |

| Weight of the concrete [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 376 | 376 | 303 | 264 | 264 |
| **10** | 443 | 443 | 303 | 303 | 264 |
| **15** | 548 | 443 | 376 | 303 | 264 |
| **20** | not possible | 548 | 376 | 303 | 264 |

| Weight of the reinforcement [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 12,27 | 5,57 | 2,88 | 1,83 | 1,05 |
| **10** | 12,27 | 6,53 | 3,01 | 1,96 | 1,31 |
| **15** | 10,44 | 9,97 | 4,88 | 2,88 | 1,83 |
| **20** | not possible | 10,44 | 5,57 | 4,19 | 2,09 |

**Figure B.2** Dimensions of the concrete hollow core slab floor according to the calculations rules of the BHH-model

#### B.1.2.2 Concrete in-situ floor

| Thickness of the floor [mm] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | not possible | 450 | 350 | 200 | 150 |
| **10** | not possible | 450 | 350 | 200 | 150 |
| **15** | not possible | 450 | 350 | 200 | 150 |
| **20** | not possible | not possible | not possible | not possible | not possible |

| Weight of the concrete [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | not possible | 1080 | 840 | 480 | 360 |
| **10** | not possible | 1080 | 840 | 480 | 360 |
| **15** | not possible | 1080 | 840 | 480 | 360 |
| **20** | not possible | not possible | not possible | not possible | not possible |

| Weight of the reinforcement [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | not possible | 21,6 | 16,8 | 9,6 | 7,2 |
| **10** | not possible | 21,6 | 16,8 | 9,6 | 7,2 |
| **15** | not possible | 21,6 | 16,8 | 9,6 | 7,2 |
| **20** | not possible | not possible | not possible | not possible | not possible |

**Figure B.3** Dimensions of the concrete in-situ floor according to the calculations rules of the BHH-model

### B.1.1.3 Concrete wide slab floor

| Thickness of the floor [mm] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 400 | 350 | 300 | 250 | 200 |
| **10** | 450 | 400 | 350 | 300 | 250 |
| **15** | not possible | not possible | not possible | not possible | not possible |
| **20** | not possible | not possible | not possible | not possible | not possible |

| Weight of the concrete (prefab + in-situ) [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 1000 | 875 | 750 | 625 | 500 |
| **10** | 1125 | 1000 | 875 | 750 | 625 |
| **15** | not possible | not possible | not possible | not possible | not possible |
| **20** | not possible | not possible | not possible | not possible | not possible |

| Weight of the reinforcement [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 29 | 25 | 16 | 11 | 7 |
| **10** | 44 | 25 | 16 | 11 | 7 |
| **15** | not possible | not possible | not possible | not possible | not possible |
| **20** | not possible | not possible | not possible | not possible | not possible |

**Figure B.4** Dimensions of the concrete wide slab floor according to the calculations rules of the BHH-model

### B.1.3 Concrete beams

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Concrete** | |
| Beam | $A_{b,c} = h_b \times w_b$ with $h_b = \frac{1}{10} \times L_b$ $w_b = \frac{2}{3} \times h_b$ | $A_b$: required concrete area per beam [mm²] $h_b$: height of the beam [mm] $w_b$: width of the beam [mm] |
| Reinforcement | $M_r = \frac{\frac{1}{8} \times q \times l^2 \times \rho_s \times c}{0{,}9 \times d \times f_s}$ | $M_r$: mass of required reinforcement [kg/m] q: line load on the beam [N/mm] l: length of the beam [mm] $\rho_s$: specific material weight [kg/m³] c: reinforcement factor; 4 d: useful beam height [mm] $f_s$: steel stresses in reinforcement [N/mm²] |

**Table B.2** The calculations rules for concrete beams based on the BHH-model

### B.1.4 Concrete columns

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Concrete** | |
| Column | $A_{needed,c} = \frac{F_{column}}{f_{concrete}}$ | $A_{needed,c}$: required concrete area per column [mm²] $F_{column}$: point load on the column [N] $f_{concrete}$: admissible concrete compressive stresses [N/mm²] |
| Reinforcement | $A_{needed,r} = \frac{A_{needed,c}}{p_r}$ | $A_{needed,r}$: required reinforcement area per column [mm²] $p_r$: reinforcement percentage; 1% |

**Table B.3** The calculations rules for concrete columns based on the BHH-model

### B.1.5 Concrete wall

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Concrete** | |
| Wall | $d_{needed,c} = \frac{q_{wall}}{f_{concrete}}$ | $d_{needed,c}$: required concrete thickness of the wall [mm] $q_{wall}$: point load on the column [N] $f_{concrete}$: admissible concrete compressive stresses [N/mm²] |

**Table B.4** The calculations rules for concrete wall based on the BHH-model

## B.2 Steel and hybrid structural building components

### B.2.1 Steel structural characteristics

| Strength class | Building part | Specific weight | Calculation value stresses |
|---|---|---|---|
| Reinforcement | Floors, beams and columns | 7850 kg/m³ | $\sigma_{reinforcement}$: 435 N/mm² |
| S235 | Beams | 7850 kg/m³ | $\sigma_s$: 200 N/mm² *(tension)* |
| S355 | Beams | 7850 kg/m³ | $\sigma_s$: 300 N/mm² *(tension)* |
| S460 | Beams | 7850 kg/m³ | $\sigma_s$: 400 N/mm² *(tension)* |
| S235 | Columns | 7850 kg/m³ | $\sigma_s$: 170 N/mm² *(compression)* |
| S355 | Columns | 7850 kg/m³ | $\sigma_s$: 250 N/mm² *(compression)* |
| S460 | Columns | 7850 kg/m³ | $\sigma_s$: 300 N/mm² *(compression)* |

**Table B.5** Steel structural characteristics based on the BHH-model

### B.2.2 Steel/hybrid floor systems

#### B.2.2.1 Prefabricated concrete slabs with steel I beams (slimline floor)

| **Thickness of the floor [mm]** | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 520 | 450 | 360 | 320 | 300 |
| **10** | 570 | 520 | 390 | 340 | 300 |
| **15** | 670 | 570 | 450 | 390 | 340 |
| **20** | 720 | 670 | 480 | 390 | 340 |

| **Weight of the concrete and steel beams [kg/m2]** | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 331 | 316 | 301 | 294 | 291 |
| **10** | 342 | 331 | 305 | 297 | 291 |
| **15** | 365 | 342 | 316 | 305 | 297 |
| **20** | 379 | 365 | 323 | 305 | 297 |

**Figure B.5** Dimensions of the slimline floor according to the calculations rules of the BHH-model

### B.2.3 Steel beams

| **Structural element** | **Used calculation rule** | **Explanation** |
|---|---|---|
| | **Steel** | |
| Beam | $W_{needed,s} = \frac{\frac{1}{8} \times q \times l^2}{\sigma_{s\_1}}$ | $W_{needed,s}$: required resistance moment of the beam [mm³]<br>q: line load on the beam [N/mm]<br>l: span length of the beam [mm]<br>$\sigma_{s\_1}$: admissible steel stresses [N/mm²] |

**Table B.6** The calculations rules for steel beams based on the BHH-model

## B.2.4 Steel columns

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| **Steel** | | |
| Column | $A_{needed,s} = \frac{F_{column}}{\sigma_{s\_2}}$ | $A_{needed,s}$: required steel area per column [$mm^2$]<br>$F_{column}$: point load on the column [N]<br>$\sigma_{s\_2}$: admissible steel stresses [$N/mm^2$] |

**Table B.7** The calculations rules for steel columns based on the BHH-model

# B.3 Timber structural building components

## B.3.1 Timber structural characteristics

| Strength class | Building part | Specific weight | Calculation value stresses |
|---|---|---|---|
| Kerto-Ripa | Floors | - | - |
| GL24h | Beams | 385 kg/m³ | $\sigma_t$: 14 N/mm² *(tension)* |
| GL28h | Beams | 425 kg/m³ | $\sigma_t$: 16 N/mm² *(tension)* |
| GL30h | Beams | 480 kg/m³ | $\sigma_t$: 18 N/mm² *(tension)* |
| GL24h | Columns | 385 kg/m³ | $\sigma_t$: 19,2 N/mm² *(compression)* |
| GL28h | Columns | 425 kg/m³ | $\sigma_t$: 22,3 N/mm² *(compression)* |
| C24 | Columns | 420 kg/m³ | $\sigma_t$: 14,5 N/mm² *(compression)* |

**Table B.8** Timber structural characteristics based on the BHH-model, Centrum Hout and Finnwood

## B.3.2 Timber floor systems

### B.3.2.1 Timber hollow core slab floor

| Thickness of the floor [mm] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 650 | 500 | 310 | 230 | 200 |
| **10** | not possible | not possible | 650 | 500 | 250 |
| **15** | not possible | not possible | not possible | not possible | 450 |
| **20** | not possible | not possible | not possible | not possible | 650 |

| Weight of the timber [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 81 | 58 | 42 | 38 | 36 |
| **10** | not possible | not possible | 81 | 58 | 39 |
| **15** | not possible | not possible | not possible | not possible | 52 |
| **20** | not possible | not possible | not possible | not possible | 81 |

**Figure B.6** Dimensions of the timber hollow core slab floor according to the calculations rules of the Finnwood tool

### B.3.2.1 Timber beamed floor

| Thickness of the floor [mm] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 600 | 600 | 400 | 350 | 240 |
| **10** | 750 | 600 | 450 | 400 | 240 |
| **15** | 750 | 600 | 500 | 400 | 300 |
| **20** | 750 | 750 | 600 | 450 | 300 |

| Weight of the timber [kg/m2] | | | | | |
|---|---|---|---|---|---|
| | *Span [m]* | | | | |
| *Load [kN/m2]* | **12,6** | **10,8** | **7,2** | **5,4** | **3,6** |
| **5** | 73,5 | 45,8 | 38,7 | 15,8 | 13,3 |
| **10** | 95,7 | 90,8 | 47,6 | 25,8 | 14,1 |
| **15** | 143,5 | 140,7 | 58,7 | 38,7 | 21,8 |
| **20** | 181,3 | 164 | 83,3 | 47,6 | 27,6 |

**Figure B.7** Dimensions of the timber beamed floor according to the calculations rules of the Finnwood tool

### B.3.3 Timber beams

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Timber** | |
| Beam | $W_{needed,t} = \frac{\frac{1}{8} \times q \times l^2}{\sigma_{m\_0\_d}}$ | $W_{needed,t}$: required resistance moment of the beam [$mm^3$]<br>q: line load on the beam [N/mm]<br>l: span length of the beam [mm]<br>$\sigma_{m\_0\_d}$: admissible timber bending stresses [$N/mm^2$] |

**Table B.9** The calculations rules for timber beams based on the BHH-model

### B.3.4 Timber columns

| Structural element | Used calculation rule | Explanation |
|---|---|---|
| | **Timber** | |
| Column | $A_{needed,t} = \frac{F_{column}}{f_{c\_0\_d}}$ | $A_{needed,t}$: required timber area per column [$mm^2$]<br>$F_{column}$: point load on the column [N]<br>$f_{c\_0\_d}$: admissible timber compression stresses [$N/mm^2$] |

**Table B.10** The calculations rules for timber columns based on the BHH-model

### B.3.5 Timber wall

| Load-bearing capacity *[kN/m]* | Profile | Weight *[kg/m² wall]* |
|---|---|---|
| 36 | 46*96-300 | 6,18 |
| 40 | 38*140-400 | 5,59 |
| 52 | 46*121-300 | 7,79 |
| 62 | 46*146-300 | 9,40 |
| 100 | 2*46*146-300 | 18,80 |
| 115 | 2*46*146-200 | 28,21 |

**Figure B.8** Dimensions of the HSB timber wall according to the calculations rules of the BHH-model

# B.4 Rules of thumb for validation

In this section the rules of Jellema are presented (Hofkes et al., 2004). This rules of thumb are used to validate the outcome of the BHH-model.

## B.4.1 Concrete rules of thumb

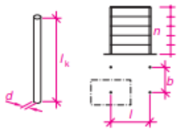
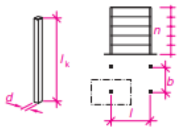
| Constructie-element | Aanzicht kolom en plattegrond gebouw | | Verhouding $\frac{b}{\ell_k}$ | Verhouding $\frac{d}{\ell_k}$ |
|---|---|---|---|---|
| Ronde kolom |  | ter plaatse gestort beton | 1 | $\frac{1}{25}\sqrt{n}$ |
| | | | $\frac{1}{2}$ | $\frac{1}{35}-\frac{1}{40}\sqrt{n}$ |
| | | prefab-beton | 1 | $\frac{1}{30}-\frac{1}{35}\sqrt{n}$ |
| | | | $\frac{1}{2}$ | $\frac{1}{45}-\frac{1}{55}\sqrt{n}$ |
| Vierkante kolom |  | ter plaatse gestort beton | 1 | $\frac{1}{25}-\frac{1}{35}\sqrt{n}$ |
| | | | $\frac{1}{2}$ | $\frac{1}{40}-\frac{1}{50}\sqrt{n}$ |
| | | prefab-beton | 1 | $\frac{1}{35}-\frac{1}{45}\sqrt{n}$ |
| | | | $\frac{1}{2}$ | $\frac{1}{55}-\frac{1}{65}\sqrt{n}$ |
| $\ell \leq 4$m | | | | |

**Figure B.9** Rules of thumb concrete columns by Hofkes et al. (2004)

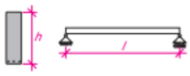
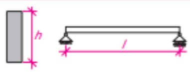
| Constructie-element | Doorsnede en aanzicht | Overspanning $\ell$ in m | Verhouding $\frac{h}{\ell}$ | Verhouding $\frac{b}{h}$ |
|---|---|---|---|---|
| Ligger ter plaatse gestort |  | 4–18 | $\frac{1}{10}$ | $\frac{1}{3}-\frac{1}{5}$ |
| Ligger prefab-voorgespannen beton |  | 5–25 | $\frac{1}{10}-\frac{1}{12}$ | $\frac{1}{3}-\frac{1}{5}$ |

**Figure B.10** Rules of thumb concrete beams by Hofkes et al. (2004)

## B.4.2 Steel and hybrid rules of thumb

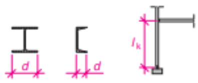
| Constructie-element | Doorsnede en zijaanzicht | Knik-lengte ($\ell_k$) in m | Doorsnede-hoogte verhouding $\frac{d}{\ell_k}$ | |
|---|---|---|---|---|
| Gewalst of gelast profiel |  | 2–8 | $\frac{1}{20}-\frac{1}{25}$ | één bouwlaag |
| | | 2–4 | $\frac{1}{7}-\frac{1}{18}$ | meer bouwlagen |

**Figure B.11** Rules of thumb steel columns by Hofkes et al. (2004)

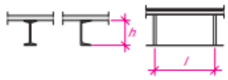
| Constructie-element | Doorsnede en zijaanzicht | Afmeting van het element (h) in mm | Overspanning ($\ell$) in m | Verhouding $\frac{h}{\ell}$ |
|---|---|---|---|---|
| Breedflens-profielen of kokers |  | 100–500 | 4–12 | $\frac{1}{18}-\frac{1}{28}$ |
| Profielstaal |  | 200–500 | 6–30 | $\frac{1}{15}-\frac{1}{20}$ |

**Figure B.12** Rules of thumb steel beams by Hofkes et al. (2004)

## B.4.3 Timber rules of thumb

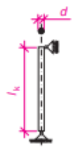
| Constructie-element | Doorsnede | Kniklengte $\ell_k$ in m | Verhouding $\frac{d}{\ell_k}$ |
|---|---|---|---|
| Ronde massief houten kolom |  | 2–4 | $\frac{1}{20}-\frac{1}{25}$ |
| Vierkante massief houten kolom |  | 2–4 | $\frac{1}{20}-\frac{1}{25}$ |

**Figure B.13** Rules of thumb timber columns by Hofkes et al. (2004)

| Constructie-element | Doorsnede en zijaanzicht | Over-span-ning $\ell$ in m | Verhou-ding $\frac{b}{h}$ | Verhou-ding $\frac{b}{a}$ | Verhou-ding $\frac{h}{\ell}$ | H.o.h.-afstand $a$ in $m$ |
|---|---|---|---|---|---|---|
| Massieve ligger |  | 2,5–8 | $\frac{1}{3}$ | – | $\frac{1}{15}-\frac{1}{20}$ | – |
| Gelamineerde ligger |  | 6–25 | $\frac{1}{6}-\frac{1}{10}$ | $\frac{1}{17}-\frac{1}{20}$ | $\frac{1}{20}$ | $\frac{\ell}{2}$ $\frac{\ell}{3}$ |

**Figure B.14** Rules of thumb timber beams by Hofkes et al. (2004)

## B.5 Specific structural requirements per function

| Function | Variable load | Fire safety | Acoustics resistance | Floor to ceiling height |
|---|---|---|---|---|
| Residential | 1,75 kN/m$^2$ | 60 min $h_{building}$< 7 m<br>90 min $h_{building}$< 13 m<br>120 min $h_{building}$> 13 m | > 52 dB | 2,6 m |
| Office | 2,50 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 2,6 m |
| Retail | 4,00 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 2,6 m |
| Sports | 5,00 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 5,0 m |
| Education | 3,00 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 2,6 m |
| Conference | 5,00 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 2,6 m |
| Industry | 5,00 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 2,6 m |
| Healthcare | 3,00 kN/m$^2$ | 30 min $h_{building}$< 5 m<br>90 min $h_{building}$< 13 m<br>90 min $h_{building}$> 13 m | - | 2,6 m |

**Table B.11** Specific structural requirements per building function

# Chapter C

# Additional requirements due to circular design strategies

The functional and technical design principles of the three circular design strategies lead to additional requirements for the structural building components. As discussed in Chapter 3 each of the structural building components is analysed on the acoustic performance, fire resistance, span length, connections and production method, see table 3.1. This section provides the explanation of the determined match between the circular design strategies and the structural building components. Firstly, the requirement of the circular design strategies are shortly stated. Secondly the analysis of characteristics of the structural building components is presented. Thirdly, the questionnaire and outcome of the expert judgement by the structural engineers is presented.

## C.1 Requirements of the circular design strategies

### C.1.1 Design for Adaptability

| | Design for Adaptability |
|---|---|
| General description | An adaptable building should be able to allow multiple type of users, meaning different functions (Kasarda et al., 2007). So, the load-bearing structure of the building, should suit a change in the building type. |
| Function | Multiple |
| Fire safety requirements | Shift in function means the strictest function is normative, so high fire resistance necessary |
| Acoustic requirements | Shift in function means the strictest function is normative, so high acoustic insulation necessary |
| Production and connections | Robust and durable system |
| Span length | Large spans of minimal 7 meters and sufficient floor to ceiling height of minimal 3,5 meters |

**Table C.1** Requirements of circular design strategy DfA

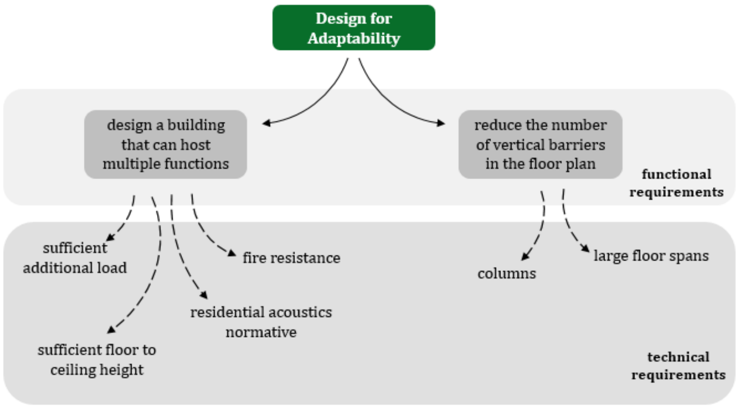



**Figure C.1** Functional and technical requirements of circular design strategy DfA (own figure)

### C.1.2 Design for Disassembly

| Design for Disassembly | |
|---|---|
| General description | At the end-of-life stage the design allows the building to be dismantlable and the released building components can be reused (Guy & Ciarimboli, 2005). |
| Function | One |
| Fire safety requirements | Based on the chosen function |
| Acoustic requirements | Based on the chosen function |
| Production and connections | Dry connections are required and prefabricated components. Additionally, it is important to consider the manageability on site of the components |
| Span length | Based on the design requirements |

**Table C.2** Requirements of circular design strategy DfD

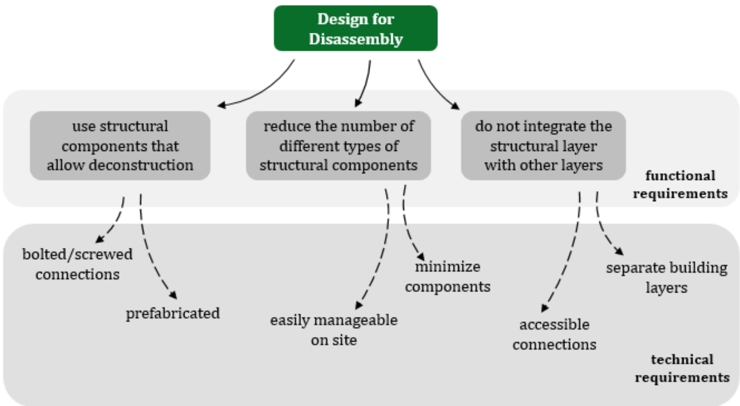



**Figure C.2** Functional and technical requirements of circular design strategy DfD (own figure)

### C.1.3 Design for Material Efficiency

| Design for Material Efficiency | |
|---|---|
| General description | To efficiently use materials, the design should be composed for one single function. Meaning the structural building components are efficiently used with a clear purpose. This will stimulate the optimisation of the load-bearing structure and the total materials needed can be reduced. |
| Function | One |
| Fire safety requirements | Based on the chosen function |
| Acoustic requirements | Based on the chosen function |
| Production and connections | As efficient as possible to limit material waste. Therefore, prefabricated elements. |
| Span length | Based on the design requirements |

**Table C.3** Requirements of circular design strategy DfME

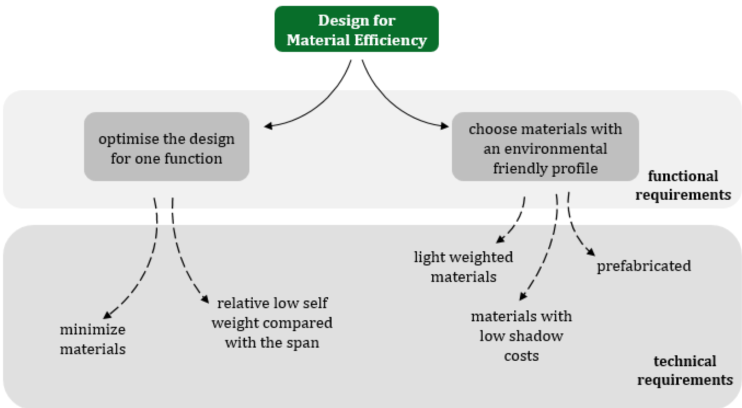



**Figure C.3** Functional and technical requirements of circular design strategy DfME (own figure)

# C.2 Characteristics of the structural building components

| Floors and roofs | Material | Technical lifespan | | | | Acoustic performance | Fire resistance | Span | Production |
|---|---|---|---|---|---|---|---|---|---|
| | | Source 1 [years] | Source 2 [years] | Source 3 [years] | Source 4 [years] | [-] | [minutes] | [m] | [-] |
| **hollow core slab floor with compression layer** | concrete | 75 | 75> | - | 75> | 3 | 60-120 | 7,5-17,0 | prefabrication and in-situ on site |
| **hollow core slab floor** | concrete | 75 | 75> | - | 75> | 3 | 60-120 | 7,5-17,0 | prefabrication |
| **in-situ floor** | concrete | 75 | 75> | - | 75> | 3 | 60-120 | 5,0-10,0 | in-situ on site |
| **wide slab floor** | concrete | 75 | 75> | - | 75> | 3 | 90 | 4,5-9,5 | prefabrication and in-situ on site |
| **combination floor** * groundfloor system | concrete | 75 | 75> | - | 75> | - | - | -6,8 | prefabrication and in-situ on site |
| **ribbed floor** * groundfloor system | concrete | 75 | 75> | - | 75> | - | - | -7,2 | in-situ on site |
| **hollow core slab floor** | timber | 75 | 30-300 | - | 75> | 1 | 60-90 | 5,0-10,0 | prefabrication |
| **beamed floor** | timber | 75 | 30-300 | - | 75> | 1 | 60-90 | 4,0-8,0 | prefabrication |
| **slimline floor** | hybrid | 75 | 50-100 | - | 75> | 2 | 120 | 5,5-11,0 | prefabrication |

| Beams | Material | Technical lifespan | | | | Acoustic performance | Fire resistance | Span | Production |
|---|---|---|---|---|---|---|---|---|---|
| | | Source 1 [years] | Source 2 [years] | Source 3 [years] | Source 4 [years] | [-] | [-] | [m] | [-] |
| **prefab concrete beams** | concrete | - | 75> | 63 | 75> | | 3 | 5,0-10,0 | prefabrication |
| **in-situ concrete beams** | concrete | - | 75> | 63 | 75> | | 3 | 5,0-7,0 | in-situ on site |
| **steel beams** | steel | - | 50-100 | 64 | 75> | | 1 | 5,0-16,0 | prefabrication |
| **timber beams** | timber | - | 30-300 | 40 | 75> | | 2 | 3,0-8,0 | prefabrication |

| Columns | Material | Technical lifespan | | | | Acoustic performance | Fire resistance | Span | Production |
|---|---|---|---|---|---|---|---|---|---|
| | | Source 1 [years] | Source 2 [years] | Source 3 [years] | Source 4 [years] | [-] | [-] | [m] | [-] |
| **prefab concrete columns** | concrete | - | 75> | 60 | 75> | | 3 | | prefabrication |
| **in-situ concrete columns** | concrete | - | 75> | 60 | 75> | | 3 | | in-situ on site |
| **steel columns** | steel | - | 50-100 | 60 | 75> | | 1 | | prefabrication |
| **timber columns** | timber | - | 30-300 | 61 | 75> | | 2 | | prefabrication |

| Walls | Material | Technical lifespan | | | | Acoustic performance | Fire resistance | Span | Production |
|---|---|---|---|---|---|---|---|---|---|
| | | Source 1 [years] | Source 2 [years] | Source 3 [years] | Source 4 [years] | [-] | [-] | [m] | [-] |
| **prefab concrete walls** | concrete | - | 75> | 60 | 75> | 3 | 3 | | prefabrication |
| **in-situ concrete walls** | concrete | - | 75> | 60 | 75> | 1 | 3 | | in-situ on site |
| **timber walls (HSB)** | timber | - | 30-300 | 75 | 75> | 1 | 2 | | prefabrication |

| Stability systems | Material | Technical lifespan | | | | Acoustic performance | Fire resistance | Span | Production |
|---|---|---|---|---|---|---|---|---|---|
| | | Source 1 [years] | Source 2 [years] | Source 3 [years] | Source 4 [years] | [-] | [minuten] | [m] | [-] |
| **prefab concrete core** | concrete | - | 75> | - | 75> | | 3 | | prefabrication |
| **in-situ core** | concrete | - | 75> | - | 75> | | 3 | | in-situ on site |
| **steel windbraces** | steel | - | 50-100 | - | 75> | | 1 | | prefabrication |
| **walls** *(see above)* | | | | | | | | | |

**Figure C.4** Assessment of characteristics of the structural building components (own figure)

## C.3 Questionnaire and results of the structural engineers

This section presents the answers of the design questionnaire. The structural engineers were asked to compose two structural design variants that are in line with the circular design strategy. This lead to a total of six structural design variants for each circular design strategy. In table 3.2 the outcome of the analysis of the answers of the structural engineers is presented.
The structural engineers are Dutch, therefore the following questionnaire is in Dutch.

## Adaptief ontwerpen

**Omschrijving van de strategie**
De ontwerpstrategie adaptief ontwerpen houdt rekening met een mogelijke verandering in functie. Dit betekent dat het ontwerp geschikt moet zijn voor **3 functies (kantoor, winkel, wonen)**. Op deze manier kan de levensduur van de draagconstructie worden verlengd en de milieu kosten worden gereduceerd. Door de extra functies worden de eisen voor de draagconstructie beinvloed, denk aan hogere akoestische eisen, brandwerendheid of grote overspanningen voor een hogere indelingsvrijheid.

**Constructeur 1**

| Variant 1 | Variant 2 |
|---|---|
| Afmetingen | Afmetingen |
| lx 21 m | lx 21 m |
| ly 12 m | ly 12 m |
| Stramien in x-richting | Stramien in x-richting |
| *1. Kies het stramien aantal* | *1. Kies het stramien aantal* |
| 3 — 7 m | 1 — 21 m |
| Stramien in y-richting | Stramien in y-richting |
| *1. Kies het stramien aantal* | *1. Kies het stramien aantal* |
| 2 — 6,00 m | 1 — 12,00 m |
| 2. Keuze begane grond vloer | 2. Keuze begane grond vloer |
| **ihwg betonvloer** | **ihwg betonvloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Relatief simpelel manier. Makkelijk te overdimensioneren met meer wapening voor toekomstige hogere belastingen. | Veel vrijheid. Gemakkelijk over te dimensioneren. |
| 3. Keuze verdiepingsvloer | 3. Keuze verdiepingsvloer |
| **breedplaatvloer** | **staalplaat betonvloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Gemakkelijker aan te passen door bijvoorbeeld gaten te boren etc en plaatselijk stukken aan te storten. Geen voorspanstrengen aanwezig. Grote massa wat goed is voor geluidisolatie. | Geeft meer vrijheid in mogelijk toekomstige sparingen. Geeft veel massa voor geluidsisolatie tussen verdiepingen. |
| 4. Keuze dak | 4. Keuze dak |
| **breedplaatvloer** | **staalplaat betonvloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Geeft de mogelijkheid om in de toekomst door te bouwen op het dak. | Geeft de vrijheid om mogelijk in de toekomst een verdieping op te bouwen. |
| 5. Keuze liggers | 5. Keuze liggers |
| **prefab beton** | **stalen liggers** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| snelle bouwtijd. Robuust voor mogelijke aanpassingen. Brandwerend en lange levensduur. Kan tegen verschillende milieuklassen ook als daarbij vocht aanwezig is. | Geeft goede detaillering met staalplaatbeton vloer. Gemakkelijk over te dimensioneren. Wel rekening houden met brandwerende bekleding. |
| 6. Keuze kolommen/wanden | 6. Keuze kolommen/wanden |
| **prefab beton kolommen** | **stalen kolommen** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Goede combi met prefab betonnen liggers. Robuust ivm brand en aanrijdbelasting. Geeft wel meer mogelijkheden dan gesloten wanden. | Goede mix met stalen liggers en staalplaatbeton vloeren qua detaillering. Geeft veel ruimte voor toekomstige wijziging in indeling. Wel rekening houden met brandwerende coating of vullen met beton voor brand. |
| 7. Keuze stabiliteit systeem | 7. Keuze stabiliteit systeem |
| **beton kern** | **staalskelet met stabiliteitsverbanden** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Geeft meer vrije indeelbaarheid in de rest van het gebouw. Kern kan benut worden als stijgpunt voor verschillende functies. | Veel open ruimte en veel vrijheid bij mogelijke wijziging in plattegrond. |
| 8. Opmerkingen over de bovenstaande variant | 8. Opmerkingen over de bovenstaande variant |
| Geeft veel overcapaciteit voor uitbreiding van toekomstige belasting. Geen issues m.b.t. brand of aanrijdbelasting. Wel veel materiaalgebruik. Lange levensduur van gebouw. | Is opzich een goede bouwmethode, maar niet veel toegepast in Nederland. Komt vooral voor in Anglosaksiche landen. Mogelijk door grote betonbranche in Nederland. De vloeren zijn qua duurzaamheid niet ideaal. Het staal van de kolommen en liggers zou normaal wel remontabel moeten zijn. |

**Constructeur 2**

**Variant 1**

Afmetingen

| | | |
|---|---|---|
| lx | 21 | m |
| ly | 12 | m |

Stramien in x-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 2 | 10,5 | m |

Stramien in y-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 2 | 6,00 | m |

2. Keuze begane grond vloer

**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Kanaalplaat met isolatie i.v.m. de warmte schil.

3. Keuze verdiepingsvloer

**slimline vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

met slimline vloeren is het mogelijk om de toplaap open te maken en de leidingwerk aan te passen naar een nieuwe functie. Omdat het ook geschikt moet zijn voor een kantoor gebouw een hogere slimline dan voor een woning toepassen

4. Keuze dak

**slimline vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

idem als verdiepingsvloeren

5. Keuze liggers

**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

liggers in de X-richting, dus hogere liggers die ook hogere belastingen moet aankunnen (winkels).

6. Keuze kolommen/wanden

**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

beter aansluiting met ligger en slanker dan beton

7. Keuze stabiliteit systeem

**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

8. Opmerkingen over de bovenstaande variant

het is op te merken dan alle constructie onderdelen voor de maatgevende belastingen moeten worden uitgerekend. Dit betekend dat er extra materiaal wordt gebruikt voor enkele periodes waarbij het niet nodig is.

**Variant 2**

Afmetingen

| | | |
|---|---|---|
| lx | 21 | m |
| ly | 12 | m |

Stramien in x-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 2 | 10,5 | m |

Stramien in y-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 2 | 6,00 | m |

2. Keuze begane grond vloer

**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

3. Keuze verdiepingsvloer

**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

met een verlaagd plafond voor installaties.

4. Keuze dak

**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

5. Keuze liggers

**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

6. Keuze kolommen/wanden

**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

7. Keuze stabiliteit systeem

**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

8. Opmerkingen over de bovenstaande variant

**Constructeur 3**

| Variant 1 | Variant 2 |
|---|---|
| Afmetingen | Afmetingen |
| lx 21 m | lx 21 m |
| ly 12 m | ly 12 m |
| Stramien in x-richting | Stramien in x-richting |
| *1. Kies het stramien aantal* | *1. Kies het stramien aantal* |
| *4* 5,25 m | *4* 5,25 m |
| Stramien in y-richting | Stramien in y-richting |
| *1. Kies het stramien aantal* | *1. Kies het stramien aantal* |
| *1* 12,00 m | *1* 12,00 m |
| 2. Keuze begane grond vloer | 2. Keuze begane grond vloer |
| **kanaaplaat vloer** | **kanaaplaat vloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Lichter dan ihwg, wel een grote overspanning | Lichter dan ihwg |
| 3. Keuze verdiepingsvloer | 3. Keuze verdiepingsvloer |
| **kanaalplaat vloer** | **breedplaatvloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Lichter dan ihwg, wel een grote overspanning | Alvast massa toevoegen wanneer woningen een optie kunnen zijn, groot draagvermogen |
| 4. Keuze dak | 4. Keuze dak |
| **kanaalplaat vloer** | **kanaalplaat vloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Lichter dan ihwg, wel een grote overspanning | Lichter, geen geluidseis, maar wel sterkt genoeg voor extra belasting voor bijv daktuin |
| 5. Keuze liggers | 5. Keuze liggers |
| **prefab beton** | **prefab beton** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Brandwerendheid. Mits bekend blijft welke wapening aanwezig is voor eventuele toekomsite veranderingen. | Grote overspanning mogelijk |
| 6. Keuze kolommen/wanden | 6. Keuze kolommen/wanden |
| **prefab beton kolommen** | **prefab beton kolommen** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Brandwerendheid. Mits bekend blijft welke wapening aanwezig is voor eventuele toekomsite veranderingen. | Brandwerendheid |
| 7. Keuze stabiliteit systeem | 7. Keuze stabiliteit systeem |
| **betonskelet met stabiliteitsverbanden** | **betonskelet met stabiliteitsverbanden** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? |
| Het is niet echt heel logisch om verbanden toe te passen in een betonskelet, maar ik denk dat een gebouw adaptiever is als er geen kern aanwezig is. | Het is niet echt heel logisch om verbanden toe te passen in een betonskelet, maar ik denk dat een gebouw adaptiever is als er geen kern aanwezig is. |
| 8. Opmerkingen over de bovenstaande variant | 8. Opmerkingen over de bovenstaande variant |
| Leidingen niet instorten. Vloeroverspanning over 12m. | Geen leidingen instorten, liggeroverspanning 12m en vloeroverspanning 5,25. |

## Losmaakbaar ontwerpen

**Omschrijving van de strategie**
De ontwerpstrategie losmaakbaar ontwerpen focust op het ontwerpen van een constructie voor **1 functie (kantoor)** waar wanneer het einde van de levensduur wordt bereikt, de onderdelen los te maken zijn en kunnen worden ingezet voor hergebruik en een verlenging van de levensduur van de constructieve componenten. Om dit mogelijk te maken is het belangrijk dat er nagedacht wordt over materialen en bijpassende verbindingen die daarvoor geschikt zijn, denk aan prefab elementen, droge verbindingen of eenvoudige bouwmethodes.

**Constructeur 1**

| | Variant 1 | Variant 2 |
|---|---|---|
| Afmetingen | | |
| lx | 21 m | 21 m |
| ly | 12 m | 12 m |
| Stramien in x-richting – *1. Kies het stramien aantal* | 4 – 5,25 m | 1 – 21 m |
| Stramien in y-richting – *1. Kies het stramien aantal* | 2 – 6,00 m | 1 – 12,00 m |
| 2. Keuze begane grond vloer | **kanaaplaat vloer** | **kanaaplaat vloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Kanaalplaatvloer kan zonder druklaag eventueel worden hergebruikt. Druklaag voor bg vloer is in principe niet per se noodzakelijk. | Zonder druklaag is dit nog te hergebruiken. Druklaag is voor bg vloer niet per se noodzakelijk. |
| 3. Keuze verdiepingsvloer | **houten kanaalplaat** | **slimline vloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Detaillering is in alle gevallen mbv bouten of schroeven. Deze zijn gemakkelijk terug los te halen. | prefab elementen verbonden dmv bouten. Gemakkelijk los te halen. |
| 4. Keuze dak | **houten balkenvloer** | **houten balkenvloer** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Gemakkelijk terug los te halen. Belasting voor dak is lager, dus houten kanaalplaatvloeren zijn niet per se noodzakelijk. | prefab elementen verbonden dmv bouten. Gemakkelijk los te halen. |
| 5. Keuze liggers | **houten liggers** | **stalen liggers** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Detaillering is in alle gevallen mbv bouten of schroeven. Deze zijn gemakkelijk terug los te halen. | mits gebout, gemakkelijk los te halen na einde levensduur. |
| 6. Keuze kolommen/wanden | **houten kolommen** | **stalen kolommen** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Detaillering is in alle gevallen mbv bouten of schroeven. Deze zijn gemakkelijk terug los te halen. | mits gebout, gemakkelijk los te halen na einde levensduur. |
| 7. Keuze stabiliteit systeem | **houtskelet met stabiliteitsverbanden** | **staalskelet met stabiliteitsverbanden** |
| Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element? | Detaillering is in alle gevallen mbv bouten of schroeven. Deze zijn gemakkelijk terug los te halen. | mits gebout, gemakkelijk los te halen na einde levensduur. |
| 8. Opmerkingen over de bovenstaande variant | Qua remontabel bouwen is hout ideaal. Alles wordt vastgezet met schroeven of bouten, dit maakt het remontabel. | Slimline vloeren zijn alleen geschikt voor kantoren en zelfs dan niet heel erg gemakkelijk in de uitvoering. Ik heb er zelf slechte ervaringen mee. |

**Constructeur 2**

**Variant 1**

Afmetingen

| | | |
|---|---|---|
| lx | 21 | m |
| ly | 12 | m |

Stramien in x-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 3 | 7 | m |

Stramien in y-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 2 | 6,00 | m |

2. Keuze begane grond vloer

**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

3. Keuze verdiepingsvloer

**slimline vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

4. Keuze dak

**slimline vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

5. Keuze liggers

**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

6. Keuze kolommen/wanden

**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

7. Keuze stabiliteit systeem

**betonskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

8. Opmerkingen over de bovenstaande variant

**Variant 2**

Afmetingen

| | | |
|---|---|---|
| lx | 21 | m |
| ly | 12 | m |

Stramien in x-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 3 | 7 | m |

Stramien in y-richting

*1. Kies het stramien aantal*

| | | |
|---|---|---|
| 3 | 4,00 | m |

2. Keuze begane grond vloer

**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

3. Keuze verdiepingsvloer

**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

4. Keuze dak

**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

5. Keuze liggers

**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

6. Keuze kolommen/wanden

**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

7. Keuze stabiliteit systeem

**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

(denk aan materiaal eigenschappen zoals brandwerendheid, akoestiek, overspanning, bouwmethode, technische levensduur en meer)

8. Opmerkingen over de bovenstaande variant

**Constructeur 3**

| **Variant 1** | |
|---|---|
| Afmetingen | |
| lx | 21 m |
| ly | 12 m |
| Stramien in x-richting | |
| *1. Kies het stramien aantal* | |
| 3 | 7 m |
| Stramien in y-richting | |
| *1. Kies het stramien aantal* | |
| 1 | 12,00 m |

2. Keuze begane grond vloer
**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Prefab, dus makkelijker losmaakbaar dan ihwg

3. Keuze verdiepingsvloer
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Prefab, dus makkelijker losmaakbaar dan ihwg, druklaag wel een discussiepunt

4. Keuze dak
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Prefab, dus makkelijker losmaakbaar dan ihwg, druklaag wel een discussieopunt

5. Keuze liggers
**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Makkelijkste droge verbindingen maken

6. Keuze kolommen/wanden
**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Makkelijkste droge verbindingen maken

7. Keuze stabiliteit systeem
**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Makkelijkste droge verbindingen maken

8. Opmerkingen over de bovenstaande variant

Vloeroverspanning 12m. Zo groot mogelijke overspanningen. Je kan altijd een element korter maken, maar nooit langer.

| **Variant 2** | |
|---|---|
| Afmetingen | |
| lx | 21 m |
| ly | 12 m |
| Stramien in x-richting | |
| *1. Kies het stramien aantal* | |
| 4 | 5,25 m |
| Stramien in y-richting | |
| *1. Kies het stramien aantal* | |
| 1 | 12,00 m |

2. Keuze begane grond vloer
**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Licht

3. Keuze verdiepingsvloer
**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Ik denk goed herbruikbaar, omdat het een standaardproduct is, nog meer dan gewone kanaalplaat

4. Keuze dak
**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Ik denk goed herbruikbaar, omdat het een standaardproduct is, nog meer dan gewone kanaalplaat

5. Keuze liggers
**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Makkelijkste droge verbindingen maken

6. Keuze kolommen/wanden
**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Makkelijkste droge verbindingen maken

7. Keuze stabiliteit systeem
**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Makkelijkste droge verbindingen maken

8. Opmerkingen over de bovenstaande variant

Vloer overspanning 5,25. Liggeroverspanning 12m, omdat je wel korter kan maken, maar niet langer.

## Materiaal efficient ontwerpen

**Omschrijving van de strategie**
De ontwerpstrategie materiaal efficiënt ontwerpen focust op het realiseren van een constructie voor **1 functie (kantoor)** waar zo min mogelijk materiaal voor wordt gebruikt. Op deze manier wordt het gebruik van nieuwe materialen geoptimaliseerd en kan er gekozen voor materialen met een zo'n laag mogelijke milieu impact. Door de hoeveelheid en de milieu impact van materialen te minimaliseren wordt de draagconstructie beinvloed, denk aan lichtgewicht, efficientere bouwmethodes of een hoge recycle waarde.

**Constructeur 1**

### Variant 1

Afmetingen
lx 21 m
ly 12 m

Stramien in x-richting
*1. Kies het stramien aantal*
3 — 7 m

Stramien in y-richting
*1. Kies het stramien aantal*
1 — 12,00 m

2. Keuze begane grond vloer
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Relatief laag eigen gewicht door voorspanning, heel efficient materiaalgebruik. Goed bestand tegen issues m.b.t. vocht etc vanuit fundering.

3. Keuze verdiepingsvloer
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Laag eigen gewicht door voorspanning, grote overspanningen mogelijk. Installaties etc. kunnen onder verlaagd plafond verwerkt worden. Goedkoop. Snelle bouwmethode. Schijfwerking mogelijk door toepassen druklaag.

4. Keuze dak
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Laag eigen gewicht door voorspanning, grote overspanningen mogelijk. Installaties etc. kunnen onder verlaagd plafond verwerkt worden. Goedkoop. Snelle bouwmethode. Schijfwerking mogelijk door toepassen druklaag. Bij alle vloeren zelfde type toepassen geeft schaalvoordelen en voorkomt verwarring op de bouwplaats.

5. Keuze liggers
**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Snelle montage en remontabel. Lichte elementen. Goede verbindingen mogelijk met kanaalplaatvloer. Brandwerende bekleding is wel noodzakelijk.

6. Keuze kolommen/wanden
**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Snelle montage en remontabel. Lichte elementen. Goede verbindingen mogelijk met kanaalplaatvloer. Brandwerende bekleding is wel noodzakelijk. Geeft veel open ruimte, maximaal vloeroppervlak

7. Keuze stabiliteit systeem
**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Geeft een goede combinatie met stalen liggers, kolommen en kanaalplaatvloeren. Relatief open en licht. Wel een druklaag nodig voor schijfwerking.

8. Opmerkingen over de bovenstaande variant

Beproefd systeem waarmee snel en goedkoop gebouwd kan worden. Overspanningen voor kantoorfunctie mogelijk tot 16 m. Staalconstructie is remontabel. Maar hergebruik van kanaalplaatvloeren met losse druklaag is een fabeltje, dus qua duurzaamheid kom je er niet goed vanaf.

### Variant 2

Afmetingen
lx 21 m
ly 12 m

Stramien in x-richting
*1. Kies het stramien aantal*
4 — 5,25 m

Stramien in y-richting
*1. Kies het stramien aantal*
2 — 6,00 m

2. Keuze begane grond vloer
**ihwg betonvloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

qua stramien maten zijn redelijk wat kolommen noodzakelijk. Met een ihg vloer kunnen poeren en vloer als één element meegenomen worden. De overspanningen zijn niet praktisch met kanaalplaatvloeren, teveel zaag werk.

3. Keuze verdiepingsvloer
**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Laag in eigen gewicht. Door toepassing van LVL is een hogere materiaalsterkte aanwezig (hogere dan bij normale balken). Brandwerendheid is wel een ding. Mogelijk afwerken met verlaagd plafond met brandwerende bekleding.

4. Keuze dak
**houten balkenvloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Elementen zijn goedkoper. Dakbelasting is minimaal, dus balkenvloer voldoet dan ook bij éénzelfde overspanning.

5. Keuze liggers
**houten liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Gelamineerde liggers toepassen. Deze zijn verkrijgbaar in alle maten. Door relatief laag eigen gewicht van hout is dit materiaal efficienter dan beton. Bovendien natuurlijke brandwerendheid door koollaagvorming.

6. Keuze kolommen/wanden
**houten kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Gelamineerde kolommen toepassen, past qua uitstraling en detaillering het beste bij houten liggers. Bovendien natuurlijke brandwerendheid door koollaagvorming.

7. Keuze stabiliteit systeem
**houtskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Geeft meest slanke optie en sluit daarnaast goed aan op de liggers en de kolommen van hout. Schijfwerking bij houten kanaalplaatvloeren is alleen niet helemaal bekend bij mijzelf.

8. Opmerkingen over de bovenstaande variant

Veel belovend voor de toekomst. Houten kanaalplaatvloeren kunnen na sloop altijd gedowncycled worden tot andere houtproducten zoals bijvoorbeeld OSB en MDF. Op de einde van de cyclus geeft het dan biomassa. Dit geeft een veel betere cyclus dan voor beton. Bij hout is deze wel realistisch. Trillingen, geluid en brand zijn wel een ding bij houten kanaalplaatvloeren.

**Constructeur 2**

**Variant 1**

Afmetingen

| | | |
|---|---|---|
| lx | 21 | m |
| ly | 12 | m |

Stramien in x-richting

*1. Kies het stramien aantal*

*3* — 7 m

Stramien in y-richting

*1. Kies het stramien aantal*

*2* — 6,00 m

2. Keuze begane grond vloer

**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Kanaalplaat met isolatie i.v.m. de warmte schil.

3. Keuze verdiepingsvloer

**slimline vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Slimline vloeren omdat het demontabelbaar is, het heeft een lage eigengewicht en heeft relatief minder volume dan overige vloertypes.

4. Keuze dak

**slimline vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

idem als verdiepingsvloer

5. Keuze liggers

**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Stalen liggers om een beter combinatie(aansluiting) met de slimline vloeren te maken.

6. Keuze kolommen/wanden

**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

idem als liggers en om meer openruimte te creeren, in een kantoor is dat gewenst

7. Keuze stabiliteit systeem

**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

past goed bij het overige

8. Opmerkingen over de bovenstaande variant

**Variant 2**

Afmetingen

| | | |
|---|---|---|
| lx | 21 | m |
| ly | 12 | m |

Stramien in x-richting

*1. Kies het stramien aantal*

*4* — 5,25 m

Stramien in y-richting

*1. Kies het stramien aantal*

*2* — 6,00 m

2. Keuze begane grond vloer

**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Kanaalplaat met isolatie i.v.m. de warmte schil.

3. Keuze verdiepingsvloer

**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

lage eigen gewicht en holle kanalen voor leidingen

4. Keuze dak

**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

idem als verdiepingsvloeren

5. Keuze liggers

**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

stalen liggers om slanker te construeren t.o.v. houten en betonnen liggers, wel aandachtspunt voor brandwerendheid

6. Keuze kolommen/wanden

**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Beter aansluiting met de stalen liggers.

7. Keuze stabiliteit systeem

**staalskelet met stabiliteitsverbanden**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Stabiliteitsverbanden is betere combinatie met stalen liggers en kolom i.v.m. aansluitingen en meer openruimte t.o.v. stabiliteitswanden

8. Opmerkingen over de bovenstaande variant

extra aandacht voor aansluiting houten vloeren op stalen liggers. Extra aandacht voor brandwerendheid en geluid.

**Constructeur 3**

**Variant 1**

Afmetingen
lx 21 m
ly 12 m

Stramien in x-richting
*1. Kies het stramien aantal*
4 — 5,25 m

Stramien in y-richting
*1. Kies het stramien aantal*
1 — 12,00 m

2. Keuze begane grond vloer
**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Lichter dan ihwg, wel een grote overspanning

3. Keuze verdiepingsvloer
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Lichter dan ihwg, wel een grote overspanning

4. Keuze dak
**kanaalplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Lichter dan ihwg, wel een grote overspanning

5. Keuze liggers
**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Lichtgewicht

6. Keuze kolommen/wanden
**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Lichtgewicht

7. Keuze stabiliteit systeem
**beton kern**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Vermoed dat je dan het minste materiaal toe hoeft te passen

8. Opmerkingen over de bovenstaande variant

Meest standaard kantoor, omdat zo vrij eenvoudig grote overspanningen gemaakt kunnen worden. Vloeroverspanning over 12m

**Variant 2**

Afmetingen
lx 21 m
ly 12 m

Stramien in x-richting
*1. Kies het stramien aantal*
5 — 4,2 m

Stramien in y-richting
*1. Kies het stramien aantal*
2 — 6,00 m

2. Keuze begane grond vloer
**kanaaplaat vloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Lichter dan ihwg

3. Keuze verdiepingsvloer
**houten balkenvloer**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Door kantoor minder hoge geluidseis dan woning, verwachte lagere milieuprestatie, lichtgewicht (houten balklaag zou voor milieupresatie nog beter zijn, maar veel trillingen en geluid, dus niet echt voor de hand liggend)

4. Keuze dak
**houten kanaalplaat**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Verwachte lagere milieuprestatie lichtgewicht

5. Keuze liggers
**stalen liggers**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Meer bekend over technische eigenschappen, zoals brandwerendheid. Wel licht.

6. Keuze kolommen/wanden
**stalen kolommen**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Meer bekend over technische eigenschappen, zoals brandwerendheid. Wel licht.

7. Keuze stabiliteit systeem
**beton kern**

Waarom of op basis van welke eigenschap heb je gekozen voor het bovenstaande element?

Vermoed dat je dan het minste materiaal toe hoeft te passen

8. Opmerkingen over de bovenstaande variant

Vloer overspanning over 5,25m

# Chapter D

# Environmental impact calculations

## D.1 Environmental data

The following tables show the environmental data used from the NMD.

**Table D.1** LCA input for the production life cycle phase

**Table D.2** LCA input for the transport to site life cycle phase

**Table D.3** LCA input for the transport to processing/demolition site life cycle phase

**Table D.4** LCA input for the processing (i.e. recycling/incineration) life cycle phase

**Table D.5** LCA input for the demolition life cycle phase

**Table D.1** LCA input for the production life cycle phase

| Productie | A1-A3 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| **Naam** | **Materiaal** | **Onderdeel** | **Aantal** | **Eenheid** | **Bouwafval** | **Levensduur** | **Hergebruik** | **Stort** | **Vebranding** | **Recycling** | **Global warming (GWP100)** | **Ozone layer depletion (ODP)** | **Human toxicity** | **Aquatic tox fresh water (sweet)** | **Aquatic tox fresh water (salt)** | **Terrestrial toxicity** | **Photochemical oxidation** | **Acidification** | **Eutrophication** | **Abiotic resources depletion** | **Fossil energy carriers depletion** | **Schaduwprijs** | **Eenheid** |
| Kanaalplaat met druklaag | | | | | | | | | | | 2,42E+00 | 1,34E-07 | 3,23E+00 | 2,19E-02 | 9,56E+00 | 9,03E-02 | 3,13E-03 | 1,06E-02 | 1,58E-03 | 9,45E-06 | 1,52E-02 | 0,48 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 1,27E-01 | 2,31E-09 | 1,20E-02 | 2,35E-04 | 1,54E+00 | 1,42E-04 | 3,78E-05 | 4,61E-04 | 6,98E-05 | 1,02E-07 | 1,68E-04 | 0,01 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,20E+00 | 1,28E-07 | 3,21E+00 | 2,15E-02 | 6,80E+00 | 8,99E-02 | 3,07E-03 | 9,93E-03 | 1,45E-03 | 9,25E-06 | 1,47E-02 | 0,47 | l/kg |
| Druklaag | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,63E-02 | 3,61E-09 | 9,96E-03 | 2,44E-04 | 1,22E+00 | 1,90E-04 | 2,40E-05 | 2,55E-04 | 5,63E-05 | 9,98E-08 | 2,94E-04 | 0,01 | l/kg |
| Kanaalplaat | | | | | | | | | | | 2,32E+00 | 1,30E-07 | 3,22E+00 | 2,17E-02 | 8,34E+00 | 9,01E-02 | 3,11E-03 | 1,04E-02 | 1,52E-03 | 9,35E-06 | 1,49E-02 | 0,48 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 1,27E-01 | 2,31E-09 | 1,20E-02 | 2,35E-04 | 1,54E+00 | 1,42E-04 | 3,78E-05 | 4,61E-04 | 6,98E-05 | 1,02E-07 | 1,68E-04 | 0,01 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,20E+00 | 1,28E-07 | 3,21E+00 | 2,15E-02 | 6,80E+00 | 8,99E-02 | 3,07E-03 | 9,93E-03 | 1,45E-03 | 9,25E-06 | 1,47E-02 | 0,47 | l/kg |
| Beton ihwg vloer | Beton,in het werk gestort, C30/37; incl,wapening | | | | | | | | | | 2,29E+00 | 1,31E-07 | 3,22E+00 | 2,17E-02 | 8,02E+00 | 9,01E-02 | 3,09E-03 | 1,02E-02 | 1,51E-03 | 9,35E-06 | 1,50E-02 | 0,47 | l/kg |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,63E-02 | 3,61E-09 | 9,96E-03 | 2,44E-04 | 1,22E+00 | 1,90E-04 | 2,40E-05 | 2,55E-04 | 5,63E-05 | 9,98E-08 | 2,94E-04 | 0,01 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 1000 | | 5% | 5% | 90% | 2,20E+00 | 1,28E-07 | 3,21E+00 | 2,15E-02 | 6,80E+00 | 8,99E-02 | 3,07E-03 | 9,93E-03 | 1,45E-03 | 9,25E-06 | 1,47E-02 | 0,47 | l/kg |
| Houten kanaalplaatvloer | Verdiepingsvloer van geprefabriceerde houten kanaalplaten, De houten kanaalplaat van gelamineerd europees naalhout uit duurzame bosbouw (met keurmerk) met vierkante holle kanalen, | | | | | | | | | | 4,43E-01 | 5,60E-08 | 1,92E-01 | 6,56E-03 | 1,47E+01 | 1,74E-03 | 5,82E-04 | 2,72E-03 | 6,34E-04 | 1,34E-06 | 3,28E-03 | 0,06 | l/kg |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | 4,43E-01 | 5,60E-08 | 1,92E-01 | 6,56E-03 | 1,47E+01 | 1,74E-03 | 5,82E-04 | 2,72E-03 | 6,34E-04 | 1,34E-06 | 3,28E-03 | 0,06 | l/kg |
| Houten balkenvloer | europees naaldhouten multiplex; duurzame bosbouw | | | | | | | | | | 1,16E+00 | 1,39E-07 | 5,22E-01 | 1,89E-02 | 4,70E+01 | 3,82E-03 | 1,39E-03 | 7,16E-03 | 1,95E-03 | 4,25E-06 | 9,33E-03 | 0,16 | l/kg |
| | SBK 275 Vuren, schroten, FSC | balken | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | 2,46E-01 | 2,55E-08 | 9,68E-02 | 2,70E-03 | 7,08E+00 | 8,20E-04 | 2,30E-04 | 1,34E-03 | 2,33E-04 | 9,63E-07 | 1,68E-03 | 0,03 | l/kg |
| | SBK 167 Vuren, Multiplex, duurzame bosbouw | bekleding | 1 | kg | 5% | 1000 | | 5% | 95% | 0% | 9,18E-01 | 1,13E-07 | 4,25E-01 | 1,62E-02 | 3,99E+01 | 3,00E-03 | 1,16E-03 | 5,82E-03 | 1,72E-03 | 3,29E-06 | 7,65E-03 | 0,13 | l/kg |
| Prefab beton schil met I-profielen | | | | | | | | | | | 6,03E+00 | 1,59E-07 | 3,38E+00 | 2,80E-02 | 3,07E+01 | 9,17E-02 | 4,73E-03 | 2,08E-02 | 2,55E-03 | 9,59E-06 | 3,48E-02 | 0,74 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 1,27E-01 | 2,31E-09 | 1,20E-02 | 2,35E-04 | 1,54E+00 | 1,42E-04 | 3,78E-05 | 4,61E-04 | 6,98E-05 | 1,02E-07 | 1,68E-04 | 0,01 | l/kg |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | constructie st | 1 | kg | | | 49% | 0% | 0% | 51% | 9,80E-01 | 1,55E-08 | 3,33E-02 | 3,02E-03 | 6,43E+00 | 4,68E-04 | 3,30E-04 | 3,38E-03 | 3,74E-04 | -1,34E-07 | 5,21E-03 | 0,07 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,20E+00 | 1,28E-07 | 3,21E+00 | 2,15E-02 | 6,80E+00 | 8,99E-02 | 3,07E-03 | 9,93E-03 | 1,45E-03 | 9,25E-06 | 1,47E-02 | 0,47 | l/kg |
| *Topvloer aangenomen staalplaatbetonvloer op rubbers* | S3, met 50% granulaat, PRODUCTIE, c2 | beton | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | 6,04E-02 | 3,27E-09 | 1,02E-02 | 2,37E-04 | 2,23E+00 | 9,74E-05 | 2,49E-05 | 2,48E-04 | 3,46E-05 | 1,25E-07 | 2,50E-04 | 0,01 | l/kg |
| | 330 Steel, Light Construction | | | | | | | | | | | | | | | | | | | | | | |

| Productie | A1-A3 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| **Naam** | **Materiaal** | **Onderdeel** | **Aantal** | **Eenheid** | **Bouwafval** | **Levensduur** | **Hergebruik** | **Stort** | **Vebranding** | **Recycling** | **Global warming (GWP100)** | **Ozone layer depletion (ODP)** | **Human toxicity** | **Aquatic tox fresh water (sweet)** | **Aquatic tox fresh water (salt)** | **Terrestrial toxicity** | **Photochemical oxidation** | **Acidification** | **Eutrophication** | **Abiotic resources depletion** | **Fossil energy carriers** | **Schaduwprijs** | **Eenheid** |
| Staal voor constructie producten | Staal | | | | | | | | | | | | | | | | | | | | | | |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | | 1 | kg | | | 49% | 0% | 0% | 51% | 9,80E-01 | 1,55E-08 | 3,33E-02 | 3,02E-03 | 6,43E+00 | 4,68E-04 | 3,30E-04 | 3,38E-03 | 3,74E-04 | -1,34E-07 | 5,21E-03 | 0,07 | l/kg |
| Wapeningsstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,20E+00 | 1,28E-07 | 3,21E+00 | 2,15E-02 | 6,80E+00 | 8,99E-02 | 3,07E-03 | 9,93E-03 | 1,45E-03 | 9,25E-06 | 1,47E-02 | 0,47 | l/kg |
| Voorspanstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,20E+00 | 1,28E-07 | 3,21E+00 | 2,15E-02 | 6,80E+00 | 8,99E-02 | 3,07E-03 | 9,93E-03 | 1,45E-03 | 9,25E-06 | 1,47E-02 | 0,47 | l/kg |
| Betonmortel C30/37 | Beton | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,63E-02 | 3,61E-09 | 9,96E-03 | 2,44E-04 | 1,22E+00 | 1,90E-04 | 2,40E-05 | 2,55E-04 | 5,63E-05 | 9,98E-08 | 2,94E-04 | 0,01 | l/kg |
| Betonmortel C53/65 | Beton | | | | | | | | | | | | | | | | | | | | | | |
| | Betonmortel C53/65 (o,b,v, 75% CEM III | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 1,14E-01 | 4,26E-09 | 1,17E-02 | 2,88E-04 | 1,44E+00 | 2,24E-04 | 2,83E-05 | 3,01E-04 | 6,64E-05 | 1,18E-07 | 3,47E-04 | 0,01 | l/kg |
| Europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 275 Vuren, schroten, FSC | | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | 2,46E-01 | 2,55E-08 | 9,68E-02 | 2,70E-03 | 7,08E+00 | 8,20E-04 | 2,30E-04 | 1,34E-03 | 2,33E-04 | 9,63E-07 | 1,68E-03 | 0,03 | l/kg |
| Hout gelamineerd europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | 4,43E-01 | 5,60E-08 | 1,92E-01 | 6,56E-03 | 1,47E+01 | 1,74E-03 | 5,82E-04 | 2,72E-03 | 6,34E-04 | 1,34E-06 | 3,28E-03 | 0,06 | l/kg |

**Table D.2** LCA input for the transport to site life cycle phase

| Constructie - Transport | A4 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| Naam | Materiaal | Onderdeel | Aantal | Eenheid | Bouwafval | Levensduur | Hergebruik | Stort | Verbranding | Recycling | Global warming (GWP100) | Ozone layer depletion (ODP) | Human toxicity | Aquatic tox fresh water (sweet) | Aquatic tox fresh water (salt) | Terrestrial toxicity | Photochemical oxidation | Acidification | Eutrophication | Abiotic resources depletion | Fossil energy carriers | Schaduwprijs | Eenheid |
| Transport | SBK 900t Transport, freight, lorry, unspecified | | 1 | tkm | | | | | | | 1,32E-01 | 2,43E-08 | 5,27E-02 | 1,55E-03 | 5,58E+00 | 1,87E-04 | 7,77E-05 | 5,71E-04 | 1,14E-04 | 3,75E-07 | 9,72E-04 | | I/tkm |
| Kanaalplaat met druklaag | | | | | | | | | | | | | | | | | | | | | | | |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| Druklaag | SBK 847 Betonmortel C30/37 (o.b.v. 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 18 | | km | | | 2,37E-03 | 4,37E-10 | 9,48E-04 | 2,78E-05 | 1,00E-01 | 3,36E-06 | 1,40E-06 | 1,03E-05 | 2,06E-06 | 6,75E-09 | 1,75E-05 | 0,00 | I/kg |
| Kanaalplaat | | | | | | | | | | | 3,95E-02 | 7,29E-09 | 1,58E-02 | 4,64E-04 | 1,67E+00 | 5,60E-05 | 2,33E-05 | 1,71E-04 | 3,43E-05 | 1,13E-07 | 2,92E-04 | 0,00 | I/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| Beton ihwg vloer | Beton,in het werk gestort, C30/37; incl,wapening | | | | | | | | | | 4,74E-03 | 8,75E-10 | 1,90E-03 | 5,56E-05 | 2,01E-01 | 6,72E-06 | 2,80E-06 | 2,06E-05 | 4,11E-06 | 1,35E-08 | 3,50E-05 | 0,00 | I/kg |
| | SBK 847 Betonmortel C30/37 (o.b.v. 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 18 | | km | | | 2,37E-03 | 4,37E-10 | 9,48E-04 | 2,78E-05 | 1,00E-01 | 3,36E-06 | 1,40E-06 | 1,03E-05 | 2,06E-06 | 6,75E-09 | 1,75E-05 | 0,00 | I/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 18 | | km | | | 2,37E-03 | 4,37E-10 | 9,48E-04 | 2,78E-05 | 1,00E-01 | 3,36E-06 | 1,40E-06 | 1,03E-05 | 2,06E-06 | 6,75E-09 | 1,75E-05 | 0,000 | I/kg |
| Houten kanaalplaatvloer | Verdiepingsvloer van geprefabriceerde houten kanaalplaten, De houten kanaalplaat van gelamineerd europees naalhout uit duurzame bosbouw (met keurmerk) met vierkante holle kanalen, | | | | | | | | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,002 | I/kg |
| Houten balkenvloer | Europees naaldhouten balken met europees naaldhouten multiplex; duurzame bosbouw | | | | | | | | | | 3,95E-02 | 7,29E-09 | 1,58E-02 | 4,64E-04 | 1,67E+00 | 5,60E-05 | 2,33E-05 | 1,71E-04 | 3,43E-05 | 1,13E-07 | 2,92E-04 | 0,00 | I/kg |
| | SBK 275 Vuren, schroten, FSC | balken | 1 | kg | 5% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,002 | I/kg |
| | SBK 167 Vuren, Multiplex, duurzame bosbouw | bekleding | 1 | kg | 5% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,002 | I/kg |
| Prefab beton schil met I-profielen | | | | | | | | | | | 7,23E-02 | 1,30E-08 | 2,67E-02 | 8,73E-04 | 3,21E+00 | 1,20E-04 | 4,79E-05 | 3,31E-04 | 6,91E-05 | 2,05E-07 | 5,34E-04 | 0,01 | I/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | betonmortel | 1 | kg | 0% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,002 | I/kg |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | constructie st | 1 | kg | | | | | | | 1,96E-02 | 3,24E-09 | 5,64E-03 | 2,55E-04 | 9,83E-01 | 4,54E-05 | 1,68E-05 | 1,03E-04 | 2,34E-05 | 5,54E-08 | 1,45E-04 | 0,002 | I/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| *Topvloer aangenomen staalplaatbetonvloer op rubbers* | S3, met 50% granulaat, PRODUCTIE, c2 | beton | 1 | kg | 3% | 50 | | km | | | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,001 | I/kg |
| | 330 Steel, Light Construction Products PRODUCTIE, BmS, 2013, c2 | staal | 1 | kg | 3% | 50 | | km | | | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,001 | I/kg |

| Constructie - Transport | A4 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| Naam | Materiaal | Onderdeel | Aantal | Eenheid | Bouwafval | Levensduur | Hergebruik | Stort | Verbranding | Recycling | Global warming (GWP100) | Ozone layer depletion (ODP) | Human toxicity | Aquatic tox fresh water (sweet) | Aquatic tox fresh water (salt) | Terrestrial toxicity | Photochemical oxidation | Acidification | Eutrophication | Abiotic resources depletion | Fossil energy carriers | Schaduwprijs | Eenheid |
| Transport | SBK 900t Transport, freight, lorry, unspecified | | 1 | tkm | | | | | | | 1,32E-01 | 2,43E-08 | 5,27E-02 | 1,55E-03 | 5,58E+00 | 1,87E-04 | 7,77E-05 | 5,71E-04 | 1,14E-04 | 3,75E-07 | 9,72E-04 | | I/tkm |
| Staal voor constructie producten | Staal 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | | 1 | kg | | | | | | | 1,96E-02 | 3,24E-09 | 5,64E-03 | 2,55E-04 | 9,83E-01 | 4,54E-05 | 1,68E-05 | 1,03E-04 | 2,34E-05 | 5,54E-08 | 1,45E-04 | 0,00 | I/kg |
| Wapeningsstaal | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| Voorspanstaal | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| Betonmortel C30/37 | Beton SBK 847 Betonmortel C30/37 (o.b.v. 75% CEM III en 25% CEM I | betonmortel | 1 | kg | 0% | 18 | | km | | | 2,37E-03 | 4,37E-10 | 9,48E-04 | 2,78E-05 | 1,00E-01 | 3,36E-06 | 1,40E-06 | 1,03E-05 | 2,06E-06 | 6,75E-09 | 1,75E-05 | 0,00 | I/kg |
| Betonmortel C53/65 | Beton Betonmortel C53/65 (o.b.v. 75% CEM III | betonmortel | 1 | kg | 0% | 18 | | km | | | 2,37E-03 | 4,37E-10 | 9,48E-04 | 2,78E-05 | 1,00E-01 | 3,36E-06 | 1,40E-06 | 1,03E-05 | 2,06E-06 | 6,75E-09 | 1,75E-05 | 0,00 | I/kg |
| Europees naaldhout; duurzame bosbouw | SBK 275 Vuren, schroten, FSC | | 1 | kg | 5% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |
| Hout gelamineerd europees naaldhout; duurzame bosbouw | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 150 | | km | | | 1,98E-02 | 3,65E-09 | 7,90E-03 | 2,32E-04 | 8,37E-01 | 2,80E-05 | 1,17E-05 | 8,56E-05 | 1,71E-05 | 5,63E-08 | 1,46E-04 | 0,00 | I/kg |

**Table D.3** LCA input for the transport to processing/demolition site life cycle phase

| Einde levensduur - Transport | C2 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| **Naam** | **Materiaal** | **Onderdeel** | **Aantal** | **Eenheid** | **Bouwafval** | **Levensduur** | **Hergebruik** | **Stort** | **Vebranding** | **Recycling** | **Global warming (GWP100)** | **Ozone layer depletion (ODP)** | **Human toxicity** | **Aquatic tox fresh water (sweet)** | **Aquatic tox fresh water (salt)** | **Terrestrial toxicity** | **Photochemical oxidation** | **Acidification** | **Eutrophication** | **Abiotic resources depletion** | **Fossil energy carriers** | **Schaduwprijs** | **Eenheid** |
| Transport | SBK 900t Transport, freight, lorry, unspecified | | 1 | tkm | | | | | | | 1,32E-01 | 2,43E-08 | 5,27E-02 | 1,55E-03 | 5,58E+00 | 1,87E-04 | 7,77E-05 | 5,71E-04 | 1,14E-04 | 3,75E-07 | 9,72E-04 | | |
| Kanaalplaat met druklaag | | | | | | | | | | | 2,01E-02 | 3,71E-09 | 8,03E-03 | 2,36E-04 | 8,51E-01 | 2,85E-05 | 1,18E-05 | 8,71E-05 | 1,74E-05 | 5,72E-08 | 1,48E-04 | 0,00 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 6,91E-03 | 1,28E-09 | 2,77E-03 | 8,11E-05 | 2,93E-01 | 9,80E-06 | 4,08E-06 | 3,00E-05 | 6,00E-06 | 1,97E-08 | 5,10E-05 | 0,00 | l/kg |
| Druklaag | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | | | 2% | 0% | 98% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,00 | l/kg |
| Kanaalplaat | | | | | | | | | | | 1,35E-02 | 2,49E-09 | 5,40E-03 | 1,58E-04 | 5,72E-01 | 1,91E-05 | 7,96E-06 | 5,85E-05 | 1,17E-05 | 3,84E-08 | 9,96E-05 | 0,00 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 6,91E-03 | 1,28E-09 | 2,77E-03 | 8,11E-05 | 2,93E-01 | 9,80E-06 | 4,08E-06 | 3,00E-05 | 6,00E-06 | 1,97E-08 | 5,10E-05 | 0,00 | l/kg |
| Beton ihwg vloer | Beton,in het werk gestort, C30/37; incl,wapening | | | | | | | | | | 1,35E-02 | 2,49E-09 | 5,40E-03 | 1,58E-04 | 5,72E-01 | 1,91E-05 | 7,96E-06 | 5,85E-05 | 1,17E-05 | 3,84E-08 | 9,96E-05 | 0,00 | l/kg |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 1000 | | 5% | 5% | 90% | 6,91E-03 | 1,28E-09 | 2,77E-03 | 8,11E-05 | 2,93E-01 | 9,80E-06 | 4,08E-06 | 3,00E-05 | 6,00E-06 | 1,97E-08 | 5,10E-05 | 0,00 | l/kg |
| Houten kanaalplaatvloer | Verdiepingsvloer van geprefabriceerde houten kanaalplaten, De houten kanaalplaat van gelamineerd europees naalhout uit duurzame bosbouw (met keurmerk) met vierkante holle kanalen, | | | | | | | | | | 1,28E-02 | 2,37E-09 | 5,14E-03 | 1,51E-04 | 5,44E-01 | 1,82E-05 | 7,58E-06 | 5,57E-05 | 1,11E-05 | 3,66E-08 | 9,48E-05 | 0,00 | l/kg |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | 1,28E-02 | 2,37E-09 | 5,14E-03 | 1,51E-04 | 5,44E-01 | 1,82E-05 | 7,58E-06 | 5,57E-05 | 1,11E-05 | 3,66E-08 | 9,48E-05 | 0,00 | l/kg |
| Houten balkenvloer | Europees naaldhouten balken met europees naaldhouten multiplex; duurzame bosbouw | | | | | | | | | | 2,50E-02 | 4,62E-09 | 1,00E-02 | 2,94E-04 | 1,06E+00 | 3,55E-05 | 1,48E-05 | 1,08E-04 | 2,17E-05 | 7,13E-08 | 1,85E-04 | 0,00 | l/kg |
| | SBK 275 Vuren, schroten, FSC | balken | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | 1,22E-02 | 2,25E-09 | 4,87E-03 | 1,43E-04 | 5,16E-01 | 1,73E-05 | 7,19E-06 | 5,28E-05 | 1,06E-05 | 3,47E-08 | 8,99E-05 | 0,00 | l/kg |
| | SBK 167 Vuren, Multiplex, duurzame bosbouw | bekleding | 1 | kg | 5% | 1000 | | 5% | 95% | 0% | 1,28E-02 | 2,37E-09 | 5,14E-03 | 1,51E-04 | 5,44E-01 | 1,82E-05 | 7,58E-06 | 5,57E-05 | 1,11E-05 | 3,66E-08 | 9,48E-05 | 0,00 | l/kg |
| Prefab beton schil met I-profielen | | | | | | | | | | | 3,31E-02 | 5,73E-09 | 1,10E-02 | 4,13E-04 | 1,55E+00 | 6,45E-05 | 2,48E-05 | 1,62E-04 | 3,51E-05 | 9,38E-08 | 2,45E-04 | 0,00 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,001 | l/kg |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | constructie st | 1 | kg | | | 49% | 0% | 0% | 51% | 1,96E-02 | 3,24E-09 | 5,64E-03 | 2,55E-04 | 9,83E-01 | 4,54E-05 | 1,68E-05 | 1,03E-04 | 2,34E-05 | 5,54E-08 | 1,45E-04 | 0,002 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 6,91E-03 | 1,28E-09 | 2,77E-03 | 8,11E-05 | 2,93E-01 | 9,80E-06 | 4,08E-06 | 3,00E-05 | 6,00E-06 | 1,97E-08 | 5,10E-05 | 0,001 | l/kg |
| *Topvloer aangenomen staalplaatbetonvloer op rubbers* | S3, met 50% granulaat, PRODUCTIE, c2 | beton | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | - | l/kg |
| | 330 Steel, Light Construction Products PRODUCTIE, BmS, 2013, c2 | staal | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | - | l/kg |

| Einde levensduur - Transport | C2 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| **Naam** | **Materiaal** | **Onderdeel** | **Aantal** | **Eenheid** | **Bouwafval** | **Levensduur** | **Hergebruik** | **Stort** | **Vebranding** | **Recycling** | **Global warming (GWP100)** | **Ozone layer depletion (ODP)** | **Human toxicity** | **Aquatic tox fresh water (sweet)** | **Aquatic tox fresh water (salt)** | **Terrestrial toxicity** | **Photochemical oxidation** | **Acidification** | **Eutrophication** | **Abiotic resources depletion** | **Fossil energy carriers** | **Schaduwprijs** | **Eenheid** |
| Transport | SBK 900t Transport, freight, lorry, unspecified | | 1 | tkm | | | | | | | 1,32E-01 | 2,43E-08 | 5,27E-02 | 1,55E-03 | 5,58E+00 | 1,87E-04 | 7,77E-05 | 5,71E-04 | 1,14E-04 | 3,75E-07 | 9,72E-04 | | l/tkm |
| Staal voor constructie producten | Staal 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | | 1 | kg | | | | | | | 1,96E-02 | 3,24E-09 | 5,64E-03 | 2,55E-04 | 9,83E-01 | 4,54E-05 | 1,68E-05 | 1,03E-04 | 2,34E-05 | 5,54E-08 | 1,45E-04 | 0,00 | l/kg |
| Wapeningsstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 6,91E-03 | 1,28E-09 | 2,77E-03 | 8,11E-05 | 2,93E-01 | 9,80E-06 | 4,08E-06 | 3,00E-05 | 6,00E-06 | 1,97E-08 | 5,10E-05 | 0,00 | l/kg |
| Voorspanstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 6,91E-03 | 1,28E-09 | 2,77E-03 | 8,11E-05 | 2,93E-01 | 9,80E-06 | 4,08E-06 | 3,00E-05 | 6,00E-06 | 1,97E-08 | 5,10E-05 | 0,00 | l/kg |
| Betonmortel C30/37 | Beton SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,00 | l/kg |
| Betonmortel C53/65 | Beton Betonmortel C53/65 (o,b,v, 75% CEM III | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 6,58E-03 | 1,22E-09 | 2,63E-03 | 7,73E-05 | 2,79E-01 | 9,33E-06 | 3,89E-06 | 2,85E-05 | 5,71E-06 | 1,88E-08 | 4,86E-05 | 0,00 | l/kg |
| Europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 275 Vuren, schroten, FSC | | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | 1,22E-02 | 2,25E-09 | 4,87E-03 | 1,43E-04 | 5,16E-01 | 1,73E-05 | 7,19E-06 | 5,28E-05 | 1,06E-05 | 3,47E-08 | 8,99E-05 | 0,00 | l/kg |
| Hout gelamineerd europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | 1,28E-02 | 2,37E-09 | 5,14E-03 | 1,51E-04 | 5,44E-01 | 1,82E-05 | 7,58E-06 | 5,57E-05 | 1,11E-05 | 3,66E-08 | 9,48E-05 | 0,00 | l/kg |

**Table D.4** LCA input for the processing (i.e. recycling/incineration) life cycle phase

**Einde levensduur - Bewerking** C3

| Naam | Materiaal | Onderdeel | Aantal | Eenheid | Bouwafval | Levensduur | Hergebruik | Stort | Vebranding | Recycling | Global warming (GWP100) | Ozone layer depletion (ODP) | Human toxicity | Aquatic tox fresh water (sweet) | Aquatic tox fresh water (salt) | Terrestrial toxicity | Photochemical oxidation | Acidification | Eutrophication | Abiotic resources depletion | Fossil energy carriers | Schaduwprijs | Eenheid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| Kanaalplaat met druklaag | | | | | | | | | | | -2,51E-01 | -8,55E-09 | -1,73E-02 | -2,04E-03 | -4,43E+00 | -3,54E-04 | -1,33E-04 | -4,54E-04 | -7,96E-05 | -3,11E-06 | -1,26E-03 | -0,02 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 9,81E-04 | 1,34E-10 | 2,47E-04 | 4,89E-06 | 1,82E-02 | 2,62E-06 | 5,74E-07 | 4,60E-06 | 1,02E-06 | 9,02E-10 | 7,68E-06 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | -2,53E-01 | -8,81E-09 | -1,78E-02 | -2,05E-03 | -4,46E+00 | -3,59E-04 | -1,34E-04 | -4,63E-04 | -8,16E-05 | -3,11E-06 | -1,28E-03 | -0,02 | l/kg |
| Druklaag | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,43E-04 | 1,28E-10 | 2,37E-04 | 4,70E-06 | 1,75E-02 | 2,52E-06 | 5,52E-07 | 4,42E-06 | 9,80E-07 | 8,67E-10 | 7,38E-06 | 0,00 | l/kg |
| Kanaalplaat | | | | | | | | | | | -2,52E-01 | -8,67E-09 | -1,76E-02 | -2,04E-03 | -4,44E+00 | -3,57E-04 | -1,33E-04 | -4,58E-04 | -8,06E-05 | -3,11E-06 | -1,27E-03 | -0,02 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 9,81E-04 | 1,34E-10 | 2,47E-04 | 4,89E-06 | 1,82E-02 | 2,62E-06 | 5,74E-07 | 4,60E-06 | 1,02E-06 | 9,02E-10 | 7,68E-06 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | -2,53E-01 | -8,81E-09 | -1,78E-02 | -2,05E-03 | -4,46E+00 | -3,59E-04 | -1,34E-04 | -4,63E-04 | -8,16E-05 | -3,11E-06 | -1,28E-03 | -0,02 | l/kg |
| Beton ihwg vloer | Beton,in het werk gestort, C30/37; incl,wapening | | | | | 1000 | | | | | -2,52E-01 | -8,68E-09 | -1,76E-02 | -2,04E-03 | -4,44E+00 | -3,57E-04 | -1,34E-04 | -4,58E-04 | -8,06E-05 | -3,11E-06 | -1,27E-03 | -0,02 | l/kg |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,43E-04 | 1,28E-10 | 2,37E-04 | 4,70E-06 | 1,75E-02 | 2,52E-06 | 5,52E-07 | 4,42E-06 | 9,80E-07 | 8,67E-10 | 7,38E-06 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 1000 | | 5% | 5% | 90% | -2,53E-01 | -8,81E-09 | -1,78E-02 | -2,05E-03 | -4,46E+00 | -3,59E-04 | -1,34E-04 | -4,63E-04 | -8,16E-05 | -3,11E-06 | -1,28E-03 | -0,02 | l/kg |
| Houten kanaalplaatvloer | Verdiepingsvloer van geprefabriceerde houten kanaalplaten, De houten kanaalplaat van gelamineerd europees naalhout uit duurzame bosbouw (met keurmerk) met vierkante holle kanalen, | | | | | | | | | | -4,56E-01 | -3,67E-08 | -1,34E-02 | 3,87E-04 | -2,93E+00 | -2,21E-04 | -2,73E-05 | -5,27E-04 | -1,03E-04 | -1,01E-07 | -3,83E-03 | -0,03 | l/kg |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | -4,56E-01 | -3,67E-08 | -1,34E-02 | 3,87E-04 | -2,93E+00 | -2,21E-04 | -2,73E-05 | -5,27E-04 | -1,03E-04 | -1,01E-07 | -3,83E-03 | -0,03 | l/kg |
| Houten balkenvloer | Europees naaldhouten balken met europees naaldhouten multiplex; duurzame bosbouw | | | | | | | | | | -8,72E-01 | -7,64E-08 | -3,51E-02 | -1,48E-03 | -7,57E+00 | -1,20E-03 | -6,63E-05 | -4,73E-04 | -1,51E-04 | -1,98E-07 | -7,42E-03 | -0,05 | l/kg |
| | SBK 275 Vuren, schroten, FSC | balken | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | -4,09E-01 | -3,29E-08 | -1,21E-02 | -4,86E-04 | -2,74E+00 | -1,98E-04 | -2,45E-05 | -4,73E-04 | -9,19E-05 | -9,10E-08 | -3,43E-03 | -0,03 | l/kg |
| | SBK 167 Vuren, Multiplex, duurzame bosbouw | bekleding | 1 | kg | 5% | 1000 | | 5% | 95% | 0% | -4,64E-01 | -4,35E-08 | -2,29E-02 | -9,98E-04 | -4,84E+00 | -9,98E-04 | -4,18E-05 | 0,00E+00 | -5,96E-05 | -1,07E-07 | -3,99E-03 | -0,03 | l/kg |
| Prefab beton schil met I-profielen | | | | | | | | | | | -1,85E+00 | 2,94E-09 | -3,76E-03 | -3,65E-03 | -1,23E+00 | -2,69E-04 | -9,36E-04 | -3,27E-03 | -1,97E-04 | -5,25E-06 | -9,13E-03 | -0,11 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 9,81E-04 | 1,34E-10 | 2,47E-04 | 4,89E-06 | 1,82E-02 | 2,62E-06 | 5,74E-07 | 4,60E-06 | 1,02E-06 | 9,02E-10 | 7,68E-06 | 0,00 | l/kg |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | constructie st | 1 | kg | | | 49% | 0% | 0% | 51% | 4,03E-02 | 6,01E-09 | 7,27E-03 | 4,58E-04 | 1,95E+00 | 4,03E-05 | 2,71E-05 | 2,32E-04 | 5,49E-05 | 4,53E-09 | 2,56E-04 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | -2,53E-01 | -8,81E-09 | -1,78E-02 | -2,05E-03 | -4,46E+00 | -3,59E-04 | -1,34E-04 | -4,63E-04 | -8,16E-05 | -3,11E-06 | -1,28E-03 | -0,02 | l/kg |
| *Topvloer aangenomen staalplaatbetonvloer op rubbers* | S3, met 50% granulaat, PRODUCTIE, c2 | beton | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | 2,81E-03 | 4,43E-10 | 8,94E-04 | 3,50E-05 | 1,48E-01 | 8,46E-06 | 2,31E-06 | 1,46E-05 | 3,32E-06 | 7,15E-09 | 2,11E-05 | 0,00 | l/kg |
| | 330 Steel, Light Construction Products PRODUCTIE, BmS, 2013, c2 | staal | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | -1,64E+00 | 5,16E-09 | 5,64E-03 | -2,10E-03 | 1,11E+00 | 3,87E-05 | -8,32E-04 | -3,06E-03 | -1,75E-04 | -2,15E-06 | -8,13E-03 | -0,10 | l/kg |

**Einde levensduur - Bewerking** C3

| Naam | Materiaal | Onderdeel | Aantal | Eenheid | Bouwafval | Levensduur | Hergebruik | Stort | Vebranding | Recycling | Global warming (GWP100) | Ozone layer depletion (ODP) | Human toxicity | Aquatic tox fresh water (sweet) | Aquatic tox fresh water (salt) | Terrestrial toxicity | Photochemical oxidation | Acidification | Eutrophication | Abiotic resources depletion | Fossil energy carriers | Schaduwprijs | Eenheid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| Staal voor constructie producten | Staal | | | | | | | | | | | | | | | | | | | | | | |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | | 1 | kg | | | 49% | 0% | 0% | 51% | -4,72E-01 | 2,29E-09 | -1,58E-03 | -1,41E-03 | 1,95E+00 | -1,40E-02 | -1,57E-04 | -1,28E-03 | -9,81E-05 | 1,00E-07 | -2,46E-03 | -0,03 | l/kg |
| Wapeningsstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | -2,53E-01 | -8,81E-09 | -1,78E-02 | -2,05E-03 | -4,46E+00 | -3,59E-04 | -1,34E-04 | -4,63E-04 | -8,16E-05 | -3,11E-06 | -1,28E-03 | -0,02 | l/kg |
| Voorspanstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | -2,53E-01 | -8,81E-09 | -1,78E-02 | -2,05E-03 | -4,46E+00 | -3,59E-04 | -1,34E-04 | -4,63E-04 | -8,16E-05 | -3,11E-06 | -1,28E-03 | -0,02 | l/kg |
| Betonmortel C30/37 | Beton | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,43E-04 | 1,28E-10 | 2,37E-04 | 4,70E-06 | 1,75E-02 | 2,52E-06 | 5,52E-07 | 4,42E-06 | 9,80E-07 | 8,67E-10 | 7,38E-06 | 0,00 | l/kg |
| Betonmortel C53/65 | Beton | | | | | | | | | | | | | | | | | | | | | | |
| | Betonmortel C53/65 (o,b,v, 75% CEM III | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 9,43E-04 | 1,28E-10 | 2,37E-04 | 4,70E-06 | 1,75E-02 | 2,52E-06 | 5,52E-07 | 4,42E-06 | 9,80E-07 | 8,67E-10 | 7,38E-06 | 0,00 | l/kg |
| Europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 275 Vuren, schroten, FSC | | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | -4,09E-01 | -3,29E-08 | -1,21E-02 | -4,86E-04 | -2,74E+00 | -1,98E-04 | -2,45E-05 | -4,73E-04 | -9,19E-05 | -9,10E-08 | -3,43E-03 | -0,03 | l/kg |
| Hout gelamineerd europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | -4,56E-01 | -3,67E-08 | -1,34E-02 | 3,87E-04 | -2,93E+00 | -2,21E-04 | -2,73E-05 | -5,27E-04 | -1,03E-04 | -1,01E-07 | -3,83E-03 | -0,03 | l/kg |

**Table D.5** LCA input for the demolition life cycle phase

| **Einde levensduur - Stort** | C4 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| **Naam** | **Materiaal** | **Onderdeel** | **Aantal** | **Eenheid** | **Bouwafval** | **Levensduur** | **Hergebruik** | **Stort** | **Vebranding** | **Recycling** | **Global warming (GWP100)** | **Ozone layer depletion (ODP)** | **Human toxicity** | **Aquatic tox fresh water (sweet)** | **Aquatic tox fresh water (salt)** | **Terrestrial toxicity** | **Photochemical oxidation** | **Acidification** | **Eutrophication** | **Abiotic resources depletion** | **Fossil energy carriers** | **Schaduwprijs** | **Eenheid** |
| Kanaalplaat met druklaag | | | | | | | | | | | 3,51E-04 | 1,39E-10 | 1,56E-04 | 3,78E-06 | 1,27E-02 | 3,58E-07 | 3,81E-07 | 2,58E-06 | 5,46E-07 | 3,77E-10 | 5,44E-06 | 0,00 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 4,42E-05 | 1,75E-11 | 1,96E-05 | 4,76E-07 | 1,59E-03 | 4,51E-08 | 4,80E-08 | 3,25E-07 | 6,88E-08 | 4,75E-11 | 6,85E-07 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,21E-04 | 8,76E-11 | 9,79E-05 | 2,38E-06 | 7,97E-03 | 2,26E-07 | 2,40E-07 | 1,63E-06 | 3,44E-07 | 2,37E-10 | 3,42E-06 | 0,00 | l/kg |
| Druklaag | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I) | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 8,59E-05 | 3,40E-11 | 3,80E-05 | 9,24E-07 | 3,10E-03 | 8,76E-08 | 9,32E-08 | 6,32E-07 | 1,34E-07 | 9,22E-11 | 1,33E-06 | 0,00 | l/kg |
| Kanaalplaat | | | | | | | | | | | 2,65E-04 | 1,05E-10 | 1,18E-04 | 2,86E-06 | 9,56E-03 | 2,71E-07 | 2,88E-07 | 1,95E-06 | 4,13E-07 | 2,85E-10 | 4,11E-06 | 0,00 | l/kg |
| | Prefab beton C30/37 XC2, 0% puingranulaat, CEM I | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 4,42E-05 | 1,75E-11 | 1,96E-05 | 4,76E-07 | 1,59E-03 | 4,51E-08 | 4,80E-08 | 3,25E-07 | 6,88E-08 | 4,75E-11 | 6,85E-07 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,21E-04 | 8,76E-11 | 9,79E-05 | 2,38E-06 | 7,97E-03 | 2,26E-07 | 2,40E-07 | 1,63E-06 | 3,44E-07 | 2,37E-10 | 3,42E-06 | 0,00 | l/kg |
| Beton ihwg vloer | Beton,in het werk gestort, C30/37; incl,wapening | Vloeren | | | | | | | | | 3,07E-04 | 1,22E-10 | 1,36E-04 | 3,30E-06 | 1,11E-02 | 3,13E-07 | 3,33E-07 | 2,26E-06 | 4,78E-07 | 3,30E-10 | 4,75E-06 | 0,00 | l/kg |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I) | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 8,59E-05 | 3,40E-11 | 3,80E-05 | 9,24E-07 | 3,10E-03 | 8,76E-08 | 9,32E-08 | 6,32E-07 | 1,34E-07 | 9,22E-11 | 1,33E-06 | 0,00 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | 1000 | | 5% | 5% | 90% | 2,21E-04 | 8,76E-11 | 9,79E-05 | 2,38E-06 | 7,97E-03 | 2,26E-07 | 2,40E-07 | 1,63E-06 | 3,44E-07 | 2,37E-10 | 3,42E-06 | 0,00 | l/kg |
| Houten kanaalplaatvloer | Verdiepingsvloer van geprefabriceerde houten kanaalplaten, De houten kanaalplaat van gelamineerd europees naalhout uit duurzame bosbouw (met keurmerk) met vierkante holle kanalen, | | | | | | | | | | 3,85E-03 | 1,37E-10 | 2,59E-04 | 5,34E-06 | 1,84E-02 | 8,61E-07 | 1,17E-06 | 2,95E-06 | 1,44E-06 | 6,25E-10 | 5,64E-06 | 0,00 | l/kg |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | 3,85E-03 | 1,37E-10 | 2,59E-04 | 5,34E-06 | 1,84E-02 | 8,61E-07 | 1,17E-06 | 2,95E-06 | 1,44E-06 | 6,25E-10 | 5,64E-06 | 0,00 | l/kg |
| Houten balkenvloer | Europees naaldhouten balken met europees naaldhouten multiplex; duurzame bosbouw | | | | | | | | | | 1,15E-02 | 4,10E-10 | 7,78E-04 | 1,37E-05 | 5,22E-02 | 2,58E-06 | 3,50E-06 | 8,85E-06 | 4,33E-06 | 1,87E-09 | 1,69E-05 | 0,00 | l/kg |
| | SBK 275 Vuren, schroten, FSC | balken | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | 7,67E-03 | 2,73E-10 | 5,18E-04 | 8,33E-06 | 3,38E-02 | 1,72E-06 | 2,33E-06 | 5,90E-06 | 2,89E-06 | 1,25E-09 | 1,13E-05 | 0,00 | l/kg |
| | SBK 167 Vuren, Multiplex, duurzame bosbouw | bekleding | 1 | kg | 5% | 1000 | | 5% | 95% | 0% | 3,85E-03 | 1,37E-10 | 2,59E-04 | 5,34E-06 | 1,84E-02 | 8,61E-07 | 1,17E-06 | 2,95E-06 | 1,44E-06 | 6,25E-10 | 5,64E-06 | 0,00 | l/kg |
| Prefab beton schil met I-profielen | | | | | | | | | | | -5,12E-01 | -3,61E-09 | -8,73E-03 | -1,87E-03 | 7,78E-03 | -1,40E-02 | -1,84E-04 | -1,51E-03 | -1,53E-04 | 9,58E-08 | -2,72E-03 | -0,04 | l/kg |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I) | prefab beton | 1,00 | kg | 3% | | | 1% | 0% | 99% | 4,42E-05 | 1,75E-11 | 1,96E-05 | 4,76E-07 | 1,59E-03 | 4,51E-08 | 4,80E-08 | 3,25E-07 | 6,88E-08 | 4,75E-11 | 6,85E-07 | 0,00 | l/kg |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | constructie st | 1 | kg | | | 49% | 0% | 0% | 51% | -5,12E-01 | -3,72E-09 | -8,85E-03 | -1,87E-03 | -1,78E-03 | -1,40E-02 | -1,84E-04 | -1,51E-03 | -1,53E-04 | 9,55E-08 | -2,72E-03 | -0,04 | l/kg |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,21E-04 | 8,76E-11 | 9,79E-05 | 2,38E-06 | 7,97E-03 | 2,26E-07 | 2,40E-07 | 1,63E-06 | 3,44E-07 | 2,37E-10 | 3,42E-06 | 0,00 | l/kg |
| *Topvloer aangenomen staalplaatbetonvloer op rubbers* | S3, met 50% granulaat, PRODUCTIE, c2 | beton | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | - | l/kg |
| | 330 Steel, Light Construction Products PRODUCTIE, BmS, 2013, c2 | staal | 1 | kg | 3% | 1000 | | 0% | 0% | 0% | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | - | l/kg |

| **Einde levensduur - Stort** | C4 | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 0,05 | 30,00 | 0,09 | 0,03 | 0,0001 | 0,06 | 2,00 | 4,00 | 9,00 | 0,16 | 0,16 | | |
| **Naam** | **Materiaal** | **Onderdeel** | **Aantal** | **Eenheid** | **Bouwafval** | **Levensduur** | **Hergebruik** | **Stort** | **Vebranding** | **Recycling** | **Global warming (GWP100)** | **Ozone layer depletion (ODP)** | **Human toxicity** | **Aquatic tox fresh water (sweet)** | **Aquatic tox fresh water (salt)** | **Terrestrial toxicity** | **Photochemical oxidation** | **Acidification** | **Eutrophication** | **Abiotic resources depletion** | **Fossil energy carriers** | **Schaduwprijs** | **Eenheid** |
| Staal voor constructie producten | Staal | | | | | | | | | | | | | | | | | | | | | | |
| | 900 kg sections (10% BF and 90% EAF); 100 kg plate (BF) | | 1 | kg | | | 49% | 0% | 0% | 51% | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 | - | l/kg |
| Wapeningsstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,21E-04 | 8,76E-11 | 9,79E-05 | 2,38E-06 | 7,97E-03 | 2,26E-07 | 2,40E-07 | 1,63E-06 | 3,44E-07 | 2,37E-10 | 3,42E-06 | 0,00 | l/kg |
| Voorspanstaal | | | | | | | | | | | | | | | | | | | | | | | |
| | 767pr SBK Wapeningsstaal | wapening | 1,00 | kg | 3% | | | 5% | 5% | 90% | 2,21E-04 | 8,76E-11 | 9,79E-05 | 2,38E-06 | 7,97E-03 | 2,26E-07 | 2,40E-07 | 1,63E-06 | 3,44E-07 | 2,37E-10 | 3,42E-06 | 0,00 | l/kg |
| Betonmortel C30/37 | Beton | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 847 Betonmortel C30/37 (o,b,v, 75% CEM III en 25% CEM I | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 8,59E-05 | 3,40E-11 | 3,80E-05 | 9,24E-07 | 3,10E-03 | 8,76E-08 | 9,32E-08 | 6,32E-07 | 1,34E-07 | 9,22E-11 | 1,33E-06 | 0,00 | l/kg |
| Betonmortel C53/65 | Beton | | | | | | | | | | | | | | | | | | | | | | |
| | Betonmortel C53/65 (o,b,v, 75% CEM III | betonmortel | 1,00 | kg | 0% | 1000 | | 2% | 0% | 98% | 8,59E-05 | 3,40E-11 | 3,80E-05 | 9,24E-07 | 3,10E-03 | 8,76E-08 | 9,32E-08 | 6,32E-07 | 1,34E-07 | 9,22E-11 | 1,33E-06 | 0,00 | l/kg |
| Europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 275 Vuren, schroten, FSC | | 1 | kg | 5% | 1000 | | 10% | 85% | 5% | 7,67E-03 | 2,73E-10 | 5,18E-04 | 8,33E-06 | 3,38E-02 | 1,72E-06 | 2,33E-06 | 5,90E-06 | 2,89E-06 | 1,25E-09 | 1,13E-05 | 0,00 | l/kg |
| Hout gelamineerd europees naaldhout; duurzame bosbouw | | | | | | | | | | | | | | | | | | | | | | | |
| | SBK 077 Grenen, planken, gelamineerd, duurzame bosbouw | grenen | 1,00 | kg | 5,00% | 75 | | 5% | 95% | 0% | 3,85E-03 | 1,37E-10 | 2,59E-04 | 5,34E-06 | 1,84E-02 | 8,61E-07 | 1,17E-06 | 2,95E-06 | 1,44E-06 | 6,25E-10 | 5,64E-06 | 0,00 | l/kg |

## D.2 Environmental impact calculation

This section will present a example calculation for the environmental impact. The example illustrates how the data retrieved from the structural calculations, Bill of Materials [BoM] and the environmental data of the NMD is used. To explain the calculations, screenshots of the design tool are used.

### Step 1: Create the BoM

The design tool presents a general overview of the materials required per structural design variant to the user, see figure D.1.

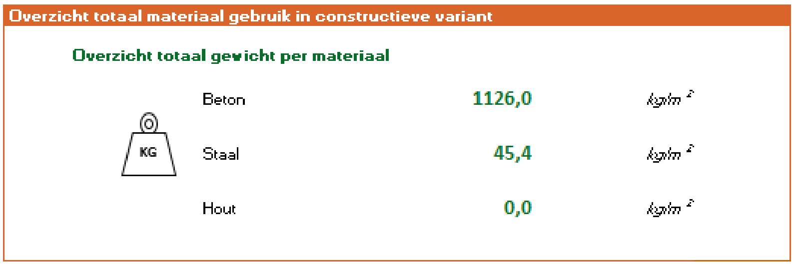



**Figure D.1** Overview of applied materials for each structural design variant

The tool also creates a table that more specifically per building parts determines the required amount of concrete, steel and timber. Steel is divided into reinforcement steel and construction steel.

| Variant 1 | Naam Deel 1 | Naam Deel 2 | Naam Deel 3 | Totaal kg/m² | Beton C30/37 kg/m² | Beton C53/65 kg/m² | Beton kg/m² | constructief Staal voorsp./wap. kg/m² | Staal kg/m² | Hout kg/m² |
|---|---|---|---|---|---|---|---|---|---|---|
| **Begane grondvloer** | kanaalplaatvloer met druklaag | | | **456,87** | nvt | nvt | 447 | 6,9 | nvt | nvt |
| **Verdiepingsvloer** | kanaalplaatvloer | | | **380,88** | nvt | nvt | 376 | 4,880083333 | nvt | nvt |
| **Dak** | kanaalplaatvloer | | | **306,01** | nvt | nvt | 303 | 3,009166667 | nvt | nvt |
| **Liggers** | staal | S235_ | HEA | **19,41** | nvt | nvt | nvt | nvt | 19,41 | nvt |
| **Verticale draagelementen** | skelet | geschoord | gewalst staal S23! | **9,55** | nvt | nvt | nvt | nvt | 9,55 | nvt |
| **Stabiltiteit** | windverbanden | staal standaard kwaliteit | | **1,73** | nvt | nvt | nvt | nvt | 1,73 | nvt |
| | | | | | **0,0** | **0,0** | **1126,0** | **14,8** | **30,69** | **0,0** |

**Figure D.2** More specific BoM as output of the structural calculations

### Step 2: Define the environmental impact of the structural building components

As the user can combine various structural building components, the design tool calculates for each component the environmental impact. This mean even though the component is not applied, for the determined geometry and spans all the structural building components are evaluated. The output of this calculations are showed in figure D.3. The warning at the walls means that this system is not chosen, but columns are preferred. Additionally, not for all situations every structural building components is suitable this is indicated with *'kan niet'*.

**Figure D.3** Overview of environmental impact of the structural building components based on the BoM

| Begane grondvloeren | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Dikte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| kanaalplaatvloer met druklaag | 303 | 144 | 6,87 | 3 | 0 | 0 | 456,9 | | 8,75 | 0,77 | 0,36 | -0,13 | 0,0 | **9,75** | | 81,40 | 73,90 | -2,06 | 2,8% |
| betonvloer ihwg | 0 | 660 | 0 | 12 | 0 | 0 | 672,0 | | 10,53 | 0,19 | 0,52 | -0,15 | 0,01 | **11,10** | | 93,56 | 89,89 | -2,41 | 2,7% |
| combinatie vloer | | | | | | | | | | | | | | | | | | | |
| ribbenvloer | | | | | | | | | | | | | | | | | | | |

| Verdiepingsvloeren | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Dikte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| kanaalplaatvloer met druklaag | 376 | 51,12 | 4,88 | 3 | 0 | 0 | 435,0 | 320 | 7,87 | 0,91 | 0,34 | -0,10 | 0,0 | **9,03** | | 78,85 | 69,84 | -1,58 | 2,3% |
| kanaalplaatvloer | 376 | 0 | 4,88 | 0 | 0 | 0 | 380,9 | 260 | 6,09 | 0,89 | 0,30 | -0,05 | 0,00 | **7,23** | | 67,51 | 58,33 | -0,87 | 1,5% |
| betonvloer ihwg | 0 | 840 | 0 | 16,8 | 0 | 0 | 856,8 | 350 | 14,11 | 0,24 | 0,67 | (0,22) | 0,01 | **14,81** | | 122,05 | 117,76 | -3,46 | 2,9% |
| houten kanaalplaatvloer | 0 | 0 | 0 | 0 | 0 | kan niet | kan niet | kan niet | #VALUE! | #VALUE! | #VALUE! | #VALUE! | #VALUE! | **#VALUE!** | | #VALUE! | #VALUE! | #VALUE! | #VALUE! |
| houten balkenvloer | 0 | 0 | 0 | 0 | 0 | 58,67 | 58,8 | 500 | 1,76 | 0,14 | 0,08 | -1,47 | 0,03 | **0,54** | | -7,19 | 14,45 | -23,97 | 165,9% |
| prefab beton schil met I-profielen | 168 | 0 | 0 | 1,48 | 40,92 | 0 | 316,3 | 450 | 6,95 | 0,57 | 0,23 | -0,38 | -1,45 | **5,91** | | 64,28 | 86,43 | 1,44 | -1,7% |
| breedplaatvloer | kan niet | kan niet | 0 | kan niet | 0 | 0 | 0,0 | kan niet | #VALUE! | #VALUE! | #VALUE! | #VALUE! | #VALUE! | **#VALUE!** | | | | | |

| Dak | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Dikte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| kanaalplaatvloer met druklaag | 303 | 51,12 | 3,01 | 3 | 0 | 0 | 360,1 | 320 | 6,26 | 0,74 | 0,28 | -0,07 | 0,0 | **7,21** | | 63,93 | 56,48 | -1,18 | 2,1% |
| kanaalplaatvloer | 303 | 0 | 3,01 | 0 | 0 | 0 | 306,0 | 260 | 4,48 | 0,71 | 0,24 | -0,02 | 0,00 | **5,41** | | 52,59 | 44,97 | -0,46 | 1,0% |
| betonvloer ihwg | 0 | 840 | 0 | 16,8 | 0 | 0 | 856,8 | 350 | 14,11 | 0,24 | 0,67 | (0,22) | 0,01 | **14,81** | | 122,05 | 117,76 | -3,46 | 2,9% |
| houten kanaalplaatvloer | 0 | 0 | 0 | 0 | 0 | 81 | 81,0 | kan niet | 4,82 | 0,19 | 0,12 | -2,27 | 0,02 | **2,88** | | 1,91 | 35,91 | -36,96 | 102,9% |
| houten balkenvloer | 0 | 0 | 0 | 0 | 0 | 47,64 | 47,6 | 500 | 1,43 | 0,11 | 0,07 | -1,20 | 0,02 | **0,44** | | -5,84 | 11,74 | -19,46 | 165,9% |
| prefab beton schil met I-profielen | 168,00 | 0 | 0 | 1,48 | 30,08 | 0 | 199,6 | 450 | 6,18 | 0,55 | 0,20 | -0,42 | -1,07 | **5,43** | | 58,35 | 75,81 | 1,00 | -1,3% |
| breedplaatvloer | 144 | 731 | 0 | 16 | 0 | 0 | 891,0 | kan niet | | | | | | - | | | | | |

| Liggers | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Hoogte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| prefab | 115,2 | 0,0 | 0,0 | 12,0 | 0,0 | 0,0 | 127,2 | 720 | 6,47 | 0,06 | 0,10 | -0,20 | 0,00 | **6,43** | | 35,94 | 37,51 | -2,94 | 7,8% |
| ihwg | 0,0 | 115,2 | 0,0 | 12,0 | 0,0 | 0,0 | 127,2 | 720 | 6,47 | 0,03 | 0,10 | -0,20 | 0,00 | **6,40** | | 35,94 | 37,51 | -2,94 | 7,8% |
| S235_ | 0,0 | 0,0 | 0,0 | 0,0 | 19,4 | 0,0 | 19,4 | 440 | 1,38 | 0,04 | 0,04 | -0,60 | - | **0,87** | | 10,63 | 19,02 | -9,15 | 48,1% |
| S355_ | 0,0 | 0,0 | 0,0 | 0,0 | 17,3 | 0,0 | 17,3 | 390 | 1,23 | 0,04 | 0,04 | -0,54 | - | **0,77** | | 9,49 | 16,99 | -8,18 | 48,1% |
| GL24h | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 8,9 | 8,9 | 1000 | 0,53 | 0,02 | 0,01 | -0,25 | 0,00 | **0,32** | | 0,21 | 3,95 | -4,07 | 102,9% |
| GL28h | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 9,8 | 9,8 | 1000 | 0,59 | 0,02 | 0,01 | -0,28 | 0,00 | **0,35** | | 0,23 | 4,36 | -4,49 | 102,9% |
| GL30h | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 11,1 | 11,1 | 1000 | 0,66 | 0,03 | 0,02 | -0,31 | 0,00 | **0,40** | | -1,36 | 2,74 | -4,54 | 165,9% |

| Kolommen | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Diepte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| prefab beton C30/37 | 28,27 | 0,00 | 0,00 | 0,92 | 0,00 | 0,00 | 29,2 | 330 | 0,64 | 0,01 | 0,02 | -0,01 | 0,00 | **0,66** | | 4,82 | 4,74 | -0,21 | 4,3% |
| prefab beton C53/65 | 16,23 | 0,00 | 0,00 | 0,52 | 0,00 | 0,00 | 16,7 | 250 | 0,36 | 0,01 | 0,01 | -0,01 | 0,00 | **0,37** | | 3,03 | 2,98 | -0,12 | 3,9% |
| ihwg beton C30/37 | 0,00 | 35,54 | 0,00 | 1,10 | 0,00 | 0,00 | 36,6 | 370 | 0,78 | 0,01 | 0,03 | -0,02 | 0,00 | **0,81** | | 5,95 | 5,85 | -0,25 | 4,2% |
| ihwg beton C53/65 | 0,00 | 26,58 | 0,00 | 0,83 | 0,00 | 0,00 | 27,4 | 320 | 0,59 | 0,01 | 0,02 | -0,01 | 0,00 | **0,60** | | 4,92 | 4,84 | -0,18 | 3,8% |
| gewalst staal S235 | 0,00 | 0,00 | 0,00 | 0,00 | 9,55 | 0,00 | 9,6 | 300 | 0,68 | 0,02 | 0,02 | -0,30 | - | **0,43** | | 5,23 | 9,36 | -4,51 | 48,1% |
| gewalst staal S355 | 0,00 | 0,00 | 0,00 | 0,00 | 6,52 | 0,00 | 6,5 | 240 | 0,46 | 0,01 | 0,01 | -0,20 | - | **0,29** | | 3,57 | 6,39 | -3,08 | 48,1% |
| gelamineerd hout GL24h | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 4,26 | 4,3 | 320 | 0,25 | 0,01 | 0,01 | -0,12 | 0,00 | **0,15** | | 0,10 | 1,89 | -1,95 | 102,9% |
| gelamineerd hout GL28h | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 4,14 | 4,1 | 300 | 0,25 | 0,01 | 0,01 | -0,12 | 0,00 | **0,15** | | 0,10 | 1,83 | -1,89 | 102,9% |
| naaldhout C24 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 6,22 | 6,2 | 370 | 0,19 | 0,01 | 0,01 | -0,16 | 0,00 | **0,06** | | -0,76 | 1,53 | -2,54 | 165,9% |

| Wanden | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Diepte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| prefab beton C30/37 | #N/A | 0 | 0 | #N/A | 0 | 0 | #N/A | | #N/A | #N/A | #N/A | - | - | **#N/A** | | #N/A | #N/A | #N/A | #N/A |
| prefab beton C53/65 | #N/A | 0 | 0 | #N/A | 0 | 0 | #N/A | | #N/A | #N/A | #N/A | - | - | **#N/A** | | #N/A | #N/A | #N/A | #N/A |
| ihwg beton C30/37 | 0 | #N/A | 0 | #N/A | 0 | 0 | #N/A | | #N/A | #N/A | #N/A | - | - | **#N/A** | | #N/A | #N/A | #N/A | #N/A |
| ihwg beton C53/65 | 0 | #N/A | 0 | #N/A | 0 | 0 | #N/A | | #N/A | #N/A | #N/A | - | - | **#N/A** | | #N/A | #N/A | #N/A | #N/A |
| hout | 0 | 0 | 0 | 0 | 0 | #N/A | #N/A | | #N/A | #N/A | #N/A | #N/A | #N/A | **#N/A** | | #N/A | #N/A | #N/A | #N/A |

| Stabiliteit | Hoeveelheden [kg/m2] Prefab beton | Ihwg beton | Voorspan. Staal | Wapening Staal | Constructief Staal | Hout | TOTAAL | Diepte [mm] | Schaduwkosten per module [€/m2] A1-A3 | A4 | C2 | C3 | C4 | Totaal | Opmerkingen | CO2 productie kg-eq./m2 | A1-A3 | C3 | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| beton prefab | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | | | - | - | - | - | - | - | | 0,00 | 0,00 | 0,00 | #DIV/0! |
| beton ihwg | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | | | - | - | - | - | - | - | | 0,00 | 0,00 | 0,00 | #DIV/0! |
| staal standaard kwaliteit | 0,00 | 0,00 | 0,00 | 0,00 | 1,73 | 0,00 | | | 0,12 | 0,00 | 0,00 | -0,05 | - | **0,08** | | 0,94 | 1,69 | -0,81 | 48,1% |
| staal hoge kwaliteit | 0,00 | 0,00 | 0,00 | 0,00 | 1,73 | 0,00 | | | 0,12 | 0,00 | 0,00 | -0,05 | - | **0,08** | | 0,94 | 1,69 | -0,81 | 48,1% |

## Step 3: Determine the shadow costs of the applied structural building components

From the data showed in figure D.3 the specific required shadow costs of the applied structural building components are collected in one table. The shadow costs are per structural building component per life cycle phase presented. This can be used to determine the total environmental impact, total shadow costs. Dividing the total shadow costs by the Gross Floor Area and expected service life, the MPG of the structural design variant is calculated.

| Variant 1 | | Totaal kg/m² | Schaduwprijs [€/m2] | Schaduwprijs [€/m2] | Schaduwprijs [€/m2] | Schaduwprijs [€/m2] | Schaduwprijs [€/m2] | Schaduwprijs [€/m2] | Totaal [€/m2] | | CO2 [kg eq./m2] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Module A1-A3 Productie | Module A4 Transport | Module B Gebruik | Module C2 Transport | Module C3 Bewerking | Module C4 Stort | | | | |
| Begane grondvloer | kanaalplaatvloer met druklaag | 456,87 | € 8,75 | € 0,77 | € - | € 0,36 | € -0,13 | € 0,00 | € **2,44** | *m2BVO* | 20,35 | *m2BVO* |
| Verdiepingsvloer | kanaalplaatvloer | 380,88 | € 6,09 | € 0,89 | € - | € 0,30 | € -0,05 | € 0,00 | € **5,42** | *m2BVO* | 50,63 | *m2BVO* |
| Dak | kanaalplaatvloer | 306,01 | € 4,48 | € 0,71 | € - | € 0,24 | € -0,02 | € 0,00 | € **1,35** | *m2BVO* | 13,15 | *m2BVO* |
| Liggers | staal | 19,41 | € 1,38 | € 0,04 | € - | € 0,04 | € -0,60 | € - | € **0,87** | *m2BVO* | 10,63 | *m2BVO* |
| Verticale draagelementen | skelet | 9,55 | € 0,68 | € 0,02 | € - | € 0,02 | € -0,30 | € - | € **0,43** | *m2BVO* | 5,23 | *m2BVO* |
| Stabiltiteit | windverbanden | 1,73 | € 0,12 | € 0,00 | € - | € 0,00 | € -0,05 | € - | € **0,08** | *m2BVO* | 0,94 | *m2BVO* |
| **Totaal** | | | Productie | Transport | Gebruik | Transport | Bewerking | Stort | | | 100,93 | |
| | | [€/m2BVO] | € **10,06** | € **1,11** | € - | € **0,44** | € **-1,03** | € **0,00** | | | | |

| | | | |
|---|---|---|---|
| **Schaduwprijs per BVO** | € | 10,58 | [€/m2] |
| **Totale schaduwprijs** | € | 17.611,74 | [€] |
| **MPG score** | € | 0,07 | [€/m2/jaar] |

| | | |
|---|---|---|
| **CO2 per BV** | 100,93 | [kg-eq/m2] |
| **Totaal CO2** | 167946,5 | [kg-eq] |

**Figure D.4** Overview of shadow costs of the created structural design variant


| | | | |
|---|---|---|---|
| Schaduwprijs per BVO | € | 10,58 | [€/m2] |
| Totale schaduwprijs | € | 17.611,74 | [€] |
| MPG score | € | 0,07 | [€/m2/jaar] |


The following calculations are performed;

Total shadow costs structural design variant $_{\text{per Gross Floor Area}}$ *[€/m²GFA]* =
Shadow costs $_{\text{per structural building component}}$ *[€/m²GFA]* · gross floor area *[m²GFA]*

MPG $_{\text{structural design variant}}$ *[€/m²GFA/year]* =
Total shadow costs structural design variant $_{\text{per Gross Floor Area}}$ *[€/m²GFA]* / expected service life

The expected service life is based on the chosen circular design strategy. The calculations are dynamic, so when a adjustment is made in the structural design variant, the outcome will directly change.

# Chapter E

# Design tool

## E.1 Final output design tool case study 1 Accelerator and case study 2 Ambachtslaan

## E.1 Case study 1: Accelerator Utrecht

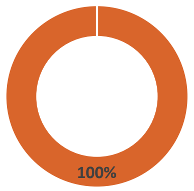
### Overzicht resultaten Circulaire Ontwerptool

#### Uitkomsten

**Projectnaam** Accelerator Utrecht
**Datum**
**Ingevuld door** Sophie Kuijpers

| Circulaire ontwerp strategie | Ontwerp principes | Levensduur | Ontwerp | Materiaalgebruik | CO2 productie | MPG | Bouwkosten |
|---|---|---|---|---|---|---|---|

**Adaptief Ontwerpen**




**Functionele ontwerp principes**

Het ontwerp is geschikt voor het faciliteren van meerdere functies

Reduceer de hoeveelheid vertciale elementen die een belemmering vormen voor de indeling

**Levensduur:** 150 jaar

**Constructieve variant 1**

Overspanning vloeren 12,6 m
Overspanning liggers 5,4 m

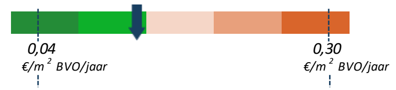
Verberg

**Klik hier** voor meer details van de gekozen variant met betrekking tot Materiaalgebruik, CO2, MPG en bouwkosten

**Materiaalgebruik:**
Beton 1510,5 kg/m²
Staal 39,4 kg/m²
Hout 0,0 kg/m²

**CO2 productie:** 981.388,2 kg-eq.

**MPG:** € 0,13 €/m² BVO/jaar



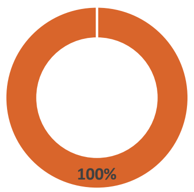

**Bouwkosten:** € 80,44 €/m² BVO

**Technische ontwerp principes**

1. Pas extra draagvermogen bij de vloeren toe
2. Zorg voor voldoende, 3 meter, vrije vloerhoogte
3. Brandveiligheid en akoestische eisen maatgevend voor 'woning' functie
4. Gebruik maken van kolommen
5. Maak gebruik van grote vloeroverspanningen van minimaal 7 meter

| | | Materiaal hoeveelheden | | | CO2 productie | | MPG | | Bouwkosten |
|---|---|---|---|---|---|---|---|---|---|
| | | beton [kg/m²] | staal [kg/m²] | hout [kg/m²] | | | | | |
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 5 | nvt | 19,38 | kg/m² BVO | € 2,22 | €/m² BVO | € 4,23 |
| **Verdiepingsvloer** | kanaalplaatvloer | 548 | nvt | nvt | 78,71 | kg/m² BVO | € 9,03 | €/m² BVO | € 30,00 |
| **Dak** | kanaalplaatvloer | 443 | nvt | nvt | 23,10 | kg/m² BVO | € 2,87 | €/m² BVO | € 6,40 |
| **Liggers** | beton prefab | 37,03 | 9 | nvt | 21,71 | kg/m² BVO | € 4,40 | €/m² BVO | € 15,00 |
| **Verticale draagelementen** | geschoord prefab beton C30/37 | 35 | 1 | nvt | 5,98 | kg/m² BVO | € 0,81 | €/m² BVO | € 20,68 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 0,91 | kg/m² BVO | € 0,07 | €/m² BVO | € 4,14 |

**Adaptief Ontwerpen**




**Functionele ontwerp principes**

Het ontwerp is geschikt voor het faciliteren van meerdere functies

Reduceer de hoeveelheid vertciale elementen die een belemmering vormen voor de indeling

**Levensduur:** 150 jaar

**Constructieve variant 2**

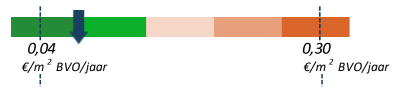
Overspanning vloeren 12,6 m
Overspanning liggers 5,4 m

Verberg

**Materiaalgebruik:**
Beton 783,0 kg/m²
Staal 191,1 kg/m²
Hout 0,0 kg/m²

**CO2 productie:** 789.101,9 kg-eq.

**MPG:** € 0,07 €/m² BVO/jaar




**Bouwkosten:** € 155,19 €/m² BVO

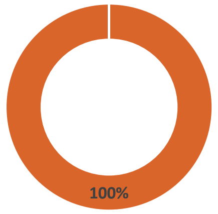
**Technische ontwerp principes**

1. Pas extra draagvermogen bij de vloeren toe
2. Zorg voor voldoende, 3 meter, vrije vloerhoogte
3. Brandveiligheid en akoestische eisen maatgevend voor 'woning' functie
4. Gebruik maken van kolommen
5. Maak gebruik van grote vloeroverspanningen van minimaal 7 meter

| | | Materiaal hoeveelheden | | | CO2 productie | | MPG | | Bouwkosten |
|---|---|---|---|---|---|---|---|---|---|
| | | beton [kg/m²] | staal [kg/m²] | hout [kg/m²] | | | | | |
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 8 | nvt | 19,38 | kg/m² BVO | € 2,22 | €/m² BVO | € 4,23 |
| **Verdiepingsvloer** | prefab beton schil met I-profielen | 168 | 90 | nvt | 68,23 | kg/m² BVO | € 6,07 | €/m² BVO | € 70,35 |
| **Dak** | prefab beton schil met I-profielen | 168 | 66 | nvt | 19,54 | kg/m² BVO | € 1,76 | €/m² BVO | € 19,95 |
| **Liggers** | staal S235_ HEA | nvt | 11 | nvt | 6,07 | kg/m² BVO | € 0,49 | €/m² BVO | € 27,72 |
| **Verticale draagelementen** | geschoord gewalst staal S235 | nvt | 12 | nvt | 6,31 | kg/m² BVO | € 0,51 | €/m² BVO | € 28,80 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 0,91 | kg/m² BVO | € 0,07 | €/m² BVO | € 4,14 |

**Figure E.1** Final overview design tool case study Accelerator Utrecht structural design variants 1 and 2

**Losmaakbaar Ontwerpen**




### Functionele ontwerp principes

Kies componenten geschikt voor het losmaken van een constructie

Reduceer het gebruik van verschillende type componenten

Bouwlagen met een andere levensduur moeten gescheiden blijven

**100 jaar**

### Constructieve variant 3

Overspanning vloeren 12,6 m

Overspanning liggers 5,4 m

Verberg

| | | |
|---|---|---|
| **Beton** | 1438 | kg/m² |
| **Staal** | 54,89 | kg/m² |
| **Hout** | 0 | kg/m² |

**881.099,8** kg-eq.

**€ 0,16** €/m² BVO/jaar

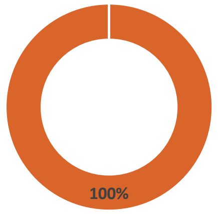

**€ 101,29** €/m² BVO

### Technische ontwerp principes

1. Droge verbindingen zoals schroef en bout verbindingen
2. Gebruik maken van geprefabriceerde componentenx
3. Rekening houden met de toepasbaarheid op de bouwplaats
4. Minimaliseer het gebruik van verschillende componenten
5. Bouwlagen (constructie, installaties, afwerking etc.) gescheiden houden
6. Toegankelijk houden van de verbindingen voor het uit elkaar halen

| | | Materiaal hoeveelheden | | | CO2 productie | | MPG | | Bouwkosten |
|---|---|---|---|---|---|---|---|---|---|
| | | beton [kg/m²] | staal [kg/m²] | hout [kg/m²] | | | | | |
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 8 | nvt | 19,38 | kg/m² BVO | € 2,22 | €/m² BVO | € 4,23 |
| **Verdiepingsvloer** | kanaalplaatvloer | 548 | nvt | nvt | 78,71 | kg/m² BVO | € 9,03 | €/m² BVO | € 30,00 |
| **Dak** | kanaalplaatvloer | 443 | nvt | nvt | 23,10 | kg/m² BVO | € 2,87 | €/m² BVO | € 6,40 |
| **Liggers** | staal S235_ HEA | nvt | 11 | nvt | 6,07 | kg/m² BVO | € 0,49 | €/m² BVO | € 27,72 |
| **Verticale draagelementen** | geschoord gewalst staal S235 | nvt | 12 | nvt | 6,31 | kg/m² BVO | € 0,51 | €/m² BVO | € 28,80 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 0,91 | kg/m² BVO | € 0,07 | €/m² BVO | € 4,14 |

**Losmaakbaar Ontwerpen**




### Functionele ontwerp principes

Kies componenten geschikt voor het losmaken van een constructie

Reduceer het gebruik van verschillende type componenten

Bouwlagen met een andere levensduur moeten gescheiden blijven

**100 jaar**

### Constructieve variant 4

Overspanning vloeren 12,6 m

Overspanning liggers 5,4 m

Verberg

| | | |
|---|---|---|
| **Beton** | 783 | kg/m² |
| **Staal** | 191,1 | kg/m² |
| **Hout** | 0 | kg/m² |

**789.101,9** kg-eq.

**€ 0,12** €/m² BVO/jaar


**€ 155,19** €/m² BVO

### Technische ontwerp principes

1. Droge verbindingen zoals schroef en bout verbindingen
2. Gebruik maken van geprefabriceerde componentenx
3. Rekening houden met de toepasbaarheid op de bouwplaats
4. Minimaliseer het gebruik van verschillende componenten
5. Bouwlagen (constructie, installaties, afwerking etc.) gescheiden houden
6. Toegankelijk houden van de verbindingen voor het uit elkaar halen

| | | Materiaal hoeveelheden | | | CO2 productie | | MPG | | Bouwkosten |
|---|---|---|---|---|---|---|---|---|---|
| | | beton [kg/m²] | staal [kg/m²] | hout [kg/m²] | | | | | |
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 8 | nvt | 19,38 | kg/m² BVO | € 2,22 | €/m² BVO | € 4,23 |
| **Verdiepingsvloer** | prefab beton schil met I-profielen | 168 | 90 | nvt | 68,23 | kg/m² BVO | € 6,07 | €/m² BVO | € 70,35 |
| **Dak** | prefab beton schil met I-profielen | 168 | 66 | nvt | 19,54 | kg/m² BVO | € 1,76 | €/m² BVO | € 19,95 |
| **Liggers** | staal S235_ HEA | nvt | 11 | nvt | 6,07 | kg/m² BVO | € 0,49 | €/m² BVO | € 27,72 |
| **Verticale draagelementen** | geschoord gewalst staal S235 | nvt | 12 | 11,52138 | 6,31 | kg/m² BVO | € 0,51 | €/m² BVO | € 28,80 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 0,91 | kg/m² BVO | € 0,07 | €/m² BVO | € 4,14 |

**Figure E.2** Final overview design tool case study Accelerator Utrecht structural design variants 3 and 4

## E.2 Case study 2: Ambachtslaan Veldhoven

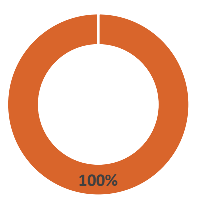
**Overzicht resultaten Circulaire Ontwerptool**

### Uitkomsten

| | |
|---|---|
| Projectnaam | Ambachtslaan Veldhoven |
| Datum | 30-4-2021 |
| Ingevuld door | Sophie Kuijpers |

| Circulaire ontwerp strategie | Ontwerp principes | Levensduur | Ontwerp | Materiaalgebruik | CO2 productie | MPG | Bouwkosten |
|---|---|---|---|---|---|---|---|

**Materiaal Efficient Ontwerpen**




**Functionele ontwerp principes**

Optimaliseer het ontwerp voor één functie

Kies materialen met een milieu vriendelijk profiel

**Levensduur:** 75 jaar

**Constructieve variant 1**

Overspanning vloeren 3,6 m
Overspanning liggers 7,2 m

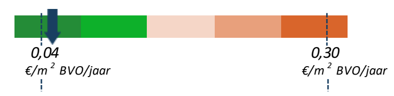
Verberg

**Klik hier** voor meer details van de gekozen variant met betrekking tot Materiaalgebruik, CO2, MPG en bouwkosten

**Materiaalgebruik:**
Beton 447,0 kg/m²
Staal 7,8 kg/m²
Hout 94,8 kg/m²

**CO2 productie:** 91.606,6 kg-eq.

**MPG:** € 0,04 €/m² BVO/jaar



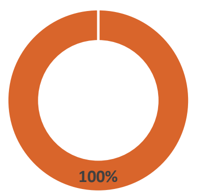

**Bouwkosten:** € 88,07 €/m² BVO

**Technische ontwerp principes**

1. Minimaliseer het materiaalgebruik
2. Materialen met een relatief laag eigen gewicht t.o.v. de overspanning
3. Gebruik maken van lichte materialen
4. Toepassen van componenten met lage schaduwkosten
5. Gebruik maken van geprefabriceerde componenten

| | | Materiaal hoeveelheden beton [kg/m²] | staal [kg/m²] | hout [kg/m²] | CO2 productie | | MPG | | Bouwkosten | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 6 | nvt | 14,73 | kg/m² BVO | € 1,60 | €/m² BVO | € | 3,38 |
| **Verdiepingsvloer** | houten kanaalplaatvloer | nvt | nvt | 39 | 0,73 | kg/m² BVO | € 1,11 | €/m² BVO | € | 24,00 |
| **Dak** | houten balkenvloer | nvt | nvt | 38,67 | -0,95 | kg/m² BVO | € 0,07 | €/m² BVO | € | 5,60 |
| **Liggers** | hout GL28h | nvt | nvt | 12,59 | 0,30 | kg/m² BVO | € 0,45 | €/m² BVO | € | 33,18 |
| **Verticale draagelementen** | geschoord naaldhout C24 | nvt | nvt | 4,54 | -0,56 | kg/m² BVO | € 0,04 | €/m² BVO | € | 17,31 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 1,01 | kg/m² BVO | € 0,08 | €/m² BVO | € | 4,61 |

**Materiaal Efficient Ontwerpen**




**Functionele ontwerp principes**

Optimaliseer het ontwerp voor één functie

Kies materialen met een milieu vriendelijk profiel

**Levensduur:** 75 jaar

**Constructieve variant 2**

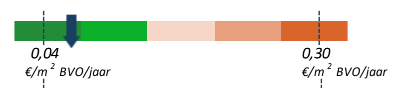
Overspanning vloeren 7,2 m
Overspanning liggers 3,6 m

Verberg

**Materiaalgebruik:**
Beton 447,0 kg/m²
Staal 7,8 kg/m²
Hout 130,3 kg/m²

**CO2 productie:** 105.824,5 kg-eq.

**MPG:** € 0,06 €/m² BVO/jaar




**Bouwkosten:** € 107,02 €/m² BVO

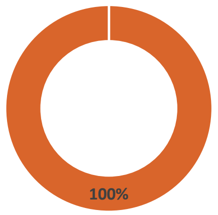
**Technische ontwerp principes**

1. Minimaliseer het materiaalgebruik
2. Materialen met een relatief laag eigen gewicht t.o.v. de overspanning
3. Gebruik maken van lichte materialen
4. Toepassen van componenten met lage schaduwkosten
5. Gebruik maken van geprefabriceerde componenten

| | | Materiaal hoeveelheden beton [kg/m²] | staal [kg/m²] | hout [kg/m²] | CO2 productie | | MPG | | Bouwkosten | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 6 | nvt | 14,73 | kg/m² BVO | € 1,60 | €/m² BVO | € | 3,38 |
| **Verdiepingsvloer** | houten kanaalplaatvloer | nvt | nvt | 81 | 1,52 | kg/m² BVO | € 2,31 | €/m² BVO | € | 62,40 |
| **Dak** | houten kanaalplaatvloer | nvt | nvt | 42,00 | 0,20 | kg/m² BVO | € 0,30 | €/m² BVO | € | 7,44 |
| **Liggers** | hout GL24h | nvt | nvt | 3,77 | 0,09 | kg/m² BVO | € 0,13 | €/m² BVO | € | 15,65 |
| **Verticale draagelementen** | geschoord gelamineerd hout GL24h | nvt | nvt | 3,55 | 0,08 | kg/m² BVO | € 0,13 | €/m² BVO | € | 13,54 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 1,01 | kg/m² BVO | € 0,08 | €/m² BVO | € | 4,61 |

**Figure E.3** Final overview design tool case study Ambachtslaan Veldhoven structural design variants 1 and 2

**Losmaakbaar Ontwerpen**




**Functionele ontwerp principes**

Kies componenten geschikt voor het losmaken van een constructie

Reduceer het gebruik van verschillende type componenten

Bouwlagen met een andere levensduur moeten gescheiden blijven

**100 jaar**

**Constructieve variant 3**

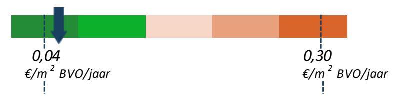
| | | |
|---|---|---|
| Overspanning vloeren | 7,2 | m |
| Overspanning liggers | 3,6 | m |

Verberg

| | | |
|---|---|---|
| Beton | 447 | $kg/m^2$ |
| Staal | 21,56 | $kg/m^2$ |
| Hout | 123 | $kg/m^2$ |

**150.030,4** kg-eq.

**€ 0,05** €/$m^2$ BVO/jaar



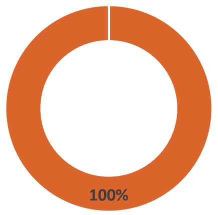

**€ 112,26** €/$m^2$ BVO

**Technische ontwerp principes**

1. Droge verbindingen zoals schroef en bout verbindingen
2. Gebruik maken van geprefabriceerde componentenx
3. Rekening houden met de toepasbaarheid op de bouwplaats
4. Minimaliseer het gebruik van verschillende componenten
5. Bouwlagen (constructie, installaties, afwerking etc.) gescheiden houden
6. Toegankelijk houden van de verbindingen voor het uit elkaar halen

| | | Materiaal hoeveelheden | | | CO2 productie | | MPG | | Bouwkosten |
|---|---|---|---|---|---|---|---|---|---|
| | | beton [$kg/m^2$] | staal [$kg/m^2$] | hout [$kg/m^2$] | | | | | |
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 6 | nvt | 14,73 | $kg/m^2$ BVO | € 1,60 | €/$m^2$ BVO | € 3,38 |
| **Verdiepingsvloer** | houten kanaalplaatvloer | nvt | nvt | 81 | 1,52 | $kg/m^2$ BVO | € 2,31 | €/$m^2$ BVO | € 62,40 |
| **Dak** | houten kanaalplaatvloer | nvt | nvt | 42 | 0,20 | $kg/m^2$ BVO | € 0,30 | €/$m^2$ BVO | € 7,44 |
| **Liggers** | staal S235_ HEA | nvt | 7 | nvt | 3,84 | $kg/m^2$ BVO | € 0,31 | €/$m^2$ BVO | € 17,53 |
| **Verticale draagelementen** | geschoord gewalst staal S235 | nvt | 7 | nvt | 3,70 | $kg/m^2$ BVO | € 0,30 | €/$m^2$ BVO | € 16,90 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 1,01 | $kg/m^2$ BVO | € 0,08 | €/$m^2$ BVO | € 4,61 |

**Losmaakbaar Ontwerpen**




**Functionele ontwerp principes**

Kies componenten geschikt voor het losmaken van een constructie

Reduceer het gebruik van verschillende type componenten

Bouwlagen met een andere levensduur moeten gescheiden blijven

**100 jaar**

**Constructieve variant 4**

| | | |
|---|---|---|
| Overspanning vloeren | 7,2 | m |
| Overspanning liggers | 3,6 | m |

Verberg

| | | |
|---|---|---|
| Beton | 783 | $kg/m^2$ |
| Staal | 84,69 | $kg/m^2$ |
| Hout | 0 | $kg/m^2$ |

**489.798,4** kg-eq.

**€ 0,08** €/$m^2$ BVO/jaar


**€ 97,02** €/$m^2$ BVO

**Technische ontwerp principes**

1. Droge verbindingen zoals schroef en bout verbindingen
2. Gebruik maken van geprefabriceerde componentenx
3. Rekening houden met de toepasbaarheid op de bouwplaats
4. Minimaliseer het gebruik van verschillende componenten
5. Bouwlagen (constructie, installaties, afwerking etc.) gescheiden houden
6. Toegankelijk houden van de verbindingen voor het uit elkaar halen

| | | Materiaal hoeveelheden | | | CO2 productie | | MPG | | Bouwkosten |
|---|---|---|---|---|---|---|---|---|---|
| | | beton [$kg/m^2$] | staal [$kg/m^2$] | hout [$kg/m^2$] | | | | | |
| **Begane grondvloer** | kanaalplaatvloer met druklaag | 447 | 6 | nvt | 14,73 | $kg/m^2$ BVO | € 1,60 | €/$m^2$ BVO | € 3,38 |
| **Verdiepingsvloer** | prefab beton schil met I-profielen | 168 | 30 | nvt | 46,68 | $kg/m^2$ BVO | € 4,35 | €/$m^2$ BVO | € 43,68 |
| **Dak** | prefab beton schil met I-profielen | 168 | 30 | nvt | 11,67 | $kg/m^2$ BVO | € 1,09 | €/$m^2$ BVO | € 10,92 |
| **Liggers** | staal S235_ HEA | nvt | 7 | nvt | 3,84 | $kg/m^2$ BVO | € 0,31 | €/$m^2$ BVO | € 17,53 |
| **Verticale draagelementen** | geschoord gewalst staal S235 | nvt | 7 | 6,761048 | 3,70 | $kg/m^2$ BVO | € 0,30 | €/$m^2$ BVO | € 16,90 |
| **Stabiltiteit** | windverbanden | nvt | 2 | nvt | 1,01 | $kg/m^2$ BVO | € 0,08 | €/$m^2$ BVO | € 4,61 |

**Figure E.4** Final overview design tool case study Ambachtslaan Veldhoven structural design variants 3 and 4