
# The transition of traditional construction to circular construction

"An analysis of key parameters related to the transition process of building circular viaducts and bridges."

Virania S. Jankie

Master Thesis

TU Delft

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## The transition from traditional construction to circular construction

"An analysis of key parameters related to the transition process of building circular viaducts and bridges"

By
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# Colophon

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# Preface

This graduation thesis with the title ''The transition from traditional construction to circular construction: An analysis of the key parameters related to the transition process of building circular viaducts and bridges'', marks the final step of my journey towards the Master of Science in Construction Management and Engineering at the Delft University of Technology. After completing my Bachelor of Science degree in Infrastructure, specializing in civil engineering, at the Anton de Kom University of Suriname, I discovered that this field and especially civil structures fascinates me and made me explore further into it. Thus, I decided to pursue a master's in Construction Management and Engineering at Delft University of Technology. I chose this master's to dive deeper into the management part of civil engineering and to specialize further in systems thinking and engineering. Currently, the construction sector in the Netherlands is facing a major challenge in the need for working fully circular by 2030. The current need for limiting the usage of primary raw materials in the construction process and transition process towards circular construction makes it even more interesting to apply by obtained knowledge during the past three years during this research.

This research is supported by the Delft University of Technology and Dura Vermeer Infra Landelijke Projecten, a construction company which allowed me to apply my knowledge in their company and collect the necessary data. During the past six months many challenges were faced due to (self-determined) deadlines and the urge to finish before the end of this year. However, with determination and motivation, I managed to overcome the obstacles and maintained the focus on the end goal. I was fortunate and honored to have a thesis committee who have efficiently guided me throughout the research period and have continuously supported me in achieving my deadlines. I would like express my gratitude to prof. dr. Henk Jonkers for always taken the time in guiding me from the start of the thesis process, brainstorming on thesis topics, up until the end. Furthermore, I would also like to express my gratitude to dr.ir. Maria Nogal Macho for also taken the time in guiding me and finding the interface between the research topic and her expertise. The right feedback and advice from both their expertise's have helped every time in getting one step further to my end goal.

I would like to express my utmost gratitude to the company, Dura Vermeer Infra Landelijke Projecten B.V. (DVILP), for giving me the opportunity to conduct my research at their company and providing an excellent collaboration. I would like to express my utmost gratitude to the company supervisor, BEng. Marleen Versteegen, for the weekly supervision and guidance throughout the research period and the flexibility and understanding for putting my focus entirely in the research. I would also like to thank the DVILP Sustainability Team for making me part of their team and for their guidance and supervision, Furthermore, I would also like to express my gratitude to all experts providing the data and information needed for the research. Lastly, I would like to thank technical expert of DVILP for the supervision throughout the research period and providing technical insight into my research.

Last but not least, I would like to express my deep gratitude to my family for the sacrifices they made in order for me to obtain this degree and supporting me throughout the entire process. Lastly, I would like to thank the most special person in my life, my fiancé, for being my anchor in life and supporting all dreams. The last three years were one of the greatest, but also most challenging, chapters in my life. However, the lessons I learned are extremely valuable and have made me into the person I am today.

*Virania Jankie*
*Delft, November 2022*

## Management Summary

The aim of this research was to develop a user-friendly tool for the construction industry that contributes to the decision-making of making first choices towards circular building in the initial phase of project and helps in considering the factors that play a role when reusing elements and reducing the usage of primary raw materials. With changing climate conditions and awareness of sustainable working, there has been a change in market demand to prevent raw materials from being exhausted and the living environment being affected. The current traditional industry is building with primary raw materials and is being challenged towards sustainable construction, but how the transition from traditional construction to sustainable construction will take place, is rather unclear. This resulted in the need for a good overview of different factors and aspects involved in the transition from traditional building towards circular building. A good overview was still missing and more research was needed into the innovation of reusing elements. Furthermore, the current calculation tools did not provide an insight into the total transition process from traditional building to circular building. Thus, for the construction sector, who currently has to minimize the usage of primary raw materials and reuse as much as possible, it was not clear which factors play a role in the transition process towards circular construction. Therefore, an overview of all factors involved in the transition process was necessary in the initial design phase of a project in order to be able to make a choice in the between design alternatives that meet the requirements drawn up by the project.

Therefore, this research tried to fill in the gap and bring an overview of all factor involved in the transition process explored opportunities to make a trade-off of design alternatives in an early design stage. Thus, the development statement was formulated:

***To develop a framework and user-friendly tool for the construction industry that enables a comparison of design alternatives based on key parameters involved in the transition of traditional building to circular building and provides insights for decision-making of design alternatives in an early-design stage.***

In order to arrive at the solution of this research and the development statement, this research has been executed in three parts. In Part I the literature review took place and the theoretical framework were drawn up. During Part I, the key-parameters were identified. The key-parameters identified are the Environmental Impact, Financial Impact, Supply and Demand, Detachability and Reusability. These were further defined and elaborated in sub-parameters. Further, the design alternatives were defined based on the research conducted, going from a traditional design to circular design. In order to make a comparison between the design alternatives, research was done into quantification methods for the defined (sub)parameters. For the environmental impact and financial impact, existing measuring methods were found. The standardized methods used in order to define these (sub)parameter were the life cycle analysis method, circularity performance method and life cycle costing using the activity-based costing method. For the supply and demand of secondary prefab concrete beams, detachability of beams and reusability of prefab concrete beams, no standardized methods were found. Thus, in order to quantify these (sub)parameters, an approach was developed for quantifying the effects of the design alternatives on these parameters. In order to find the results using the developed method, semi-structured interviews were conducted with experts within construction sector. This research was conducted with and for the construction sector, in collaboration with the construction company: Dura Vermeer Infra Landelijke Projecten (DVILP). Thus, the experts interviewed were part from this company. Furthermore, information and data for the standardized methods were also obtained from the company.

Part II of this research summarizes the research results found during Part I of the research. This led to development of the framework for the to-be developed tool. Figure 0.1. illustrates the conceptual model of the drawn-up framework. This framework described the steps taken, in order to define the effect of each design alternative (variants) of the (sub)parameter. It also elaborates on the additional information needed in order to arrive at the trade-off of design alternatives. With help of this framework, the tool was developed.

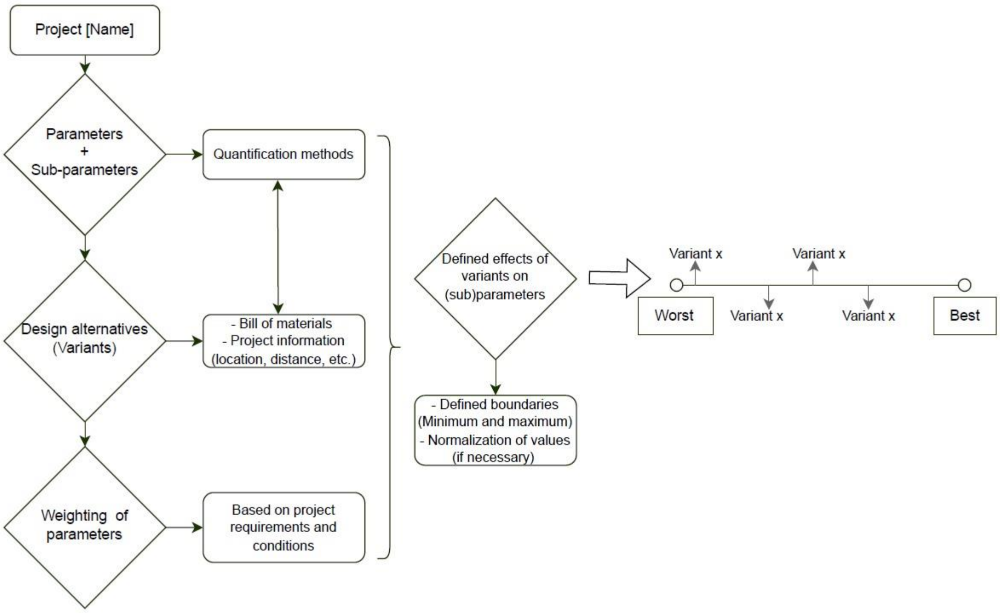


*Figure 0.1 Conceptual model of drawn up framework*

The tool was developed in Microsoft Excel, by elaborating each step taken in spreadsheets in order to arrive at the final result. However, in order to make a comparison of the design alternatives defined during this research and built the tool, it was necessary to define a case study. Through the case study, values could be entered for the design alternatives and a comparison could be made. After analysing the results for the design alternatives through the case study, conclusions could be drawn for the transition process towards building circular viaducts and bridges. This research specifically focused on the circular building of viaducts and bridges, zooming in on an element level, only looking at inverted T-prefab concrete beams.

This research clearly illustrates the challenges for the traditional building of viaducts and bridges, but it also illustrates the current challenges for the transition towards circular viaducts and bridges. However, it also illustrates the future research possibilities and opportunities for making the transition to circular building.

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# Part I

## 1. Introduction

With changing climate conditions and awareness of sustainable working, there has been a change in market demand to prevent raw materials from being exhausted and the living environment being affected. The current traditional industry is building with primary raw materials and is being challenged towards sustainable construction, but how the transition from traditional construction to sustainable construction will take place, is rather unclear. By sustainable construction is meant using renewable and recyclable materials when building new structures, as well as reducing energy consumption and waste. The primary goal of sustainable construction is to reduce the building construction industry's impact on the environment (Gatley, 2021).

As the research of The Consumer Goods Transition Team (2018) states ''A number of resources are being exhausted, the environment is being polluted, and excessive use of fossil fuels impacts the climate. This requires a transition towards a way of working and living without unnecessarily exhausting natural resources, polluting the living environment, and affecting ecosystems. The final goal: a circular economy in 2050.''. However, the question still arises whether a fully circular economy is feasible in the specified time? Thus, this brings a growing realization for the construction industry to work in a different way and to make the first transition steps towards circular building. In research from Platform CB'23 (2020b), Circular building is defined as ''developing, using and reusing of buildings, areas and infrastructure without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems. Carrying out construction such that it is economically justifiable and contributes to the welfare of people and animals. Here and there, now and later.''

Reducing the use of primary raw materials and reusing as much as possible secondary materials are currently much discussed in the literature and practice. In research Platform CB'23 (2020b), multiple terms are defined related to circular building. This document is used as a guideline for unambiguous terms and definitions, which is also called the ''lexicon circular building''. There primary materials are defined as (building) materials produced from primary raw materials, whereby primary raw materials are raw materials produced by the earth and used by humans to produce materials and products. In contrast to that, secondary materials are materials originating from previous use or from residual flows from another product system and which replaces primary materials or other secondary materials (Platform CB'23, 2020b).

However, a good overview of different factors and aspects involved in the transition from traditional building towards circular building is still missing and more research is needed into the innovation of reusing elements in pilot projects to large-scale application (Donker, 2021). Furthermore, research of Klarenbeek (2021) mentioned that the measurability of circularity in early design phases is crucial. To enable some distinction in circularity in an early stage of the process and the trade-off of alternatives, the measurability of circularity in the exploration phase (initial design stage of a project) should be made possible which will give a more specific and clearer overview in the trade-off of design alternatives. Therefore, a way to include aspects such as the multiple lifecycles and the cost of adaption, renovation or replacement in a later stage, supply and demand of secondary materials and the reuse potential in a later stage, in a tool would be required to make a well-founded comparison between variants.

Currently, many existing bridges and viaducts built in the 60' in the Netherlands need to be renovated or replaced. This offers a great opportunity to apply circular design principles such as prevention, value retention and value creation in the renovation and replacement task of Rijkswaterstaat. With value retention is meant to extend service life, reuse parts and materials and design future-proof. Therefore, in 2020 Rijkswaterstaat announced the Strategic Business Innovation Research (SBIR) circular viaducts and bridges to give a boost in development of innovations for the replacement task of Bridges and Viaducts. Strategic Business Innovation Research, SBIR for short, is a purchasing method that stimulates innovations in the market (Ministerie van Infrastructuur en Waterstaat, 2022).

Many of the viaducts that are being demolished have not yet reached the end of their technical lifespan but are being replaced due to functional reasons. Therefore, it regularly happens that parts of viaducts that are being replaced are still usable. The beams or girders that are released from the replacement of viaducts therefore have the potential to be reused. By reusing these beams or girders, it will not only limit the usage of primary raw materials by not producing new elements, but it will also help to limit the significant environmental impact which comes from the exhaustion of primary raw materials and the production process. By reusing as many ass possible element and reducing the usage of primary raw materials, it will enable us to contribute to the climate goals set in a short term.

**This research is conducted to bring a better understanding of the current situation and challenges related to parameters involved in making the transition towards circular building and insights needed in the total process. Therefore, several parameters involved in the transition from traditional building to circular building are analysed. Further, the effect of different design alternatives or design trade-off's, also known as variants, will be analysed and the effect of each variant on the given parameters. The analysis will be briefly described and quantified in a framework and a tool will be developed whereby a trade-off or design alternative can be made based on the given parameters. The five main parameters involved within this research in the transition of traditional building to circular building are the environmental impact, financial impact, the supply and demand of existing elements and newly produced elements, the detachability and the reuse potential. The effect of four design variants will be analysed on the parameters, these design variants vary from a fully traditional design up until a fully circular build design.**

Thus, the aim of this research is to provide insights in the total process by analysing critical parameters in the transition from traditional building to circular building and the effect of different design alternatives within the transition on the parameters. The objective is to develop a user-friendly tool for the construction industry that contributes to the decision-making of making first choices towards circular building in the initial phase of project and helps in thinking about which factors to consider when reusing elements and reducing the usage of primary materials.

### Reading guide

This research consists of three parts. In part I, the research design (Chapter 2) has been drawn up which is followed during this research and the necessary literature research (Chapter 3) is conducted in order to solve this problem. Afterwards, the theoretical framework (Chapter 4) has been drawn up which elaborates on the findings of the literature research, the setup of the to be developed framework and tool, and the next steps for data collection. In part II, Chapter 5 is elaborated, in which the research results of the literature findings and the theoretical framework are described. In the last part of the research, part III, the tool is developed in Chapter 6 corresponding to the framework drawn up in part II and the validation of the tool takes place. In the next chapter, Chapter 7 the results found during this research are discussed. Lastly, in Chapter 8 the overall conclusion of the research is described.

# 2. Research Design

In this chapter the research set-up will be explained. First the scope of the research is explained in Chapter 2.1. Next, the research questions are discussed in Chapter 2.2. After the scope and the research questions are discussed, the research methodology is drawn up in Chapter 2.3. In Chapter 2.4. and 2.5. the data sampling and data analysis will be discussed. Lastly, in Chapter 2.6. the criteria to which this research has to comply to is described.

## 2.1. Scope of the research

In this chapter the research problem will be described and the scope of the research will be discussed. The goal is to elaborate on the research problem and to clarify the boundaries within which the research will be executed.

### Problem description

The renovation and replaced task for viaducts and bridges built in the 60' announced by Rijkswaterstaat in 2020 offered an opportunity to apply the circular design principles such as prevention, value retention and value creation. With value retention is meant to extend service life, reuse parts and material and design future-proof. Through the Strategic Business Innovation Research (SBIR) project - circular viaducts and bridges, multiple stakeholders in the construction market are looking at different possibilities of building circular viaduct and bridges. The stakeholders in stakeholders involved differ from the supplier, national government, consultancy firms, contractors and even universities and colleges. The focus of all stakeholders in the transition towards circular building lies mainly reducing the usage of primary raw materials and reusing as much as possible.

This research focuses on infrastructural projects and then mainly on the civil structures' viaducts and bridges, for which a renovation a replacement task is given.  In the transition process from traditional building to circular building for building circular viaduct and bridges, this research zooms in on the element ''prefab concrete beams'' that appear in these civil structures. In some existing viaducts and bridges, the prefab concrete beams were made of high quality due to the fact that they had to withstand the highest traffic loads and had a much longer lifespan than the design lifespan of circa eighty years. Calculations show that prefab concrete beams can last for another hundred years. After prevention of material use, this is the highest form of circularity, because the prefab concrete beams can be used in the function for which they were made (Reuse) (Heidinga, 2021). Besides reusing, the goal is to make new bridges and viaducts (civil structures) in the future from ''Lego blocks''. With this is meant that each element of a bridge or viaduct will be in Lego blocks form so that the elements can be easily demountable and be used in the same function elsewhere in the 2$^{nd}$ lifecycle. This will reduce the use of raw materials in the future, and create a circular and cost-efficient civil structure (Heidinga, 2021). The implementation and concept of circular viaducts and bridges and the harvesting of prefab concrete beams in existing civil structures are illustrated in Figure 2.1. by Rijkswaterstaat (2022). Figure 2.2. further illustrates released prefab concrete beams beams after the 1$^{st}$ lifecycle and storage in order to be reused.

Based on previous researches, a good overview of different factors and aspects involved in the transition from traditional building towards circular building is still missing and the measurability of circularity in initial design phases is crucial (Donker, 2021; Klarenbeek, 2021). Therefore, to enable some distinction in circularity in an early stage of the process and the trade-off of alternatives, the measurability of circularity in the exploration phase (initial design stage of a project) should be made possible which will give a more specific and clearer overview in the trade-off of design alternatives Klarenbeek (2021). Thus, the aim of this research is to drawn up a framework of the different factors and aspects involved in the transition from traditional building to circular building and contribute to the decision-making in an initial design stage of a project which enables the trade-off of design alternatives.

### Included in the scope of this research

As explained above, this research will focus on transition process of traditional building towards circular building for the construction industry. The main focus lies on the initial design phase in the whole process, where design several design alternatives can be compared with one another based on key parameters involved in the transition process. The key parameters will be described based on the experiences of a contractor in the construction industry during the initial design phase in a tender process.  Therefore, this research only focuses on the contractor side in the transition process. The goal of the developed framework is to make design trade-offs in the initial design phase. Lastly, the research focusses on the civil structures viaducts and bridges mainly focusing on the reusability of prefab concrete beams.

### Not included in the scope of the research

As the research focusses on the initial design phase of project, additional factors other phases in a project will not be included or looked at. The whole civil structure of a viaduct or bridge will not be taken into account as the research focusses on an element level, prefab concrete beams. As this research is conducted at the construction company Dura Vermeer B.V., the focus only lies on a contractor as a stakeholder. Other stakeholders will not be taken into account.

*Figure 2.1 The implementation of circular viaducts and bridges (Rijkswaterstaat, 2021)*

*Figure 2.2 Released and reusable prefab concrete beams after 1st life cycle (Heidinga, 2021)*

## 2.2. Problem statement and development statement

### Problem statement

Based on the introduction in Chapter 1 and the problem description and defined scope in Chapter 2.1., it can be concluded what is still unknown about the topic. Therefore, the following problem statement is developed:

*''The current calculation tools do not provide an insight into the total transition process from traditional building to circular building. For the construction sector, who currently has to minimize the usage of primary raw materials and reuse as much as possible, it is not clear which factors play a role in the transition process towards circular construction. This overview of all factors involved in the transition process is necessary in the initial design phase of a project in order to be able to make a choice in the between design alternatives that meet the requirements drawn up by the project.''*

**The objective is to develop a user-friendly tool for the construction industry that contributes to the decision-making of making first choices towards circular building in the initial phase of project and helps in considering the factors that play a role when reusing elements and reducing the usage of primary raw materials.**

### Development statement and sub-questions

Based on the above problem statement and research objective, the following development statement has been formulated:

***To develop a framework and user-friendly tool for the construction industry that enables a comparison of design alternatives based on key parameters involved in the transition of traditional building to circular building and provides insights for decision-making of design alternatives in an early-design stage.***

In order to arrive at the framework for the tool with the necessary inputs and outputs as described in the development statement, sub-questions are formulated:

- ***Q1:*** *How to define and elaborate on each parameter involved in the given design for the decision-making in the initial phase of a construction project?*
- ***Q2:*** *Which design alternatives need to be considered for the first steps towards the circular building of viaducts and bridges?*
- ***Q3:*** *How to define the effect of the design alternatives on the parameters involved in the transition process from traditional building towards circular building?*
- ***Q4:*** *How to make a user-friendly tool, based on the developed framework, in order to have an added value for the construction industry in the decision-making process of the initial design stage and validate it?*

### Substantiation of the chosen sub-research questions

In order to solve the problem of this research, a framework and user-friendly tool needs to be developed that enables the comparison of design alternatives based on key parameters involved in the transition process. The development of the framework has been done within the scope boundaries discussed in Chapter 2.1. In order to develop the framework, first information need to be gained on which parameters are involved in the transition from traditional building to circular building for the construction industry and how to define each of the parameters based on their own characteristics in the transition process towards circular building (Q1). The first sub-question corresponds to the problem described in the introduction and in Chapter 2.1. The aim is to elaborately define each key parameter and qualitatively drawn up the framework for the to be developed tool. Secondly, information needs to be gained on the types of design alternatives that are being considered in the construction industry when making the first steps towards building circular viaducts bridges using prefab concrete beams (Q2). The aim of the second sub-question is to have a clear overview of the design alternatives that are considered during this research and differences between each design alternative. This also contributes to the qualitatively drawn up framework for the to be developed tool. Thirdly, the effect of each design alternative on the defined key parameters needs to be researched (Q3). For the third sub-question, research need to be done on how to define the effects. The aim here is to quantitatively build up on the qualitatively drawn up framework of Q1 and Q2. The elaboration on the effect of the design alternatives on the key parameters contributes to the to be developed tool which will help in the decision-making process for the trade-off of design alternatives in the initial design phase. Lastly, **the developed framework, from Q1, Q2 and Q3, needs to be translated into a user-friendly tool in order to have an added value for the construction industry in the decision-making process in the initial design stage and the validation needs to take place (Q4).**

## 2.3. Research methodology

In order to find a solution for the development statement and the answers for the sub research questions stated in Chapter 2.2, the research has been executed in three parts following the scheme in Figure 2.3. The main methods used during this research are: literature review, observations and personal communication, interviews, data analysis, tool development and validation of the tool through a case study. Part I of this research is the literature review and theoretical framework of this research. During this part, the interviews will also be conducted. The results of the literature review, theoretical framework and interviews lead to the answers on the sub-questions Q1, Q2 and Q3. Part II consists of an in depth qualitative and quantitative analysis of the answers found in part I and lead to the development of the framework which forms a basis for part III. In part III, the developed framework is translated into a user-friendly tool. The overall research methods during this research can be indicated as mixed-method research considering that the complete research included both qualitative and quantitative and combined qualitative-quantitative method. The qualitative research provides insights and understand of the problem setting of this research and it meant to gain an in-depth understanding of the topics concerned through this research (Ahmad et al., 2019). The aim of the qualitative method is partially answering the sub-questions Q1 and Q2. The quantitative research is a form of research that relies on the methods of natural sciences, which produces numerical data (Ahmad et al., 2019). By combining the quantitative research method with the qualitative method (mixed-method), the sub-question Q3 can be answered.

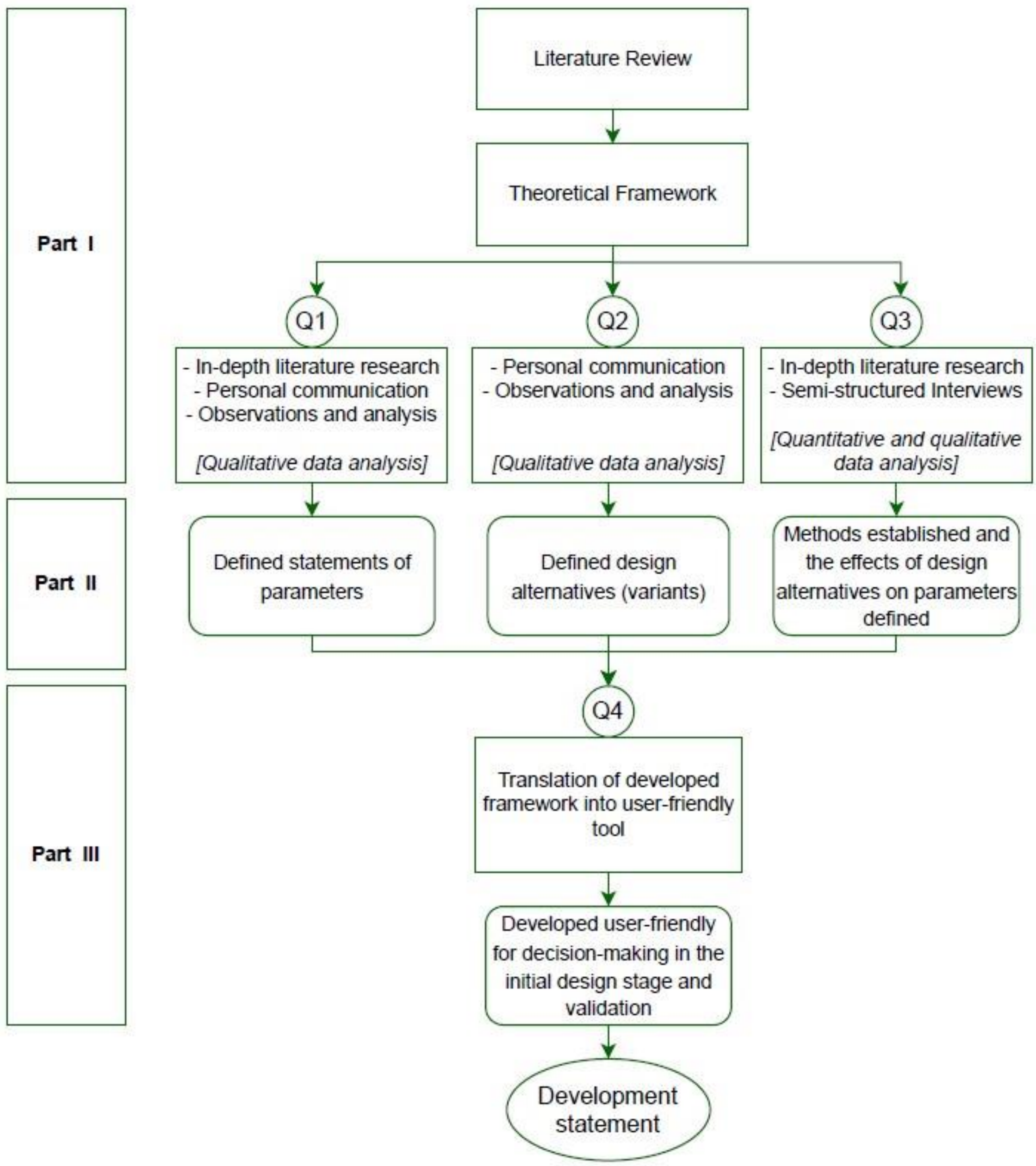


*Figure 2.3 Schematic overview of the research strategy*

## Literature review

The literature review is conducted in order to partly answer the sub-questions Q1, Q2 and Q3. It contributes to designing the framework. During the literature review, specific topics related to this research will be reviewed. The topics on which literature review will be executed are related to the key parameters involved in the transition from traditional building to circular building for the construction sector. In the constructor sector, a project is divided in several phases. The undergoes several phases. The phases differ from the design phase up until the project delivery. This research focuses on the initial design phase of a project, therefore topics related to key parameters involved in the initial design phase and calculations will be researched.

## Personal communication and observations

This research is conducted at the construction company Dura Vermeer B.V. in the department: Infra Landelijke Projecten (DVILP). By conducting this research at the construction company, a clear view is obtained of the contractor's method of working and the day-to-day experiences and challenges in the practical field. During this period data has been collected through personal communications, this includes one-on-one conversations with experts within the company, emails, phone calls and data with information from executed project. These communications will place throughout the research with experts within the company and relevant to the topics of this research. The personal communications and observations relate to data which are not recoverable. However, this data has been used in partly finding the answers to the sub-research questions and forming the framework for the to-be developed tool.

#### Interviews

Interviews will be conducted during this research in order to test the literature using practical experience and to collect additional information which cannot be obtained from the literature in the given research period. The interviews will be held in order to answer sub-question Q3, the effect of each design alternative on the key parameters. For the interviews, a selection is made of people with a specific background relevant to this research and conditions are set. The goal of the interviews is to add the additional missing information to the framework based on the experience of experts in the construction sector. During this research, the chosen experts are limited to the construction company Dura Vermeer B.V. The type of interview that will be conducted are semi-structured expert interviews. During this type of interview, the topics to be discussed are fixed, but the order may be changed. Additional questions may also be asked during the interview (Baarda et al., 2017). In Appendix A the plan of action for the interviews is drawn up.

#### Data analysis

The data gained through the qualitative research method (literature review, personal communication and observations, interviews) and quantitative research method (interviews: to gain quantitative data) will be analysed. The data will be analysed and validated based on pre-set standards and requirements.

#### Tool development

In order to find a solution for the problem stated in Chapter 2.2, a framework will be drawn up which, in the last part of the research, will be translated into a tool. This tool will be developed using Microsoft Excel.

#### Validation: through a case study

In order to reflect in the discussion in Chapter 7, the tool will be developed using a case study developed during the research, which is resulted from existing cases and current practices. The information and data for the case study will be gained in collaboration with the construction company (Dura Vermeer Infra Landelijke Projecten (DVILP)) with whom this research is being conducted. In the end, the tool will be validated on pre-set conditions: user friendly tool, added value to the construction sector and contribute in the decision-making of design alternatives. The pre-set conditions will be tested through experts in the company.

### 2.4. Research criteria

This research should comply to several research criteria stated beforehand. This means the that the research will be conducted in a certain way so that the research criteria are met in the end. In Chapter 7 it will then be discussed if the research meets the research criteria stated beforehand. Below the criterion are explained.

### Effectiveness and Efficiency

Firstly, the effectiveness and efficiency of the research are important. With this is meant that research result should meet the research objective. Further, it is important to meet the research objective as efficiently as possible. For this research it means that the research conducted should solve the problem as stated in the Problem statement. By finding an answer to the research sub-questions it is expected by the researcher that the problem will be solved and solution will be found for the development statement. In the Discussion, it will be discussed if this is indeed the case and if the research objective is met.

### Reliability

Second the reliability of the research is important. For the quantitative part of the research this means it is important that the used data set and measuring methods are reliable (Hernon & Schwartz, 2009). For the qualitative part of the research the reliability refers to the consistency of the data and information gained (Hernon & Schwartz, 2009) and how this is described. To ensure the reliability of the information gained, it will continuously throughout the research stated how and from whom this information gained. Furthermore, the background information of the experts (from Dura Vermeer B.V.) will be given who will contribute to this research. This will increase variation in the dataset, which is important for this research and thus reliability of the data set.

### Reproducibility

Next the research should be reproducible. This means another or the same researcher should be able to execute the research in a similar way and obtain more or less the same research results (Klumpers, 2018). To make sure the research is reproducible, all decisions and steps made during the research have should be clearly elaborated in this final report. All assumptions made during the research due to limited data should also be elaborated since this is a subject which is continuously developed now. Further, it is important that the reliability of the research is of a high level to make sure the research is reproducible (Hernon & Schwartz, 2009). Also using all new researches conducted after this, the reproduced research will only be sharpened even more.

# 3. Literature Review

In this chapter the literature review is described. The literature review has been executed because it is important to gain an understanding of what is already known about the research topic based on previous research. The literature review investigates what is already known, also known as the ''state-of-the-art'', and what still needs to be researched about the topic and the key concepts relevant to this research.

## 3.1. Framework for transition towards circular building

The Netherlands is currently in a critical point of transitioning from a linear economy to a circular economy. In Figure 3.1 an overview is giving of the difference between a linear economy, reuse economy and a circular economy. The ambition of the Dutch national scheme 'Nederland Circular in 2050' clearly indicates the direction of a 50% reduction in primary raw material consumption by 2030, and a fully circular economy by 2050. The term 'circular' is currently both in society as well as the construction sector as elsewhere a main theme. Therefore, the current (traditional) construction industry is forced to transition towards circular construction. The circular construction is a way to reduce the global consumption of raw materials and reduce waste production (ABOUT PLATFORM CB'23, n.d.). However, this shift towards circular construction has number of consequences for the construction sector including more and better reuse of construction -materials, -products and -elements and a different approach to the production, tendering for, design and implementation of construction projects (ABOUT PLATFORM CB'23, n.d.).

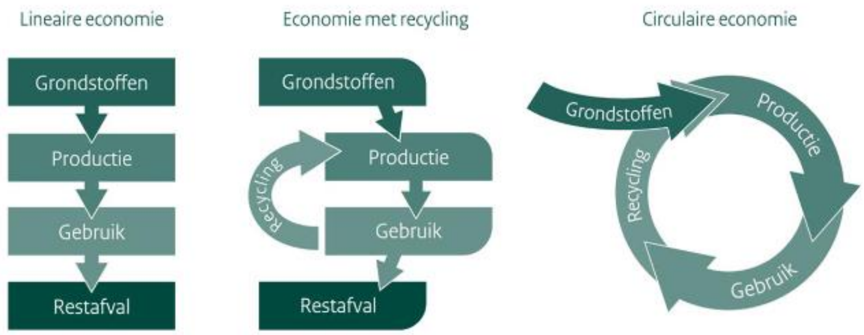


*Figure 3.1 From linear economy towards circular economy; From Wijnstra et al., 2021*

The CB'23 platform (Circular Building 2023) is a platform which wants to connect building-wide parties with circular ambitions, both in civil engineering and in residential and non-residential construction (Platform CB'23, 2019). This Platform has created a framework which provides an overview of the definitive terminologies and language regarding circular building in the transition from traditional building to circular construction. These terminologies are relevant for either the client, contractor, engineer, architect, wrecker or supplier (Platform CB'23, 2019). In research from Platform CB'23 (2019), an overview is given of what is expected by circular building and how the transition towards circular building is expected to be and how it could be scaled up. Figure 3.2 gives a general overview of what is expected in the process towards circular building. However, the research from Platform CB'23 (2019) recommends to have a further interpretation and elaboration on the definitions by experiences from the field/practice in order to get a clearer picture of what circular design principles, circular products, elements and materials are. Thus, the various stakeholders use the guidelines of Platform CB'23 in practice and supplement them in their own way after implementation.

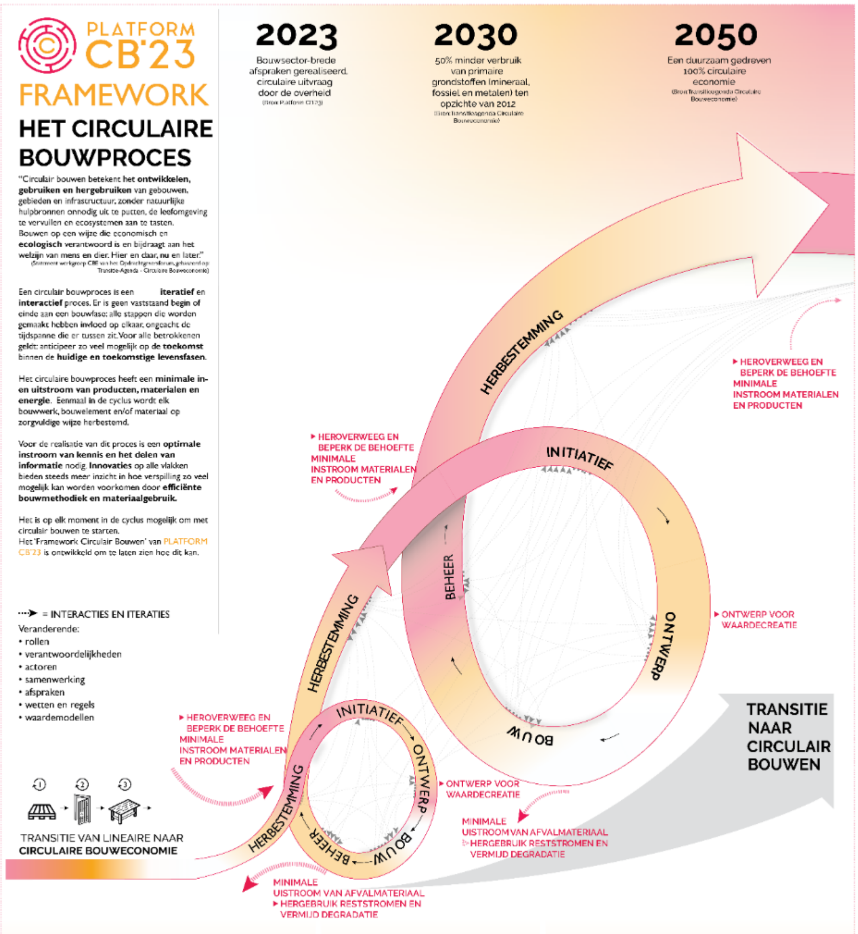


*Figure 3.2 The circular building process, From: Platform CB'23 (2019)*

As further depletion of natural resources is expected, it will lead to an increased pressure on the production flow for building materials (Van Maastrigt, 2019). Thus, the need to work towards a circular economy keeps increasing. A circular economy is an economic system of closed loops in which raw materials, components and products lose their value as little as possible, renewable energy sources are used and systems thinking is at the core. It is focused on the optimal use and re-use of resources. Therefore, it's becoming increasingly important to work with circular building material and their circular end-products. A circular building material is a building material that is used in a circular manner (Van Dijk, 2018). This means that the material is can be completely reused and be recycled at its end of life when the properties do not fulfil the quality requirements. The material is circular when after recycling, a product with same properties and functions can be made out of (Van Dijk, 2018).

A good functioning circular economy consist of the following elements:

- Being able to re-use every time:
    a. Artefacts/products;
    b. building element/parts;
    c. materials;
    d. substances;
- The maximum retention of value;
- Circular design so that the above elements become feasible;
- Material choices so that the above elements become feasible (Van Dijk, 2018).

### 3.2.10-R principles

The traditional building system is sequential and has a beginning and an end. Starting with the initiative and ending with the demolition of the object. In this linear process, no thought is given beforehand to reuse material or entire parts of the object elsewhere. However, people are increasingly aware that raw materials needed for the production of these materials are not inexhaustible. In addition, a lot of energy (and thus released $CO_2$) is often required to harvest these raw materials and get them to location. By applying the 10 R's method in the initial phase (tender phase) and preliminary design of a contractor, the linear construction process can increasingly be abandoned and a transition can be made to a circular construction process (Wijnstra et al., 2021). The 10R-model is a further elaboration of Lansink's Ladder: hierarchy for reuse of released (waste) material. This ladder covers both 'soft' circularity aspects (example: 'refuse' is a choice not to do something), and more 'hard' circularity aspects (example: 're-use' refers to actual reuse) (Platform CB’23, 2019). In Figure 3.3, the 10R-model for circularity has been drawn up and each design strategy can be categorized. The rule of thumb in process towards a circular economy is the more circularity is being implemented, the less raw materials will be used and the environmental pressure will be reduced.

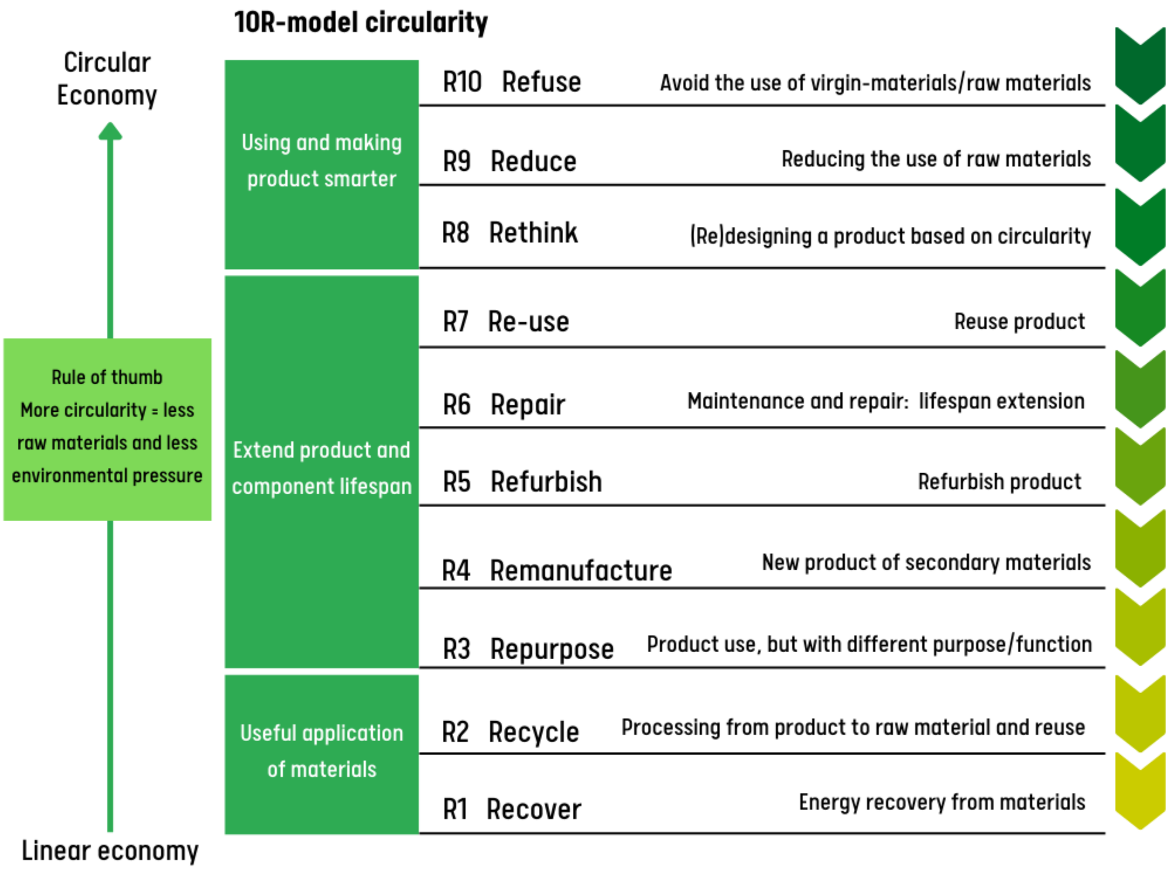


*Figure 3.3 10R-model circularity, own illustration adapted from: Platform CB'23 (2019)*

#### Elaboration on 10R-model design strategy’s

In exploration research of Wijnstra et. al (2021), the 10R design strategies were translated using the experience that a contractor has in practice in the transition process (Expert 8 Project manager, personal communication, July 7, 2022) from a linear economy towards a circular economy. An elaboration of each design strategy of the 10R-model for circularity is described below:

- *$R_{10}$ Refuse:* The refuse strategy can be seen as a strategy where the focus is placed on designs for prevention of using virgin-materials or primary raw materials.

- *$R_9$ Reduce:* Within the reduce design strategy, the focus is on reducing the use of materials.

- *$R_8$ Rethink:* The rethink design strategy relates to intensifying product use by making it multifunctional.

- *$R_7$ Reuse:* The reuse design strategy relates to maximizing the reuse of a product or material.

- *$R_6$ Repair:* The repair design strategy is focused on repairing the objects that are already there, so that new (primary) raw materials do not have to be extracted to realize new objects.

- *$R_5$ Refurbish:* The refurbish, or refurbishing, design strategy means that old materials are refurbished in construction in order to for it to meet the requirements set, or to improve the appearance.

- *$R_4$ Remanufacture:* The remanufacture strategy focuses on reusing discarded products or parts and remanufacturing it after checking which parts can still be reused.

- *$R_3$ Repurpose:* The repurpose design strategy is to see which materials and objects are released within the project and in which ways can these objects can be reused, but with a different function (downcycling).

- *$R_2$ Recycling:* In this design strategy, recycling products is the penultimate way to process products sustainably. From this R on, there is no longer talk of extending the lifespan of products or parts, but only about the useful application of the old materials.

- *$R_1$ Recover:* This last step, the recover design strategy, offers the lowest value in circularity and is based on recovering energy by burning the material.

In the current transition process from traditional building towards circular building, each of the design principles are being applied indirectly and directly. In Figure 3.3, the 10R design strategies can be categorized in three main parts. For a contractor, in this case Dura Vermeer B.V., whom is involved in the the execution of residential construction, utility construction, infrastructure and technology whereby the core activities include the design, development and realization of construction and infrastructure projects, including maintenance, renovation and transformation (|Wij zijn, 2022), the focus lies on the two main parts namely the extension of product and element lifespan and using products and elements smarter.

As mentioned before, the focus for this research in the initial design phase of a project. For this, the main R design strategies that will be focused on are: R9 Reduce design strategy and R7 Re-use design strategy. After those two main strategies, the R8 Rethink design strategy and R6 Repair strategy are also taken into account.

## 3.3. Product Lifecycle Models

A civil structure is made up of various structural elements and structural material in order to form a whole. Each of these structural elements, also seen as products, have their own product lifecycle. A structural element is a load-bearing (concrete) element in a civil structure. A product lifecycle the process of raw material extraction, processing or manufacturing into the product, the transportation, retail and use of the product and waste that remains at the end of the product lifecycle. An illustration of the product lifecycle and the visualization of a product lifecycle related to the cradle to grave and cradle to cradle concepts can be seen in Figure 3.4. In order to contribute to circular economy, a product be made fully circular and fulfil the cradle-to-cradle concept. In a cradle-to-cradle approach, the waste stage for the product lifecycle is exchanged with a reusable potential in a second lifecycle, without essentially ‘’closing the loop’’ (Liebsch, 2021).  Cradle to cradle is positioned by the authors William McDonough and Michael Braungart as a new approach towards sustainable design (C.A. Bakker et al., 2010).

By using the cradle-to-cradle approach and creating a sustainable and circular design, attention must be paid whether the reused products are not being downcycled after the products 1st lifecycle. By downcycling is meant the reprocessing of materials or building products recovered at the end of service life and building or producing new materials or design of lesser quality and reduced functionality (Van Maastrigt, 2019). A product is not being downcycled when the function in the 2nd lifecycle stays the same as which it was made for.

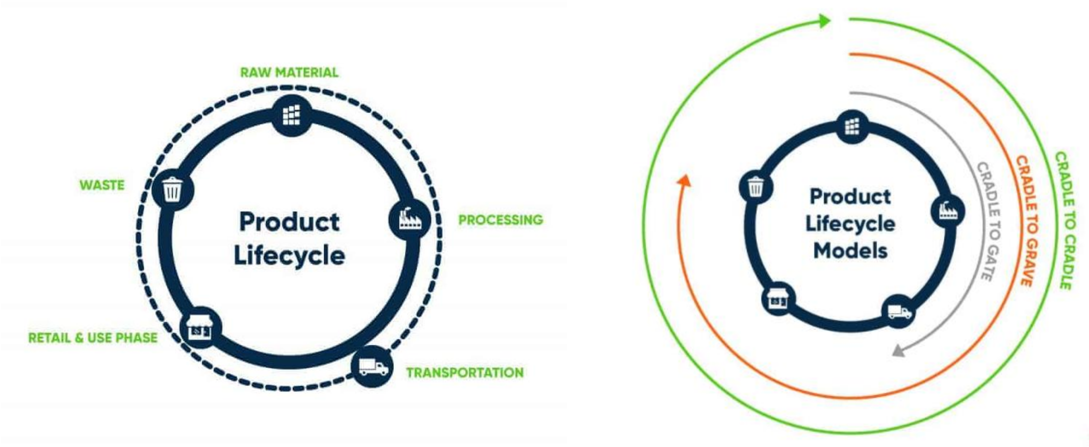


*Figure 3.4 Product lifecycle and product lifecycle models, From Liebsch (2021)*

This research will be conducted for the initial design stage in a project for civil structures, bridges and viaducts, on an element level (prefab concrete beams). In order transition towards circular building, the reusable prefab concrete beams need meet the requirement of having the same function in the 2nd lifecycle.

## 3.4. Common barriers in the transition towards circular building

One of the common barriers in the transition towards circular building is uncertainty. Uncertainty about the materials, residual life, processes, costs and environmental impact. Insight into the process as a whole, including the environmental impact, the financial impact, supply and demand of materials and the dismantling of the constructive parts, is necessary to allow the reuse of structural elements in the Dutch infrastructure sector and to gain insight into the total process (Donker, 2021). Another common barrier is the limitation that the current calculation tools show a result that gives insights on one main aspect within the whole process for the transition towards circular building. For example, existing environmental impact calculation tools must be adapted so that all reuse advantages and disadvantages are included in the calculation and a fair comparison between processes and products can be made. Currently, the reuse of building elements is not properly included in the ECI (environmental cost indicator) calculation and DuboCalc (Donker, 2021). DuboCalc is a software tool for quickly and easily calculating the environmental costs of design variants of civil engineering works. Another example is the circularity performance calculation method. In this method the percentage of circularity in a project is calculated which gives an indication about the quantity of secondary material used in a design, the quantity of material that is released during the execution and that can be reused (replacement statement) and the quantity of elements designed for the project and easy to reuse in the future (demountable). However, both for the calculation methods do not include the other factors, such as residual life, costs, supply and demand, which the uncertainty barrier in the research of Donker (2018) describes. Furthermore, it is important to take into account the barriers, the boundary conditions and the key processes involved in the reuse of infrastructural elements in the transition towards circular building, otherwise innovating will be difficult due to the fact that the total workload is not foreseen (Donker, 2021).

In research from Klarenbeek (2021), another shortcoming is the measurability of circularity in the exploration phase (the initial phase of a project). This should be enabled, in order to provide a more specific and clearer overview when considering a trade-off of circularity design alternatives. By including the measurability in the exploration phase, multiple lifecycles can be included and the cost of adaption, renovation or replacement in a later stage in the calculation tool would therefore be required to make a decent comparison between variants.

## 3.5. Existing methods for sustainable and circular construction

Sustainable Construction is a topic that has become increasingly important with the increasing attention to the environment. The climate problem and the depletion of raw materials have led initiatives to be taken on various levels (government, but also market parties) in the field of sustainable construction (Frank Tool, 2010). This includes encouraging the use of sustainable techniques and materials or setting requirements regarding $CO_2$ emissions, energy saving and renewable energy. Related developments and tools used in construction the construction sector in order to build more sustainable are the implementation of Life Cycle Analysis (LCA). Besides that, another method developed by the platform CB'23 is the Measurability of Circularity. These existing methods help several sectors as well as the construction sector to calculating the effect of certain building materials choices on the environment. Another known method is the Environment Life Cycle Costing (Environmental LCC). This method helps in assessing all cost associated with the life cycle of a product (Hunkeler et al., 2008).

In order to build a framework for the to be developed tool in this research, literature research was done of existing quantification methods. The research into existing quantification methods is needed in order to quantify the effect of design alternatives on the key parameters involved in the transition from traditional building towards circular building. For this research, the following methods were analysed further: Life cycle analysis (LCA), measurability of circularity and the life cycle costing (LCC) method. These methods will be elaborated further below.

### 3.5.1. Life Cycle Analysis

The life cycle analysis method, in short LCA, measures the environmental impacts of a product of service. This is a standardized method of describing and calculating the impact of a product on the environment (ISO, 2005). Life cycle analysis is a framework standardized by ISO 14044 and it specifies requirements and provides guidelines for the life cycle assessment (LCA). The life cycle assessment is divided in 4 main stages: goal & scope, life cycle inventory, impact assessment, interpretation. Each product, has a product life cycle and is also divided in several stages (also shown before in Figure 3.4). The product life cycle can be generalized in four categories, namely A, B, C and D: A. Production and construction phase, B. Usage phase, C. End of life phase, D. Re-use potential phase.

With the LCA, the entire life cycle of a raw material, material or product is mapped out all occurring environmental effects based on the different phases a material or product undergoes. Each of the phases and an overview of the LCA are shown in Figure 3.5. The LCA method is originally based on a 'Cradle to Grave' approach (as described in Chapter 3.3.). This also visualized in Figure 3.6.

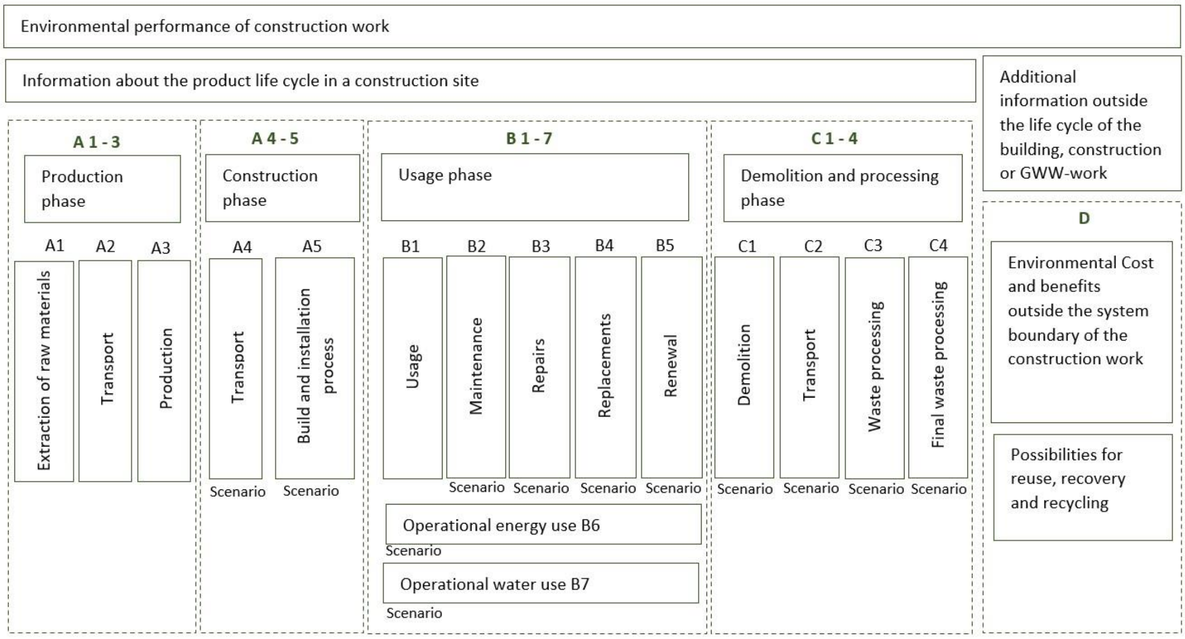


*Figure 3.5 Life Cycle Assessment, adapted from Stichting Bouwkwaliteit (2019)*

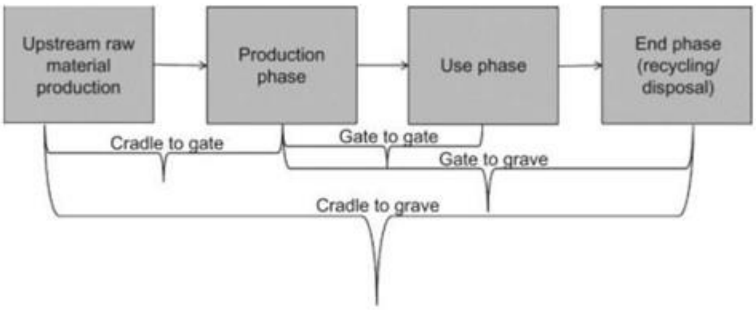


*Figure 3.6 Product life cycle models related to LCA, from Shivakumar (2021)*

## Environmental Impact

In addition to the LCA, there are developed methods to determine the environmental costs of a product throughout its life cycle, based on the environmental impacts that occur. Environmental costs are, in general terms, the costs that the society must pay to prevent and repair damage to the environment. In the Netherlands the Determination Method (*Dutch: De Bepalingsmethode*) Environmental Performance of Buildings and Civil Engineering Works (hereinafter: Determination Method) is used for calculating the environmental impact (Stichting Bouwkwaliteit, 2019). This method is developed so that the material related environmental performance of buildings and civil engineering works throughout their life cycle can be calculated unambiguously and verifiably (Stichting Bouwkwaliteit, 2019). The Determination Method is coherent with the National Environmental Database (NMD) and the calculation rules. For the calculation of the environmental impact of buildings and civil engineering works in the Dutch context, the National Environmental Database was created. The NMD includes information about products and activities prepared in accordance with the Determination Method in the form of product cards referring to environmental profiles. These product cards and environmental profiles are implemented in the various calculation tools used to measure the environmental performance of buildings and civil engineering works calculate. Together with the calculation rules, this ensures verifiable and reproducible calculation results (Stichting Bouwkwaliteit, 2019). Lastly, the Determination Method is based on the European LCA method based on NEN-EN 15804. The EN 15804 has been developed for environmental product declarations (Environmental Product Declarations (EPDs)) at a product level (Stichting Bouwkwaliteit, 2019).

#### Environmental Cost Indicator

After the calculations for the environmental impact using the Determination Method are executed, the environmental costs are obtained described in as an Environmental Cost Indicator (ECI). In other words, the environmental impact is shown in the ECI. The ECI is a value which, using the Determination Method, is defined in Euro’s (€). The lower the ECI, the lower the environmental impact and vice-versa. The ECI can drastically be impacted by several factors such as: more raw material usage can lead to higher ECI, more sustainable usage can lead to a lower ECI and the shorter transport distances can also lead to lower ECI-scores (Van der Klauw et al., 2018).

#### Core indicators in the environmental impact calculation

The indicators for implemented in the environmental impact calculation, which are defined for protecting the environment, are written as the product system impact categories in the Determination Method by the Stichting Bouwkwaliteit. These are divined in 19 core indicators. These categories are also based on the European life cycle analysis method (LCA method) for the construction sector, the NEN-EN 15804 (Platform CB’23, 2020a

### 3.5.2. Measurability of circularity

In the transition process from a linear economy towards circular economy, it is important to be able to measure the amount of circularity of a product or project. This is needed, to get an indication on how well a project or products scores on the three main goals of circular construction namely: To protect stocks of materials, environmental protection and the value retention (Platform CB’23, 2020a). The measurability of circularity can also be defined as the Circularity Performance. In research from Platform CB’23 (2020a) can be concluded that insufficient information is provided by existing measurement methods about the extent to which the circular construction goals are being met. Also, from research of Shivakumar (2021) can be concluded that there is no standardized assessment tool to measure circularity of products or materials. Therefore, for this research the circularity measurement method (also circularity performance) of Platform CB’23 (2020a) will be followed and elaborated in this chapter. However, during the literature review, other methods for the measurement of circularity will also be briefly reviewed in this chapter.

### Circularity Performance – Measurement method by Platform CB'23 (2020a)

CB'23 Platform (2020a) has developed a core measurement method for measuring circularity in the built environment. The method divides the indicators into three aspects that will contribute to achieving the three goals of circular construction namely:

1. Protect material stock
2. Protect the environment
3. Protect the existing value.

Each main goal, described as an indicator for the measurement method, consists of several sub-indicators. These will be elaborately described below. Currently, the second version of the guide (Platform CB'23, 2020a) focuses on the first two indicators and provides calculation rules for each sub-indicator. However, the guide does not give weights for indicators due to which it is difficult to arrive at a single score. The elaboration of each main goal and their sub-indicators are described as follows:

- Core indicators for protecting existing stocks of materials

  The core indicators for protecting existing stocks of materials largely match the materials balance used in environmental impact analyses (described in Chapter 3.5.1). The method for determining the indicators has been changed for some of them. This has made the indicators suitable for measuring circularity (Platform CB'23, 2020a).

  1. The quantity of materials used (input)
  2. The quantity of materials available for the next cycle (output)
  3. The quantity of materials lost (output)

- Core indicators for protecting the environment

  The indicators for protecting the environment have been copied from the product system impact categories from the SBK method. These categories are based on the European life cycle analysis method (LCA method) for the construction sector, NEN-EN 15804 (Platform CB'23, 2020a). These sub-indicators are the same 19 indicators described in Chapter 3.5.1. In the second version of the guide these are described as main and sub-indicators as follow:

  4. Impact on the environment

- Core indicators for value retention

  Since no existing methods are available for measuring the indicators for value retention, the action team of Platform CB'23 (2020a) has created their own indicators. This broken down into techno-functional value and economic value.

  5. The quantity of initial value (input)
  6. The quantity of value available for the next cycle (output)
  7. The quantity of existing value lost (output)

### Other circularity measurement methods:

Material Circularity Indicator (MCI) and Madaster Circularity Indicator (CI)

### Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) tool, which is part of a broader 'Circular Indicators Project' developed by The Ellen MacArthur Foundation and Granta Design and allows companies to identify additional, circular value from their products and materials, and mitigate risks from material price volatility and material supply (MADASTER CIRCULARITY INDICATOR, 2022). It is a web-based commercially available tool to measure circularity at the product level (Shivakumar, 2021). The MCI is based on three parameters: the mass of virgin materials (V), the mass of unrecoverable waste (W) and the utility factor (X) which represents the lifetime of products (Haupt & Hellweg, 2019; Cottafava & Ritzen, 2021; Shivakumar, 2021). A product that is produced using only virgin materials and at the end of its use phase, it ends up in landfill, is fully linear. On the other hand, a product that is manufactured with recycled materials or reused components and having 100% recycling efficiency is fully circular. Thus, the tool provides an MCI score that ranges between 0 (100% linear) to 1 (100% circular) (Shivakumar, 2021).

#### Madaster Circularity Indicator (CI)

The Madaster Circularity Indicator (CI) is built upon the MCI and is designed to assign circularity scores (ranging from 0-100%) to buildings. The CI measures the circularity level for the whole life cycle, namely: the construction phase, the use phase and the end-of-life phase (Madaster, 2018). Similar to MCI, CI scores the indicators ranging between 0% and 100% (Shivakumar, 2021). In the model, CI score is given to each stage. For the construction stage, a CI of 100% is given when secondary materials are used completely (no virgin materials). In this stage, the recycling efficiency and waste generated during the recycling process is also considered. For the use phase, a CI score of 100% is given when the functional lifetime of a product is more than the industrial lifetime. In the last phase, a CI score of 100% is given when the output materials are fully recoverable. Finally, the scores of all the three stages are aggregated to provide a single CI score for the building (Shivakumar, 2021).

### 3.5.3. Life Cycle Costing

Life Cycle Costing (LCC) is the process of compiling all costs that the owner or producer of an asset will incur over its lifespan. These costs include the initial investment, future additional investments, and annually recurring costs, minus any salvage value (Bragg, 2022). An LCC model is necessary to complement CE and closed-loop of flow elements to attain a true sustainable future (Bradley et al., 2018). It is a useful tool for choosing between investment alternatives and to decide trade-offs for design alternatives. For this research, the term LCC will be used for assessing the life cycle costs that include all costs connected the traditional building or implementation of prefab concrete beams in a design up until a circular design build with modular prefab concrete beams. As this research focusses on the key parameters involved in the transition process, with parameters which are still new in the construction sector, the LCC can be executed used the Activity-Based Costing method (ABC method). Activity-based costing is a costing method that identifies activities in a process and assigns the cost of each activity to all products and services according to the actual consumption by each. Thus, this model assigns more indirect costs into direct costs. By using the LCC in combination with the ABC-method, the financial impact in the transition process towards circular building can be calculated.

### 3.5.4. Reuse potential indicator

The reuse potential indicator relates to the extent in which a material or element has the potential to be reused or is defined as waste after its lifecycle. A material or element evolves from a waste into a resource, as we develop knowledge of how to reuse it: what determines the final fate of the material to the extent of technological innovation for reuse. The reuse potential indicator expresses the amount in value between potential for reuse and waste. This is a real value between 0 and 1. It is equal to 0, when all material is defined as waste and equal to 1 when all materials or an entire element (without damage) can be reused (no waste during disassembly). An RP indicator of 1 is the most attainable and high value that can be assigned to an element. This is illustrated in Figure 3.7 and 3.8. Based on the knowledge found in the paper of Park & Chertow (2014), an idea was drawn on how to quantify the a qualitatively described factor or parameter. Thus, the indicator method was developed which is further elaborated in Chapter 4.5.

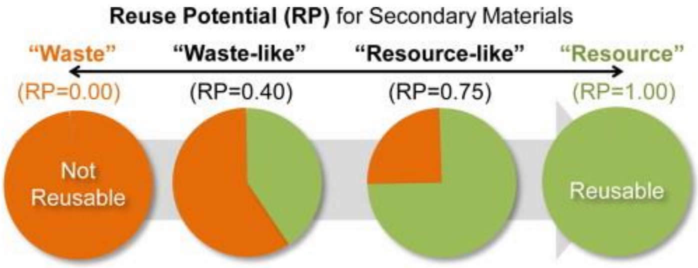


*Figure 3.7 Reuse potential (RP) indicator Secondary Materials, from Park & Chertow (2014)*

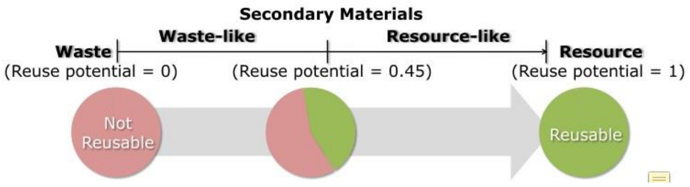


*Figure 3.8 RP indicator: From waste to resource, from: Park & Chertow (2014)*

# 4. Theoretical Framework

In this chapter the theoretical framework is drawn up. The theoretical framework is an extension of the literature review described in Chapter 3. In this chapter the literature review will be critically evaluated based on the existing research related to the concepts of this research. This chapter will now present the boundary conditions of the research in the form of the theoretical framework and will further elaborate on the key concepts of this research. First, conclusions will be drawn in Chapter 4.1. about the topic and existing knowledge by an interpretation of what has been found during the literature review. In Chapter 4.2. to 4.5, the theoretical framework will be supplemented with information supporting the search of key parameters and design alternatives involved in the transition process from traditional building to circular building.

## 4.1. Interpretation of literature review

In this section, what has been found in the literature review in Chapter 3 will be interpreted. After the interpretation of the literature review, it can be summarized what the found information means for this research and what knowledge is still missing. Afterwards, based on that conclusion, the framework for this research will be set up.

### Current status in the transition from traditional construction to circular construction

- The CB'23 platform (Circular Building in 2023), is the platform which currently is doing researches into circular building principles and methods in order to connect building wide parties with circular ambitions, both in civil engineering and in residential and non-residential construction. This platform has created several frameworks and guides in order to help the construction sector with an unambiguous basis. As shown in Figure 3.1. and 3.2., an overview is given of what is expected by circular building and how the transition towards circular building is expected to be and how it could be scaled up. However, CB'23 platform recommends to have a further interpretation and elaboration on the frameworks and guides set up by experiences from the field/practice in order to have a clearer picture of what the bottlenecks are of circular design principles and their implementation.
- In research of Donker (2021) and Klarenbeek (2021) several barrier and bottlenecks were identified in the transition towards circular building. One of the barriers mentioned by Donker (2021) is the uncertainty about the materials, residual life, processes, costs and environmental impact. It could be concluded that insight into the process as a whole, including the environmental impact, the financial impact, supply and demand of materials and the dismantling of the constructive parts, is necessary to allow the re-use of building elements in the Dutch infrastructure sector and to gain insight into the total process (Donker, 2021). Another barrier identified is the limitation of the existing calculation tools. Currently, each tool gives a result which defines one aspect within the whole transition towards limiting the impact on the environment. A In research of Klarenbeek (2021) has been found that especially the measurability of circularity the initial design phase of a project should be enabled in order to have more specific clearer overview when considering a trade-off of circularity design alternatives. By including the measurability in the exploration phase, multiple lifecycles can be included and the cost of adaption, renovation or replacement in a later stage in the calculation tool would therefore be required to make a decent comparison between variants (Klarenbeek, 2021).
- The existing methods for sustainable and circular construction are also limited as described in Chapter 3.5. For calculating the environmental impact (in terms of an environmental cost indicator) and defining the financial impact, there are existing methods. For the measurability of circularity, there is no standardized method yet. However, there is a guide developed by Platform

CB'23 for measuring the circularity prestation. Besides the existing methods, several researches are using an indication method by defining the minimum and maximum value within their scope.

- Currently, the construction sector is facing multiple challenges in the transition of reducing the usage of primary materials and reusing as much as possible. In every renovation or demolition project, it is very critically examined which materials are released and how these can be reused immediately. In addition, for each new project, it is analysed which materials are released on the market from other projects and how these can be used again (Project manager; tender manager, personal communication, July, 2022). This is done, in order to use less raw materials in the production of new elements. However, making the first steps towards reducing the usage of raw materials and reusing as much as possible has several challenges and the challenges differ based on every project's requirement. This also relates to the Strategic Business Innovation Research (SBIR) project - circular viaducts and bridges, announced by Rijkswaterstaat, whereby multiple stakeholders in the construction market are looking at different possibilities of building circular viaduct and bridges.

Based on the current status of in the transition process from traditional building towards circular building can be stated that there is a need for more insights in the initial design stage of a project where trade-off of design alternatives can be considered which can help in the decision-making for making the first steps of the transition towards circular building.

## 4.2. Initial design phase

Every construction project consists of a construction process, which are the detailed steps required to complete a construction project. The execution of a construction process can be broken down into five phases – Planning/design, pre-construction, procurement, construction, and post-construction. Before the detailed execution of the five construction processes starts in a project, first the project is put out for tender. For civil engineering works in the Netherlands, the tender is done by Rijkswaterstaat (implementing organization of the Ministry of Infrastructure and Water Management) or by municipalities. The tenders are being announced online on websites such as TenderNed.nl, which is a platform where all governments contracts can be found and where companies can register for projects. Thus, in order to be offered a project, various market parties can register for the projects. The requirements for winning each tender differ and so do the requirements within each project. This varies from a limited budget for a specific project, minimal $CO_2$ emissions and as sustainable as possible, to even aesthetic requirements. A construction company is one of the market parties who undergoes all the steps mentioned in the total process.

In the transition to circular building and the announced SBIR project – circular viaducts and bridges, there is continuously looked for opportunities to reduce materials consumption and reuse as much as possible. Currently, a lot of attention is being paid to the reusability of prefab concrete beams. This research also focuses on the reusability of prefab concrete beams in the transition to circular construction. In the initial design phase for the construction sector, during the first steps from traditional construction to circular construction, optimization possibilities are examined to reduce raw material consumption and reuse as much as possible. Each design is being rethought on how it can be improved to eventually be able to build completely circular. The rethinking and reconsideration are important in the initial design phase, because a number of factors play a role when moving towards circular construction compared to the traditional construction process, which all need to be taken into account at the start. Thus, the following chapter builds further on the design alternatives to be taken into account in the transition process and the key parameters involved which need to be taken into account from the beginning. This will support in building up the framework related to the problem statement of this research and the to-be developed tool.

## 4.3. Insights in whole transition process

In this chapter, insight in the whole process initial design process will be drawn up by identifying and elaborating on the parameters involved in the transition process from traditional construction to circular construction. This partially answers the sub-question Q1. The key parameters involved will be briefly described in Chapter 4.3.1. Afterwards, and elaboration on each key parameter defined as sub-parameters will be given in Chapter 4.3.2. Lastly, an overview will be given in Chapter 4.3.3. on how to define the proportion of each sub-parameter within the given key parameter.

### 4.3.1. Key parameters

Based on the findings in the literature review described in Section 4.1. and the personal communications conducted within the construction company, this research focusses on key parameters involved in the total process of the transition from traditional building to circular building focused on the reuse of prefab concrete beams and reduction of the use or primary materials in the construction process of building circular viaducts and bridges. Therefore, 5 key parameters were identified in the transition process. These are: *environmental impact, financial impact, the supply and demand, the detachability of prefab concrete beams and the reusability of prefab concrete beams.* Below, the key parameters are listed and an elaboration on each parameter within the scope described in Chapter 2.1., is given.

#### Environmental impact

The environmental impact is defined as the unfavourable or favourable change in the environment fully or partly resulting from an organisation's activities or products (Platform CB'23, 2020b). The cause of such an impact can be caused due the emissions that take place and/or the choice of materials used in a construction process. Therefore, reusing materials is an excellent strategy to reduce the overall environmental impacts of a construction project. Reuse not only contributes to avoiding impacts related to the end of life of the original material, but it also prevents the need to produce new materials and the impacts related to their manufacturing (Gobbo et al., n.d.).

#### Financial impact

The financial impact is determined by the cost price of the type and amount of prefab concrete beams used in the design. The cost price determination of prefab concrete beams and the financial impact of a design in the end, is related to the purchase value of a newly produced prefab concrete beam and/or the price of all activities executed for harvesting prefab concrete beams. The cost price of a traditional or modular new produced prefab concrete beam is gained from the supplier. For a residual prefab concrete beam, the cost price is determined by the activities that need to be performed. These are activities such as all handlings for the dismantling of prefab concrete beams from current civil structures, residual value determination, storage costs until repurposing and processing costs before repurposing.

#### Supply and demand of secondary prefab concrete beams

By the supply and demand of secondary prefab concrete beams is meant the related to a specific product offer in terms of the type of released prefab concrete beams and sizes and the uncertainty in the availability and suitability of residual elements for a new to-be executed projects. This occurs in the current initial design stage that even though a pre-design is drawn based on reused elements, it is still uncertain if there will be enough supply of reusable material the during the execution of the project.

### Detachability of prefab concrete beams

In a traditional construction process, the prefab concrete beams were made project specific and attached to each other without keeping the future in mind such as the need for using secondary materials instead of primary material due to the fact that the natural resources are being exhausted. Therefore, the detachability of existing prefab elements and materials brings multiple challenges with it. The challenges that it brings with relate to the damage that may occur during the dismantling of the beams from the whole structure and the constructive attachments made to it in the 1st life cycle. Another major challenge in the construction sector is the traffic disruption cause due to cautious dismantling of the elements.

### Reuse potential of prefab concrete beams

In order to make the transition from traditional building towards circular building, it is important to look at whether the elements used in existing civil structures (viaducts and bridges) have a potential to be reused. The reuse potential relates the ability to be directly reused without making any modifications and adjustments. Another aspect the residual quality that the released prefab concrete beam has after the 1st life cycle. Further, a challenge in the reusability potential is the norms and standards due to the fact that the current norms are not yet adapted or created for circular building and/or finding the certification of the released element. Lastly, another important aspect is the aesthetics requirements stated in the project requirements and conditions and the disruption it causes.

## 4.3.2. Sub-parameters

Each parameter defined in Chapter 4.3.1. has been elaborated in several sub-parameters. The sub-parameters are defined in order to elaborate on the definitions of each parameter and to conclude how it seen during this research and in the transition process from traditional building to circular building. Each key-parameter and its sub-parameter are elaborated in Table 4.1. and the argumentation of the choice for the sub-parameter within the scope of this research. Based on the literature review in Chapter 3 and indication is given of how each parameter will be quantified.

<table>
<tr><td>Parameter</td><td>Sub-parameter</td></tr>
<tr><td rowspan="2">1. Environmental Impact</td><td>a. Life cycle analysis of element – Environmental Cost Indicator (ECI)</td></tr>
<tr><td>b. Circularity performance – Using Key Performance Indicators (% Circularity)</td></tr>
<tr><td colspan="2">Definition/Description:<br>1. Life cycle analysis (LCA) of an element is the process of determining and evaluating the effects a product has on the environment over its entire life cycle translated into environmental costs. The environmental costs, also described as environmental cost indicator (ECI), are the financial translation of all negative impacts a product or system has on the environment which occurs as a result of the design, realization and use of a structure (Platform CB'23, 2020b). The LCA is a method based on the Determination method by the SBK-bepalingsmethode for civil engineering work for Ground, Road – and Waterworks). The life cycle of a product is divided in 4 phases:<br>A. Production and construction phase;<br>B. Usage phase;<br>C. Demolition phase;<br>D. End-of-life phase;</td></tr>
</table>

In the Netherlands, Rijkswaterstaat (Ministery of Infrastructure and Environment) uses DuboCalc as one of the instruments for fulfilling the sustainability criterion and asks the construction sector to use this standardized tool for calculating the ECI value.

➔ By summing up the values of each phase (A, B, C and D) the ECI is calculated in Euros (€) and gives an indication of the unfavourable impact on the environment.

*Method: European Life Cycle Assessment Method (LCA method) for construction products, EN 15804; The Environmental Cost Indicator (ECI) will be determined using DuboCalc, a software tool for quickly and easily calculating the environmental costs of design variants of civil engineering works.*

2. The measuring of circularity is a method described in research of Platform CB'23 (2020a) and is used to determine impact indicators in order to comply to the 3 main goals of circular building: protecting material stocks, protecting the environment and protecting existing value of materials. The impact indicators, also described as key performance indicators (KPI), is a measurable value that shows how the reuse objectives are achieved in a design. The total % of circularity in a design or of an element can be calculated by summing up the three main KPI's:
   A. Percentage of secondary material used in a design
   B. Percentage of materials that is released during the execution and that can be reused (replacement statement)
   C. Percentage of elements designed for the project and easy to reuse in the future (demountable)

   *Method: Measuring of circularity based on Measuring circularity – working agreements for circular construction' Guide [CB'23 – 2 juli 2020]*

Argumentation of relevance sub-parameters:
The sub-parameters Environmental costs indicator and circularity performance (%) are chosen to define the environmental impact related to the transition from traditional building to circular building during this research. The environmental costs indicator (ECI), which rolls out of an LCA of a product, will point out the differences in the several phases for a traditional build design and a circular build design. The circularity performance in % will also point the quantity of circularity in a traditional build design and circular build design.

| | |
|---|---|
| 2. Financial Impact<br>*Method: Life Cycle Costs using activity-based costs (LCC)* | Cost price determination of the type of prefab concrete beams in the relevant design alternative. |
| | ▪ Traditional prefab concrete beam |
| | ▪ Modular (circular) prefab concrete beam |
| | ▪ Residual prefab concrete beams |

Definition/Description:
Financial impact is defined by the cost price determination of a product. The cost price is determined based on the type of the relevant design alternative. As this research focusses on the transition from traditional construction to circular construction, the type of prefab concrete beams also varies based on the design which is considered. For a contractor, the cost price can be determined based on the purchase value of the prefab concrete beam. However, the determination of the purchase value differs for a newly produced prefab concrete beam and a residual prefab concrete beam.

- Traditional prefab concrete beams
  The purchase value of a new produced traditional prefab concrete beam is determined by the supplier. However, the final cost price is determined based on the additional activities

conducted by a contractor such as the engineering and calculation costs, overhead costs and transport costs.
*Method: Life Cycle Costs using activity-based costs (LCC)*

- Circular (modular) prefab concrete beams
  The purchase value of a new produced circular (modular) prefab concrete beam, which is reusable and future-proof, is also determined by the supplier by whom it is produced. However, the final cost price is determined by the additional activities conducted by a contractor as the engineering and calculation costs, overhead costs and transport costs. Currently, circular beams have not yet been produced and applied. However, as this is a new product on the market and it might be designed more robust and future-proof, the final cost price will be higher than a traditionally produced prefab concrete beam.
  *Method: Life Cycle Costs using activity-based costs (LCC)*

- Residual prefab concrete beam
  The cost price of a residual prefab concrete beam is currently uncertain as the previous owner is unknown. However, the cost price is currently determined by all activities and work carried out from harvesting the prefab concrete beam up to its repurposing.
  The main activities that determine and influences the final cost price are the research and overhead costs, handling costs, logistical costs and temporary storage and processing costs.
  *Method: Life Cycle Costs (LCC) with Activity-Based Costs method (ABC method)*

  To further elaborate on the activities:
  a. The research and overhead costs. This relates to the field work and inspection that needs to be done beforehand of the existing civil structure site. The research and development costs that are done into the beam condition and applicability/suitability for the new civil structure. The laboratory research into the (residual) quality. Further the engineering and construction calculation by the contractor and lastly the inspection of the processed and adjusted residual beams, which is done by an independent agency but is at the cost of the contractor.

  *b.* The *handling costs* such as the drilling and sawing of the beam from the existing civil structure. The drilling is done in order to disassemble the beams from the beam-ends and between the beam fields / abutments. Then hoisting and lifting of the beams from the existing viaduct onto the truck for transportation. The handling costs also cover the additional costs and partly the extra time needed, which are strongly dependent on the relevant artwork. For example, the way in which the beams are attached to each other and the conditions of/around/near the artwork. Further, extra lead time of a project also adds up in the costs which is caused due to cautious and controlled disassembly that needs to be done in order not harm the constructive connections. This is crucial in the harvesting process of prefab concrete beams in order for it to be reused.

  c. *The logistical costs*. This related to the transportation of the residual prefab concrete beams from the harvest site to the temporary storage site/location and the transportation from storage location to the new destination. In an ideal situation the repurpose location of the residual beams are already known and the transportation goes from harvest site to the new destination. This also minimizes the transportation costs (transport over fewer kilometres). Further the location of the relevant civil structure and the reusable secondary materials (beams) also adds up to the final costs. This relates to the extra time needed (longer lead time) in order to carefully dismantle the prefab concrete beams.

<table>
<tr><td colspan="2">
Beam fields above water: Detaching prefab concrete beams with minimal damage takes less extra time compared to demolition (Limits longer lead time). The demolition works of an artwork above water in the traditional building is the same compared to the circular building. Therefore, it is a known practice and would have limited extra costs and lead time.<br>
Beam fields over a road: The additional costs and extra time much more due to the high importance of nuisance for the environment. Therefore, in case of traditional building, the demolition is quicker compared to disassembling for secondary usage. In case of harvesting beams from an artwork for secondary usage, attention needs to be paid to limiting the nuisance for the environment.<br><br>
d. Lastly, the temporary storage location and modification/processing costs are important in case of secondary materials. In case of the transition towards circular building, the released reusable elements often do not have specific repurpose yet. Therefore, a temporary storage place is needed for the unmodified and processed elements. When the repurpose of the element is known, then the modification of the element takes place based on the repurpose requirements. This leads to storage costs and modification costs until the repurpose is known. In cases of a known repurpose, the element can be transported directly to the repurpose location and can be modified there. The last modification of the beams is the removal of the deck using a drilling machine and shortening of the beams based on the repurpose requirements (in the span length required). Therefore, having reusable element whereby the specific repurpose is an idealistic situation.<br><br>
Argumentation of the definition:<br>
The financial impact is not defined in sub-parameters but as the cost price determination of the type of prefab concrete beams in the relevant design alternatives related to the transition from traditional building to circular building during this research. The type of beams considered are newly produced traditional and circular prefab concrete beams and residual prefab concrete beams. Thus, the purchase value and cost price determination point out the differences in costs when building traditional with primary elements, producing new reusable elements and residual elements which are entering their 2nd life cycle. The difference in costs of a circular prefab concrete beam and traditional prefab concrete beam has to do with the extra activities (such as the processing and research and development costs) involved in making a prefab concrete beam modular which has to be more robust and demountable so that it can be reused in the future. Lastly, the costs price determination of a residual beam is different from a new produced beam. The price determination of residual beams is based on all activities conducted in order to harvest the beams and reuse them again. These costs are important to take into account in this transition process towards circular building and making circular designs.
</td></tr>
<tr><td rowspan="2">3. Supply and demand secondary elements</td><td>a. Product specific offer</td></tr>
<tr><td>b. Uncertainty in the supply: availability and suitability</td></tr>
<tr><td colspan="2">
Definition/Description:<br>
The supply and demand of secondary elements and/or materials can be divined further in two main sub-parameters<br><br>
a. Product specific offer<br>
In the construction of a viaduct or bridge, there are specific sizes and models of prefab concrete beams that are/were frequently used. This research specifically focusses on inverted T-beams. The inverted T-beams are one of the most common secondary elements in the dimensions 15-40 meters that are released. Other commonly used beams are the contact beams and box beams but currently, there is no best solution yet to detach the
</td></tr>
</table>

deck or pressure layer attached to the contact beams. However, in case of box beams, even though it higher in investment compared to the inverted T-beams, it could be a good investment with the idea of being able to reuse it in the future due to the fact there is no deck or pressure layer attached in current design. Besides the detachability of several beam types, the released beams mostly have a length between 15 meter and 40 meters, which limits the application in a new construction. Further, when working towards a fully circular economy and thus a building 100% circular, the existing designs of the several beams should be adjusted to future-proof design in order to be able to reuse the beams for a 2nd life cycle.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

b. Uncertainty in supply: availability and suitability
Currently, when making a preliminary design with secondary elements (residual beams), there is an uncertainty in whether the type of girder assumed in the design will be available in time when the execution of the project starts. Quite uncertainty in the availability of secondary beams at the time of execution when making the preliminary design. Besides the availability, the suitability in terms of required strength (bearing load) and size for a next project are also uncertain especially when it comes to fulfilling the required spans. In case beams with a large span, modification is possible into the required span. However, in case short span prefab concrete beam and modification is not possible in the required span, it limits the repurpose of the released element.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

However, a risk that may occur if from now on designs are made with rresidual secondary beams, the demand for released beams will be higher than the supply. Further, to increase the chance of reuse, it is important that the released beams are placed as early as possible in registration areas such as the national bridge bank (nationale bruggenbank).

Argumentation of relevance sub-parameters:
The sub-parameters product specific offer and uncertainty in availability and suitability are chosen to define the supply and demand of secondary elements and/or materials. This parameter and sub-parameters are one of the main challenges in the transition from traditional building towards circular building. The product specific supply points out the challenges and limitations when making a preliminary design and implementing circular building approaches, but it also points out opportunities for new ‘’traditional’’ design with box beams, instead of inverted T-beams. The uncertainty in availability and suitability points out the challenge that may be faced when the execution of a project starts. However, it does point out a point of interest for new produced future-proof elements to be suitable enough for multiple lifecycles in terms of strength (bearing capacity) and size.

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| 4. Detachability of existing and newly produced elements (prefab concrete beams) | a. Dismantling of prefab concrete beams<br>b. Traffic disruption |

Definition/Description:
The detachability of existing and newly produced elements (prefab concrete beams) can be divined in two main sub-parameters

a. Dismantling of prefab concrete beams (damage)
The structure of a viaduct or bridge consists among other parts of prefab concrete beams and a deck (pressure layer) on top of it. In order to reuse the existing beams in such a structure, the deck needs to be dismantled first. However, the dismantling of the deck can damage the beams (of the traditionally built viaducts and bridges). Therefore, attention and

time is needed to detach the prefab concrete beams without causing damage to the beams. Currently, there is no technical solution available for dismantling construction parts (by technical solution is meant that there is no waste when releasing the deck (pressure layer) and no damage to beams is caused.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

b. Traffic disruption
One of the main challenges faced while making a planning for a project with regards to detachability is taking into account the traffic disruption that may or may not occur during the dismantling of beams with beams field over a road. In order to limit the traffic disruption, specific time frames to be chosen in order to execute dismantling works. Beside traffic disruption, safety measures need to be taken when dismantling to prevent accidents and environmental nuisance need to be taken into account in order.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

In general, there is limited information and data available of existing artworks, such as previous designs (for constructive attachments of construction parts) and element specific (the design and technical lifespan). From now on, when making new design and executing infrastructural project, it should be precondition to note or register this information in order to make future-work easier (future-proof thinking).

Argumentation of relevance sub-parameters:
The sub-parameters dismantling of prefab concrete beams and traffic disruption are chosen to define the detachability of existing and newly produced elements. This parameter and its sub-parameters elaborate especially on the dismantling of prefab concrete beams from existing structures and the challenges and current shortcomings faced in the transition from traditional building towards circular building. The traditionally build artworks were build using a traditional construction method and was based on a design whereby a structure would be demolished at the end of its life. Since the first steps are currently being taken towards circular building, it is necessary to have as little waste as possible and to reuse as much as possible from existing constructions. However, the dismantling of prefab concrete elements is quite a challenge in existing structures due to the fact there is not yet a technical solution for detaching the deck from the beams. Furthermore, time and attention are also needed to do the dismantling process as carefully as possible so that no damage occurs. In addition to looking at existing construction, innovations need to be thought of how the designs can be adapted to circular building and to reuse released elements for a 2$^{nd}$ life phase in the future without damage caused to the elements and by needing less time and carefulness. In the detachability process of existing elements, a lot of attention is put into traffic disruption. From current requirements and conditions, the traffic disruption is aspect that needs to be as limited as possible.

| | |
|---|---|
| 5. Reuse potential | a. Reusable potential |
| | b. (Residual) quality |
| | c. Norms, standards and certification |
| | d. Aesthetic requirements |

Definition/Description:
The reuse potential of existing and new produced elements (prefab concrete beams) has been divided in four sub-parameters.

a. Reusable potential
The potential of reuse and waste is defined in a reuse potential (RP) indicator. This define to what extent an element is fully reusable or not. The reuse potential indicator expresses

the amount of potential for re-use and waste in a value between 0 and 1. The value is equal to 0 when all material is waste and equal to 1 when all materials/entire element can be reused (no waste during disassembly). A RP indicator of 1 is the most attainable and high value that can be assigned to an element. In Figure 3.7 it can be seen how the division between 0 and 1 is done in the literature.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

b. (Residual) quality
The (residual) quality defines the (residual) technical load-bearing capacity and (residual) lifespan that remains after a prefab concrete beam is harvested from the 1st lifecycle. The (residual) quality is an important aspect when considering the reusability of prefab concrete elements in a 2nd lifecycle. It will define whether the residual element (from a traditionally build artwork) is suitable and implementable in a new design/project. In case of new produced element which directly contribute to circular building, it important to design and develop the prefab concrete beams with same of higher quality due to the fact that multiple lifecycles need to be reached.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

c. Norms, standards and certification for reuse
One of the main challenges when looking into the constructive (technical) feasibility of reusability of elements (in this case prefab concrete beams), is the fact that current norms and standards focus on new construction have not yet been adjusted and adapted for reuse. This makes it difficult to test residual elements if it meets the necessary requirements. According to research of CB'23 (Platform CB'23, 2022) it is suggested that current norms and standards need to be adapted in order to stimulate and enable the reuse of secondary elements.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

d. Aesthetic requirements
In designs there are certain aesthetic requirements. However, when making new designs with secondary elements, it often occurs that it is aesthetically not feasible to use secondary beams due an image quality requirement. If there is room for adaptation of the aesthetic requirements, secondary elements (residual prefab concrete beams) can be used in new design.
*Method: Developed indicator method/approach (see Chapter 4.5.2.)*

A general challenge that requires more thought and practice is the fact that there is currently little expertise and knowledge, both internal and external, for the reuse (implementation) of secondary elements.

Argumentation of relevance sub-parameters:
The sub-parameters potential for reuse or waste, (residual) quality, norms and standards for reuse and aesthetic requirements are chosen to define the reuse potential. The reuse potential in the transition for traditional building to circular building can be defined based on different aspects such as the quality and aesthetics. The potential for reuse or waste gives a good indication when looking at a traditionally build structure and a circularly build construction. It states the difference in reusable resources or waste by attaching a value between 0 and 1 to the elements or even whole structure. When looking at the (residual) quality, it defines whether a traditionally build structure, after its first lifecycle, still meets the technical requirements and has residual lifespan in order to be reused. The norms and standards, which have currently not yet been adapted for reuse, give a good indication why the transition from traditional building towards circular building and why limiting

| |
|---|
| waste production and reusing as much as possible is challenging. Lastly, the aesthetic requirement is designs make it challenging to build circular as well unless there is room for adjusting of the requirement. |

*Table 4.1 Defined sub-parameters and elaboration*

### 4.3.3. Overview of parameters and sub-parameters

In this chapter, an overview will be given of how to define the proportion of each sub-parameter within the given key parameter. The proportion of each sub-parameter within a parameter is needed, in order to determine the performance of the design alternatives in that specific main parameter. The importance and ratio between sub-parameters are related to the requirements and conditions of a certain project. For this research, a fictional case-study will be drawn up and the developed tool. Thus, it is assumed that all sub-parameters within each parameter weight evenly and the main parameters relative to each other also weight evenly. This is shown in Table 4.2.

| Parameter | Sub-parameters and ratio in parameter | |
|---|---|---|
| 1. Environmental Impact | 1. Environmental Impact | 100% |
| | a. Life Cycle Analysis (ECI) | 50% |
| | b. % Circularity (using KPI's) | 50% |
| 2. Financial Impact | 2. Financial Impact | 100% |
| | Cost price value (determination) of the prefab concrete beams in the relevant design alternative | 100% |
| 3. Supply and demand secondary elements | 3. Supply and demand | 100% |
| | a. Product specific offer | 50% |
| | b. Uncertain availability and suitability | 50% |
| 4. Detachability of elements | 4. Detachability of elements | 100% |
| | a. Dismantling of prefab concrete beams | 50% |
| | b. Traffic disruption | 50% |
| 5. Reuse potential | 5. Reuse potential | 100% |
| | a. Potential for reuse or waste | 25% |
| | b. (Residual) quality | 25% |
| | c. Norms and standards for reuse | 25% |
| | d. Aesthetic requirements | 25% |
| Total ratio paramaters | | 100% |
| 1. Environmental Impact | | 20% |
| 2. Financial Impact | | 20% |
| 3. Supply and demand | | 20% |
| 4. Detachibility of elements | | 20% |
| 5. Reuse potential | | 20% |

*Table 4.2 Proportion of sub-parameters within parameter*

## 4.4. Design alternatives (variants)

As mentioned before, insights in the initial design phase are needed in order for the trade-off of design alternatives. Thus, the possible design alternatives that need to be considered should also be drawn up. This chapter will elaborate on the design alternatives will be considered during this research. This also contributes to the sub-question Q2.

As this research in conducted in collaboration with Dura Vermeer Landelijke Projecten B.V., several example project and information were provided in order to drawn up the design alternatives for this research. The example projects were either already executed projects or in the initial design/planning phase before the execution of the project. All of the examples related to construction projects of viaducts and bridges with prefab concrete beams. In these examples, the considerations of the prefab concrete beams were made out of either partly reused prefab concrete beams and partly traditional produced concrete beams or totally traditionally build with 1st life cycle concrete beams due to several factors which are described in Chapter 4.3. The design alternatives will hereinafter be called ''Variants''. Below, an overview with sketch drawings will be given of the variants that will be considered during this research.

### Variant 0: Traditional design – complete of traditional beams made of primary materials

This design variant is related to the traditional construction. It will be put in the framework and tool as a reference. In this design alternatives, all prefab concrete beams are produced in a traditionally way and are made of primary materials. In the figure below the front-view of a viaduct or bridge is drawn up with all related main elements whereby the prefab concrete beam is being highlighted. The colour of the prefab concrete beam gives an indication that it is a tradition prefab concrete beam.

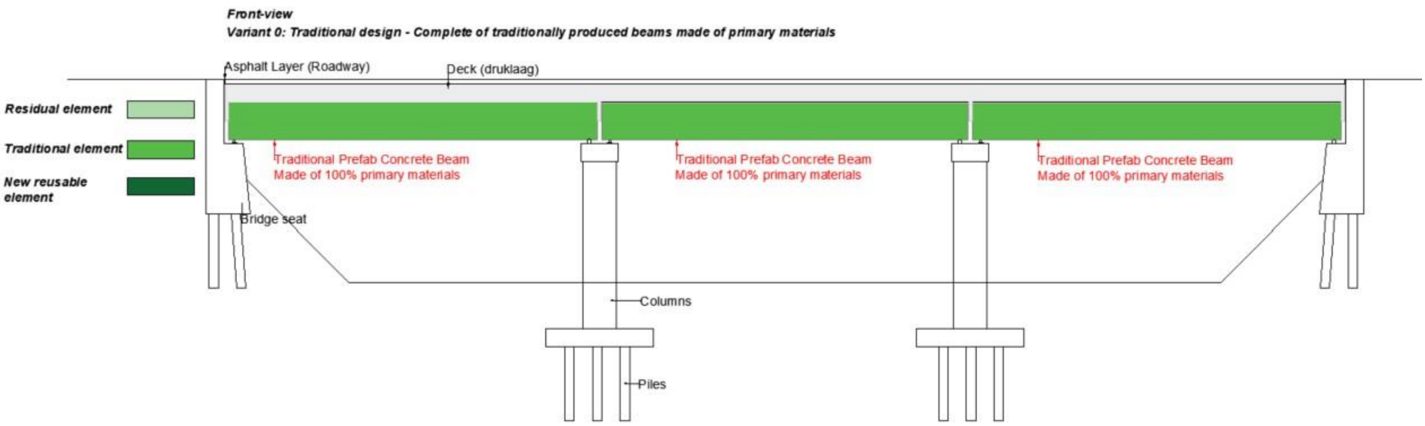



*Figure 4.1 Variant 0: Traditional design*

### Variant 1: Circular design – complete new-reusable and future-proof beams (Modular beams)

This is design alternative is related to the circular construction. This design alternative is put in the framework and tool as the most optimal design for the prefab concrete beams, due to the fact that they are circular. These circular prefab concrete beams are defined as new-reusable and future-proof prefab concrete beams (Modular beams). In this design alternative, each modular prefab concrete beams are newly produced and entering their 1st lifecycle. However, their design is modular and it complies to certain specifications in order to be reused and have multiple lifecycles in the future.

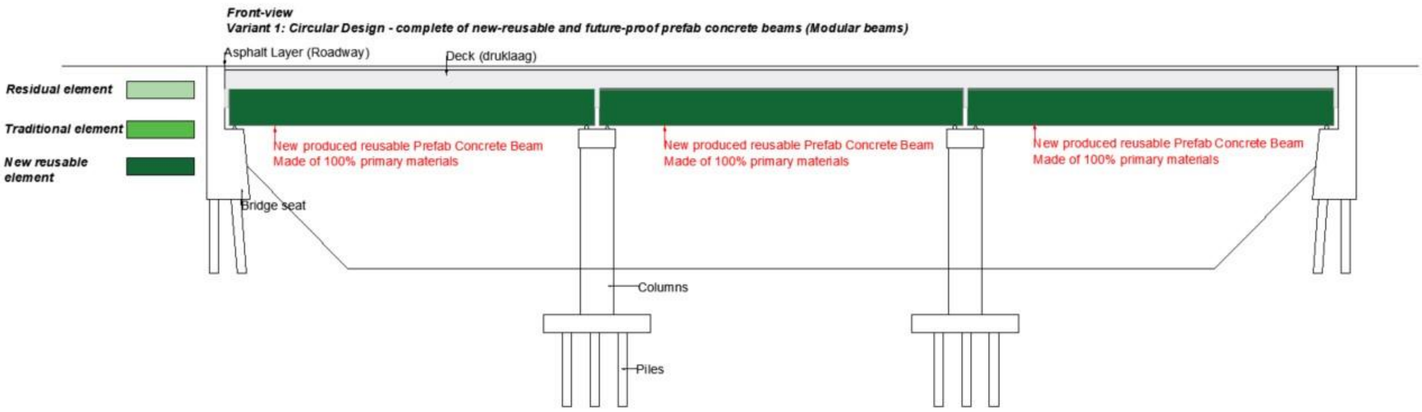



*Figure 4.2 Variant 1: Circular design*

### Variant 2: Combination design of new-reusable/future-proof (modular) beams and residual beams

This design alternative is a combination of new-reusable and future-proof prefab concrete beams (Modular) and residual. This design alternative is put into the framework and tool as this design with combination of both, as this design corresponds to making the first steps of reducing the usage of primary materials and reusing as much as possible residual elements. This also corresponds to current practical situation and the transition process from traditional building towards circular building.

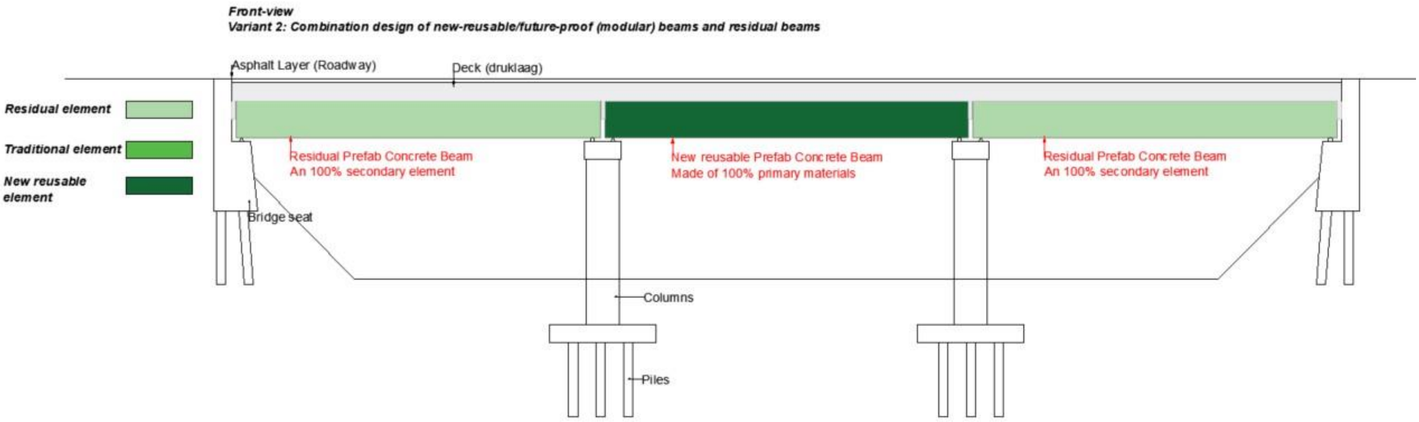



*Figure 4.3 Variant 2: Combination design of new-reusable and residual beams*

### Variant 3: Residual design of complete residual (secondary prefab concrete beams)

This design alternative is a design made of complete residual prefab concrete beams (secondary elements). This design alternative is put into the framework and tool because it corresponds the most with the current circularity goals as no raw materials are used for the production of the prefab concrete beams and all beams implemented in the design are reused. Thus, all prefab concrete beams in this design are going in their 2$^{nd}$ lifecycle. This also corresponds to current practical situation and the transition process from traditional building towards circular building.

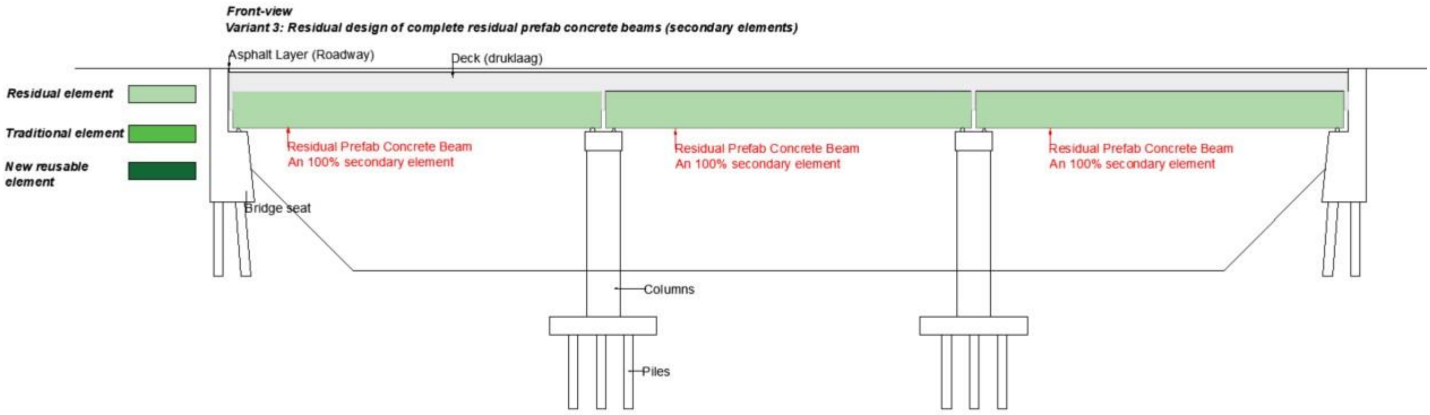



*Figure 4.4 Variant 3: Residual design*

All four design alternatives, Variant 0 to 3, will be put into the framework in order see what their effect is on the key parameters transition process. By having insights in the design alternatives, a trade-off can be made and this can contribute in the decision-making process in the initial design stage.

## 4.5. Quantification methods

In this chapter the quantification methods will be explained in order to define the effect of design alternatives on parameters involved in the transition process from traditional construction to circular construction. By using quantification methods, the effect of the different design alternatives can be quantified for the qualitatively described parameters. After doing some research, existing and standardized measuring methods were found for the environmental impact and financial impact. However, for the other three parameter, no existing and standardized methods were found. Therefore, an approach is developed in order to quantify the effect on these parameters. Thus, all parameters were divided into existing measuring methods and developed measuring method or approach. Therefore, this chapter will elaborate on the existing measuring methods (Chapter 4.5.1.) and the developed measuring method or approach (Chapter 4.5.2.)

### 4.5.1. Existing measuring methods

In this paragraph, an overview is given of the existing and standardized measuring methods which will be used for quantifying the effect of design alternatives on parameters. The (sub)parameters for which existing measuring methods were found are the environmental impact and the financial impact. In Table 4.3. an overview is given of how the effect of each design alternative will be determined on each sub-parameter and which measuring method will be used in order to do that.

#### Parameter 1 and 2

| (Sub) Parameter | Traditional | (New) Circular | Complete reused | Combination New and reused | Measuring method |
|---|---|---|---|---|---|
| 1. **Environmental impact** | | | | | |
| a. Life Cycle Analysis | ECI (€) | ECI (€) | ECI (€) | ECI (€) | LCA based on the European Determination Method (based on EN 15804) and DuboCalc |
| b. Circularity performance | % circularity | % circularity | % circularity | % circularity | Measurability of circularity [CB'23 – 2 Juli 2020] |
| 2. **Financial impact** | | | | | |
| Cost price determination based on beams type in the relevant design alternative:<br>▪ Traditional prefab concrete beam<br>▪ Modular (circular) prefab concrete beam<br>▪ Residual prefab concrete beams | € | € | € | € | Life Cycle Costing (LCC) using Activity-Based Costing Method |

*Table 4.3 Existing methods used for the (sub)parameter quantification and units considered*

**NOTE:** For the existing measurement methods, the necessary data is collected (as described in the indicated measurement method) which is necessary to calculate the effect of the variant on the parameter. The missing data, for example for the circular designs and/or combination designs, is supplemented with the help of the experts in the field of sustainability and financial/cost calculations.

### 4.5.2. Developed measuring method/approach

In this paragraph, an overview is given of the developed measuring method or approach, which will be used for quantifying the effect of design alternatives on parameters. The (sub)parameters for which no existing measuring methods were found, are the supply and demand, detachability and reusability. Thus, a method is developed based on the literature findings described in Chapter 3.5.4. The method is developed by defining indicators, from 0 to 1, whereby 0 corresponds to the most undesirable scenario and 1 corresponds to the most desirable scenario. Figure 4.5. illustrates that the value chosen varies from 0 to 1. Figure 4.6. shows the output of the developed measuring method. For each of the (sub)parameters, the most desirable and most undesirable scenario will be defined and the conditions on which terms a scenario is desirable or undesirable. Defining the maximum and minimum value for each (sub)parameter is necessary in order to normalize the final results. The normalized values (final results) of the (sub)parameters are needed in order to compare the results. Since the minimum and maximum values for this developed measuring method are already between 0 and 1, no normalization is needed.

Thus, the most desirable and undesirable scenarios are the boundaries and are further elaborated interview questions, through which an indicator between 0 and 1 will be obtained from the interviewee for each sub-parameter. The questions and the obtained output values have to do with the extent to which the relative design alternative has a desirable or undesirable effect on the sub-parameter. This data will be collected through interviews with different experts within the company.

The definition of the minimum and maximum of each sub-parameter is elaborated in Appendix A.


*Figure 4.5 Developed measuring method: value between 0 and 1*


*Figure 4.6 Output of the developed measuring method*

### Parameter 3, 4 and 5

In Table 4.4 an overview is given based on the information described above and illustration of Figure 4.5 of how the effect of each design alternative will be determined on each sub-parameter using the minimum and maximum definitions.

Further, in Table 4.5. the elaboration on the definitions (minimum and maximum) is given. This forms the basis for conducting interviews with experts. The definitions are elaborated in the form of questions which will be ask to the interviewee.

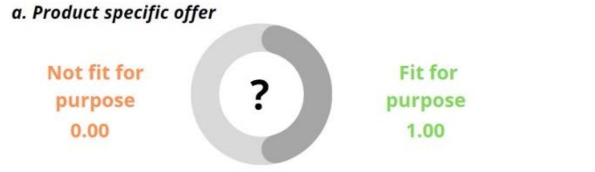
| (Sub) Parameter | Traditional | (New) Circular | Complete reused | Combination new en reused | Definition indicators |
|---|---|---|---|---|---|
| **3. Supply and Demand of secondary prefab concrete beams** | | | | | |
| a. Product specific offer | [-] | [-] | [-] | [-] |  |
| b. Uncertainty in supply: delivery risk regarding availability and suitability | [-] | [-] | [-] | [-] |  |
| **4. Detachability of prefab concrete beams** | | | | | |
| a. Damage to beams during dismantling | [-] | [-] | [-] | [-] |  |
| b. Traffic disruption during dismantling | [-] | [-] | [-] | [-] |  |
| **5. Reusability of prefab concrete beams** | | | | | |
| a. Reusable potential | [-] | [-] | [-] | [-] |  |
| b. (Residual) quality | [-] | [-] | [-] | [-] |  |
| c. Norms and standards | [-] | [-] | [-] | [-] |  |
| d. Aesthetic requirements | [-] | [-] | [-] | [-] |  |

*Table 4.4 Developed method used for the (sub)parameter quantification and units considered*

**NOTE:** The indicators are defined from 0 to 1, where 0 defines the most undesirable scenario of the variant on the sub-parameter and 1 the most desirable scenario for the transition process towards circular building. This is done through interviews with experts and is further elaborated in Appendices A and B.

<table>
<tr><th>(Sub) parameter</th><th>Defined condition</th></tr>
<tr><td colspan="2">3. Supply and Demand</td></tr>
<tr><td>a. Product specific offer<br><br></td><td>To what extent is the type (inverted T-beam), dimensions (length of beam) and adjustability of the released beam fit for its purpose in the relevant design alternative?<br>Considering: beams <u>before</u> ''1st life cycle'' of relevant design alternative</td></tr>
<tr><td>b. Uncertainty in the availability and suitability<br><br></td><td>To what extent does the timely availability and suitability (size) of released beams pose a supply or delivery risk before the start of the project?<br>Considering: beams <u>before</u> ''1st life cycle'' of relevant design alternative</td></tr>
<tr><td colspan="2">4. Detachability</td></tr>
<tr><td>a. Damage to beams during dismantling<br><br></td><td>To what extent can dismantling of the beams from the entire structure (into its first form) in the relevant design alternative lead to damage to the beams? No technical solution for dismantling.<br>Considering: beams <u>after</u> ''1st life cycle'' of design alternative</td></tr>
<tr><td>b. Traffic disruption during dismantling<br><br></td><td>To what extent should extra time be taken into account in the planning for the dismantling of beams for the structure of the relevant design alternative in order to cause as little traffic disruption as possible?<br>Considering: beams <u>after</u> ''1st life cycle'' of relevant design alternative</td></tr>
<tr><td colspan="2">5. Reusability</td></tr>
<tr><td>a. Reusable Potential<br><br></td><td>To what extent is the precast concrete beam in the relevant design fully reusable, without waste production during detachment and adjustment for re-use?<br>Considering: beams <u>after</u> ''1st life cycle'' of relevant design alternative</td></tr>
<tr><td>b. (Residual) quality<br><br></td><td>What is the technical (residual) bearing capacity and (residual) lifespan after the 1st life cycle of the beam?<br>Considering: beams <u>after</u> ''1st life cycle'' of relevant design alternative</td></tr>
<tr><td>c. Norms, standards and certification (abbreviated: N&S)<br><br></td><td>Is there a norm and standard or certification available for the prefab concrete beams in the relevant design alternative to test the constructive feasibility and to confirm the standards?<br>Considering: beams <u>before</u> ''1st life cycle'' of relevant design alternative</td></tr>
</table>

| | |
|---|---|
|  | To what extent is there a client acceptance if the aesthetic quality requirements are not meant and does it pose a barrier when building with the precast concrete beams of the relevant design alternative?<br>Considering: beams before ''1st life cycle'' of relevant design alternative |

*Table 4.5 Effect quantification with developed measuring method*

### 4.5.3. Normalization of values

After all input values have been determined, from both the existing measuring method and the developed measuring method, the final results of each effect of the design alternative on the specific parameter can be given in the relevant unit as well. However, some of the results are unitless values between 0 and 1 and some have a unit of in € or %. In order to be able to compare the values with one another, the values must be normalized so that all of the results end up ranging between 0 and 1. This is also known as the Min-Max scaling.

The normalization takes place using the following formula:

$$x' = \frac{X - Xundesirable}{Xdesirable - Xundesirable}$$

Xdesirable and Xundesirable are the defined boundaries for each sub-parameter. However, a further elaboration on the defined desirable and undesirable boundaries for the sub-parameters, where the normalization of values is applicable, is described below:

1. *Environmental impact*
   a. The Xundesirable value is related to the most undesirable scenario for the environmental costs. This is the highest value that occur between the design alternatives of a project. This means that in the case of the environmental costs, the higher the value, the less desirable the case is. Thus, in this research it is the highest value between Variant 0 and 3. The Xdesirable value that can occur for the environmental impact is €0, this means no environmental impact. This is the most desirable or best case.
   b. The Xundesirable value for the circularity performance is defined as 0%. This means 0% on circularity performance is the most undesirable scenario. The Xdesirable value is defined as 100%. This means 100% on circularity performance, which is related to the most desired scenario.
2. *Financial impact*

The Xdesirable and Xundesirable boundary definition for the financial impact is the more or less the same as the environmental impact. The Xundesirable value is defined as the highest value that will occur between the design alternatives in a project. Thus, in this research it is the highest value between Variant 0 and 3. The Xdesirable value that can occur for each of the sub-parameters in the financial costs is €0, this means no financial impact thus no costs that occur. This is the most desirable or best case.

3. *Supply and demand, detachability and reusability*

The Xdesirable and Xundesirable boundary for the supply and demand, detachability and reusability are defined as 0, for the most undesirable scenario and 1 for the most desirable scenario. As previously described in Chapter 4.5.2, no normalization is needed for the obtained results as they are between 0 and 1 and are unitless.

The determination of the desirable and undesirable boundary is done in such a way that design alternatives within one project can be compared to each other.

### 4.5.4. Liability and risk when using residual beams

In the current transition process towards circular building there is currently a lot of uncertainties regarding the liability and risk when applying residual prefab concrete beams. Even though there is a need for reducing the usage of primary raw materials and reusing as much as possible, and thus building circular fully circular by 2030, there is no fixed contractual procedure of how to cope with the liability and risks that come with the application of residual prefab concrete beams in new projects. As current practice experience is showing that prefab concrete beams may have a higher life span of 200 years instead of their developed life span of 100 years, the liability after delivery of a project where residual prefab concrete beam would be applied is still a frequently discussed topic between the client and contractor and often forms barrier in this transition process towards circular building. Thus, based on information gained through personal communication with a contract manager and tender manager within Dura Vermeer, the process of the liability and risk division between a client and contractor has been drawn up and is illustrated in Figure 4.7.

#### Elaboration on current liability and risk process

In the flowchart in Figure 4.7. can be seen that, based on current practical experiences, the initiation of applying residual prefab concrete beams play a big role in the end decision for the contractual determination after delivery of a project. If the application of residual beams is initiated by the client, then this was already implemented in the tender as a tender requirement. But, in this case, the source and delivery of the prefab concrete beams could either be from the client (and therefore the requirement in tender) or it could be that it defined as a tender requirement in order to stimulate circular building. In the case if the source and delivery of prefab concrete beams are by the client for the project, then this has been contractually included in the start and the client is 100% liable for the residual beams provided after delivery. If the contractor needs to find a source of released beams a deliver it themselves, then it can be determined with the client on how the residual quality (residual lifespan a bearing capacity) should be decided and what conditions it must meet. However, it should also state beforehand that because it was initiated by the client, the liability should also lie there after project delivery. The liable period after delivery can always be determined based on mutual agreement.

If the application of the residual beams is initiated by the contractor, then it could be that this also a tender requirement in the sense of that it influences the EMVI-score (Economic Most Advantageous Registration). The EMVI-score is a score which leads to a fictive discount of the tender price registered by a contracted, which helps in winning a tender. If this is the case, then mutual agreement can be determined with the client on the requirements for the residual quality and the liability period after delivery. If the application is not a requirement of a tender and does not specifically influence the EMVI-score, but is initiated by a contractor with the intention to build circular and work more sustainable, the liability and risk that come with should be negotiable with the client. The success of this negotiation can then lean executing the project with residual concrete beams and thus reducing the usage primary raw materials which leads to a step closer to building fully circular by 2030. If it is not possible to negotiate and the liability and risk fully rely on the contractor, it will lead to the project not being executed with residual beams but with new produced prefab concrete beams due to high risks.

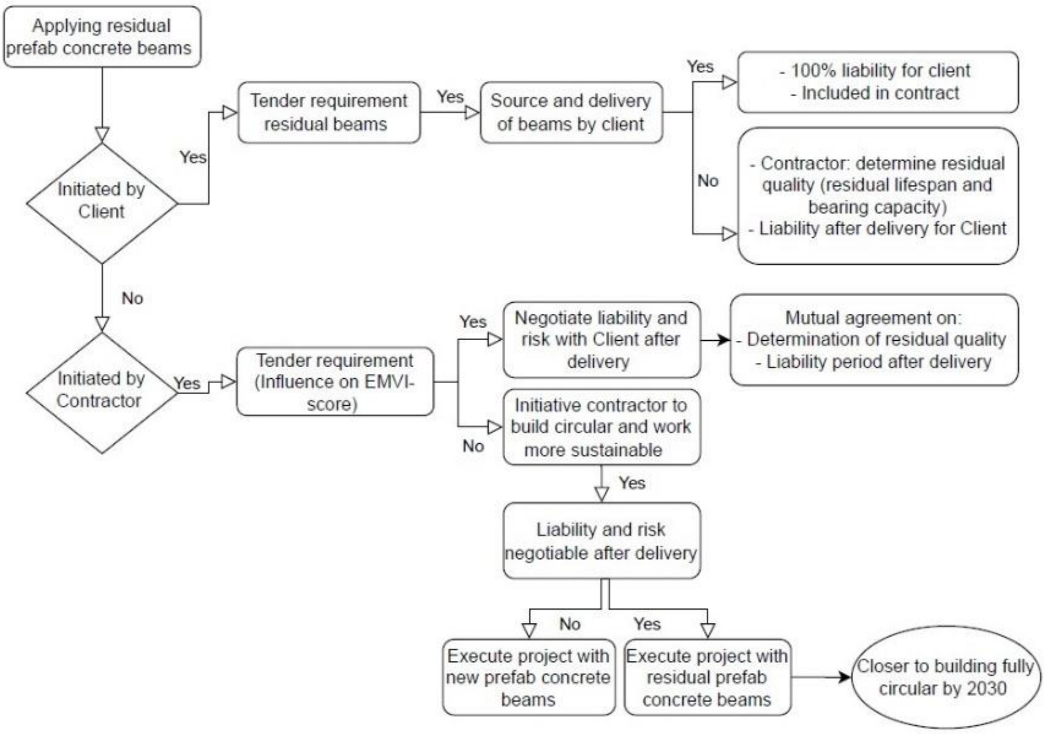



*Figure 4.7 Flowchart liability and risk current process between client and contractor*

# Part II

## 5. Research results: Theoretical framework

In the theoretical framework, described in Chapter 4, research was conducted to find the results on sub-questions Q1, Q2 and Q3. This chapter will now present an elaborate overview of the sub-questions Q1, Q2 and Q3 and their aim described in Chapter 2.2. and the corresponding research results found in Chapter 4. The results correspond to the key parameters involved in the transition process from traditional building to circular building, the corresponding design alternatives and the effect of different design alternatives on the key-parameters involved. This will be described in chapter 5.1. to 5.3. and the combined results will be described in Chapter 5.4. The combined results will form the framework for the to be developed tool and is the basis for the tool development of Chapter 6.

### 5.1. Results of Q1

The first sub-question Q1 is related to the research needed in order to define each parameter involved in the transition process for the decision-making in the initial design phase of a construction project. The first sub-question Q1 was described as follow:

***Q1:*** *How to define and elaborate on each parameter involved in the given design for the decision-making in the initial phase of a construction project?*

In order to know what the key-parameters are in the transition process; in-depth literature research has been conducted and described in Chapter 3, information was gained at Dura Vermeer through personal communications with several experts and observations were made within the construction sector. Thus, 5 key-parameters were identified in the current transition process. These are the Environmental Impact, Financial Impact, Supply and Demand of secondary prefab concrete beams, Detachability of prefab concrete beams and the Reusability of prefab concrete beams. In order to define and elaborate on each parameter, each of them was further elaborated in sub-parameters. The aim of this question was to elaborately define each key parameter and qualitatively drawn up the framework for the to be developed tool. These are elaborately described in the sub-chapters of Chapter 4.3.

### 5.2. Results of Q2

The second sub-question Q2 is related to the research needed in order to define the design alternatives that need to be considered in the transition process from traditional building to circular building and will contribute in making the first steps towards the circular building of viaducts and bridges. The second sub-question Q2 was described as follow:

***Q2:*** *Which design alternatives need to be considered for the first steps towards the circular building of viaducts and bridges?*

First, in order to delineate the research, it was established that this research will be conducted on an element level of viaducts and bridges, zooming in on prefab concrete beams. Therefore, in order to define the design alternatives which, need to be considered, information was gained through personal communication with experts within the company and by analysing existing projects and approaches for reusing prefab concrete beams of current projects which are in the initial design phase. Thus, 4 design alternatives were formulated for this research based on the information gained, going from a design corresponding to the traditional construction with traditional prefab concrete beams to a design corresponding to the circular construction with circular, thus modular, concrete beams. Therefore, the *first design alternative* is the traditional design, which is made of complete traditionally produced prefab concrete beams. This is called *variant 0*, as this will be put as the reference variant in the to-be developed tool. The *second design alternative*, and thus *variant 1*, is the fully circular design which is made out of completely new reusable and future proof beams (thus modular beams). The *third design alternative*, which is *variant 2* in this research, correspond to a combination design of modular beams and residual beams. And lastly, the *fourth design alternative*, which is *variant 3*, is a design made of complete residual beams, therefore it fully consists of secondary beams going into their 2nd life cycle. These are elaborately described in Chapter 4.4. including sketch drawings of all alternatives and their key differences in types of prefab concrete beams. Thus, the four design alternatives drawn up give an overview of which variants to consider, on element level, in the initial design phase for constructing a viaduct or bridge.

## 5.3. Results of Q3

The third sub-question Q3 is related to the research needed in order to define the effect of each design alternatives (Q2) on the defined key parameters (Q1) in the transition process from traditional building to circular building. The aim of sub-question Q3 was to quantitatively build up on the qualitatively drawn up framework of Q1 and Q2. The elaboration on the effect of the design alternatives on the key parameters contributes to the to be developed tool which will help in the decision-making process for the trade-off of design alternatives in the initial design phase. The third sub-question Q3 was described as follow:

***Q3:*** *How to define the effect of the design alternatives on the parameters involved in the transition process from traditional building towards circular building?*

For the third sub-question, research was done on how to define the effects of the design alternatives of the key-parameters. The aim here was to quantitatively build up on the qualitatively described parameters and design alternatives of Q1 and Q2. For sub-question Q3, multiple steps were taken in order to define the effect of the design alternatives on the parameters involved in the transition process from traditional building to circular building.

First, research was done in order to find measuring methods for each of the defined parameters and sub-parameters. The measuring method was needed to define the effect of the design alternative on each sub-parameter in the transition process. After doing some research, existing standardized measuring methods were found for the environmental impact and financial impact. For the sub-parameters within the environmental impact the methods Life Cycle Analysis of an element and circularity performance of an elements will be used in order to define the environmental impact on each design alternative. Further, for the sub-parameters within the financial impact the Life Cycle Costing method will be used in order to define the financial impact of each design alternative. However, for the parameters supply and demand, detachability and reusability, no existing and standardized methods were found. Therefore, an approach was developed in order to quantify the effect on these parameters. Thus, all parameters were divided into existing measuring methods and developed measuring method or approach. This is elaborately described in Chapter 4.5.

## 5.4. Combined results of Q1, Q2 and Q3

After research was conducted for sub-question Q1, Q2 and Q3, framework could be drawn up for the to be developed tool. This framework will form the basis for the tool development which will be elaborately described in Chapter 6. Therefore, in this chapter the combined results are given chapter 5.1., 5.2. and 5.3. which are the results of Q1, Q2 and Q3. Figure 5.1 gives a summarized overview of the combined results. This figure shows that first the parameters and sub-parameters were defined. Afterwards, the design alternatives, which are also described as the variants, during this research were defined. Further, the effect of each variant is defined using the methods described before. Lastly, by adding a certain weight to each of the sub-parameters, the variants can be compared to each other based on which performs the best or worst for the given parameter. The merged results form the framework for the to be developed tool and is the basis for the tool development of Chapter 6.

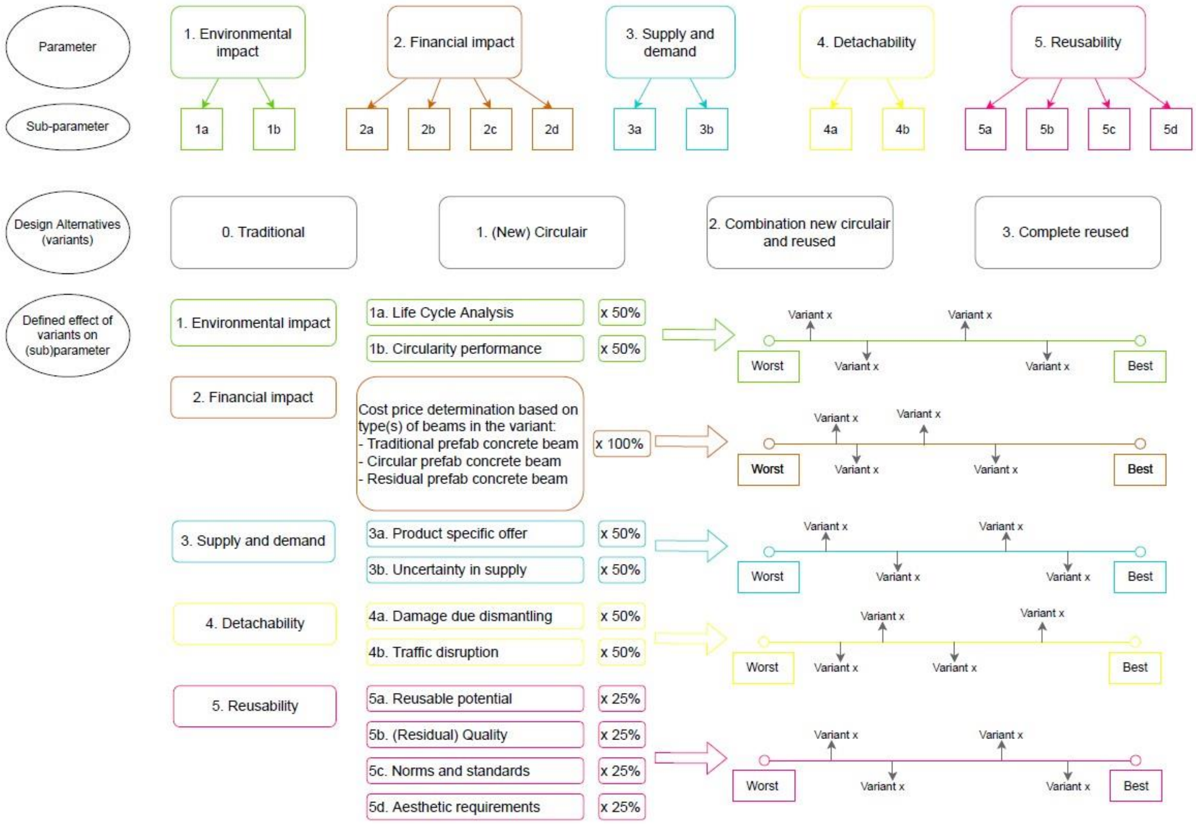


*Figure 5.1 Combined results Q1, Q2 and Q3*

## 5.5. Conceptual model

After combining the research results of Q1, Q2 and Q3 the framework has been drawn up and forms the basis for the to-be developed tool. Thus, in this chapter a conceptual model will be given which forms the basis of the tool. Figure 5.2. illustrates the conceptual model of the framework. In this figure it is illustrated which steps to take and what information is needed in order to arrive at the final result which will help in the decision-making in the initial design stage.

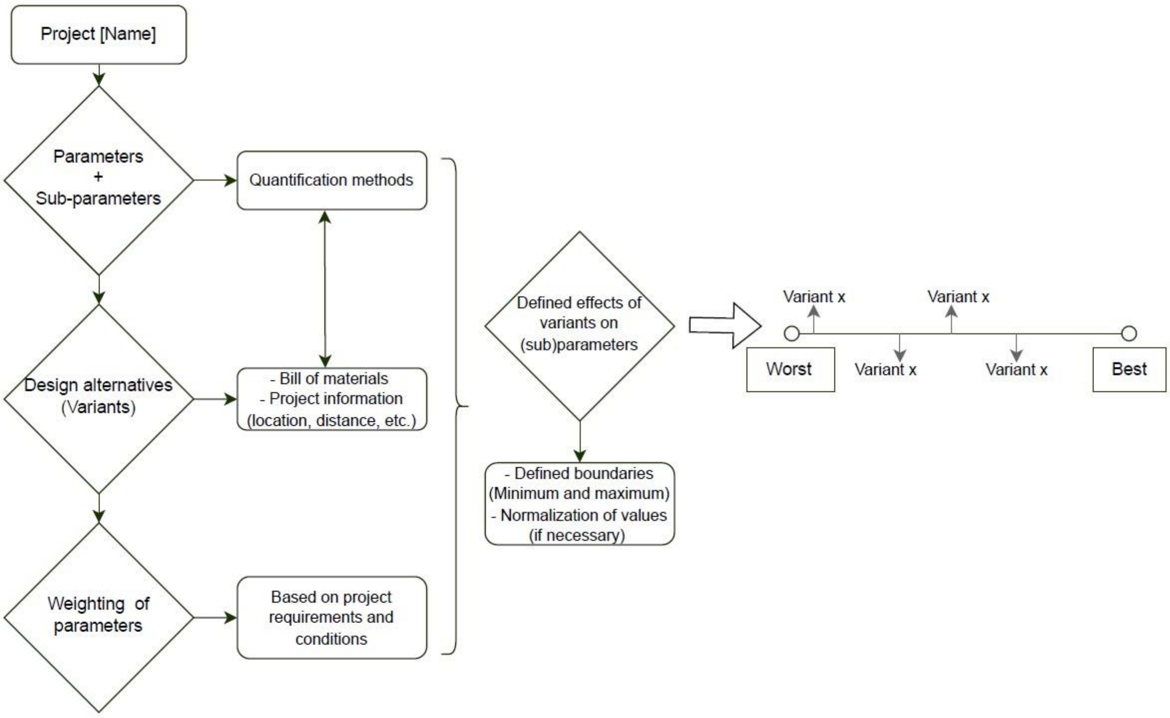



*Figure 5.2 Conceptual model Framework*

# Part III

# 6. Tool development

Based on the previous parts of this research, part I and II, an overview has been formed on what the transition process from traditional construction to circular construction holds and how the analysis of key parameters related to the transition process of building circular viaducts and bridges can be done. First, in Chapter 6.1. the transition from part I and II to part III is highlighted and the relationship of the last part (part III) with sub-question Q4 is given. In Chapter 6.2. the foundation of the tool will be described which described how the tool should look like. In Chapter 6.3. the application of the tool takes place using a case study and elaborates on the information needed in order to apply the tool. Lastly, in Chapter 6.4. the validation of the tool takes place.

## 6.1. Results and approach of Q4

In this part, the approach and results for the last sub-question will be described. Based on the results found and the framework drawn up Chapter 5.4., a user-friendly tool will be developed for the construction industry which contributes in the decision-making process of the initial design stage of a project. This relates to the fourth sub-question Q4 of this research and the goal of this part is to find an answer for Q4. Thus, the fourth sub-question Q4 was described as follow:

***Q4:*** *How to make a user-friendly tool, based on the developed framework, in order to have an added value for the construction industry in the decision-making process of the initial design stage and validate it?*

In order to answer sub-question Q4, several software programs were explored in order to develop a user-friendly tool for the construction industry. After analysing the current tools and software programs used in the company, it was established to develop the user-friendly tool in Microsoft Excel. Microsoft Excel is a spreadsheet software program and is a powerful data visualization and analysis tool. Thus, the developed framework will be translated into Microsoft Excel, using the spreadsheets and will visualize the final combined results. Further, the visualized data and results can then be further analysed. The development of the tool takes place based on the results found described in Chapter 5.1., 5.2. and 5.3. These chapters describe the theoretical input values needed in the tool. These consist of 1. The parameters and sub-parameters, 2. The design alternatives and 3. Methods in order to define the effects of each design alternative on the parameters. Further, using a fictional case-study build up during the research. Thus, in Chapter 6.2. the foundation of the tool will be described. This elaborates on how the user-friendly decision-making tool should look like. In Chapter 6.3. the application of the tool takes place using a case study. This elaborates further on the information needed from a project, which is determined using the quantification methods and forms the input values in the tool. Afterwards, the tool is validated through expert within the construction company and will be validated on the pre-set conditions: user friendly tool, added value to the construction sector and contribute in the decision-making of design alternatives. This will be further elaborated in Chapter 6.4.

## 6.2. Foundation of the tool

Based on the research results of part I and II, it has been decided on how the user-friendly decision-making tool should look like. As described before, the tool will be developed in Microsoft Excel. In this chapter the foundation of the tool will be described. Based on the research executed and the observations made in the construction sector, the tool should comply to a certain set of requirements.

- The tool should be user-friendly so that it can be implemented in the decision-making process in the initial design phase of a project at the company;
- The steps in the procedure should be clear by using spreadsheets of Microsoft Excel and they should be clearly linked with each other;
- There should be room for describing the assumptions in each step of the tool. The description of the assumptions forms an important basis for the end result. After analysing the end results, it should be trace-able based on what assumptions a certain result has been found. By describing the assumption, this process and tool can be adjusted and/or reproduced for other types of projects.

In Figure 6.1. and 6.2. illustrate the front-page of the tool in Microsoft Excel is given. It starts with an introduction, mentions the key-parameters and design alternatives and then describes the working method of the tool. This is a screenshot of the 1st sheet, the front-page. Figure 6.2. further illustrates a summary of the information and methods in the following sheets. The tool consists in total of seven sheets which lead to the end result. In Chapter 6.3.2. to 6.5.3. further details of each sheet are given.

**Introduction**

This tool is part of the graduation research "The transition from traditional construction to circular construction".
An analysis of key parameters related to the transition process of building circular viaducts and bridges.

The tool has been developed for the construction sector and is intended to contribute to the decision-making of making first choices towards circular building in the initial phase of project and helps in considering the factors that play a role when reusing elements and reducing the usage or primary raw materials.

In this tool design alternatives are compared based on the key parameters that play a role in the transition process.
The key parameters considered and the design alternatives are described below. Further, the working method of the tool is also described below.

**Key parameters**

5 key parameters were identified in the transition process and further substantiated in sub-parameters

| **Parameters** | **Sub-parameters** | **Determination of:** |
|---|---|---|
| 1. Environmental impact | a. Life Cycle Analys | Environmental Cost Indicator (€) |
| | b. Circularity measurement | Circularity performance (%) |
| 2. Financial impact | Cost price determination based on type(s) of beams in design: | |
| | a. Traditional prefab conrete beam | Cost price of design (€) |
| | b. Circular prefab concrete beam | |
| | c. Residual prefab concrete beam | |
| 3. Supply and demand | a. Product specific offer | Indicator (-) |
| | b. Uncerntainty in supply | Indicator (-) |
| 4. Detachibility | a. Damage during dismantling | Indicator (-) |
| | b. Traffic disruption during dismantlin | Indicator (-) |
| 5. Reusability | a. Reusable potential | Indicator (-) |
| | b. (Residual) quality | Indicator (-) |
| | c. Norms, standards and certification | Indicator (-) |
| | d. Aesthetic requirements | Indicator (-) |

**Design alternatives - Variants**

Based on the research conducted, the design alternatives are drawn up, hereinafter to be called "Variants".
The variants vary from a traditional design to a circular design. Thus, 4 variants are drawn up.
In this research a Viaduct is considered, where on element level only prefab concrete beams are considered.

| **Variant** | **Prefab concrete beam** | **Remarks** |
|---|---|---|
| 0. Traditional design | traditional beams, made of primary raw materi | Reference variant |
| 1. Circular design | Modular beams, made of primary raw materials | New-reusable and future-proof beams |
| 2. Combination design | Modular beams and residual beams | Residual and New-reusable and future-proof beams |
| 3. Residual design | Residual beams | All beams in this design are going in their 2nd lifecycle |

*Figure 6.1 First sheet in developed tool - Introduction*

| Working method Tool<br>Each sheet of this Excel-file elaborates on the input values needed and method used in order to quantifiy the effect of the design alternatives on the parameters. | |
|---|---|
| General | **1. Input values**<br>In this sheet the input values of the case study and design alternatives are given. These are:<br>**I.** The surface (length and width) of the civil structure and span-length of the prefab concrete beams<br>**II.** Determination of prefab concrete beam profile type<br>**III.** Material quantities determination of a prefab concrete beam and the design alternative(s) - Bill of Materials<br>**IV.** Project information: Transportation distance and harvesting effort for residual prefab concrete beams |
| Environmental Impact | **2. Life Cycle Analysis - Environmental Costs determination**<br>In this sheet the environmental cost indicator (ECI) is calculated for each design alternative.<br>**I.** The ECI is determined using DuboCalc. Thus, the necessary input values for the case study considered are given.<br>These input values were obtained from the company.<br>**II.** The ECI value for each design alternative (variant) is calculated. The unit of this value is in €.<br>**III.** The assumptions made for each design alternative and their Life Cycle Analysis is also given.<br><br>**3. Circularity performance**<br>In this sheet the circularity performance of each design alternative is calculated. This method is described by Platform CB'23.<br>**I.** The necessary input values of the case study for the circularity performance calculation are given.<br>These are values regarding the specific weight of materials considered.<br>**II.** The impact indicators, described as Key Perfomance Indicators (KPI) of each design alternative is defined.<br>The circularity performance of each design alternative is calculated by summing up the main KPI's of that design alternative:<br>A. Percentage of secondary material used in a design<br>B. Percentage of materials that is released during the execution and that can be reused (replacement statement)<br>C. Percentage of elements designed for the project and easy to reuse in the future (demountable) |
| Financial impact | **4. Life Cycle Costing - Cost price determination**<br>In this sheet the cost price is determined of the design alternatives. The final cost price is determined based on the type(s) of prefab concrete beams in the design alternative.<br>**I.** Cost price determination of the types of beams considered:<br>A. Traditional prefab concrete beams: Cost price obtained from company (includes costs of additional activities)<br>B. Circular prefab concrete beams: Cost price obtained from company (includes costs of additional activities)<br>C. Residual prefab concrete beams: Cost price determined based on the costs of the activities executed for harvesting and repurposing of beams. Cost per activity obtained from company. |
| Supply and Demand, Detachibility, Reusability | **5. Indicators interviews results**<br>In this sheet the results of the expert interviews are given.<br>**I.** The effect of each design alternative on the sub-paramater is given of each expert<br>**II.** The average value is calculated based on the number of interviewee's<br>**III.** A substantiation is given of the average value (defined effect of the design alternative on sub-parameter)<br>**IV.** The results of the design alternatives are then compared for each sub-parameter |
| Results | **Results**<br>In this sheet the results are given.<br>**I.** The results of the previous sheets are summarized in this sheet<br>**II.** The boundaries (minimum and maximum) for each (sub)paramater is given<br>**III.** The results are then normalized<br>**IV.** The weights of each (sub)parameter are given<br>**V.** The final combined results are then visualized in a Radar chart and compared |

*Figure 6.2 First sheet in developed tool - Working method and summary of sheets*

## 6.3. Application - Case study

In order to set up the tool, a fictional case study has been used. This build further upon the defined design alternatives drawn up in Chapter 4.4. In the section below the case study will be described. As this research focusses on the transition process towards circular construction of viaducts and bridges, a bridge or viaduct will be considered. Further, the case study will also only zoom in further on an element level, namely of prefab concrete beams.

## Project description

The case study considers the construction of a viaduct of 75 meters long. The viaduct is divided in 3 girders field with each a span of 25 meters. For this project several design alternatives are being considered in the initial design stage, whereby different alternatives of inverted T prefab concrete beams are being considered. The alternatives vary from a traditional prefab concrete beams (newly produced) to a new reusable and future proof circular beams (modular beam). The amount of material used in order to produce the beams and which are input values for quantifying the effect of the environmental impact and financial impact, are further described in Appendix C. The inverted T-beam is chosen based on the span-length of a prefab concrete beam using the span diagram on the website of Haitsma Beton, which is also further elaborated in Appendix C1.

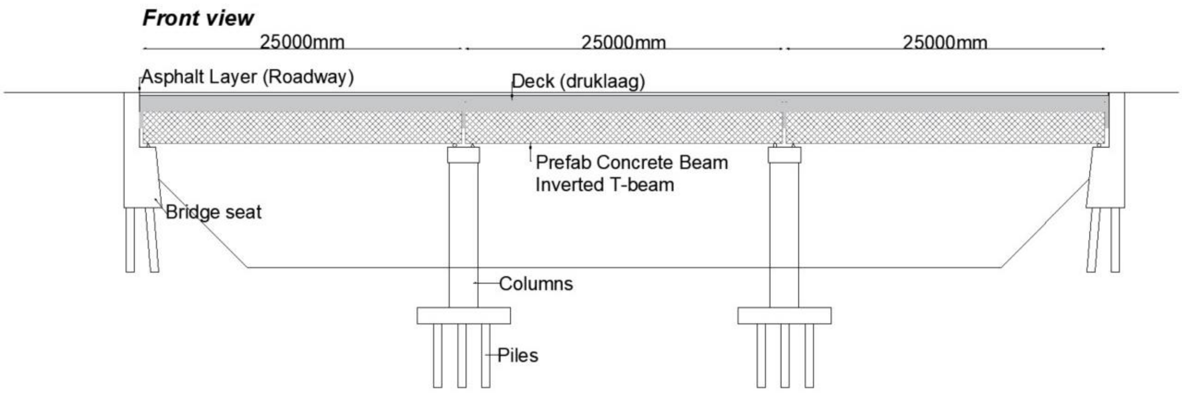



*Figure 6.3 Front view Case study Viaduct*

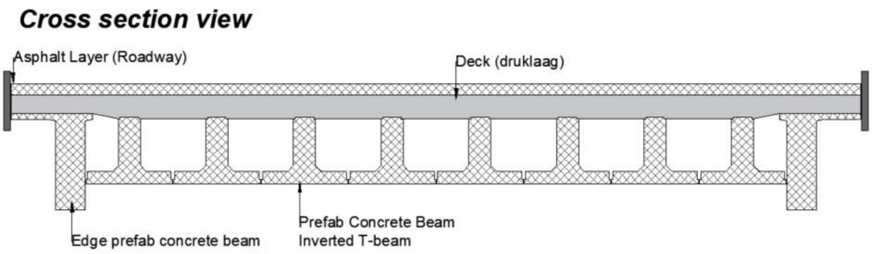



*Figure 6.4 Cross-section view Case study Viaduct*

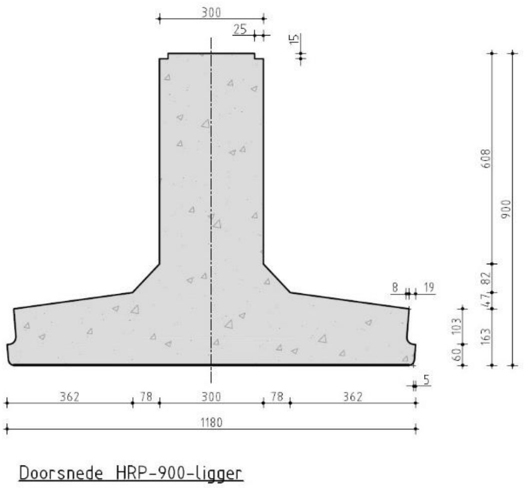



*Figure 6.5 Detail cross-section of Inverted T-beam (HRP-900), from haitsma beton (2009)*

### 6.3.1. Input values

In this chapter will be described what type of information is needed from a project in order to perform the calculations using the quantifications methods stated and why this information is needed. In Table 6.1. is elaborated on the input values needed in the tool. Each of the background information on the collection of these input values are elaborated in the following chapters and appendices. In Appendix A and B, the input values for the key-parameters 3, 4 and 5 are given. Their substantiations and final results are given in Chapter 6.3.5. In Chapter 6.3.3 and 6.3.4. the input values for using for the existing methods are elaborated. In Chapter 6.3.1 and 6.3.2. the input values for parameter 1 are elaborated. In Chapter 6.3.4. the input values for parameter 2 are elaborated. In the table below, Table 6.1., a summarized overview is given of the input values in the tool for each sub-parameter and parameter.

| Parameter | Sub-parameter | Input values in tool |
|---|---|---|
| 1. Environmental Impact | a. Life Cycle Analysis (LCA) | ○ Material quantities: concrete class and amount of concrete, steel, additional activities<br>This is elaborated in Chapter 6.3.1.<br>Environmental cost indicator (ECI) input values per material type obtained from DuboCalc (based on National Environmental Database)<br>This is elaborated in Chapter 6.3.3.1.<br>○ Minimum and maximum defined ECI in order to normalize values. |
| | b. Circularity Measurement | ○ Material quantities: type and amount of concrete class [m3] and steel [tonnes]<br>This is elaborated in Chapter 6.3.1.<br>○ The specific weight [ton/ unit] of each material type<br>This is elaborated in Chapter 6.3.3.2.<br>○ Input values of the main KPI's:<br>A. Percentage of secondary and biobased materials used in the project<br>B. Percentage of materials that are released during the project and that reused (high or equivalent)<br>C. Percentage of objects that are designed in such a way that they can be easily reused in the future.<br>○ Minimum and maximum defined circularity performance [%] in order to normalize values |
| 2. Financial Impact | Cost price determination based on type(s) of beams in design:<br>a. Traditional prefab concrete beam<br>b. Circular prefab concrete beam<br>c. Residual prefab concrete beam | ○ Traditional prefab concrete beam: Cost price [€/$m^2$] obtained from company (includes costs of additional activities)<br>○ Circular prefab concrete beams: Cost price [€/$m^2$] obtained from company (includes costs of additional activities)<br>○ Residual prefab concrete beams: Cost price determined based on the costs of the activities executed for harvesting and repurposing of beams. Cost per activity [€/$m^2$] obtained from company.<br>This elaborated in Chapter 6.3.4.<br>○ Design alternatives material quantities in $m^2$.<br>This is elaborated in Chapter 6.3.4. |

| | | |
|---|---|---|
| | | ○ Minimum and maximum defined cost price in order to normalize values. |
| 3. Supply and demand | a. Product specific offer | ○ Defined average indicator through expert interviews |
| | b. Uncertainty in demand | ○ Defined average indicator through expert interviews |
| 4. Detachability | a. Damage to beams during dismantling | ○ Defined average indicator through expert interviews |
| | b. Traffic disruption during dismantling | ○ Defined average indicator through expert interviews |
| 5. Reusability | a. Reusable potential | ○ Defined average indicator through expert interviews |
| | b. (Residual) quality | ○ Defined average indicator through expert interviews<br>○ Liability and risk factor (described in Chapter 4.5.3) |
| | c. Norms and standards | ○ Defined average indicator through expert interviews |
| | d. Aestetic requirements | ○ Defined average indicator through expert interviews |

*Table 6.1 Summarized overview information input values*

### 6.3.2. Material quantities determination – Bill of Materials

The case study in this research is based on the design alternatives elaborated for the transition from traditional building to circular building. The design alternatives are considered to be a viaduct with three beam fields of each the same beam span. However, in order to perform further calculations a more detailed design was needed, whereby the beam span is stated clearly. After deciding on the beam span, the profile type of inverted T-beam can be chosen. Thus first, a beam span has been indicated of 25000mm. This can be seen in Figure 6.6. This choice has been made based on the information gained from the company and field practices, whereby the common prefab concrete beam length used in the past and which is currently mostly being released from existing civil structures has a span between 20-25m.

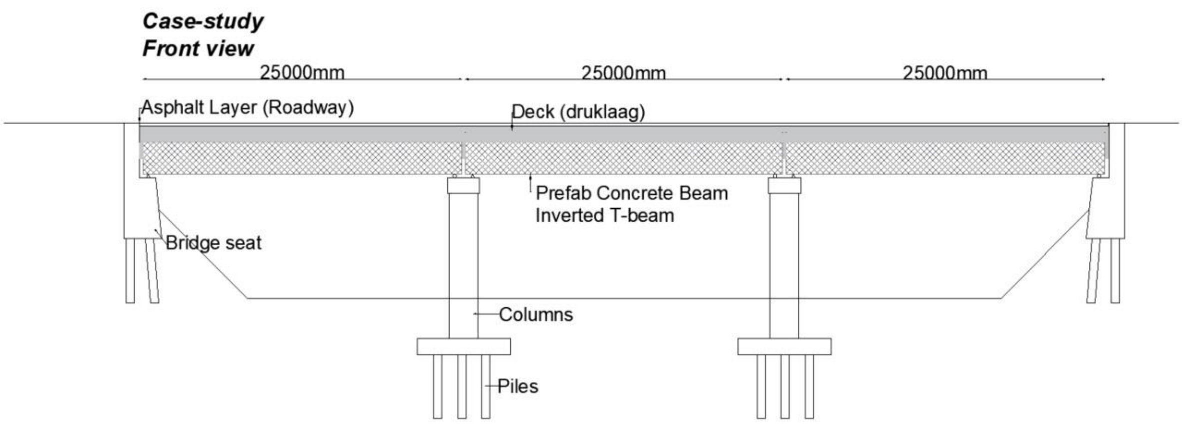



*Figure 6.6 Front view Case study viaduct - beam span indicated*

An inverted precast concrete T-beam consists of:

- Concrete [$m^3$], of a certain concrete class;
- Prestressed steel [tonnes];
- Reinforcement steel [tonnes].

In the section below, it will be mentioned how the material quantities that occur in a prefab concrete beam are determined.

### Concrete amount [m3] and concrete class

Next, based on the prefab concrete beam span determined, the profile type of the inverted T-beam can be determined. This has been done using information gained on the website of a prefab concrete elements supplier: haitsma beton (2009). From Figure 6.7. can be determined which profile type should be chosen for the case study based on the beam span length, stated as overspanning [m] (meaning: span) on the x-axis of the graph. Based on that information a profile type with a height of 900mm is chosen (Profiel HRP 900, also translated as inverted T-beam with a height of 900mm).

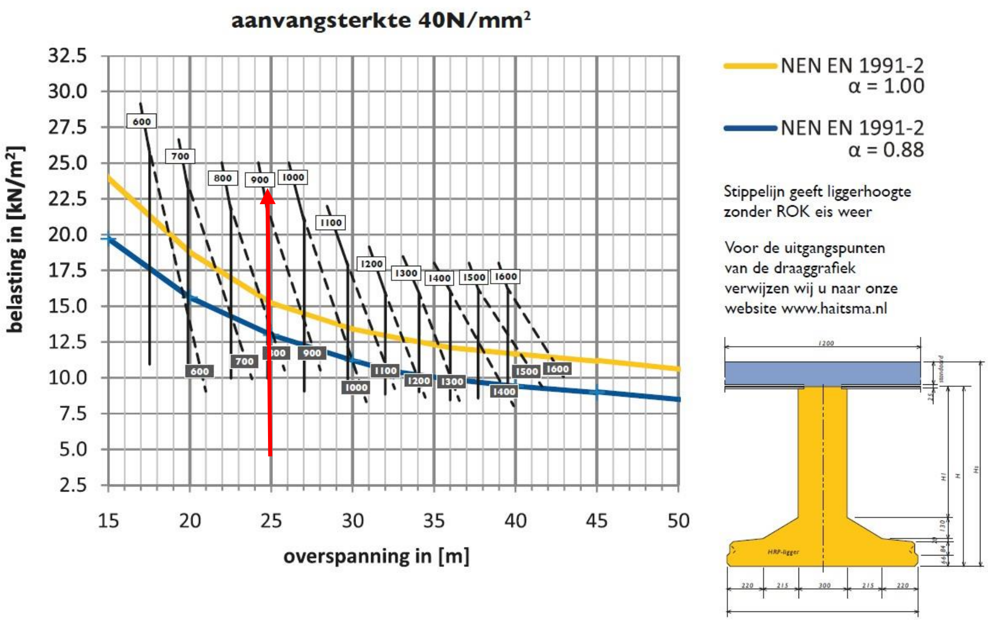



*Figure 6.7 Determination of profile type using span-length graph, from haitsma beton (2009)*

Further, the profile type has been determined, more detailed information can be found in Figure 6.8. based on profile types of inverted T-beams. From this figure the surface of a prefab concrete beam can be read in column Ab [in $mm^2$]. With this information the following amount of concrete [in $m^3$] of one prefab concrete beam can be calculated.

| | Element h.o.h. 1200mm | | | | | Samengesteld profiel, druklaag 250mm | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Profiel | B | Ab | V | I | $Q_{eg}$ | $Ab_s$ | Hs | $V_s$ | $EI_s$ | $Q_{egs}$ |
| HRP | mm[1] | mm² | mm | mm⁴ x10⁹ | kN/m | mm² | mm[1] | mm³ | Nmm² x10¹⁵ | kN/m |
| 500 | 300 | 3,15E+05 | 172 | 5,44 | 7,88 | 3,00E+05 | 750 | 373 | 1,39 | 15,38 |
| 600 | 300 | 3,45E+05 | 204 | 9,30 | 8,63 | 3,00E+05 | 850 | 424 | 1,96 | 16,13 |
| 700 | 300 | 3,75E+05 | 240 | 14,7 | 9,38 | 3,00E+05 | 950 | 475 | 2,65 | 16,88 |
| 800 | 300 | 4,05E+05 | 277 | 21,9 | 10,13 | 3,00E+05 | 1050 | 525 | 3,46 | 17,63 |
| 900 | 300 | 4,35E+05 | 316 | 30,9 | 10,88 | 3,00E+05 | 1150 | 576 | 4,4 | 18,38 |
| 1000 | 300 | 4,65E+05 | 357 | 42,1 | 11,63 | 3,00E+05 | 1250 | 626 | 5,47 | 19,13 |
| 1100 | 300 | 4,95E+05 | 398 | 55,5 | 12,38 | 3,00E+05 | 1350 | 677 | 6,68 | 19,88 |
| 1200 | 300 | 5,25E+05 | 441 | 71,3 | 13,13 | 3,00E+05 | 1450 | 728 | 8,04 | 20,63 |
| 1300 | 300 | 5,55E+05 | 485 | 89,7 | 13,88 | 3,00E+05 | 1550 | 778 | 9,55 | 21,38 |
| 1400 | 300 | 5,85E+05 | 529 | 111,0 | 14,63 | 3,00E+05 | 1650 | 828 | 11,2 | 22,13 |
| 1500 | 300 | 6,15E+05 | 573 | 135,0 | 15,38 | 3,00E+05 | 1750 | 879 | 13,1 | 22,88 |
| 1600 | 300 | 6,45E+05 | 619 | 162,0 | 16,13 | 3,00E+05 | 1850 | 929 | 15,1 | 23,63 |

- *Grafiekwaarden gebaseerd op betonkwaliteit elelementen, betonkwaliteit druklaag C30/37*
- *Profiel is tevens profielhoogt H.*
- *v (vs)= zwaartepuntsafstand (samengesteld) profiel vanaf onderzijde.*
- *Op aanvraag grotere overspanningen mogelijk.*

*Figure 6.8 Detailed information on profile types of inverted T-beams, from haitsma beton (2009)*

Lastly, the inverted prefab concrete T-beam from the case study is made of concrete with a concrete class C55/67. This has been determined using the help of the technical expert within the company whereby based on the experience in the field practices, the concrete class for beam with span of 20-25m is C55/67.

### Prestressed steel and reinforcement steel

Precast concrete beams are produced by a precast concrete supplier on the basis of a project and the project requirements. This makes it difficult to specify the amount of prestressed steel and reinforcing steel, expressed in tons, per beam type in general. However, for this research an assumption has been made with the help of prefab concrete beams produced for a previous project and the material quantities of the 2 types of steel in a beam have been converted for the case study and then calculated.

The information obtained from the company from the design of another project and the conversion for the case study are shown in Table 6.1.

| Material type | Span of beam [m] | Conversion factor | Quantity [kg /beam] | Quantity [ton /beam] |
|---|---|---|---|---|
| Precast concrete beam (information gained from company) | 14,145 | - | - | - |
| Prestressed steel | - | - | 266,5 | 0,2665 |
| Reinforced steel | - | - | 609 | 0,609 |
| | | | | |
| Precast concrete beam | 25 | $\frac{25m}{14{,}145m} = 1{,}76741$ | - | - |
| Prestressed steel | - | $1{,}76741\ x\ 266{,}5\ kg$ | 471,014 | 0,471 |
| Reinforced steel | - | $1{,}76741\ x\ 609\ kg$ | 1076,35 | 0,1076 |

*Table 6.2 Material quantities determination for steel in beam using conversion factor*

Note: the actual prestressed and reinforced steel amount in an inverted prefab concrete T-beam with a span of 25m and height of 900mm may slightly differ as the calculation has been conducted with a conversion factor.

Material quantities - Case study

In Table 6.3. the material information is given for further calculations of the environmental impact. In Table 6.4. the material quantities are determined.

| Inverted T-beam profile | HRP 900 | | Note: |
|---|---|---|---|
| **Concrete class** | C55/67 (CEMI-CEMIII) | m3 | The amount of concrete mortar (m3) in a beam can be calculated using the information in the table and span-length of beam and the specified concrete class is needed for the LCA calculation |
| **Prestressed steel** | No specification needed | Kg or Tonnes | The amount of steel in a prefab concrete beam varies and is produced by a supplier based on project requirements; No specification needed for calculations |
| **Reinforcement steel** | No specification needed | Kg or Tonnes | The amount of steel in a prefab concrete beam varies and is produced by a supplier based on project requirements; No specification needed for calculations |

*Table 6.3 Material information for further calculations*

| Quantity m3 Concrete mortar C55/67 (CEMI-CEMIII) | | | | | | |
|---|---|---|---|---|---|---|
| Profile type | Ab | Span-length | mm3/beam | # Beams | Total | Total |
| | mm2 | mm | | 3 fields x 8 | mm3 | m3 |
| HRP 900 | 435000 | 25000 | 10875000000 | 24 | 2,61E+11 | 261 |

| Quantity steel in HRP 900 | | | | | | |
|---|---|---|---|---|---|---|
| Profile type | 1 Beam | 1 Beam | | # Beams | Total | Total |
| | kg | Tonnes | | 3 velden x 8 | kg | Tonnes |
| Prestressed steel | 471,01 | 0,47 | | 24 | 11304,35 | 11,30 |
| Reinforcement steel | 1076,35 | 1,08 | | 24 | 25832,45 | 25,83 |

*Table 6.4 Materials quantification Case study*

The information described in this chapter is needed in order to determine the Environment Cost Indicator (ECI) [€] using the software tool DuboCalc in which the Life Cycle Analysis of an element is implemented and for determining the Circularity Performance [%] of the design alternatives.

### 6.3.3. Environmental impact determination

In this chapter the Environmental impact input values and results will be described that come out of the existing calculation method. These are the results of the Life Cycle Analysis whereby the ECI determined using the values from DuboCalc and circularity performance using the method described by Platform CB'23.

#### 6.3.3.1. Life Cycle Analysis

In order to perform a correct Life Cycle Analysis of a product, an Environmental Product Declaration (EPD) is needed. This EPD is obtained from the supplier of a product. An EPD indicates the environmental performance of a supplier's product. The supplier has this assessment carried out by an independent institute in order to emphasize the environmental performance of their product. In order to perform the correct Life Cycle Analysis for prefab concrete beams, the EPD would be needed from a prefab concrete supplier. However, on closer inspection, it is more pragmatic to make use of DuboCalc for making considerations in the initial design phase of the project. With this instrument a trade-off can be made between variants on the environmental impact with less detailed data. Using the correct LCA methodology requires more detailed information that is not available at this stage of the project (initial design stage), mainly because the exact supplier is still unknown.

Input values from DuboCalc

These values have been obtained from DuboCalc and are displayed in Table 6.3. as the ECI/unit in order to calculate the total ECI of the design alternatives in this research. This table consists of ECI values of the materials (concrete, prestressed steel and reinforcement steel) and additional activities (Transport, drilling and sawing of beams). For newly produced prefab concrete beams the materials information is enough. However, for residual beams, the environmental impact of the activities performed in order to harvest beams and make them reusable need to be taken into account.

| Item | Item name as written in Dubocalc | amount | unit | Environmental Cost Indicator |
|---|---|---|---|---|
| Concrete mortar C55/67 (CEMI-CEM III) | Betonmortel C55/67 (CEMI-CEMIII) | 1 | m3 | 35,17 |
| Prestressed steel | Voorspanstaal | 1 | ton | 115,14 |
| Reinforcement steel | Betonstaal | 1 | ton | 106,24 |
| Transport bulk (by road) - Concrete | Transport bulk (over de weg) | 2,437 | tonkm | 5,6625 |
| Drilling beams | Compr.diesel 3.5-10.0 m3/min | 1 | h | 4,48 |
| Sawing beams | Compr.diesel 3.5-10.0 m3/min | 1 | h | 4,48 |

*Table 6.5 Input values DuboCalc*

Environmental cost indicator determination for Variant 0 to 3

In this part the calculated environmental cost indicators will be given. The adjusted Life Cycle Analysis for the relevant variant will also be given and de substantiation of the calculations and assumptions.

*Variant 0: Traditional design*

The environmental cost calculation for Variant 0 is given in Table 6.6. This design is made out of 100% raw primary materials. The corresponding Life Cycle Analysis is given in Figure 6.9. For the traditional design the obtained values from DuboCalc are used and not adjusted to specific Life Cycle Analysis for that design.

| ECI Value Variant 0: Traditional design | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| Prefab concrete beam | Concrete mortar C55/67 (CEMI-CEM III) | 261 | m3 | € 35,17 | € 9.179,37 |
| | Prestressed steel | 11 | Tonnes | € 115,14 | € 1.301,58 |
| | Reinforcement steel | 26 | Tonnes | € 106,24 | € 2.744,44 |
| **Total** | | | | | **€ 13.225,39** |

*Table 6.6 ECI determination Variant 0*

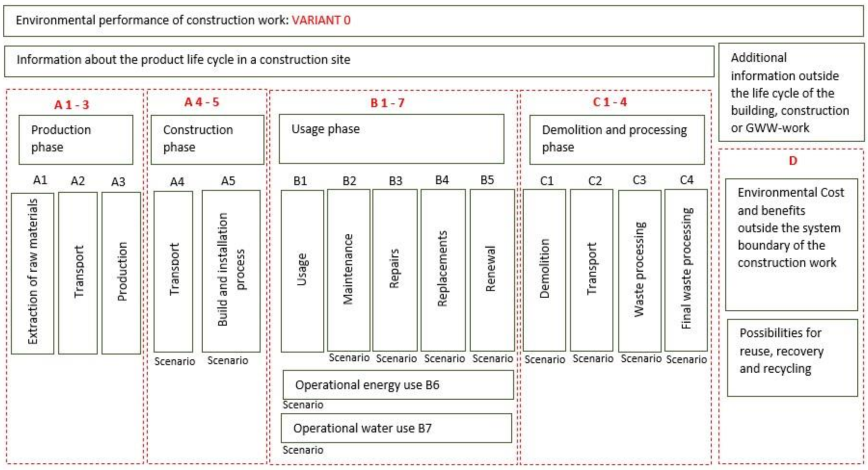



*Figure 6.9 Life Cycle Analysis Variant 0*

*Variant 1: Circular design*

The environmental cost calculation for Variant 1 is given in Table 6.7. The corresponding Life Cycle Analysis is given in Figure 6.10. Additional notes for Variant 1:

1. The prefab concrete beams are made out of 100% primary materials and same composition as the traditional beam; however, the beams are modular and thus reusable and future-proof
2. The composition in materials of the modular beams = Composition in materials of traditional beams
3. The quantity of materials traditionally produced beam with primary material = newly produced modular beam
4. For both the concrete and steel in a prefab concrete beam, a product lifespan of 100 years is determined in DuboCalc and included in the ECI and LCA. According to recent studies, prefab concrete beams can last for 200 years. Thus, it is assumed that the total environmental costs are spread over 200 years as this design considers modular beams and the environmental burden of the variant in the 1st lifecycle counts for ½.
5. The product life span of 100 years is divided in reality over an actual lifespan of 200 years = 100/200 = ½

| ECI Value Variant 1: Circular design with new produced modular beams | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| Prefab concrete beam | Concrete mortar C55/67 (CEMI-CEM III) | 261 | m3 | € 35,17 | € 9.179,37 |
| | Prestressed steel | 11 | Tonnes | € 115,14 | € 1.301,58 |
| | Reinforcement steel | 26 | Tonnes | € 106,24 | € 2.744,44 |
| | ½ x Total ECI at expense of current project | ½ | | | € -6.612,70 |
| **Totaal** | | | | | **€ 6.612,70** |

*Table 6.7 ECI determination Variant 1*

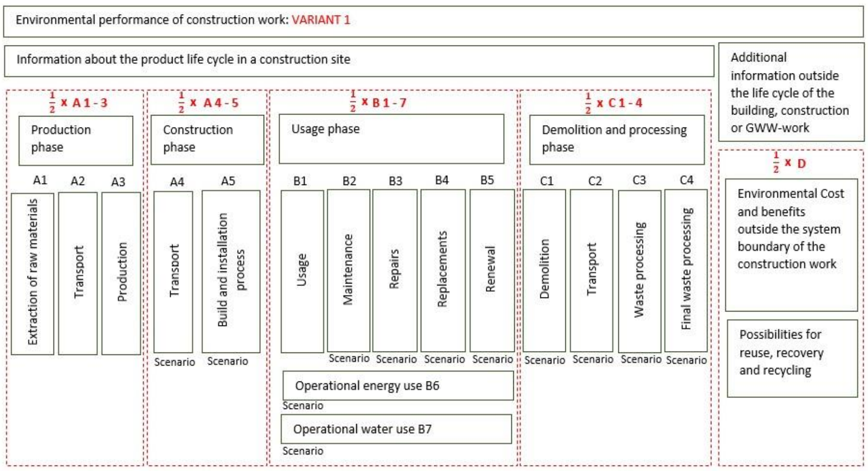



*Figure 6.10 Life Cycle Analysis Variant 1*

*Variant 2: Combination design*

The environmental cost calculation for Variant 2 is given in Table 6.8. The corresponding Life Cycle Analysis is given in Figure 6.11. and 6.12. Additional notes for Variant 2:

1. This design consists of 1/3 new produced reusable modular beam and 2/3 residual beams
2. The 1/3 new reusable beams are of the same composition as described in Variant 2
3. The 2/3 residual beams are going in their 2$^{nd}$ lifecycle; thus, they are free from environmental costs for the production, construction, usage phase. However, the transportation and harvesting effort are taken into account

4. The transportation (in km) is divided = half of the environmental costs is at the expense of the harvesting location and half is at the expense of the new to-be built project (this variant). This is also implemented in the transport bulk ECI/unit value.

| ECI Value Variant 2: Combination design of new-reusable modular beams (1/3) and residual beams (2/3) | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| 1/3 modular prefab concrete beams | Concrete mortar C55/67 (CEMI-CEM III) | 87 | m3 | € 35,17 | € 3.059,79 |
| | Prestressed steel | 4 | Tonnes | € 115,14 | € 433,86 |
| | Reinforcement steel | 9 | Tonnes | € 106,24 | € 914,81 |
| | ½ x Total ECI at expense of current project | | | | € 2.204,23 |
| | | | | | |
| 2/3 residual prefab concrete beams | Concrete mortar C55/67 (CEMI-CEM III) | 174 | m3 | € - | € - |
| | Prestressed steel | 8 | Tonnes | € - | € - |
| | Reinforcement steel | 17 | Tonnes | € - | € - |
| Transport | Transport bulk (by road) - Concrete | 424 | tonkm | € 5,66 | € 2.401,12 |
| Drilling beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 201,6 | h | € 4,48 | € 903,17 |
| Sawing beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 16 | h | € 4,48 | € 71,68 |
| Sawing beams (Modifying) | Compr.diesel 3.5-10.0 m3/min | 16 | h | € 4,48 | € 71,68 |
| **Totaal** | | | | | **€ 5.651,88** |

*Table 6.8 ECI determination Variant 2*

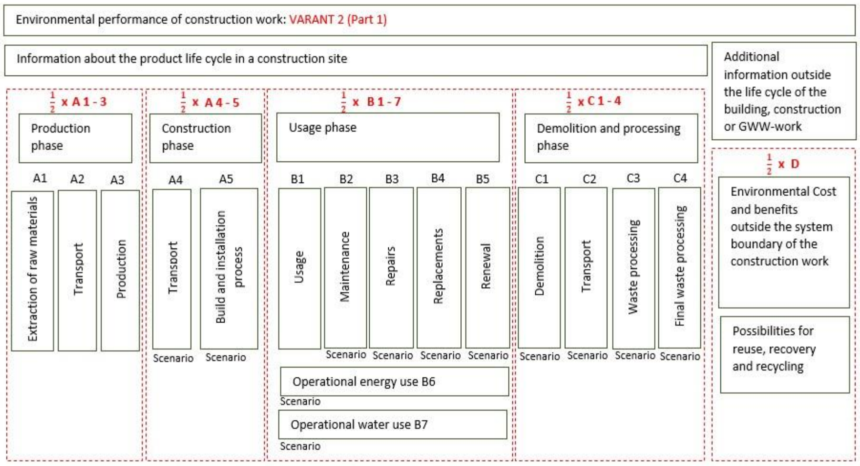



*Figure 6.11 Life Cycle Analysis Variant 2 (Part 1)*

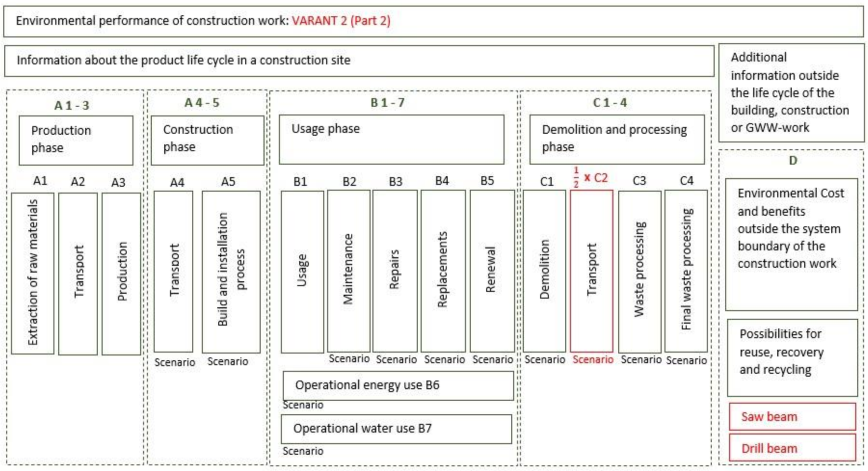



*Figure 6.12 Life Cycle Analysis Variant 2 (Part 2)*

*Variant 3: Residual design*

The environmental cost calculation for Variant 3 is given in Table 6.9. The corresponding Life Cycle Analysis is given in Figure 6.13. Additional notes for Variant 3:

1. All residual beams in this design are going in their 2nd lifecycle, thus they are free from environmental costs for the production, construction, usage phase. However, the transportation and harvesting effort (Drilling and Sawing of beams) are taken into account.
2. The transportation (in km) is divided; Thus, half of the environmental costs is at the expense of the harvesting location and half is at the expense of the new to-be built project (this variant). This is implemented in the transport bulk ECI/unit value.

| ECI Value Variant 3: Residual design | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| Residual prefab concrete beams | Concrete mortar C55/67 (CEMI-CEM III) | 261,0 | m3 | € - | € - |
| | Prestressed steel | 11,3 | ton | € - | € - |
| | Reinforcement steel | 25,8 | ton | € - | € - |
| Transport | Transport bulk (by road) - Concrete | 636 | tonkm | € 5,66 | € 3.601,67 |
| Drilling beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 302 | h | € 4,48 | € 1.354,75 |
| Sawing beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 24 | h | € 4,48 | € 107,52 |
| Sawing beams (Modifying) | Compr.diesel 3.5-10.0 m3/min | 24 | h | € 4,48 | € 107,52 |
| **Totaal** | | | | | **€ 5.171,46** |

*Table 6.9 ECI determination Variant 3*

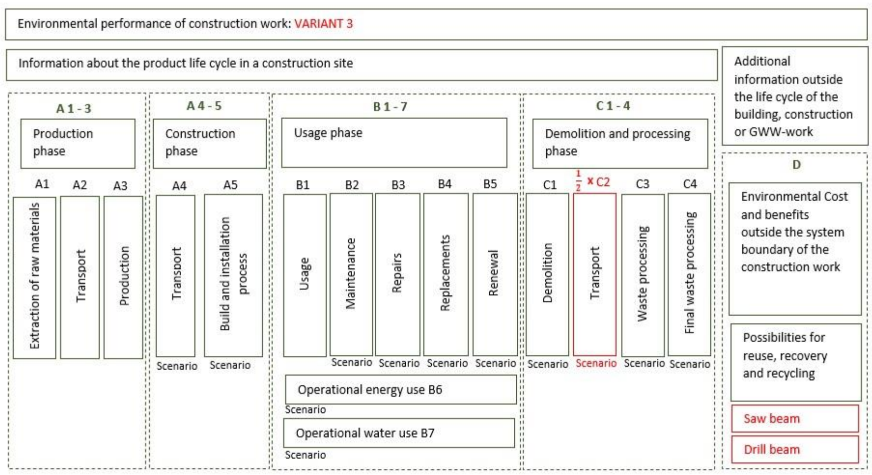



*Figure 6.13 Life Cycle Analysis Variant 3*

In order to compare the results of the Life Cycle Analysis with the other (sub)parameters, the results obtained in this process will be normalized. The normalization of values has been described in Chapter 4.5.3. The most undesirable scenario for the environmental costs (ECI) is the highest value that occurs between the design alternatives of the project. This means that in the case of the environmental costs, the higher the value, the less desirable the case is. Thus, in this research it is the highest value between Variant 0 and 3. The maximum value that can occur for the environmental impact is €0, this means no environmental impact which is the most desirable scenario. This is the most desirable or best case. The final results will be given in Chapter 6.4.

### 6.3.3.2. Circularity performance

In this part the circularity performance is determined. This is determined using the method described by Platform CB'23 and the implementation of this method by the company. In order to perform this calculation, the company has provided their own developed Microsoft Excel template for determining the circularity performance of a project. As this considers a civil structure on element level, the provided template and calculation was also simplified on element level and only the necessary information is described.

<u>Input values for circularity performance; obtained from the company</u>
These values have been obtained from the company in order to perform the circularity performance. This is given in Table 6.10. The original values of the specific weights come from the determination method 3.0.

| MATERIAAL SUPPLY | Unit | Phase | Specific weight (tonnes/unit) | Source Bepalingsmethode 3.0 |
|---|---|---|---|---|
| **Prefab concrete beam** | | | | |
| Concrete mortar C55/67 | **m3** | **A1-A3** | **2,437** | 2437 kg 0165-fab&Betonmortel C55/67 (o.b.v. 75% CEM III en 25% CEM I), 2437 kg/m3 - Nationale Milieudatabase v3.2 (obv Ecoinvent 3.5) per 1 uses 2,437 kg 275.36655 kg $CO_2$-eq x |
| Prestressed steel | **ton** | **A1-A3** | **1,000** | 1000 kg 0167-fab&Staal, wapening (betonstaal, wapeningsnet, vezels, voorspanstaal) (o.b.v. Reinforcing steel (GLO)\| market for \| Cut-off, U; 84% primair, 16% secundair) - Nationale Milieudatabase v3.2 (obv Ecoinvent 3.5) per 1 uses 1,000 kg 2,107.82603 kg $CO_2$-eq x |
| Reinforcement steel | **ton** | **A1-A3** | **1,000** | 1000 kg 0167-fab&Staal, wapening (betonstaal, wapeningsnet, vezels, voorspanstaal) (o.b.v. Reinforcing steel (GLO)\| market for \| Cut-off, U; 84% primair, 16% secundair) - Nationale Milieudatabase v3.2 (obv Ecoinvent 3.5) per 1 uses 1,000 kg 2,107.82603 kg $CO_2$-eq x |

*Table 6.10 Input values Circularity Performance calculation*

<u>Circularity performance determination for Variant 0 to 3</u>
In this part the circularity performance of each variant is determined. The approach for the relevant variant will also be given and de substantiation of the calculations. For each variant calculation, the input values of the main KPI's will be given. These are:
A. The % of secondary and biobased materials used in the project
B. The % of materials that are released during the project and that are reused (high or equivalent)
C. The % of objects that are designed in such a way that they can be easily reused in the future (demountable)

The percentage circularity of is determined using the following formula:

$$\text{Circularity performance } [\%] = \frac{Total\ weight\ circular\ per\ KPI\ [Tonnes]}{Total\ weight\ [Tonnes]} \text{ x } 100\%$$

*Variant 0: Traditional design*
The circularity performance calculation for Variant 0 is given in Table 6.10. This design is made out of 100% raw primary materials. Thus, all main KPI's are 0%.

| **Variant 0 Traditional design** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
| Concrete mortar C55/67 | **m3** | 261,0 | 2,4 | 636,057 | 0% | | 0,0 | 0,0 | 0% | | 636,1 | 0% | |
| Prestressed steel | **ton** | 11,3 | 1,0 | 11,3 | 0% | | 0,0 | 0,0 | 0% | | 11,3 | 0% | |
| Reinforcement steel | **ton** | 25,8 | 1,0 | 25,8 | 0% | | 0,0 | 0,0 | 0% | | 25,8 | 0% | |
| **TOTAL** | | | | | | | | | | | | | |
| Total weight | **ton** | | | 673,2 | | | | 0,0 | | | 673,2 | | |
| Total % per KPI | **%** | | | | 0% | | | | | | | 0% | |
| Total weight circular per KPI | **ton** | | | | 0 | | | | | | | 0 | |
| **% circularity of variant** | **%** | | | | | | | | | | | | **0%** |

*Table 6.11 Circularity performance Variant 0*

*Variant 1: Circular design*
The circularity performance calculation for Variant 1 is given in Table 6.12. The prefab concrete beams are made out of 100% primary materials and same composition as the traditional beam; however, the beams are modular and thus reusable and future-proof. Thus, KPI C is defined as 100%.

| Variant 1 Circular design | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
| Concrete mortar C55/67 | m3 | 261,0 | 2,4 | 636,057 | 0% | | 0,0 | 0,0 | 0% | | 636,1 | 100% | |
| Prestressed steel | ton | 11,3 | 1,0 | 11,3 | 0% | | 0,0 | 0,0 | 0% | | 11,3 | 100% | |
| Reinforcement steel | ton | 25,8 | 1,0 | 25,8 | 0% | | 0,0 | 0,0 | 0% | | 25,8 | 100% | |
| TOTAL | | | | | | | | | | | | | |
| Total weight | ton | | | 673,2 | | | | 0,0 | | | 673,2 | | |
| Total % per KPI | % | | | | 0% | | | | | | | 100% | |
| Total weight circular per KPI | ton | | | | 0 | | | | | | | 673,2 | |
| % circularity of variant | % | | | | | | | | | | | | 50% |

*Table 6.12 Circularity performance Variant 1*

### *Variant 2: Combination design*

The circularity performance calculation for Variant 2 is given in Table 6.13. This is a combination design of residual prefab concrete beams and newly produced modular prefab concrete beams. Thus, for KPI A, it is stated that 67% of the total weight are secondary materials used in this project. KPI B is 0%, because the released beams are assumed to be from another project, thus not released within the same project and reused. KPI C is 33%, this is for the 1/3 parts of this design which is made out of new produced modular beams. These objects are produced in such a way that they can be reused in the future.

| Variant 2 Combination design | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
| Concrete mortar C55/67 | m3 | 261,0 | 2,4 | 636,057 | 67% | 2/3*100% are secundary beams | 174,0 | 424,0 | 0% | | 636,1 | 33% | 1/3*100% are modular beams |
| Prestressed steel | ton | 11,3 | 1,0 | 11,3 | 67% | 2/3*100% are secundary beams | 7,5 | 7,5 | 0% | | 11,3 | 33% | 1/3*100% are modular beams |
| Reinforcement steel | ton | 25,8 | 1,0 | 25,8 | 67% | 2/3*100% are secundary beams | 17,2 | 17,2 | 0% | | 25,8 | 33% | 1/3*100% are modular beams |
| TOTAL | | | | | | | | | | | | | |
| Total weight | ton | | | 673,2 | | | | 448,8 | | | 673,2 | | |
| Total % per KPI | % | | | | 67% | | | | 0% | | | 33% | |
| Total weight circular per KPI | ton | | | | 448,8 | | | | 0 | | | 224,4 | |
| % circularity of variant | % | | | | | | | | | | | | 37% |

*Table 6.13 Circularity performance Variant 2*

### *Variant 3: Combination design*

The circularity performance calculation for Variant 3 is given in Table 6.14. This is a design with residual prefab concrete beams. Thus, for KPI A, it is stated that 100% of the prefab concrete beams used are secondary.

| Variant 3 Residual design | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
| Concrete mortar C55/67 | m3 | 261,0 | 2,4 | 636,057 | 100% | 2/3*100% are secundary beams | 261,0 | 636,1 | 0% | | 636,1 | 0% | |
| Prestressed steel | ton | 11,3 | 1,0 | 11,3 | 100% | 2/3*100% are secundary beams | 11,3 | 11,3 | 0% | | 11,3 | 0% | |
| Reinforcement steel | ton | 25,8 | 1,0 | 25,8 | 100% | 2/3*100% are secundary beams | 25,8 | 25,8 | 0% | | 25,8 | 0% | |
| TOTAL | | | | | | | | | | | | | |
| Total weight | ton | | | 673,2 | | | | 673,2 | | | 673,2 | | |
| Total % per KPI | % | | | | 100% | | | | 0% | | | 0% | |
| Total weight circular per KPI | ton | | | | 673,2 | | | | 0 | | | 0 | |
| % circularity of variant | % | | | | | | | | | | | | 33% |

*Table 6.14 Circularity performance Variant 3*

In order to compare the results of the Circularity Performance with the other (sub)parameters, the results obtained in this process will be normalized. The normalization of values has been described in Chapter 4.5.3. The most undesirable value for the circularity performance is defined as 0%. This means a 0% on circularity performance which most undesirable scenario that can occur. The maximum value is defined as 100%. This means 100% on circularity performance, which is the best or most desired scenario. The final results will be given in Chapter 6.4.

### 6.3.4. Financial Impact determination

In this chapter the financial impact determination is described. The financial impact of the design alternatives will be determined based on the type of prefab concrete beam in the relevant design alternatives. Looking at the design alternatives and zooming in on element level, thus only looking at prefab concrete beams, it can be determined that there are three types of prefab concrete beams divided over the four design alternatives. In the case study during this research these are:

1. Traditional precast concrete beam (new produced)
2. Circular (modular) precast concrete girder (new produced)
3. Released residual inverted prefab concrete T-beams

For each of the types, the cost price will be determined. However, the determination of the cost price differs based on the type of beam and the costs of the process for obtaining the beams. Table 6.15. shows the cost price determination per prefab concrete beam type. The activities are also elaborated which must be included for the cost price determination of the prefab concrete beam types. The elaboration of the activities relates to the Activity-Based Costing method in combination with the Life Cycle Costs for determining the cost price of a civil structure. The cost prices in €/m$^2$ are obtained from the company. The approach used in this part is simplified, there the translation of cost prices in €/m$^2$. When considering costs for a real project, the price per m$^2$ is strongly dependent on the type of beam used for that design. Thus, the price per m$^2$ given in this research are not representative as real values. However, they are detailed enough for this research in order to make a comparison of design alternatives in the initial design phase.

| Cost Price Determination | Costs | Unit |
|---|---|---|
| **1. Traditional prefab concrete beam - purchased from precast concrete producer / supplier** | **360,00** | **€/m2** |
| A. Engineering and calculation costs | | |
| B. Transportation costs - from suplier to project location | | |
| C. Overhead costs | | |
| | | |
| **2. Circular prefab concerete beam - purchased from concrete producer / supplier** | **378,00** | **€/m2** |
| A. Engineering and calculation costs | | |
| B. Transportation costs - from suplier to project location | | |
| C. Overhead costs | | |
| D. Extra engineering, development and processing costs for making a modular beam | | |
| NOTE: the cost price of a modular beam is determined to be 5% higher in costs compared to a traditional beam | | |
| | | |
| **3. Residual prefab concrete beam - from existing civil structure** | **433,34** | **€/m2** |
| A. Research and overhead costs | 35,24 | €/m2 |
| A.1. Field work, inspection harvesting beam from existing civil structure | | |
| A.2. Research and development costs into beam condition and applicability/suitability for new civil structure | | |
| A.3. Laboratory research into (residual) quality | | |
| A.4. Inspection of processed and adjusted residual beam (by an independent agency) | | |
| A.5. Engineering and construction calculation | | |
| A.6. Second opinion (If another assessment is required after the first assessment) | | |
| A.7. Overhead costs | | |
| | | |
| B. Handling Cost = Costs to harvest the beam from existing civil structure | 129,99 | €/m2 |
| B.1. Drilling beam and sawing from existing civil structure (from beam field) (Material + manpower) | | |
| B.1.1. Disassembling of beam ends between beam fields / abutments | | |
| B.1.2. Decoupling of beams by sawing between the in-situ pressure layer | | |
| B.2. Lifting the beam for reuse from existing civil structure (from civil structure to trailer for transport) | | |
| | | |
| C. Logistical costs | 58,51 | €/m2 |
| C.1. Location of beam (above land/road or water) and extra time needed (in planning) for careful disassembling | | |
| C.1.1. Over land = extra time needed to cause as little traffic disturbance as possible (leads to longer lead time) | | |
| C.1.2. Above water = Demolition of beams as harvesting (disassembling) takes place in the same way (no traffic disruption | | |
| C.2. Transportation costs | | |
| C.2.1. From supplier (factory) to destination | | |
| C.2.2. Transport: from harvest site to temporary storage site/location | | |
| C.2.3. Transport: from storage location to new destination | | |
| C.2.4. Transport: from harvest site to new destination (Ideal situation - no storage costs) | | |
| | | |
| D. Temporary storage costs and processing costs | 209,6 | €/m2 |
| D.1. Storage costs of beams with an unknown repurposing | | |
| D.2. Processing costs | | |
| D.2.1. Removal of deck (druklaag) using drilling machine | | |
| D.2.2. Shortening of beam on the basis of repurposing requirements (in the span length required) | | |

*Table 6.15 Cost price determination prefab concrete beams*

<u>Financial impact determination for Variant 0 to 3</u>

In this part the financial impact will be determined for Variant 0 to 3. The financial impact is determined by determining the cost price of the relevant design alternative. As stated before, the prices are given in €/m$^2$. Thus, in order to calculate the total cost price, the surface of the to-be calculated part of the civil structure should be known. Table 6.16. illustrates the financial impact of variant 0. Table 6.17. illustrates the financial impact of variant 1. Table 6.18. illustrates the financial impact of variant 2. Table 6.19. illustrates the financial impact of variant 3.

*Variant 0: Traditional design*

| **Variant 0** | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - Traditional elements | 708 | m2 |
| 1. Traditional prefab concrete beam - purchased from precast concrete producer / supplier | 360,00 | €/m2 |
| Total costs | € 254.880,00 | |

*Table 6.16 Financial impact Variant 0*

*Variant 1: Circular design*

| **Variant 1** | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - New reusable elements | 708 | m2 |
| 2. Circular prefab concrete beam - purchased from concrete producer / supplier | 378,00 | €/m2 |
| Total costs | € 267.624,00 | |

*Table 6.17 Financial impact Variant 1*

*Variant 2: Combination design*

| **Variant 2** | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - Residual element | 472 | m2 |
| Surface viaduct - New reusable elements | 236 | m2 |
| 3. Residual prefab concrete beam - from existing civil structure | 433,34 | €/m2 |
| 2. Circular prefab concrete beam - purchased from concrete producer / supplier | 378 | €/m2 |
| Total costs | € 293.744,48 | |

*Table 6.18 Financial impact Variant 2*

*Variant 3: Residual design*

| **Variant 3** | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - Residual elements | 708 | m2 |
| 3. Residual prefab concrete beam - from existing civil structure | 433,34 | €/m2 |
| Total costs | € 306.804,72 | |

*Table 6.19 Financial impact Variant 3*

In order to compare the results of the Financial Impact with the other (sub)parameters, the results obtained in this process will be normalized. The normalization of values has been described in Chapter 4.5.3. The minimum and maximum boundary are defined for the financial impact. The minimum is, is the most undesirable value, which is defined as the highest value that will occur between the design alternatives in a project. Thus, in this research it is the highest value between Variant 0 and 3. The maximum value, most desirable value, that can occur for the financial costs is €0, this means no financial impact thus no costs that occur. This is the most desirable or best case.

### 6.3.5. Supply and Demand, Reusability and Detachability determination

In this chapter the values of the parameters supply and demand, reusability and detachability will be elaborated. These values were obtained through the developed method described in Chapter 4.5.2. and interviews with experts. In Appendix A2. an elaborate overview is given of the obtained results per interviewee. In total 9 interviews were conducted. However, the final value per (sub)parameter was obtained by taking the average. In this chapter the final value will be given including the substantiation.

#### 6.3.5.1. Supply and Demand

In Table 6.20. the effect of each design alternative is determined for the sub-parameters of the supply and demand of secondary prefab concrete beams. The sub-parameters here are the product specific offer and uncertainty in supply. In addition to the final obtained results, also a substantiation is given for each value.

| (Sub)Parameter | Variants | Unit [-] | Value substantiation: |
|---|---|---|---|
| **3. Supply and demand** | | | |
| **a. Product specific offer** | 0. Traditional | 0,99 | The product specific offer of secudary beams before the first life cycle of the traditional design does not apply here. However, there will be a challenge as less primary material should be used in the future. Thus the value is not 1. |
| | 1. (New) Circular | 0,83 | The product-specific range of secundary beams before the first life cycle of the circular design presents a challenge because the connection possibilities with the abutments and between the girders must be taken into account and despite having influence on the design, you have to think about the future. |
| | 2. Combination | 0,50 | It is a challenge for having a fit-for-purpose beams due to the span-length. If the freed beam is smaller than 10m, it is no longer reusable. However, in the combination design, the part with the new beams can absorb the challenges and the beams can be newly produced for the project. |
| | 3. Complete residual | 0,24 | The product specific offer of secundary beams before the first life cycle of the residual design pose a challenge due to adaptability of the available beam size in the required size and as this design considers 100% residual beam, the shortage of residual beams can occur. |
| | | | |
| **b. Uncertainty in supply** | 0. Traditional | 0,93 | There is always a small degree of uncertainty in the supply (supply risk) before the first life cycle of the traditional due to the high demand for precast concrete beams and limited number of suppliers/producers on the market and limited primary raw material stock. |
| | 1. (New) Circular | 0,86 | There is a degree of uncertainty in the supply (supply risk) before the first life cycle of the circular design because the modular prefab concrete beams still have to be developed and are not yet available and thus the suitability and availability are unknown. |
| | 2. Combination | 0,37 | The supply risk for the combination design before the first life cycle is higher as this design considers 75% residual beams and 25% new produced modular beams. Thus it is uncertain whether beams will be available on time and thus also suitable. If this design would consider a lower % of residual beams then supply risk would be lower. |
| | 3. Complete residual | 0,17 | The uncertainty in the supply of secondary beam (supply risk) before the first life cycle of the residual design is high due to the high demand for secondary materials, the timely availability is unknown and the suitability for repurposing is unknown. |

*Table 6.20 Supply and demand determination Variant 0 to 3*

#### 6.3.5.2. Detachibility

In Table 6.21. the effect of each design alternative is determined for the sub-parameters for the reusability of prefab concrete beams. The sub-parameters here are the reusable potential, (residual) quality, norms, standards and certification and the aesthetic requirements. In addition to the final obtained results, also a substantiation is given for each value.

| (Sub)Parameter | Variants | Unit [-] | Value substantiation: |
|---|---|---|---|
| **4. Detachibility of prefab concrete beams** | | | |
| **a. Damage during dismantling** | 0. Traditional | 0,34 | During the disamantling of prefab concrete beams from the existing structure (into its original form) after the first life cycle of a traditional design, damage to the beams will occur due to the fact that was not meant to be dismantled and given the current knowledge and experience there is no technical solution for removing the pressure layer. |
| | 1. (New) Circular | 0,69 | Dismantling of prefab concrete beams from an existing structure after the first life cycle of a circular design will never go without damage due to the limited knowledge and current experience for the removal of the pressure layer. However, more thought has been given to how this can be future-proof and reusable. |
| | 2. Combination | 0,52 | determined from the amount of reused beams and new beams in the design. As this design considers 75% residual beams, which were once traditionally produced, there is some degree of damage during dismantling. |
| | 3. Complete residual | 0,43 | When considering the residual design, after the first life cycle of this design, the prefab concrete beams are going in their 3rd life cycle. Thus there will also be a certain amount of damage. However, thought might be given beforehand on the dismantling process and limitation of damage for a 3rd repurpose. |
| | | | |
| **b. Traffic disruption during dismantling** | 0. Traditional | 0,10 | Additional time needs to be planned for limited traffic disruption when harvesting the beams from an existing deck of beams, after the first life cycle of a traditional design, because something needs to be dismantled that wasn't designed to be dismantled. Further, due to the current limited experiences, more time is needed for harvesting. |
| | 1. (New) Circular | 0,61 | For the circular design it is assumed that consideration has been given in advance to detaching as efficiently as possible and to cause as little traffic disruption as possible. However, there will always be a degree of traffic disruption if the beam fields lie above another road. |
| | 2. Combination | 0,48 | Extra time in the planning, regarding traffic disruption, after the first lifecycle of a combination design should also be taken into account. However, it is limited because it is assumed that this has been considered in advance. |
| | 3. Complete residual | 0,29 | For the residual design, extra time should also be taken into account for limited traffic disruption as this design considers only residual (traditionally produced) prefab concrete beams. Thus, the same applies more or less as variant 0. |

*Table 6.21 Reusability determination Variant 0 to 3*

### 6.3.5.3. Reusability

In Table 6.22. the effect of each design alternative is determined for the sub-parameters of the reusability of prefab concrete beams. The sub-parameters here are damage to the beams during dismantling and traffic disruption during dismantling. In addition to the final obtained results, also a substantiation is given for each value.

As described in Chapter 4.5.4., the liability and risk when using residual beams play an important role in the contracting process and making it possible to execute a project with residual element. Thus, this will be taken into account in the sub-parameter (residual) quality. In this research, it is translated as an undesirable factor of 10% on the obtained value. Thus, the obtained value will decrease with 10%. However, for another project this might me adjusted according the impact of the liability and risk in the given project.

| (Sub)Parameter | Variants | Unit [-] | Value substantiation: |
|---|---|---|---|
| **5. Reusability of prefab concrete beams** | | | |
| **a. Reusable potential** | 0. Traditional | 0,46 | The degree of waste production that will take place after the first life cycle of the traditional design is high because these beams will still be adapted for reuse. |
| | 1. (New) Circular | 0,86 | The degree of waste production that will take place after the first life cycle of a circular design is limited. However, it is not possible to harvest waste-free and adjusments might be necessary be before the prefab concrete beams can be reused. |
| | 2. Combination | 0,61 | The degree of waste production that will take place after the first life cycle of a the combination design lies between the amount of variant 1 and 3 as this consider 75% residual beams and 25% modular beams. |
| | 3. Complete residual | 0,46 | The amount of waste production of the residual design after the first life cycle is more or less the same as the traditional design based on the gained results. However, in this design the residual beams are going in their 3rd life cycle thus some expert argued that the waste production would be more and less would be reusable. |
| | | | |
| **b. (Residual) quality** | 0. Traditional | 0,54 | There will be a certain amount of technical residual bearing capacity and residual lifespan after the first lifecycle of the prefab concrete beams in a traditional design (considering that the civil structure had a lifespan of 40 or 50 years) as current experience show that concrete does not age and only get better with time. |
| | 1. (New) Circular | 0,84 | For the circular design after its first lifecycle, it is assumed that the technical residual bearing capacity and residual lifespan will be higher compared to the traditional (considering that the civil structure had a lifespan of 40 or 50 years). This is due to the fact that a 2nd lifetime for the modular beams have been considered in advance. |
| | 2. Combination | 0,67 | The value for the technical residual bearing capacity and residual lifespan in the combination design lies between the circular design and full residual design as this design considers 75% residual beams and 25% new modular beams. |
| | 3. Complete residual | 0,44 | The prefab concrete beams in the residual design after the first lifecycle, will have a lower technical residual bearing capacity and residual lifespan as the residual beams are going in their 3rd lifecycle. |
| | | | |
| **c. Norms, standards and certification** | 0. Traditional | 1,00 | For a traditional design and newly produced beams there are norms, standards and certifications available. Thus, this would not be an issue before the first lifecycle of this design. |
| | 1. (New) Circular | 0,96 | As a cirular design also considers new produced prefab concrete beams before it first lifecycle, the availbe norms, standards and certifications can be used. However, as these norms were not specifically drawn up for modular beams, the value is not 1. |
| | 2. Combination | 0,54 | For the combination design it will be difficult to use the available norms, standards and certification as these were not developed for residual beams. As this design considers 75% residual beams it will be difficult to test and certify the standards. NOTE: one expert did not give a value as there are no norms available for secondary elements. |
| | 3. Complete residual | 0,48 | For the complete residual design the same applies as the combination design with 75% residual beams. However, as this design considers only residual beams the value is even lower. NOTE: one expert did not give a value as there are no norms available for secondary elements. |
| | | | |
| **d. Aesthetic requirements** | 0. Traditional | 0,97 | The aethetic requirements for a traditional design are almost no barrier in the acceptance of a client as the beams can be produced as per required. However, there could be a slighty barrier in the design when working with prefab concrete beams and their fixed prefab design. |
| | 1. (New) Circular | 0,89 | The aethetic requirements for a circular design can cause a slight barrier in the acceptance of a client as these will be produced more robust and need to be reusable in the future. |
| | 2. Combination | 0,54 | The aethetic requirements for a combination design can cause a huge barrier in the acceptance of a client as this design considers different types of beams (residual and new modular beams). Thus, this can be a challenge to get the views of the viaduct correct. |
| | 3. Complete residual | 0,61 | The aethetic requirements for a residual design will not cause a huge barrier such as the combination design, assuming that the residual beams that will be applied come from the same batch. |

*Table 6.22 Detachability determination Variant 0 to 3*

## 6.4. Results

In this chapter, the results of the applied case study will be given. In Table 6.23., the minimum and maximum value for each (sub)parameter is given, the obtained results described in previous chapter and the final (normalized) results are given. The normalized values are all between 0 and 1 and are now comparable to each other. In this research and for the final results, 0 is the minimum and means the worst scoring variant. In this research, 1 is the maximum and means the best scoring variant. In Table 6.23. the worst and best scoring variant have been coloured in red (for worst scoring) and green (for best scoring).

Based on the results last four columns of Table 6.23., conclusions can be drawn for the trade-off of design alternatives in the initial design phase of a project. In this research four design alternatives were considered, going from a traditional design to a circular design. These are the current design alternatives which are being considered in the transition process from traditional building to circular building.

| | | Boundaries | | Results [Unit] | | | | (Normalized) Results [-] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Most undesirable scenario | Most desirable scenario | Variant 0. | Variant 1. | Variant 2. | Variant 3. | Variant 0. | Variant 1. | Variant 2. | Variant 3. |
| **Parameter** | **Sub-parameter** | **Minimum** | **Maximum** | **Traditional** | **(New) Circular** | **Combination** | **Complete reused** | **Traditional** | **(New) Circular** | **Combination** | **Complete reused** |
| 1. Environmental Impact | a. Life Cycle Analysis - ECI | € 13.225,39 | € - | € 13.225,39 | € 6.612,70 | € 5.651,88 | € 5.171,46 | 0,00 | 0,50 | 0,57 | 0,61 |
| | b. Circularity performance | 0% | 100% | 0% | 50% | 37% | 33% | 0,00 | 0,50 | 0,37 | 0,33 |
| 2. Financial Impact | Cost price determination of design alternatives | € 306.804,72 | € - | € 254.880,00 | € 267.624,00 | € 293.744,48 | € 306.804,72 | 0,17 | 0,13 | 0,04 | 0,00 |
| 3. Supply and demand | a. Product specific offer | 0 | 1 | 0,99 | 0,83 | 0,50 | 0,24 | 0,99 | 0,83 | 0,50 | 0,24 |
| | b. Uncertainty in supply: availability and suitability | 0 | 1 | 0,93 | 0,86 | 0,37 | 0,17 | 0,93 | 0,86 | 0,37 | 0,17 |
| 4. Detachability | a. Damage to beams during dismanteling | 0 | 1 | 0,34 | 0,69 | 0,52 | 0,43 | 0,34 | 0,69 | 0,52 | 0,43 |
| | b. Traffic disruption during dismanteling | 0 | 1 | 0,10 | 0,61 | 0,48 | 0,29 | 0,10 | 0,61 | 0,48 | 0,29 |
| 5. Reusability | a. Reusable potential | 0 | 1 | 0,46 | 0,86 | 0,61 | 0,46 | 0,46 | 0,86 | 0,61 | 0,46 |
| | b. (Residual) quality - *Liability and risk factor (-10% on designs with residual beams)* | 0 | 1 | 0,54 | 0,84 | 0,67 | 0,44 | 0,54 | 0,84 | 0,60 | 0,40 |
| | c. Norms and standards | 0 | 1 | 1,00 | 0,96 | 0,54 | 0,48 | 1,00 | 0,96 | 0,54 | 0,48 |
| | d. Aestetic requirements | 0 | 1 | 0,97 | 0,89 | 0,54 | 0,61 | 0,97 | 0,89 | 0,54 | 0,61 |

*Table 6.23 Boundaries, non-normalized and normalized results (sub)parameters*

Based on the detailed results in Table 6.23., the following is analysed for the trade-off of the design alternatives that are considered in this research and based on the case-study:

- Variant 0, the traditional design, has the most undesirable effect on the environmental impact and scores the worst for both the life cycle analysis and circularity performance. From this can be determined that variant 0 not circular and has the most undesirable impact on the environment (based on the life cycle analysis conducted and environmental cost indicator obtained).
- However, variant 1 and variant 3, the (new) circular design and complete residual design have the most the desirable effect on the environmental impact. Variant 1, the circular design, scores the best for the circularity performance. This can be traced back to the fact that this design considers newly produced modular beams, which are designed in such a way that they can be easily reused in the future (demountable). Variant 3, the residual design, scores the best for the life cycle analysis. This can be traced back to the fact that all elements used in this design are free from their environmental burden as they do not need to be produced again. For this variant the environmental costs were determined based on the activities executed for harvesting and repurposing the prefab concrete beams.
- Looking at the financial impact, this is determined based on the total cost price of the design alternatives. Variant 3, the residual design, has the most undesirable effect on the financial impact

and scores the worst. This can be traced back to the price per beam type which was the highest for the residual prefab concrete beams. This cost price determined based on all activities conducted.

- However, variant 0, the traditional design, scores the best on the financial impact. This is can be traced back to the price per beam type, which was the lowest for the traditionally produced prefab concrete beams.
- Variant 0, traditional design, scores the best for the supply and demand of secondary prefab concrete beams. However, this value should be analysed critically as the supply and demand of prefab concrete beams are not applicable for this design alternative. Thus, the minimum and maximum definition should be considered of the sub-parameters: product specific offer and uncertainty in the availability and suitability. Looking at specifically the uncertainty in supply, this relates to the delivery risk of materials. Thus, when considering non-traditional design alternatives, the traditional design has the most certainty in material supply and least delivery risk of materials.
- In addition to the best scoring for the supply and demand, variant 3 scores the worst for both sub-parameters. This can be traced back to the fact that variant 3 is the residual design and is only executed with residual (secondary) prefab concrete beams. Thus, this variant and the residual beams needed have the highest delivery risk and risk of not being fit for purpose in terms of the type of beam that is released (inverted T-beam or another type), dimensions (length of beam) and whether it is adjustable in the required repurposing length. The delivery risk relates to not being available in time before the execution of the project.
- For the detachability, which is defined by the damage of prefab concrete beams during dismantling and the traffic disruption during dismantling, variant 0 (traditional design) scores the worst. This can be traced back to the fact that the prefab concrete beams in this design were not initially designed to be detached after their 1st lifecycle from the civil structure.
- However, variant 1 the circular design, has the most desirable effect on the detachability and thus scores the best for both damage during the dismantling of beams and traffic disruption. This is due to the fact that the prefab concrete beams in this design are modular and designed in order to be detached after their 1st lifecycle.
- Variant 3, the residual design, scores the worst for three out of four sub-parameters of the reusability. This is for the sub-parameters reusable potential, residual quality and norms, standards and certification. For the reusable potential and residual quality this can be traced back to the fact that these sub-parameters were considered for after the 1st life cycle of the design alternative. Thus, the prefab concrete beams based on the that consideration are going in their 3rd lifecycle.
- Variant 2, combination design, scores the worst for the aesthetic requirements of the parameter reusability. This can be traced back to the fact that this design considers a combination of new produced modular prefab concrete beams and residual prefab concrete beams. The aesthetic requirements for a combination design can cause a huge barrier in the acceptance of a client as this design considers different types of beams (residual and new modular beams). Thus, this can be a challenge to get the views of the viaduct correct.
- In addition, variant 1 circular design, scores the best for the reusable potential and residual quality. This is due to the fact that this design considers newly produced modular beams which are designed in for multiple lifecycles and in order to be reused again. Further, variant 0 traditional design scores the best for the norms, standard and certification and the aesthetic requirements. The norms, standard and certification process for a traditionally produced prefab concrete beams are known. The aesthetics requirements for a traditional design form almost no barrier as the prefab concrete beams can be newly produced based the requirements of the client.

## Final results including weights

In this part the final results including the weights per (sub)parameters will be given. In chapter 4.3.3. the added value of the proportion of each sub-parameter within a parameter is elaborated. The importance and ratio between sub-parameters are related to the requirements and conditions of a certain project. In this research, it is assumed that all sub-parameters weight evenly within each parameter. This weights of each (sub)parameter and the final results using the ratio are given in Table 6.24. The final results are further visualized in a radar chart illustrated in Figure 6.14. In this figure is illustrated how each of the variants perform on each parameter.

| Parameter | Sub-parameter | Weights | Results | | | |
|---|---|---|---|---|---|---|
| | | | Variant 0. | Variant 1. | Variant 2. | Variant 3. |
| | | | Traditional | (New) Circular | Combination | Complete reused |
| 1. Environmental Impact | a. Life Cycle Analysis - ECI | 50% | 0,00 | 0,50 | 0,47 | 0,47 |
| | b. Circularity Measurement | 50% | | | | |
| 2. Financial Impact | Cost price determination of design alternatives | 100% | 0,17 | 0,13 | 0,04 | 0,00 |
| 3. Supply and demand | a. Product specific offer | 50% | 0,96 | 0,84 | 0,43 | 0,21 |
| | b. Uncertainty in supply: availability and suitability | 50% | | | | |
| 4. Detachability | a. Damage to beams during dismanteling | 50% | 0,22 | 0,65 | 0,50 | 0,36 |
| | b. Traffic disruption during dismanteling | 50% | | | | |
| 5. Reusability | a. Reusable potential | 25% | 0,74 | 0,89 | 0,58 | 0,49 |
| | b. (Residual) quality | 25% | | | | |
| | c. Norms and standards | 25% | | | | |
| | d. Aestetic requirements | 25% | | | | |

*Table 6.24 Final results of the effect of the variants on the parameters (including weights)*

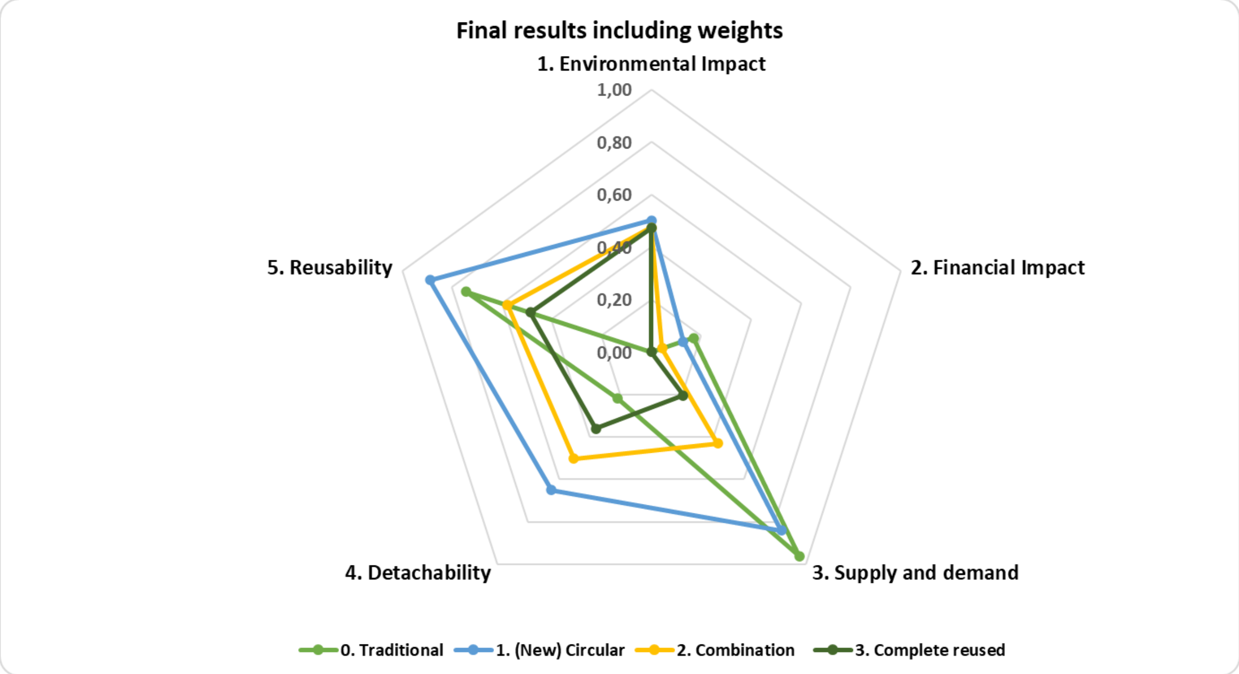



*Figure 6.14 Radar chart results key-parameters*

## 6.5. Validation of the tool

In this chapter the validation of the tool is elaborated. The developed tool, based on the framework established during this research, is validated. The validation is done based on the requirements in Chapter 6.2 and whether this meets the needs of the customer. This tool has been developed for the construction sector to make a trade-off of design alternatives in the initial design phase. Using Microsoft Excel, the established framework has been translated into a workable tool. This is done by using spreadsheets in Excel. In each sheet, the necessary information is worked out in order to finally arrive at an end result.

The following can be summarized for the validation of the tool:

- The steps of the procedure are clear in the tool; each spreadsheet elaborates on the input values and the method used.
- The assumptions and information used are described in the tool.
- The tool has been made more user-friendly by highlighting the specific cells that need to be filled in by the user. Thus, it is made clear which cells must be filled in by the user, which can possibly be filled in and which ones will be filled in automatically.
- However, the tool can be adjusted further. It should be adjusted further in terms of making it applicable for any given project. Currently, it is designed based on the case study specifically for viaducts and the design alternatives considered during this research. The case study gives a good overview of how the tool works and is applied in a project to make a trade-off of design alternatives. However, it could be made more general which will make it easier to directly implement it for another project.

# 7. Discussion

In this chapter the interpretation of the research results will be discussed. First it will be discussed if the research meets the research criteria in Chapter 7.1. Next, it will be discussed if the obtained results match with the expected results of the researcher in Chapter 7.2. Afterwards, the limitations of the research will be discussed in Chapter 7.3. Next in Chapter 7.4 the added value of the research for science and for the construction sector will be discussed. Finally, recommendations will be proposed for further research in Chapter 7.5 and recommendations for the construction sector in Chapter 7.6.

## 7.1. Verifying the research criteria

In this part will be discussed whether the research criteria stated in Chapter 2.4. are met during this research. The criteria stated at the beginning of the research were namely: Effectiveness and Efficiency, Reliability and Reproducibility.

### Effectiveness and Efficiency

The effectiveness of the research discusses whether the research conducted meets the research objective. This means that the research should try search for a strategy to cope with the problem stated in the problem statement in Chapter 2.2. The problem was that the current calculation tools did not provide an insight into the total transition process from traditional building and circular building. This insight was needed in order to make a trade-off of design alternatives in the initial design stage. Looking at the results of the research, it can be said that the drawn-up framework, illustrated in Figure 5.2., and the developed tool, demonstrate the strategy to bring insight in the total transition process and how the trade-off of design alternatives can be made. The efficiency relates to whether this research was conducted goal-oriented. Thus, it can be concluded that the research objective is met and research has been effective and in an efficient manner.

### Reliability

The reliability of the research discussed whether the methods and data used during the research are reliable. The methods used during this research were both qualitative and quantitative. The data collected during this research were through extensive literature research, personal communications and interviews with experts within the company. The data collected through personal communications and interviews with the experts have been elaborated on in this report. In part III, the results from the conducted interviews have been described. The data and results gained through personal communication and interviews with experts is reliable. This because, each expert background has been elaborated in Appendix B. Thus, the obtained value can be verified based on the expert’s experience. The data used for the standardized methods are also reliable and trace-able. This because within each method the sources are described. However, assumptions were during some of the steps. When it comes to the assumptions, the substantiation of each assumption should be taken into account.

### Reproducibility

Lastly, the research should be reproducible. In the previous chapters all steps followed have been described elaborately and the decisions made during the research are also elaborated in this report. Thus, it is believed that this research is reproducible and can be used for further research or to conduct sharpened reproduced research.

## 7.2. Research results versus expected results

The research results match with the expectation beforehand that there were indeed insights needed in all factors that play a role in the transition process from traditional building to circular building, especially for in the initial design stage. The research results confirm that by having an overview of all key-parameters involved in the transition process towards circular building, a better trade-off of design alternatives can be made. It has been made clear which factor play a role and what the effect of different design alternatives in the current transition process is on the key-parameters. However, the research results did show that in the current transition process it difficult to build with only residual elements based on all factors that play a role. Even though the construction needs to reduce their primary material consumption and reuse as much possible, several challenges are faced such as the timely availability and suitability of secondary elements and also the reusability in terms of the available current norms and standards and uncertainty in the residual quality. Thus, this research gives an overview which aspects should be worked further on in order to stimulate the reduction primary raw materials usage and to reuse as much as possible.

## 7.3. Limitations of the research

This research had a few limitations. First, there are some limitations regarding the existing literature. There is limited elaborate research on the transition process towards circular construction. Most of the current literature reflects on how a circular construction sector should be, which requirements it should fulfilled to and what the end goal is. However, there is no elaborate research on how to make the first steps towards a circular construction. Furthermore, it is also not research what the consequences might be when taking quicker steps towards circular construction.

Another limitation is that this research is conducted for and with the construction sector, whom is only one party in the practice for executing a project. Thus, the client's point of view has not been taken into account as this research focusses on developing a tool for the construction sector. However, certain formal matters such as permits and liability when using secondary materials can play a major role in the fact that the project cannot be carried out. This is an aspect that must be contractually arranged by the client. This has been briefly taken into account in Chapter 4.5.4. and as a sub-parameter ''norms, standards and certification'', but should be more substantiated.

Lastly, due to the scope of this research, the developed framework and tool are at element details level of a civil structure. However, in order to contribute and transition towards a circular level, the whole civil structure should be considered. Especially when looking at the circular building of viaduct and bridges. The adjustment and modification of the connecting parts with prefab concrete beams can lead to making a more optimal circular design. This would lead to making better design alternative trade-offs. Furthermore, this scope of this research specifically considered inverted T-prefab concrete beams. Due to the fact, that these are the most common beams which are being released. However, this led to not considering other models of prefab concrete beams such as the box prefab concrete beam and thus not considering the opportunities within that.

## 7.4. Added value of the research

The research has added value in both a practical sense and a scientific sense. The research has a practical added value for real-life construction projects in the construction sector. The information obtained from this research and the developed framework and tool can be used by the construction sector for the decision-making process in the initial design stage. This research further brings insight in all factors that play a role in the transition process from traditional building to circular building. Thus, the identified gap at the beginning of the research has been solved for both science and the construction sector. The research shows how the different design alternatives in the current transition process effect the factor that play a role. It highlights the most desired and most undesired design alternative pe (sub)parameter that plays a role. Further, due the normalization of values, the results of each different key-parameter are comparable. The previous calculation tools did not provide an overview of different results next to each other and these were not comparable. Lastly, based on the literature review and theoretical framework described in Chapter 3 and Chapter 4, it can be concluded that this research provides insights in the total transition process and further highlight the challenges faced by the construction sector.

## 7.5. Recommendations for further research

As explained in the previous chapters, this research was conducted in order to provide insight in the transition process from traditional building to circular building. However, there is still a lot of room within the transition process from traditional building to circular building which needs to be researched further. First, all formalities from the client and independent authorities should be finalized, such as the contractual matters for risk and liability and standardized norms for reusing secondary elements. By researching further into this topic and elaborate on the process on how to handle formal procedures between the contractor and client when it comes to reusing of elements, circular building can be stimulated. The liability and risk were briefly elaborated in this research in Chapter 4.5.4. based on the practical experience in the construction sector.

Secondly, more research is needed in the near-future consequences of circular building. By consequences is meant the obligation to use only secondary materials and elements may cause a shortage of reusable materials and elements. Furthermore, a lot of energy is currently being put into extracting and harvesting secondary materials from existing civil structure, partly because the materials were not designed to be reused and due limited experience, but it is not clear what the consequence of harvesting and extracting secondary materials is on the environmental and the emissions. Thus, it the obligation to work fully circular and the consequences regarding that should be researched.

Thirdly, the standardized methods used during this research were adjusted for the non-traditional design alternatives. This relates to the determination of the environmental impact and financial impact. Thus, more research is needed in developing and adjusting the standardized methods for the transition towards circular building and for circular building itself. For the parameters that did not have a standardized method in order to quantify them, further research should be conducted in developing a method. This relates to the supply and demand of secondary materials, reusability and detachability.

In Chapter 4.3.3. an overview the ratio of each sub-parameters within a parameter were given. The proportion of each sub-parameter within a parameter was needed, in order to determine the performance of the design alternatives in that specific main parameter. However, the proportion between the main parameters can also be defined, which determines the scoring of the best design alternative. The importance and ratio between sub-parameters are related to the requirements and conditions of a certain project. Therefore, during this research it was chosen to weigh each (sub)parameter evenly. However, further research is needed in the current proportions of (sub)parameters involved in the transition process towards circular building.

Finally, after the above-mentioned research is conducted, better insights can be given of the key-parameters involved in the transition process. this research zoomed in on an element level of a civil structure, only considering prefab concrete beams within viaduct. However, considering more element all factor that play a role in that process, would give a better overview and lead to making a more accurate trade-off of design alternatives.

## 7.6. Recommendations for the construction sector

In this part the recommendation for the construction sector will be discussed. For the construction sector it is recommended to dedicate more attention to the coherence and cooperation of the different factors involved in the transition process from traditional building to circular building. This research elaborates on 5 key-parameters involved in the transition process. For this research, experts within the construction company have been approach to contribute to data inputs based on their backgrounds. However, by bringing a better coherence and cooperation between the experts with different backgrounds, such as the experts with a sustainability, technical, financial and circular approach background, a better and more realistic approach can be developed for making the transition towards circular construction.

# 8. Conclusion

In this chapter a final conclusion will be drawn about the research results in the form of an answer on the solution of to the development statement. The sub-research questions Q1 to Q4 have already been answered in the chapters about the research results and have been elaborately described in Part II and first part of Part III. Thus, this will therefore not be repeated in this chapter.

The current calculation tools didn't provide an insight in the total transition process from traditional building to circular building. For the construction sector, who currently has to minimize the usage of primary raw materials and reuse as much as possible, it was not clear which factors play a role in the transition process towards circular construction. This research aimed on developing a framework and based on that a tool, which provides an overview of all factors involved in the transition process from traditional building to circular building in the initial design phase. This elaborates the gap in knowledge for the construction sector as well as science. Therefore, based on the information out of separate parts of the research, an answer can be formulated to the development statement of the research:

***To develop a framework and user-friendly tool for the construction industry that enables a comparison of design alternatives based on key parameters involved in the transition of traditional building to circular building and provides insights for decision-making of design alternatives in an early-design stage.***

The developed framework and user-friendly tool enables a trade-off of design alternatives based on the key parameters involved. 5 main key parameters were identified in the current transition process from traditional building to circular building. These key parameters are involved in the initial design stage of project and contribute to the decision-making in the trade-off of design alternatives. Each parameter was further defined in order to gain more insights. Further, design alternatives were defined which could then be compared to each other, going from a traditional design up to a circular design. This research focuses on circular building of viaduct and bridges, zooming in on an element level: prefab concrete beams. The design alternatives chosen were defined based on current experience in the construction sector and leading to the circular building of viaduct and bridges.

In order to make a comparison between the design alternatives, research was done into quantification methods for the defined (sub)parameters. Using these methods, the effect of the design alternatives on (sub)parameters were determined. This was done, in order to make a comparison of design alternatives based on the key parameters involved in the transition process. This approach describes the framework developed during this research and was translated in a user-friendly using Microsoft Excel. The development of the tool took place using a case study. Through the case study, values could be entered for the design alternatives and a comparison could be made.

After analysing the results for the design alternatives through the case study, conclusions could be drawn for the transition process towards building circular viaducts and bridges. This research clearly illustrates the challenges for the traditional building of viaducts and bridges, but it also illustrate the current challenges for the transition towards circular bridges. The main challenge for the traditional building is its impact on the environment, due to the depletion of primary raw materials for the production new elements. In the current transition process multiple options are being looked at to minimize the usage of primary raw materials by reusing prefab concrete beams which are released from existing civil structures. However, this leads to another challenge for the detachability of prefab concrete beams in their original form. This is due to the fact that damage-free dismantling should be done carefully thus takes time and causes traffic disruption.

In addition to that, for the transition towards circular building of viaducts and bridges, design alternatives with new modular prefab concrete beams, residual prefab concrete beams or a combination of both were considered. However, this firstly having an undesirable financial impact. Designing with residual or new produced modular beams are currently higher than designing with traditional prefab concrete beams. When considering residual beams, it gives bring an uncertainty in the timely availability and suitability of the beams, before the execution of the new project. Furthermore, as there are no norms and standards available for residual elements, it leads to difficulty in defining the reusability of the beams in terms of the acceptation of the client and defining the residual quality. However, when looking at design with new produced modular prefab concrete beams, can have future opportunities. Thus, future research should be conducted in the development of the modular prefab concrete beams and also looking at the technical connections that need to be made.

# 9. Reflection

This research consists of the last steps executed for pursuing my MSc in Construction Management and Engineering. Looking back at the executed research and research process itself, I can say that the research went smoothly and as planned. From finding a research topic, composing the thesis committee to finding a company where I could execute the research, the process went smoothly. I enjoyed working on a booming subject in the academy as well as in the society. As a practice-oriented person, I loved working on ''connecting-the-dots''. This especially on the (sub)topics for detailed information was still unclear or unknown. Bringing information together within the construction sector and between the construction sector and science about this topic was one of main goals of this research. This mindset was partly developed thanks to the guidance and attitude of the construction company where the research was conducted and has helped in achieving the end result.

Even though it has been a challenge to carry out this research in a (self-determined) limited time, I am satisfied with the depth of the research and the final result achieved. At the last month of the research process, a lot of important information and in-depth research was still unfinished and needed more time. However, with the support and flexibility I was able to finish on time and met the deadlines. Thus, in the end, I was able to finish the research within the planning I made.

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# Appendices

## A. Interviews set-up and Results

### A1. Interview plan of action and set-up

In appendix A1., the interview set-up has been drawn up. The goal of the interview set-up is to have a clear overview of which information the interview will contribute to this research.

***Research objective***

This research aims to provide insight into the total process by analysing critical parameters in the transition from traditional building to circular building and the interrelationship between the parameters. The aim is to develop a user-friendly construction tool that contributes to decision-making about making first choices towards circular construction in the initial phase of a project which helps to think about which factors to consider when reusing elements and reducing the waste and usage of primary materials.

***Research question (Development Statement)***

To develop a tool for the construction sector whereby design alternatives can be compared based on key parameters involved in the construction process in the transition from traditional construction to circular construction, which contributes to decision-making in the initial design phase.

***Purpose of interviews (why, what, who)***

- *Why an interview?*
  The data collection mainly consists of literature research and based on the missing information that cannot be obtained from the literature, interviews are conducted to collect additional information. In addition, the interviews are intended to test what is stated in the literature with the help of practice experience.
- *What is the central interview question and purpose?*
  Gain insights into the parameters and sub-parameters, drawn up in the research, using a quantification indicator. The quantification will be done by assigning an indicator. The maximum and minimum values of the indicator are predefined (also shown in the Table below); however, the interviewer is asked to indicate the influence of each variant on the sub-parameters.
  *<u>Question:</u>*
  Could you assign a value to the influence of the variant ... on the sub-parameter ...?

- *Type of interview and interviewee*
  The type of interview that will be conducted is a semi-structured expert interview. During this type of interview, the topics to be discussed are fixed, but the order may be changed. Additional questions may also be asked during the interview. For this research and the definitions of the sub-parameters, opinions of experts are needed on the different sub-parameters that serve as a supplement to the information found in the literature, therefore an expert interview was chosen.

***Selection of interviewees (Conditions for choosing experts for interviews)***

The interviewees for the semi-structured expert interviews are chosen based on certain criteria, namely:

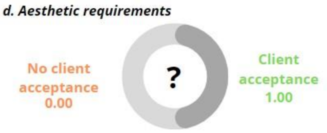
1. The interviewee works in the construction industry;

2. The interviewee has an affinity with circularity and/or has experience with implementing circularity in a project;
3. The interviewee has knowledge of one (or more) of the topics listed in the column ''parameter / sub-parameter'' in the table below.

***Interview protocol:***
A set of questionnaires was drawn up for the interviews. The duration of each interview will be approximately 50 minutes. The main purpose of the interviews is to gain insight from experts about the effect of design alternatives on the key parameters in the transition from traditional construction to circular construction. As a result, certain parameters (demand and supply, releasability, reusability), which do not have existing measurement methods, be quantified using indicators. In addition, the parameters (environmental impact and financial impact), which do have an existing measurement method, can be supplemented for the "new" circular design alternatives through practical experiences/approaches.
Each interview is divided into 3 parts:
1. The interview starts with a short introduction to the research topic explaining the objective, the confidentiality of the interview process, and the interviewee is asked for permission to record the session, which will help in analysing the results;
2. After a short introduction, the interviewee is asked to complete the set of questionnaires;
3. The interview concludes with a closing remark and the question of whether they can be contacted in the future for further assistance if necessary.

The elaboration of the data that will be collected is given in Chapter 4.5.2. including the interview questions. However, in the tables below it is briefly summarized again. The list of experts interviewed during this research is given in Appendix B. Besides interviews, there has been multiple data collection through personal communication.

**Question: Developed measuring method/approach:**
**[Parameter 3, 4 & 5]**

| *(Sub) Parameter* | *Traditional* | *(New) Circular* | *Complete reused* | *Combination new en reused* | *Definition indicators* |
|---|---|---|---|---|---|
| **1. Supply and Demand of secondary prefab concrete beams** | | | | | |
| c. Product specific demand (Challenge) | [-] | [-] | [-] | [-] | *a. Product specific offer*   |
| d. Uncertainty in the supply: availability and suitability | [-] | [-] | [-] | [-] | *b. Uncertainty in the availability and suitability*   |
| **2. Detachability of prefab concrete beams** | | | | | |
| c. Damage to beams during dismantling | [-] | [-] | [-] | [-] | *a. Damage to beams during dismantling*   |
| d. Traffic disruption during dismantling | [-] | [-] | [-] | [-] | *b. Traffic disruption during dismantling*   |
| **3. Reusability of prefab concrete beams** | | | | | |
| e. Reusable potential | [-] | [-] | [-] | [-] | *a. Reusable Potential*   |
| f. (Residual) quality | [-] | [-] | [-] | [-] | *b. (Residual) quality*   |
| g. Norms and standards | [-] | [-] | [-] | [-] | *c. Norms, standards and certification (abbreviated: N&S)*   |
| h. Aesthetic requirements | [-] | [-] | [-] | [-] | *d. Aesthetic requirements*   |

**NOTE:** The indicators are defined from 0 to 1, where 0 defines the lowest possible value and/or negative influence of the variant on the sub-parameter and 1 the highest possible value with a positive effect on the transition.

## A2. Input values developed method – Expert interviews

In this Appendix the results of the interviews with expert are given. The main goal of the interviews was to gain insights on the effect of the design alternatives on the parameters and sub-parameters of the supply and demand (3), detachability (4) and reusability (5). This was done using the indicator method developed during this research. During the interviews, each interviewee was asked (using the questions stated in Chapter 4.5.2.) to give a value between 0 and 1 which defines the effect of the deign alternative on the given sub-parameter. In this method, 0 is defined as the undesirable effect on the sub-parameter and 1 as desirable effect on the sub-parameter. In Table A.1 the results of the interviews are given. These results are further processed into an average value. All of the values, including the substantiation of the experts, will used as input value in the tool.

| | Interviewee | Interviewee 1 | Interviewee 2 | Interviewee 3 | Interviewee 4 | Interviewee 5 | Interviewee 6 | Interviewee 7 | Interviewee 8 | Interviewee 9 | # Interviewee's | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parameters** | **Variants** | | | | | | | | | | | |
| **3. Supply and demand** | | | | | | | | | | | | |
| **a. Product specific offer** | 0. Traditional | 1 | 0,9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 0,99 |
| | 1. (New) Circular | 1 | 0,8 | 0,95 | 0,75 | 0,5 | 0,75 | 1 | 1 | 0,7 | 9 | 0,83 |
| | 2. Combination | 0,5 | 0,5 | 0,4 | 0,5 | 0,4 | 0,4 | 0,7 | 0,66 | 0,4 | 9 | 0,50 |
| | 3. Complete residual | 0,3 | 0,3 | 0,25 | 0,25 | 0,4 | 0 | 0,4 | 0,1 | 0,2 | 9 | 0,24 |
| | | | | | | | | | | | | |
| **b. Uncerntainty in supply** | 0. Traditional | 0,8 | 0,99 | 0,95 | 1 | 0,9 | 1 | 0,75 | 1 | 1 | 9 | 0,93 |
| | 1. (New) Circular | 0,8 | 0,95 | 0,9 | 1 | 0,3 | 1 | 0,75 | 1 | 1 | 9 | 0,86 |
| | 2. Combination | 0,4 | 0,4 | 0,5 | 0,5 | 0,25 | 0 | 0,75 | 0,3 | 0,2 | 9 | 0,37 |
| | 3. Complete residual | 0,2 | 0,25 | 0,4 | 0,2 | 0,2 | 0 | 0,2 | 0,05 | 0 | 9 | 0,17 |
| | | | | | | | | | | | | |
| **4. Detachibility of prefab concrete beams** | | | | | | | | | | | | |
| **a. Damage during dismantling** | 0. Traditional | 0,4 | 0,2 | 0,5 | 0,5 | 0,4 | 0 | 0,75 | 0,1 | 0,2 | 9 | 0,34 |
| | 1. (New) Circular | 0,4 | 0,6 | 0,8 | 1 | 0,6 | 1 | 0,5 | 0,8 | 0,5 | 9 | 0,69 |
| | 2. Combination | 0,4 | 0,5 | 0,65 | 0,6 | 0,5 | 0,75 | 0,6 | 0,4 | 0,3 | 9 | 0,52 |
| | 3. Complete residual | 0,4 | 0,4 | 0,5 | 0,4 | 0,4 | 0,4 | 0,75 | 0,6 | 0 | 9 | 0,43 |
| | | | | | | | | | | | | |
| **b. Traffic disruption during dismantling** | 0. Traditional | 0,4 | 0 | 0,2 | 0,2 | 0,1 | 1 | 0 | 0 | 0 | 9 | 0,21 |
| | 1. (New) Circular | 0,4 | 0,8 | 0,8 | 0,6 | 0,7 | 0,5 | 0,4 | 0,8 | 0,5 | 9 | 0,61 |
| | 2. Combination | 0,5 | 0,45 | 0,5 | 0,5 | 0,4 | 0,8 | 0,4 | 0,6 | 0,2 | 9 | 0,48 |
| | 3. Complete residual | 0,6 | 0,3 | 0,2 | 0,4 | 0,1 | 0,65 | 0 | 0,3 | 0,1 | 9 | 0,29 |
| | | | | | | | | | | | | |
| **5. Reusability of prefab concrete beams** | | | | | | | | | | | | |
| **a. Reusable potential** | 0. Traditional | 0,4 | 0,3 | 0,8 | 0,3 | 0,6 | 0,25 | 0,75 | 0,4 | 0,3 | 9 | 0,46 |
| | 1. (New) Circular | 0,8 | 0,8 | 0,95 | 0,9 | 0,9 | 1 | 0,9 | 0,9 | 0,6 | 9 | 0,86 |
| | 2. Combination | 0,6 | 0,7 | 0,875 | 0,6 | 0,4 | 0,8 | 0,85 | 0,3 | 0,4 | 9 | 0,61 |
| | 3. Complete residual | 0,5 | 0,6 | 0,8 | 0,2 | 0,3 | 0,6 | 0,75 | 0,2 | 0,2 | 9 | 0,46 |
| | | | | | | | | | | | | |
| **b. (Residual) quality** | 0. Traditional | 0,6 | 0,5 | 0,75 | 0,2 | 0,8 | 0,25 | 0,9 | 0,6 | 0,3 | 9 | 0,54 |
| | 1. (New) Circular | 0,9 | 0,9 | 0,9 | 0,7 | 0,9 | 1 | 1 | 0,8 | 0,5 | 9 | 0,84 |
| | 2. Combination | 0,7 | 0,7 | 0,825 | 0,4 | 0,7 | 0,8 | 1 | 0,5 | 0,4 | 9 | 0,67 |
| | 3. Complete residual | 0,4 | 0,5 | 0,5 | 0,1 | 0,6 | 0,4 | 0,9 | 0,4 | 0,2 | 9 | 0,44 |
| | | | | | | | | | | | | |
| **c. Norms, standards and certification** | 0. Traditional | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 1,00 |
| | 1. (New) Circular | 0,8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0,8 | 9 | 0,96 |
| | 2. Combination | 0,5 | 0,55 | 0,2 | 0,8 | 0,7 | No value | 0,5 | 0,8 | 0,3 | 8 | 0,54 |
| | 3. Complete residual | 0,5 | 0,5 | 0,3 | 0,8 | 0,7 | No value | 0,1 | 0,7 | 0,2 | 8 | 0,48 |
| | | | | | | | | | | | | |
| **d. Aesthetic requirements** | 0. Traditional | 0,75 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 0,97 |
| | 1. (New) Circular | 0,75 | 0,8 | 0,9 | 0,75 | 1 | 1 | 1 | 1 | 0,8 | 9 | 0,89 |
| | 2. Combination | 0,5 | 0,3 | 0,6 | 0,2 | 0,7 | 0,75 | 0,75 | 0,7 | 0,4 | 9 | 0,54 |
| | 3. Complete residual | 0,3 | 0,5 | 0,75 | 0,5 | 0,8 | 0,75 | 0,75 | 0,7 | 0,4 | 9 | 0,61 |

*Table A.1 Indicator method results - Expert interviews*

## B. Experts / Interviewee backgrounds

In this Appendix, the background of the interviewees and other experts are described from whom information has been gained.

### Interviewee 1

The 1st interviewee is part of the sustainability team of Dura Vermeer Infra Landelijke project as sustainability advisor. The interviewee described the following background:

*''I have been working in the infrastructure construction sector since 1996. I worked for BAM until 2011 and since then I have been working for Dura Vermeer. In my career, I have fulfilled many functions from executor, calculator to project leader and after 2 years of work in Africa I became department head of the work preparation and project office. Since I started working at Dura Vermeer, I have actually fulfilled 2 functions. Until 2017 I was tender manager and for part of that period also department leader of tender management. Since 2017 I have had a role in the sustainability team of DV Landelijke Projecten. First as a team leader and later more as a consultant in the projects. In the last 5 years I have been involved in many projects where sustainability or circularity was or is a part. For example, the tender for the Floriade project, where we have realized a fully circular bridge.''*

### Interviewee 2

The 2nd interviewee is also part of the sustainability team of Dura Vermeer Infra Landelijke project as sustainability advisor. The interviewee described the following background:

*''I am a Sustainability Advisor and I am involved in making the construction sector more sustainable by advising on circular and sustainable solutions and making this transparent with ECI and* $CO_2$ *calculations. I've been doing this for four years. Currently, I am mainly involved in dyke improvements, where many local materials are released from the work, which we reuse as much as possible on the project.''*

### Interviewee 3

The 3rd interviewee is part of Dura Vermeer Urban Miner B.V. as Project Coordinator. The interviewee described the following background:

*''My 'official' position is Project Coordinator, but that is such a vague all-encompassing term. Thus, from Urban Mining I am involved to a small or large extent in all initiatives that we develop from the Participaties operating company to facilitate high-quality reuse for our projects. This can be anything from new (digital) tooling, developing business cases for processing new product flows, the search for new locations to expand our network, making our current locations more sustainable, etc. In addition, projects (especially tenders) involve me to get advice on circular opportunities within their project. Think of the reuse of released materials and objects, but also the application of new circular initiatives in the design to be realized. From my background as an industrial ecologist, in addition to circularity, I have a broad knowledge of sustainability in a general sense, so I sometimes also do an Environmental Cost Indicator (ECI) calculation. Lastly, I have been working at Dura Vermeer for over 3 years now, 2 of which at Urban Mining (since its foundation)''*

### Interviewee 4

The 4th interviewee is also part of the sustainability team of Dura Vermeer Infra Landelijke project as sustainability advisor. The interviewee described the following background:

*"Senior advisor in the field of sustainability in infrastructure, in the broadest sense of the word. After 15 years of technical designing of infrastructure, followed by 15 years of various positions within project and environmental management, the opportunity arose in 2017 to focus on sustainability within the infrastructure. I am involved in making infrastructural projects more sustainable by advising on CO2 reduction (Emissions to 0!), promoting circularity (Reuse? As often as possible!) and related themes (Greener & healthier!). In doing so, I want to contribute to a better living environment, especially for future generations."*

### Interviewee 5

The 5th interviewee is part of Dura Vermeer Infra Landelijke project B.V as a specialist technical design. The interviewee described the following background:

*'' The current position is specialist in the technical design at Dura Vermeer Infra Landelijke Projecten B.V. for the past 3 years. Before this, the position was the head of the design department for 10 years. In the previous career worked as a constructor for ± 5 years at Dirk Verstoep / NBM Amstelland. After that, started as a constructor at Royal HaskoningDHV and then progressed to design leader, project leader and finally as department head of the civil structures. After a career of ± 13 years at DHV transferred to Dura Vermeer B.V. This defines a career and work experience in the construction sector of more than 30 years.''*

### Interviewee 6

The 6th interviewee is part of Dura Vermeer Infra Landelijke project B.V. as a Tender manager. The interviewee described the following background:

*''My current position is tender manager within the tender management department of Dura Vermeer Infra Landelijke Projecten B.V. I manage multidisciplinary tenders in the field of mobility, hydraulic engineering and replacement and renovation. This usually concerns the disciplines Infra, Civil, Rail and sometimes technical installations. I have been doing this for 7 years now and have achieved a good score with my tender teams on the various projects. Before that, I worked for an SME contractor within infrastructure/civil for 23 years. Here I started as an assistant foreman, after that calculation, work preparation, project leader and the last 10 years as manager business office (about 25 colleagues).''*

### Interviewee 7

The 7th interviewee is part of Dura Vermeer Infra Participaties B.V. as Circular Manager within Dura Vermeer Infra – Participaties Urban Mining. (DVI-P Urban Mining). The interviewee described the following background:

*''As a circular manager within DVI-P Urban Mining I am responsible for expanding our activities and developing new activities. By this meant expanding our network of locations and setting up new reuse flows from infrastructure works where we take materials, process them where necessary and reuse them for a second life. I have educational background in civil engineering. Regarding work experience: I have worked in the infrastructure sector for almost 16 years, of which 8 years at Heijmans and 7.5 years at Dura Vermeer. Gained a lot of experience at Heijmans with tenders,*

*projects and management & maintenance. At Dura Vermeer I was responsible for the central design of our (current) Asset Management department, subsequently worked for DVI-LP in the role of innovation manager for 3.5 years (with many interfaces with sustainability) and now since 1st of January working in my current role. A project/activity example within my current role is the reuse of beams in which I was already involved from DVILP and am still involved now to explore whether we can do this more often (after the pilot).''*

### Interviewee 8

The 8th interviewee is part of Dura Vermeer Infra Landelijke project B.V as a project manager. The interviewee described the following background:

*''My current position is project manager. I have been employed by Dura Vermeer B.V. (in the beginning named: Vermeer Grond en Wegen) for about 35 years. So, I have been active in road construction for a long time. My previous positions were: relocation assistance, work planner, executor, commercial manager, company manager, district director, area development manager, regional director Advin (Dura Vermeer's engineering firm), design manager, permit manager, project manager/project director and energy manager. My experience with circularity: the circular bicycle-pedestrian bridge on the Floriade and I am the initiator and co-author of the writing of "Guide to circularity in practice" for Dura Vermeer Landelijke Projecten B.V.''*

### Interviewee 9

The 9th interviewee is part of Dura Vermeer Infra Landelijke project B.V (DVILP) as a project manager. The interviewee described the following background:

*''I started at the age of 21 as a junior executor in environmental technology. From there, I progressed to the position of executor, chief executor, project leader and project manager for several years now. Over the past 25 years of my work, I have seen a lot of changes, but also a growing awareness. This applies to society as well as to myself, both at home and at work. My Forest and Nature Management training means that I automatically view our responsibility differently. In environmental technology, this also showed that what we had made dirty also had to be cleaned again. Very simple, otherwise we can only use our environment once and there is not enough space in our world for that. I also continued this when it comes to the depletion of the earth. We cannot continue to exhaust the world indefinitely and use everything once. Here, I see the parallel with environmental engineering where we clean up previous man-made contaminants. We are now also doing the same with landfills and what could be better than seeing waste as a raw material? Of course, I also see that we still face many challenges when it comes to reuse and that we sometimes go too fast, causing new problems (think of the reuse of asphalt). From the latest projects, I also see that we automatically want to distinguish ourselves by aiming for more reuse, less transport distances and a low MKI value. Personally, I find it very interesting to provide guidance myself and also to follow developments so that we slowly but surely gain insight into the opportunities for our industry to work really sustainably. For this reason, I was also a sustainability ambassador for a number of years and subsequently provided guidance to the Sustainability department.''*

## C. Developed Tool in Microsoft Excel

## Introduction

This tool is part of the graduation research ''The transition from traditional construction to circular construction''.
An analysis of key parameters related to the transition process of building circular viaducts and bridges.

The tool has been developed for the construction sector and is intended to contribute to the decision-making of making first choices towards circular building in the initial phase of project and helps in considering the factors that play a role when reusing elements and reducing the usage or primary raw materials.

In this tool design alternatives are compared based on the key parameters that play a role in the transition process.
The key parameters considered and the design alternatives are described below. Further, the working method of the tool is also described below.

## Key parameters

5 key parameters were identified in the transition process and further substantiated in sub-parameters

| Parameters | Sub-parameters | Determination of: |
|---|---|---|
| 1. Environmental impact | a. Life Cycle Analys | Environmental Cost Indicator (€) |
| | b. Circularity measurement | Circularity performance (%) |
| 2. Financial impact | Cost price determination based on type(s) of beams in design: | |
| | a. Traditional prefab concrete beam | Cost price of design (€) |
| | b. Circular prefab concrete beam | |
| | c. Residual prefab concrete beam | |
| 3. Supply and demand | a. Product specific offer | Indicator (-) |
| | b. Uncerntainty in supply | Indicator (-) |
| 4. Detachibility | a. Damage during dismantling | Indicator (-) |
| | b. Traffic disruption during dismantling | Indicator (-) |
| 5. Reusability | a. Reusable potential | Indicator (-) |
| | b. (Residual) quality | Indicator (-) |
| | c. Norms, standards and certification | Indicator (-) |
| | d. Aesthetic requirements | Indicator (-) |

## Design alternatives - Variants

Based on the research conducted, the design alternatives are drawn up, hereinafter to be called ''Variants''.
The variants vary from a traditional design to a circular design. Thus, 4 variants are drawn up.
In this research a Viaduct is considered, where on element level only prefab concrete beams are considered.

| Variant | Prefab concrete beam | Remarks |
|---|---|---|
| 0. Traditional design | traditional beams, made of primary raw materials | Reference variant |
| 1. Circular design | Modular beams, made of primary raw materials | New-reusable and future-proof beams |
| 2. Combination design | Modular beams and residual beams | Residual and New-reusable and future-proof beams |
| 3. Residual design | Residual beams | All beams in this design are going in their 2nd lifecycle |

## Working method Tool

**Each sheet of this Excel-file elaborates on the input values needed and method used in order to quantifiy the effect of the design alternatives on the parameters.**

### General

**1. Input values**

In this sheet the input values of the case study and design alternatives are given. These are:
**I.** The surface (length and width) of the civil structure and span-length of the prefab concrete beams
**II.** Determination of prefab concrete beam profile type
**III.** Material quantities determination of a prefab concrete beam and the design alternative(s) - Bill of Materials
**IV.** Project information: Transportation distance and harvesting effort for residual prefab concrete beams

### Environmental Impact

**2. Life Cycle Analysis - Environmental Costs determination**

In this sheet the environmental cost indicator (ECI) is calculated for each design alternative.
**I.** The ECI is determined using DuboCalc. Thus, the necessary input values for the case study considered are given.
These input values were obtained from the company.
**II.** The ECI value for each design alternative (variant) is calculated. The unit of this value is in €.
**III.** The assumptions made for each design alternative and their Life Cycle Analysis is also given.

**3. Circularity performance**

In this sheet the circularity performance of each design alternative is calculated. This method is described by Platform CB'23.
**I.** The necessary input values of the case study for the circularity performance calculation are given.
These are values regarding the specific weight of materials considered.
**II.** The impact indicators, described as Key Perfomance Indicators (KPI) of each design alternative is defined.
The circularity performance of each design alternative is calculated by summing up the main KPI's of that design alternative:
A. Percentage of secondary material used in a design
B. Percentage of materials that is released during the execution and that can be reused (replacement statement)
C. Percentage of elements designed for the project and easy to reuse in the future (demountable)

### Financial impact

**4. Life Cycle Costing - Cost price determination**

In this sheet the cost price is determined of the design alternatives. The final cost price is determined based on the type(s) of prefab concrete beams in the design alternative.
**I.** Cost price determination of the types of beams considered:
A. Traditional prefab concrete beams: Cost price obtained from company (includes costs of additional activities)
B. Circular prefab concrete beams: Cost price obtained from company (includes costs of additional activities)
C. Residual prefab concrete beams: Cost price determined based on the costs of the activities executed for harvesting and repurposing of beams. Cost per activity obtained from company.

### Supply and Demand, Detachibility, Reusability

**5. Indicators interviews results**

In this sheet the results of the expert interviews are given.
**I.** The effect of each design alternative on the sub-paramater is given of each expert
**II.** The average value is calculated based on the number of interviewee's
**III.** A substantiation is given of the average value (defined effect of the design alternative on sub-parameter)
**IV.** The results of the design alternatives are then compared for each sub-parameter

### Results

**Results**

In this sheet the results are given.
**I.** The results of the previous sheets are summarized in this sheet
**II.** The boundaries (minimum and maximum) for each (sub)paramater is given
**III.** The results are then normalized
**IV.** The weights of each (sub)parameter are given
**V.** The final combined results are then visualized in a Radar chart and compared

## Input values Case study

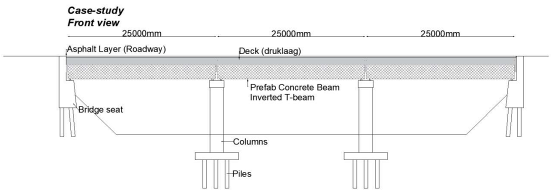
### Introduction

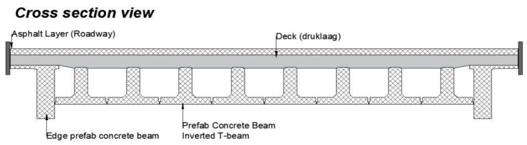
The case study which has been drawn up in order to further developed the tool and find the corresponding results of the design alternatives in this research will be given in this sheet.

| LEGEND |
|---|
| FILL IN THIS COLOR CELLS |
| POSSIBLY FILL IN THIS COLOR CELLS |
| STAY AWAY FROM THIS COLOR CELLS |

### Caste study

| | | |
|---|---|---|
| Civil structure | Viaduct | |
| Span prefab concrete beam | 25 | m |
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |

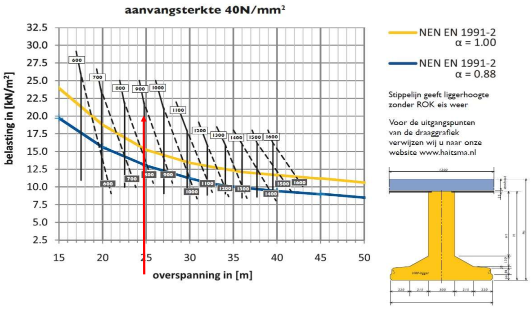



### Determination of inverted T-beam type

*Source: Haitsma beton - HRP railligger profiel (documentatie HRP en HIP en doornsede HRP pdf)*
*https://www.haitsma.nl/bruggen-viaducten/hrp-railligger-15-45m*

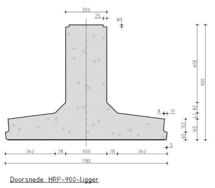
The figures illustrate how an inverted T-beam type is determined using the span-length graph and detailed information table on profile type of inverted T-beams




| Profiel | B | Ab | V | I | $Q_{eg}$ | $Ab_s$ | Hs | $V_s$ | $EI_s$ | $Q_{egs}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | Element h.o.h. 1200mm | | | | | Samengesteld profiel, druklaag 250mm | | | | |
| HRP | $mm^1$ | $mm^2$ | mm | $mm^4$ x10⁹ | kN/m | $mm^2$ | $mm^1$ | $mm^3$ | $Nmm^2$ x10¹⁵ | kN/m |
| 500 | 300 | 3,15E+05 | 172 | 5,44 | 7,88 | 3,00E+05 | 750 | 373 | 1,39 | 15,38 |
| 600 | 300 | 3,45E+05 | 204 | 9,30 | 8,63 | 3,00E+05 | 850 | 424 | 1,96 | 16,13 |
| 700 | 300 | 3,75E+05 | 240 | 14,7 | 9,38 | 3,00E+05 | 950 | 475 | 2,65 | 16,88 |
| 800 | 300 | 4,05E+05 | 277 | 21,9 | 10,13 | 3,00E+05 | 1050 | 525 | 3,46 | 17,63 |
| 900 | 300 | 4,35E+05 | 316 | 30,9 | 10,88 | 3,00E+05 | 1150 | 576 | 4,4 | 18,38 |
| 1000 | 300 | 4,65E+05 | 357 | 42,1 | 11,63 | 3,00E+05 | 1250 | 626 | 5,47 | 19,13 |
| 1100 | 300 | 4,95E+05 | 398 | 55,5 | 12,38 | 3,00E+05 | 1350 | 677 | 6,68 | 19,88 |
| 1200 | 300 | 5,25E+05 | 441 | 71,3 | 13,13 | 3,00E+05 | 1450 | 728 | 8,04 | 20,63 |
| 1300 | 300 | 5,55E+05 | 485 | 89,7 | 13,88 | 3,00E+05 | 1550 | 778 | 9,55 | 21,38 |
| 1400 | 300 | 5,85E+05 | 529 | 111,0 | 14,63 | 3,00E+05 | 1650 | 828 | 11,2 | 22,13 |
| 1500 | 300 | 6,15E+05 | 573 | 135,0 | 15,38 | 3,00E+05 | 1750 | 879 | 13,1 | 22,88 |
| 1600 | 300 | 6,45E+05 | 619 | 162,0 | 16,13 | 3,00E+05 | 1850 | 929 | 15,1 | 23,63 |

- *Grafiekwaarden gebaseerd op betonkwaliteit elelementen, betonkwaliteit druklaag C30/37*
- *Profiel is tevens profielhoogt H.*
- *v (vs)= zwaartepuntsafstand (samengesteld) profiel vanaf onderzijde.*
- *Op aanvraag grotere overspanningen mogelijk.*

**Chosen profile: HRP 900 beam**




### Material quantities determination - Bill of Materials

| | | | | |
|---|---|---|---|---|
| **Inverted T-beam profile** | HRP 900 | | | **Note:** |
| **Concrete class** | C55/67 (CEMI-CEMIII) | | m3 | The amount of concrete mortar (m3) in a beam can be calculated using the information in the table and span-length of beam and the specified concrete class is needed for the LCA calculation |
| **Prestressed steel** | No specification needed | | Kg or Tonnes | The amount of steel in a prefab concrete beam varies and is produced by a supplier based on project requirements; No specification needed for calculations |
| **Reinforcement steel** | No specification needed | | Kg or Tonnes | The amount of steel in a prefab concrete beam varies and is produced by a supplier based on project requirements; No specification needed for calculations |

**Quantity m3 Concrete mortar C55/67 (CEMI-CEMIII)**

| Profile type | Ab | Span-length | mm3/beam | # Beams | Total | Total |
|---|---|---|---|---|---|---|
| | mm2 | mm | | 3 fields x 8 beam | mm3 | m3 |
| HRP 900 | 435000 | 25000 | 10875000000 | 24 | 2,61E+11 | 261 |

**Quantity steel in HRP 900**

| Profile type | 1 Beam | 1 Beam | | # Beams | Total | Total |
|---|---|---|---|---|---|---|
| | kg | Tonnes | | 3 fields x 8 beam | kg | Tonnes |
| Prestressed steel | 471,01 | 0,47 | | 24 | 11304,35 | 11,30 |
| Reinforcement steel | 1076,35 | 1,08 | | 24 | 25832,45 | 25,83 |

### Steel quantity determinion based on information provided by Dura Vermeer B.V. from a previous project

| | | | | |
|---|---|---|---|---|
| Span-length prefab concrete beam Case study | 25 | m | | |
| **Amount conversion based on information obtained from a project :** | | | | |
| Span-length prefab concrete beam project | 14,145 | m | 1,77 | Conversion factor |
| Prestressed steel | 266,5 | Kg / beam | 471,01 | Kg / beam |
| Reinforcement steel | 609 | Kg / beam | 1076,35 | Kg / beam |

### Transportation and harvesting effort for prefab concrete beams

Distance from harvest location to repurpose location 150 km

**1. Disassembly + Transport + Storage**

1.1 Disassembly — ECI at the expense of the harvest location and included in demolition phase

1.2 Transport + Storage location distance 75 km — ½ x ECI at expense of new project

*assuming that the storage location is between the harvest location and repurpose location

**2. Harvesting effort (Inverted T prefab concrete beams)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2.1. Drilling holes for detaching beams from linkedbeam | Drilling concrete | 1 Beam | 18 Holes | 0,7 h/hole | 12,6 h/beam | *14 holes for detaching and 4 holes for lifting |
| 2.2. Sawing through deck (druklaag) = dissamling beams from existing civil structure | Sawing concrete | 1 Beam | 2 Sides | 0,5 h/side/beam | | |
| 2.3 Modification of beams = Each beam is shortened/modified on both sides, whereby correct crossing angle is applied | Sawing concrete | 1 Beam | 2 Sides | 0,5 h/side/beam | | |

### Calculating variants with residual prefab concrete beams

**Variant 2**

| | | | | | |
|---|---|---|---|---|---|
| 2.1. Drilling holes | 16 Beams | 18 Holes / beam | 288 # Holes / beam | 0,7 h/hole | 201,6 h |
| 2.2. Sawing beams | 16 Beams | 2 Sides/beam | 32 # Sides/beam | 0,5 h/side/beam | 16 h |
| 2.3. Modification of beams | 16 Beams | 2 Sides/beam | 32 # Sides/beam | 0,5 h/side/beam | 16 h |

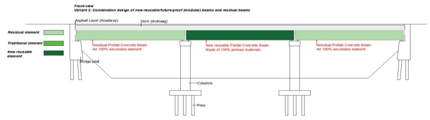
*The deck removal has not been taken into account (yet)

**Variant 3**

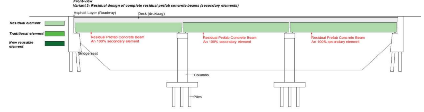
| | | | | | |
|---|---|---|---|---|---|
| 2.1. Drilling holes | 24 Beams | 18 Holes / beam | 432 # Holes / beam | 0,7 h/hole | 302,4 h |
| 2.2. Sawing beams | 24 Beams | 2 Sides/beam | 48 # Sides/beam | 0,5 h/side/beam | 24 h |
| 2.3. Modification of beams | 24 Beams | 2 Sides/beam | 48 # Sides/beam | 0,5 h/side/beam | 24 h |

*The deck removal has not been taken into account (yet)

Variant 2: 2/3 residual
1/3 new circular




Variant 3: residual beams



**ECI-value comparison of Variants (Case study Graduation Research)**

**Calculation of the Environmental Cost Indication-value of each variant using DuboCalc; based on the Life Cycle Analysis**

| LEGEND |
|---|
| FILL IN THIS COLOR CELLS |
| POSSIBLY FILL IN THIS COLOR CELLS |
| STAY AWAY FROM THIS COLOR CELLS |

**Input values from DuboCalc**

These values have been obtained from DuboCalc and are displayed in the tool as ECI/unit in order to calculate the total ECI for the variants

**DuboCalc 5.1**

**NMD versie 2.3 Dubocalc - 6.01.27092018** — **From Dubocalc**

| Item | Item name as written in Dubocalc | amount | unit | Environmental Cost Indicator |
|---|---|---|---|---|
| Concrete mortar C55/67 (CEMI-CEM III) | Betonmortel C55/67 (CEMI-CEMIII) | 1 | m3 | 35,17 |
| Prestressed steel | Voorspanstaal | 1 | ton | 115,14 |
| Reinforcement steel | Betonstaal | 1 | ton | 106,24 |
| Transport bulk (by road) - Concrete | Transport bulk (over de weg) | 2,437 | tonkm | 5,6625 |
| Drilling beams | Compr.diesel 3.5-10.0 m3/min | 1 | h | 4,48 |
| Sawing beams | Compr.diesel 3.5-10.0 m3/min | 1 | h | 4,48 |

**Remarks:** ECI DuboCalc for Transport

At 20 km (fixed) 1,51 ECI/unit — For fixed-distance concrete, this is written in the determination method. The ECI value involved for residual beams during deployment has therefore been converted (project-specific) into the number of km project/source

At 75 km 5,6625

**Variant 0**

| ECI Value Variant 0: Traditional design | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| Prefab concrete beam | Concrete mortar C55/67 (CEMI-CEM III) | 261 | m3 | € 35,17 | € 9.179,37 |
| | Prestressed steel | 11 | Tonnes | € 115,14 | € 1.301,58 |
| | Reinforcement steel | 26 | Tonnes | € 106,24 | € 2.744,44 |
| **Total** | | | | | € 13.225,39 |

**Remarks:**
1. The prefab concrete beams are made out of 100% primary raw materials

*Figure Life Cycle Analysis Variant 0*

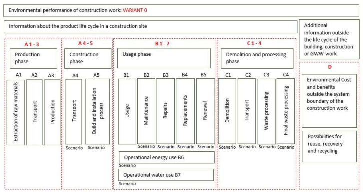
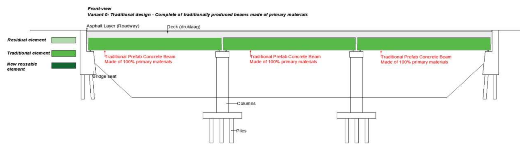


*Figure Front-view Variant 0*



**Variant 1**

| ECI Value Variant 1: Circular design with new produced modular beams | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| Prefab concrete beam | Concrete mortar C55/67 (CEMI-CEM III) | 261 | m3 | € 35,17 | € 9.179,37 |
| | Prestressed steel | 11 | Tonnes | € 115,14 | € 1.301,58 |
| | Reinforcement steel | 26 | Tonnes | € 106,24 | € 2.744,44 |
| | ½ x Total ECI at expense of current project | ½ | | | € -6.612,70 |
| **Totaal** | | | | | € 6.612,70 |

**Remarks:**
1. The prefab concrete beams are made out of 100% primary materials and same composition as the traditional beam, however the beams are modular and thus reusable and future-proof
2. Composition in materials of the modular beams = Composition in materials of traditional beams
3. Quantity of materials traditionally produced beam with primary material = newly produced modular beam
4. For both the concrete and steel in a prefab concrete beam, a product lifespan of 100 years is determined in DuboCalc and included in the ECI and LCA. According to recent studies, prefab concrete beams can last for 200 years.
Thus, It is assumed that the total environmentl costs are spread over 200 years as this design considers modular beams and the environmental burden of the variant in the 1st lifecycle counts for ½.
5. A product life span of 100 years is divided in reality over a actual lifespan of 200 years = 100/200 = ½

*Figure Life Cycle Analysis Variant 1*

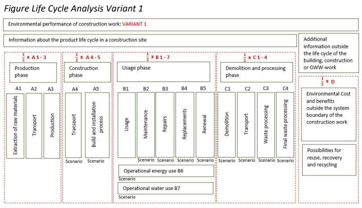
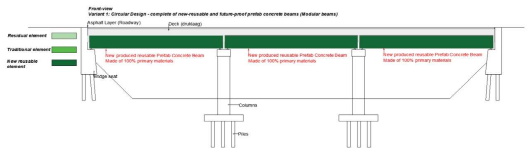


*Figure Front-view Variant 1*



**Variant 2**

| ECI Value Variant 2: Combination design of new-reusable modular beams (1/3) and residual beams (2/3) | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| 1/3 modular prefab concrete beams | Concrete mortar C55/67 (CEMI-CEM III) | 87 | m3 | € 35,17 | € 3.059,79 |
| | Prestressed steel | 4 | Tonnes | € 115,14 | € 433,86 |
| | Reinforcement steel | 9 | Tonnes | € 106,24 | € 914,81 |
| | ½ x Total ECI at expense of current project | | | | € 2.204,23 |
| | | | | | |
| 2/3 residual prefab concrete beams | Concrete mortar C55/67 (CEMI-CEM III) | 174 | m3 | € - | € - |
| | Prestressed steel | 8 | Tonnes | € - | € - |
| | Reinforcement steel | 17 | Tonnes | € - | € - |
| Transport | Transport bulk (by road) - Concrete | 424 | tonkm | € 5,66 | € 2.401,12 |
| Drilling beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 201,6 | h | € 4,48 | € 903,17 |
| Sawing beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 16 | h | € 4,48 | € 71,68 |
| Sawing beams (Modifying) | Compr.diesel 3.5-10.0 m3/min | 16 | h | € 4,48 | € 71,68 |
| **Totaal** | | | | | € 5.651,88 |

**Remarks:**
1. This design consists of 1/3 new produced reusable modular beam and 2/3 residual beams
2. The 1/3 new reusable beams are of the same composition as described in Variant 2
3. The 2/3 residual beams are going in their 2nd lifecycle, thus they are free from environmental costs for the production, construction, usage phase. However, the transportation and harvesting effort are taken into account
4. The transportion (in km) are divided = half of the environmental costs is at the expense of the harvesting location and half is at the expense of the new to-be built project (this variant) --> This is implemented in the transport bulk ECI/unit value

*Figure Life Cycle Analysis Variant 2; Part 1 for new-reusable modular beams*

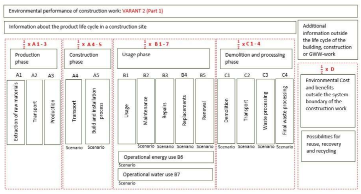


*Figure Life Cycle Analysis Variant 2; Part 2 for the residual beams*

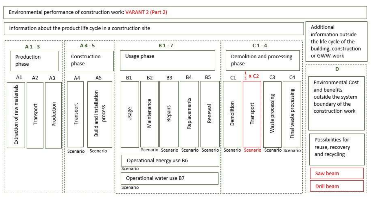
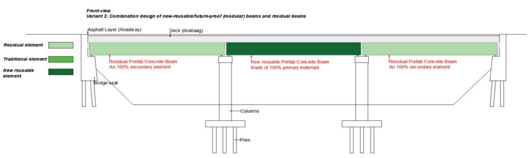


*Figure Front-view Variant 2*



**Variant 3**

| ECI Value Variant 3: Residual design | | | | | |
|---|---|---|---|---|---|
| Element | Description | Quantity | unit | ECI / unit (€) | Σ ECI (€) |
| Residual prefab concrete beams | Concrete mortar C55/67 (CEMI-CEM III) | 261,0 | m3 | € - | € - |
| | Prestressed steel | 11,3 | ton | € - | € - |
| | Reinforcement steel | 25,8 | ton | € - | € - |
| Transport | Transport bulk (by road) - Concrete | 636 | tonkm | € 5,66 | € 3.601,67 |
| Drilling beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 302 | h | € 4,48 | € 1.354,75 |
| Sawing beam (Harvesting) | Compr.diesel 3.5-10.0 m3/min | 24 | h | € 4,48 | € 107,52 |
| Sawing beams (Modifying) | Compr.diesel 3.5-10.0 m3/min | 24 | h | € 4,48 | € 107,52 |
| **Totaal** | | | | | € 5.171,46 |

**Remarks:**
1. All residual beams in this design are going in their 2nd lifecycle, thus they are free from environmental costs for the production, construction, usage phase. However, the transportation and harvesting effort are taken into account
2. The transportion (in km) are divided = half of the environmental costs is at the expense of the harvesting location and half is at the expense of the new to-be built project (this variant) --> This is implemented in the transport bulk ECI/unit value

*Figure Life Cycle Analysis Variant 3*

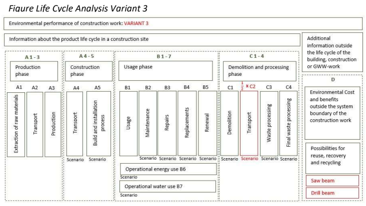
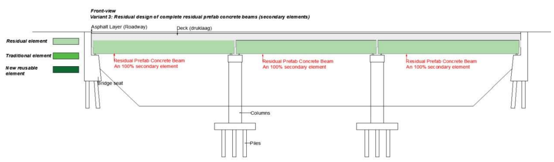


*Figure Front-view Variant 3*



**Circularity performance of Variants (Case study Graduation Research)**

**Calculation of the % circularity of each variant using the described method by platform CB'23**

**Input values**

| MATERIAAL SUPPLY | Unit | Phase | Specific weight (tonnes/unit) | Source Bepalingsmethode 3.0 |
|---|---|---|---|---|
| **Prefab concrete beam** | | | | |
| Concrete mortar C55/67 | **m3** | **A1-A3** | **2,437** | 2437 kg 0165-fab&Betonmortel C55/67 (o.b.v. 75% CEM III en 25% CEM I), 2437 kg/m3 - Nationale Milieudatabase v3.2 (obv Ecoinvent 3.5) per 1 uses 2,437 kg 275.36655 kg $CO_2$-eq x |
| Prestressed steel | **ton** | **A1-A3** | **1,000** | 1000 kg 0167-fab&Staal, wapening (betonstaal, wapeningsnet, vezels, voorspanstaal) (o.b.v. Reinforcing steel (GLO)\| market for \| Cut-off, U; 84% primair, 16% secundair) - Nationale Milieudatabase v3.2 (obv Ecoinvent 3.5) per 1 uses 1,000 kg 2,107.82603 kg $CO_2$-eq x |
| Reinforcement steel | **ton** | **A1-A3** | **1,000** | 1000 kg 0167-fab&Staal, wapening (betonstaal, wapeningsnet, vezels, voorspanstaal) (o.b.v. Reinforcing steel (GLO)\| market for \| Cut-off, U; 84% primair, 16% secundair) - Nationale Milieudatabase v3.2 (obv Ecoinvent 3.5) per 1 uses 1,000 kg 2,107.82603 kg $CO_2$-eq x |

**CO2 tabel**

| Element | Unit | Total quantitiy in pre-design | Specific weight (tonnes/unit) |
|---|---|---|---|
| **Variants** | | | |
| Concrete mortar C55/67 | **m3** | 261,0 | 2,437 |
| Prestressed steel | **ton** | 11,3 | 1,000 |
| Reinforcement steel | **ton** | 25,8 | 1,000 |

**Variants circularity performance calculation**

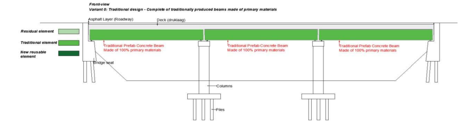
**LEGEND**

FILL IN THIS COLOR CELLS
POSSIBLY FILL IN THIS COLOR CELLS
STAY AWAY FROM THIS COLOR CELLS

A. The % of secondary and biobased materials used in the project
B. The % of materials that are released during the project and that are reused (high or equivalent)
C. The % of objects that are designed in such a way that they can be easily reused in the future (demountable)

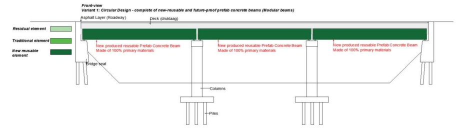
**Variant 0 Traditional design**

| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete mortar C55/67 | **m3** | 261,0 | 2,4 | 636,057 | 0% | | 0,0 | 0,0 | 0% | | 636,1 | 0% | |
| Prestressed steel | **ton** | 11,3 | 1,0 | 11,3 | 0% | | 0,0 | 0,0 | 0% | | 11,3 | 0% | |
| Reinforcement steel | **ton** | 25,8 | 1,0 | 25,8 | 0% | | 0,0 | 0,0 | 0% | | 25,8 | 0% | |
| **TOTAL** | | | | | | | | | | | | | |
| Total weight | **ton** | | | 673,2 | | | | 0,0 | | | 673,2 | | |
| Total % per KPI | **%** | | | | 0% | | | | | | | 0% | |
| Total weight circular per KPI | **ton** | | | | 0 | | | | | | | 0 | |
| **% circularity of variant** | **%** | | | | | | | | | | | | 0% |



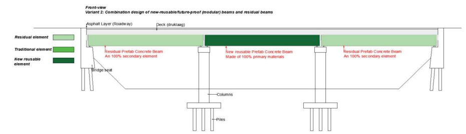
**Variant 1 Circular design**

| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete mortar C55/67 | **m3** | 261,0 | 2,4 | 636,057 | 0% | | 0,0 | 0,0 | 0% | | 636,1 | 100% | |
| Prestressed steel | **ton** | 11,3 | 1,0 | 11,3 | 0% | | 0,0 | 0,0 | 0% | | 11,3 | 100% | |
| Reinforcement steel | **ton** | 25,8 | 1,0 | 25,8 | 0% | | 0,0 | 0,0 | 0% | | 25,8 | 100% | |
| **TOTAL** | | | | | | | | | | | | | |
| Total weight | **ton** | | | 673,2 | | | | 0,0 | | | 673,2 | | |
| Total % per KPI | **%** | | | | 0% | | | | | | | 100% | |
| Total weight circular per KPI | **ton** | | | | 0 | | | | | | | 673,2 | |
| **% circularity of variant** | **%** | | | | | | | | | | | | 50% |



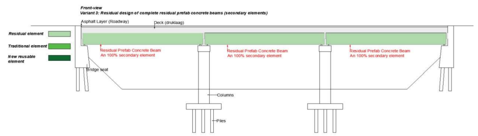
**Variant 2 Combination design**

| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete mortar C55/67 | **m3** | 261,0 | 2,4 | 636,057 | 67% | 2/3*100% are secundary beams | 174,0 | 424,0 | 0% | | 636,1 | 33% | 1/3*100% are modular beams |
| Prestressed steel | **ton** | 11,3 | 1,0 | 11,3 | 67% | 2/3*100% are secundary beams | 7,5 | 7,5 | 0% | | 11,3 | 33% | 1/3*100% are modular beams |
| Reinforcement steel | **ton** | 25,8 | 1,0 | 25,8 | 67% | 2/3*100% are secundary beams | 17,2 | 17,2 | 0% | | 25,8 | 33% | 1/3*100% are modular beams |
| **TOTAL** | | | | | | | | | | | | | |
| Total weight | **ton** | | | 673,2 | | | | 448,8 | | | 673,2 | | |
| Total % per KPI | **%** | | | | 67% | | | | 0% | | | 33% | |
| Total weight circular per KPI | **ton** | | | | 448,8 | | | | 0 | | | 224,4 | |
| **% circularity of variant** | **%** | | | | | | | | | | | | 37% |



**Variant 3 Residual design**

| Item | Unit | Total material quantity [Unit] | Specific weight [Tonnes/unit] | Converted to [Tonnes] | A. | Explanation | Total number of materials released [unit] | Total weight of released materials [Tonnes] | B. | Explanation | Total weight in design in [Tonnes] | C. | Explanation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete mortar C55/67 | **m3** | 261,0 | 2,4 | 636,057 | 100% | 2/3*100% are secundary beams | 261,0 | 636,1 | 0% | | 636,1 | 0% | |
| Prestressed steel | **ton** | 11,3 | 1,0 | 11,3 | 100% | 2/3*100% are secundary beams | 11,3 | 11,3 | 0% | | 11,3 | 0% | |
| Reinforcement steel | **ton** | 25,8 | 1,0 | 25,8 | 100% | 2/3*100% are secundary beams | 25,8 | 25,8 | 0% | | 25,8 | 0% | |
| **TOTAL** | | | | | | | | | | | | | |
| Total weight | **ton** | | | 673,2 | | | | 673,2 | | | 673,2 | | |
| Total % per KPI | **%** | | | | 100% | | | | 0% | | | 0% | |
| Total weight circular per KPI | **ton** | | | | 673,2 | | | | 0 | | | 0 | |
| **% circularity of variant** | **%** | | | | | | | | | | | | 33% |



## Life Cycle Costing using activity-based costing method (Case study Graduation Research)

### Cost Price Determnination of each variant

In this part the cost price will be determined of each variant. The costs price are given in €/m2. The costs price of residual beams is determined by all activities that take place in order to harvest the beams from the existing civil structure.

### Input values

| Cost Price Determination | Costs | Unit | Remarks: |
|---|---|---|---|
| **1. Traditional prefab concrete beam - purchased from precast concrete producer / supplier** | **360,00** | **€/m2** | |
| A. Engineering and calculation costs | | | |
| B. Transportation costs - from suplier to project location | | | |
| C. Overhead costs | | | |
| | | | |
| **2. Circular prefab concerete beam - purchased from concrete producer / supplier** | **378,00** | **€/m2** | |
| A. Engineering and calculation costs | | | |
| B. Transportation costs - from suplier to project location | | | |
| C. Overhead costs | | | |
| D. Extra engineering, development and processing costs for making a modular beam | | | |
| NOTE: the cost price of a modular beam is determined to be 5% higher in costs compared to a traditional beam | | | |

| | | | |
|---|---|---|---|
| **3. Residual prefab concrete beam - from existing civil structure** | **433,34** | **€/m2** | Illustrations of the handlings and operations for harvesting prefab concrete beams |
| **A. Research and overhead costs** | **35,24** | **€/m2** | |
| A.1. Field work, inspection harvesting beam from existing civil structure | | | |
| A.2. Research and development costs into beam condition and applicability/suitability for new civil structure | | | |
| A.3. Laboratory research into (residual) quality | | | |
| A.4. Inspection of processed and adjusted residual beam (by an independent agency) | | | |
| A.5. Engineering and construction calculation | | | |
| A.6. Second opinion (If another assessment is required after the first assessment) | | | |
| A.7. Overhead costs | | | |
| | | | |
| **B. Handling Cost = Costs to harvest the beam from existing civil structure** | **129,99** | **€/m2** | |
| B.1. Drilling beam and sawing from existing civil structure (from beam field) (Material + manpower) | | | |
| B.1.1. Disassembling of beam ends between beam fields / abutments | | | |
| B.1.2. Decoupling of beams by sawing between the in-situ pressure layer | | | |
| B.2. Lifting the beam for reuse from existing civil structure (from civil structure to trailer for transport) | | | |
| | | | |
| **C. Logistical costs** | **58,51** | **€/m2** | |
| C.1. Location of beam (above land/road or water) and extra time needed (in planning) for careful disassembling | | | |
| C.1.1. Over land = extra time needed to cause as little traffic disturbance as possible (leads to longer lead time) | | | |
| C.1.2. Above water = Demolition of beams as harvesting (disassembling) takes place in the same way (no traffic disruption | | | |
| C.2. Transportation costs | | | |
| C.2.1. From supplier (factory) to destination | | | |
| C.2.2. Transport: from harvest site to temporary storage site/location | | | |
| C.2.3. Transport: from storage location to new destination | | | |
| C.2.4. Transport: from harvest site to new destination (Ideal situation - no storage costs) | | | |
| | | | |
| **D. Temporary storage costs and processing costs** | **209,6** | **€/m2** | |
| D.1. Storage costs of beams with an unknown repurposing | | | |
| D.2. Processing costs | | | |
| D.2.1. Removal of deck (druklaag) using drilling machine | | | |
| D.2.2. Shortening of beam on the basis of repurposing requirements (in the span length required) | | | |

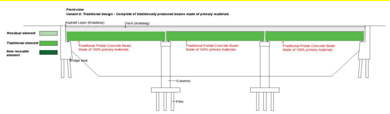



### Input values Case study viaduct

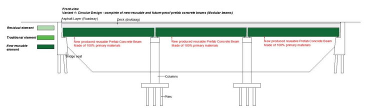
In this part the length and width of the viaduct will be determined

| | | |
|---|---|---|
| Civil structure | Viaduct | |
| Span prefab concrete beam | 25 | m |
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |

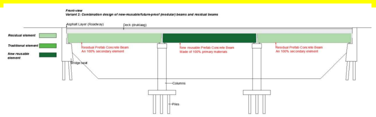
| Variant 0 | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - Traditional elements | 708 | m2 |
| 1. Traditional prefab concrete beam - purchased from precast concrete producer / supplier | 360,00 | €/m2 |
| Total costs | € 254.880,00 | |



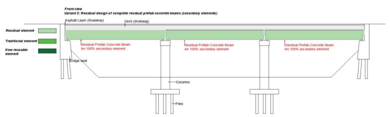
| Variant 1 | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - New reusable elements | 708 | m2 |
| 2. Circular prefab concerete beam - purchased from concrete producer / supplier | 378,00 | €/m2 |
| Total costs | € 267.624,00 | |



| Variant 2 | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9.44 | m |
| Surface viaduct - Residual element | 472 | m2 |
| Surface viaduct - New reusable elements | 236 | m2 |
| 3. Residual prefab concrete beam - from existing civil structure | 433,34 | €/m2 |
| 2. Circular prefab concerete beam - purchased from concrete producer / supplier | 378 | €/m2 |
| Total costs | € 293.744,48 | |

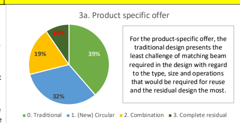


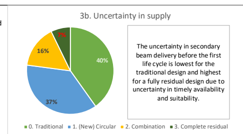
| Variant 3 | | |
|---|---|---|
| Length viaduct (excl. bridge seat) | 75 | m |
| Width viaduct (excl. Edge prefab concrete beams) | 9,44 | m |
| Surface viaduct - Residual elements | 708 | m2 |
| 3. Residual prefab concrete beam - from existing civil structure | 433,34 | €/m2 |
| Total costs | € 306.804,72 | |



| Parameters | Interviewee Variants | Interviewee 1 | Interviewee 2 | Interviewee 3 | Interviewee 4 | Interviewee 5 | Interviewee 6 | Interviewee 7 | Interviewee 8 | Interviewee 9 | # Interviewee's | Average | Value substantiation: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **3. Supply and demand** | | | | | | | | | | | | | |
| **a. Product specific offer** | 0. Traditional | 1 | 0,9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 0,99 | The product specific offer of secudary beams before the first life cycle of the traditional design does not apply here. However, there will be a challenge as less primary material should be used in the future. Thus the value is not 1. |
| | 1. (New) Circular | 1 | 0,8 | 0,95 | 0,75 | 0,5 | 0,75 | 1 | 1 | 0,7 | 9 | 0,83 | The product-specific range of secundary beams before the first life cycle of the circular design presents a challenge because the connection possibilities with the abutments and between the girders must be taken into account and despite having influence on the design, you have to think about the future. |
| | 2. Combination | 0,5 | 0,5 | 0,4 | 0,5 | 0,4 | 0,4 | 0,7 | 0,66 | 0,4 | 9 | 0,50 | It is a challenge for having a fit-for-purpose beams due to the span-length. If the freed beam is smaller than 10m, it is no longer reusable. However, in the combination design, the part with the new beams can absorb the challenges and the beams can be newly produced for the project. |
| | 3. Complete residual | 0,3 | 0,3 | 0,25 | 0,25 | 0,4 | 0 | 0,4 | 0,1 | 0,2 | 9 | 0,24 | The product specific offer of secundary beams before the first life cycle of the residual design pose a challenge due to adaptability of the available beam size in the required size and as this design considers 100% residual beam, the shortage of residual beams can occur. |
| **b. Uncerntainty in supply** | 0. Traditional | 0,8 | 0,99 | 0,95 | 1 | 0,9 | 1 | 0,75 | 1 | 1 | 9 | 0,93 | There is always a small degree of uncertainty in the supply (supply risk) before the first life cycle of the traditional due to the high demand for precast concrete beams and limited number of suppliers/producers on the market and limited primary raw material stock. |
| | 1. (New) Circular | 0,8 | 0,95 | 0,9 | 1 | 0,3 | 1 | 0,75 | 1 | 1 | 9 | 0,86 | There is a degree of uncertainty in the supply (supply risk) before the first life cycle of the circular design because the modular prefab concrete beams still have to be developed and are not yet available and thus the suitability and availability are unknown. |
| | 2. Combination | 0,4 | 0,4 | 0,5 | 0,5 | 0,25 | 0 | 0,75 | 0,3 | 0,2 | 9 | 0,37 | The supply risk for the combination design before the first life cycle is higher as this design considers 75% residual beams and 25% new produced modular beams. Thus it is uncertain whether beams will be available on time and thus also suitable. If this design would consider a lower % of residual beams then supply risk would be lower. |
| | 3. Complete residual | 0,2 | 0,25 | 0,4 | 0,2 | 0,2 | 0 | 0,2 | 0,05 | 0 | 9 | 0,17 | The uncertainty in the supply of secondary beam (supply risk) before the first life cycle of the residual design is high due to the high demand for secondary materials, the timely availability is unknown and the suitability for repurposing is unknown. |

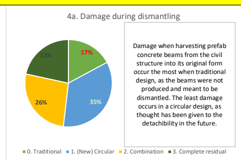
Comparison variants within sub-parameter:

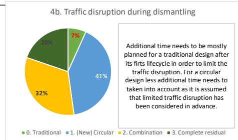



| Parameters | Interviewee Variants | Interviewee 1 | Interviewee 2 | Interviewee 3 | Interviewee 4 | Interviewee 5 | Interviewee 6 | Interviewee 7 | Interviewee 8 | Interviewee 9 | # Interviewee's | Average | Value substantiation: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **4. Detachibility of prefab concrete beams** | | | | | | | | | | | | | |
| **a. Damage during dismantling** | 0. Traditional | 0,4 | 0,2 | 0,5 | 0,5 | 0,4 | 0 | 0,75 | 0,1 | 0,2 | 9 | 0,34 | During the dismantling of prefab concrete beams from the existing structure (into its original form) after the first life cycle of a traditional design, damage to the beams will occur due to the fact that was not meant to be dismantled and given the current knowledge and experience there is no technical solution for removing the pressure layer. |
| | 1. (New) Circular | 0,4 | 0,6 | 0,8 | 1 | 0,6 | 1 | 0,5 | 0,8 | 0,5 | 9 | 0,69 | Dismantling of prefab concrete beams from an existing structure after the first life cycle of a circular design will never go without damage due to the limited knowledge and current experience for the removal of the pressure layer. However, more thought has been given to how this can be future-proof and traceable. |
| | 2. Combination | 0,4 | 0,5 | 0,65 | 0,6 | 0,5 | 0,75 | 0,6 | 0,4 | 0,3 | 9 | 0,52 | In the combination design, the degree of damage after the first life cycle of the structure can be determined from the amount of reused beams and new beams in the design. As this design considers 75% residual beams, which were once traditionally produced, there is some degree of damage during dismantling. |
| | 3. Complete residual | 0,4 | 0,4 | 0,5 | 0,4 | 0,4 | 0,4 | 0,75 | 0,6 | 0 | 9 | 0,43 | When considering the residual design, after the first life cycle of this design, the prefab concrete beams are going in their 3rd life cycle. Thus there will also be a certain amount of damage. However, thought might be given beforehand on the dismantling process and limitation of damage for a 3rd repurpose. |
| **b. Traffic disruption during disma** | 0. Traditional | 0,4 | 0 | 0,2 | 0,2 | 0,1 | 0 | 0 | 0 | 0 | 9 | 0,10 | Additional time needs to be planned for limited traffic disruption when harvesting the beams from an existing deck of beams, after the first life cycle of a traditional design, because something needs to be dismantled that wasn't designed to be dismantled. Further, due to the current limited experiences, more time is needed for harvesting. |
| | 1. (New) Circular | 0,4 | 0,8 | 0,8 | 0,6 | 0,7 | 0,5 | 0,4 | 0,8 | 0,5 | 9 | 0,61 | For the circular design it is assumed that consideration has been given in advance to detaching as efficiently as possible and to cause as little traffic disruption as possible. However, there will always be a degree of traffic disruption if the beam fields lie above another road. |
| | 2. Combination | 0,5 | 0,45 | 0,5 | 0,5 | 0,4 | 0,8 | 0,4 | 0,6 | 0,2 | 9 | 0,48 | Extra time in the planning, regarding traffic disruption, after the first lifecycle of a combination design should also be taken into account. However, it is limited because it is assumed that this has been considered in advance. |
| | 3. Complete residual | 0,6 | 0,3 | 0,2 | 0,4 | 0,1 | 0,65 | 0 | 0,3 | 0,1 | 9 | 0,29 | For the residual design, extra time should also be taken into account for limited traffic disruption as this design considers only residual (traditionally produced) prefab concrete beams. Thus, the same applies more or less as variant 0. |

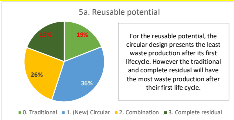
Comparison variants within sub-parameter:

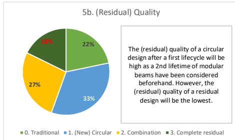


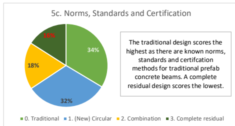



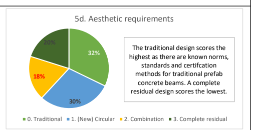

| Parameters | Interviewee Variants | Interviewee 1 | Interviewee 2 | Interviewee 3 | Interviewee 4 | Interviewee 5 | Interviewee 6 | Interviewee 7 | Interviewee 8 | Interviewee 9 | # Interviewee's | Average | Value substantiation: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **5. Reusability of prefab concrete beams** | | | | | | | | | | | | | |
| **a. Reusable potential** | 0. Traditional | 0,4 | 0,3 | 0,8 | 0,3 | 0,6 | 0,25 | 0,75 | 0,4 | 0,3 | 9 | 0,46 | The degree of waste production that will take place after the first life cycle of the traditional design is high because these beams will still be adapted for reuse. |
| | 1. (New) Circular | 0,8 | 0,8 | 0,95 | 0,9 | 0,9 | 1 | 0,9 | 0,9 | 0,6 | 9 | 0,86 | The degree of waste production that will take place after the first life cycle of a circular design is limited. However, it is not possible to harvest waste-free and adjusments might be necessary be before the prefab concrete beams can be reused. |
| | 2. Combination | 0,6 | 0,7 | 0,875 | 0,6 | 0,4 | 0,8 | 0,85 | 0,3 | 0,4 | 9 | 0,61 | The degree of waste production that will take place after the first life cycle of a the combination design lies between the amount of variant 1 and 3 as this consider 75% residual beams and 25% modular beams. |
| | 3. Complete residual | 0,5 | 0,6 | 0,8 | 0,2 | 0,3 | 0,6 | 0,75 | 0,2 | 0,2 | 9 | 0,46 | The amount of waste production of the residual design after the first life cycle is more or less the same as the traditional design based on the gained results. However, in this design the residual beams are going in their 3rd life cycle thus some expert argued that the waste production would be more and less would be reusable. |
| **b. (Residual) quality** | 0. Traditional | 0,6 | 0,5 | 0,75 | 0,2 | 0,8 | 0,25 | 0,9 | 0,6 | 0,3 | 9 | 0,54 | There will be a certain amount of technical residual bearing capacity and residual lifespan after the first lifecycle of the prefab concrete beams in a traditional design (considering that the civil structure had a lifespan of 40 or 50 years) as current experience show that concrete does not age and only get better with time. |
| | 1. (New) Circular | 0,9 | 0,9 | 0,9 | 0,7 | 0,9 | 1 | 1 | 0,8 | 0,5 | 9 | 0,84 | For the circular design after its first lifecycle, it is assumed that the technical residual bearing capacity and residual lifespan will be higher compared to the traditional (considering that the civil structure had a lifespan of 40 or 50 years). This is due to the fact that a 2nd lifetime for the modular beams have been considered in advance. |
| | 2. Combination | 0,7 | 0,7 | 0,825 | 0,4 | 0,7 | 0,8 | 1 | 0,5 | 0,4 | 9 | 0,67 | The value for the technical residual bearing capacity and residual lifespan in the combination design lies between the circular design and full residual design as this design considers 75% residual beams and 25% new modular beams. |
| | 3. Complete residual | 0,4 | 0,5 | 0,5 | 0,1 | 0,6 | 0,4 | 0,9 | 0,4 | 0,2 | 9 | 0,44 | The prefab concrete beams in the residual design after the first lifecycle, will have a lower technical residual bearing capacity and residual lifespan as the residual beams are going in their 3rd lifecycle. |
| **c. Norms, standards and certification** | 0. Traditional | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 1,00 | For a traditional design and newly produced beams there are norms, standards and certifications available. Thus, this would not be an issue before the first lifecycle of this design. |
| | 1. (New) Circular | 0,8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0,8 | 9 | 0,96 | As a cirular design also considers new produced prefab concrete beams before it first lifecycle, the availbe norms, standards and certifications can be used. However, as these norms were not specifically drawn up for modular beams, the value is not 1. |
| | 2. Combination | 0,5 | 0,55 | 0,2 | 0,8 | 0,7 | No value | 0,5 | 0,8 | 0,3 | 8 | 0,54 | For the combination design it will be difficult to use the available norms, standards and certification as these were not developed for residual beams. As this design considers 75% residual beams it will be difficult to test and certify the standards. NOTE: one expert did not give a value as there are no norms available for secondary elements. |
| | 3. Complete residual | 0,5 | 0,5 | 0,3 | 0,8 | 0,7 | No value | 0,1 | 0,7 | 0,2 | 8 | 0,48 | For the complete residual design the same applies as the combination design with 75% residual beams. However, as this design considers only residual beams the value is even lower. NOTE: one expert did not give a value as there are no norms available for secondary elements. |
| **d. Aesthetic requirements** | 0. Traditional | 0,75 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 0,97 | The aethetic requirements for a traditional design are almost no barrier in the acceptance of a client as the beams can be produced as per required. However, there could be a slighty barrier in the design when working with prefab concrete beams and their fixed prefab design. |
| | 1. (New) Circular | 0,75 | 0,8 | 0,9 | 0,75 | 1 | 1 | 1 | 1 | 0,8 | 9 | 0,89 | The aethetic requirements for a circular design can cause a slight barrier in the acceptance of a client as these will be produced more robust and need to be reusable in the future. |
| | 2. Combination | 0,5 | 0,3 | 0,6 | 0,2 | 0,7 | 0,75 | 0,75 | 0,7 | 0,4 | 9 | 0,54 | The aethetic requirements for a combination design can cause a huge barrier in the acceptance of a client as this design considers different types of beams (residual and new modular beams). Thus, this can be a challenge to get the views of the viaduct correct. |
| | 3. Complete residual | 0,3 | 0,5 | 0,75 | 0,5 | 0,8 | 0,75 | 0,75 | 0,7 | 0,4 | 9 | 0,61 | The aethetic requirements for a residual design will not cause a huge barrier such as the combination design, assuming that the residual beams that will be applied come from the same batch. |

Comparison variants within sub-parameter:



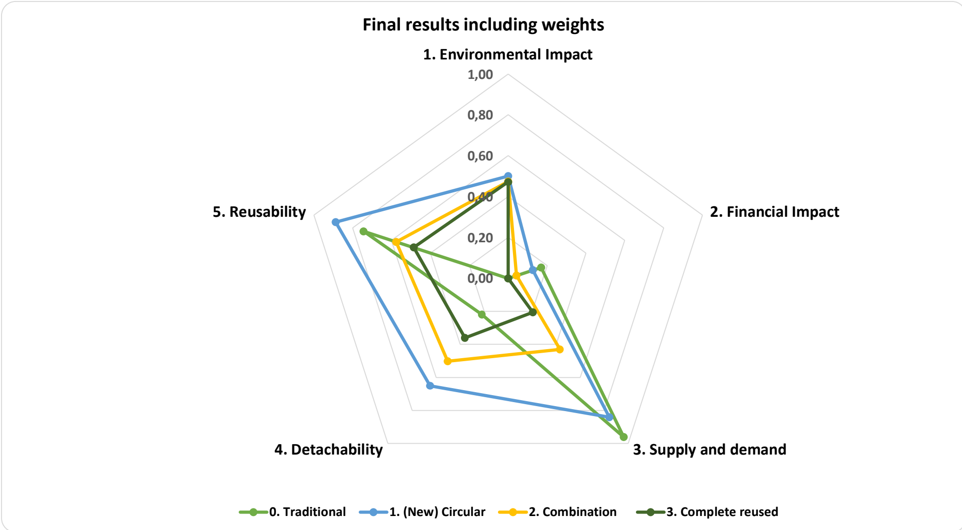



| | | Boundaries | | Results [Unit] | | | | (Normalized) Results [-] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Most undesirable scenario | Most desirable scenario | Variant 0. | Variant 1. | Variant 2. | Variant 3. | Variant 0. | Variant 1. | Variant 2. | Variant 3. |
| **Parameter** | **Sub-parameter** | **Minimum** | **Maximum** | **Traditional** | **(New) Circular** | **Combination** | **Complete reused** | **Traditional** | **(New) Circular** | **Combination** | **Complete reused** |
| 1. Environmental Impact | a. Life Cycle Analysis - ECI | € 13.225,39 | € - | € 13.225,39 | € 6.612,70 | € 5.651,88 | € 5.171,46 | 0,00 | 0,50 | 0,57 | 0,61 |
| | b. Circularity performance | 0% | 100% | 0% | 50% | 37% | 33% | 0,00 | 0,50 | 0,37 | 0,33 |
| 2. Financial Impact | Cost price determination of design alternatives | € 306.804,72 | € - | € 254.880,00 | € 267.624,00 | € 293.744,48 | € 306.804,72 | 0,17 | 0,13 | 0,04 | 0,00 |
| 3. Supply and demand | a. Product specific offer | 0 | 1 | 0,99 | 0,83 | 0,50 | 0,24 | 0,99 | 0,83 | 0,50 | 0,24 |
| | b. Uncertainty in supply: availability and suitability | 0 | 1 | 0,93 | 0,86 | 0,37 | 0,17 | 0,93 | 0,86 | 0,37 | 0,17 |
| 4. Detachability | a. Damage to beams during dismanteling | 0 | 1 | 0,34 | 0,69 | 0,52 | 0,43 | 0,34 | 0,69 | 0,52 | 0,43 |
| | b. Traffic disruption during dismanteling | 0 | 1 | 0,10 | 0,61 | 0,48 | 0,29 | 0,10 | 0,61 | 0,48 | 0,29 |
| 5. Reusability | a. Reusable potential | 0 | 1 | 0,46 | 0,86 | 0,61 | 0,46 | 0,46 | 0,86 | 0,61 | 0,46 |
| | b. (Residual) quality - *Liability and risk factor (-10% on designs with residual beams - adjustable)* | 0 | 1 | 0,54 | 0,84 | 0,67 | 0,44 | 0,54 | 0,84 | 0,60 | 0,40 |
| | c. Norms, standards and certification | 0 | 1 | 1,00 | 0,96 | 0,54 | 0,48 | 1,00 | 0,96 | 0,54 | 0,48 |
| | d. Aestetic requirements | 0 | 1 | 0,97 | 0,89 | 0,54 | 0,61 | 0,97 | 0,89 | 0,54 | 0,61 |

| **Parameter** | **Sub-parameter** | **Weights** | **Results** | | | |
|---|---|---|---|---|---|---|
| | | | Variant 0. | Variant 1. | Variant 2. | Variant 3. |
| | | | Traditional | (New) Circular | Combination | Complete reused |
| 1. Environmental Impact | a. Life Cycle Analysis - ECI | 50% | 0,00 | 0,50 | 0,47 | 0,47 |
| | b. Circularity Measurement | 50% | | | | |
| 2. Financial Impact | Cost price determination of design alternatives | 100% | 0,17 | 0,13 | 0,04 | 0,00 |
| 3. Supply and demand | a. Product specific offer | 50% | 0,96 | 0,84 | 0,43 | 0,21 |
| | b. Uncertainty in supply: availability and suitability | 50% | | | | |
| 4. Detachability | a. Damage to beams during dismanteling | 50% | 0,22 | 0,65 | 0,50 | 0,36 |
| | b. Traffic disruption during dismanteling | 50% | | | | |
| 5. Reusability | a. Reusable potential | 25% | 0,74 | 0,89 | 0,58 | 0,49 |
| | b. (Residual) quality | 25% | | | | |
| | c. Norms, standards and certification | 25% | | | | |
| | d. Aestetic requirements | 25% | | | | |




| Final results | | | | |
|---|---|---|---|---|
| **Parameter** | **0. Traditional** | **1. (New) Circular** | **2. Combination** | **3. Complete reused** |
| **1. Environmental Impact** | 0,00 | 0,50 | 0,47 | 0,47 |
| **2. Financial Impact** | 0,17 | 0,13 | 0,04 | 0,00 |
| **3. Supply and demand** | 0,96 | 0,84 | 0,43 | 0,21 |
| **4. Detachability** | 0,22 | 0,65 | 0,50 | 0,36 |
| **5. Reusability** | 0,74 | 0,89 | 0,58 | 0,49 |