A tool to compare civil engineering design alternatives on the aspect of circularity

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Witteveen + Bos

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A tool to compare civil engineering design alternatives on the aspect of circularity

Thesis for the degree of
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By

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MANAGEMENT SUMMARY

The Dutch government wants to transform the Dutch economy into a circular economy (CE) in 2050. The construction sector has to comply with the concept of CE and is looking how to incorporate circularity into infrastructure objects, such as a bridge. Main aspects of circularity are the material use and energy use for the construction of an infrastructure object and its 'end of life strategy'. Ideally only renewable energy is used for the processes of construction and breaking down of the infrastructure object. The used materials should be returned to the ecosystem without harm, or should be reused again at their end of life so no materials are lost. The construction sector is searching for a way to incorporate the aspect of circularity in the design of infrastructure objects.

During the design of an infrastructure object design decisions have to be made. Various design alternatives are possible as function fulfiller for certain subsystems or elements. In design decision processes, different design alternatives are compared using various assessment criteria, to ultimately choose a design alternative that satisfies the requirements. Examples of assessment criteria are costs and safety. Yet circularity is not an assessment criterion yet, while design alternatives can have impact 'on the circularity of an infrastructure object'. To incorporate the aspect of circularity in infrastructure objects circularity should become a design assessment criterion. However, currently there is not a systematic method to compare design alternatives on the aspect of circularity. The goal of this research was *develop an instrument that allows comparison of civil engineering design alternatives on the aspect of circularity.*

In the future the developed instrument, an indicator framework with a proposed scoring system, might lead to more circularity in infrastructure objects. During the early design phase design decisions are made that could impact the circularity. In early design phases detailed information is not available and detailed calculations cannot be made. The proposed descriptive scoring system allows designers to score the indicators already during the early design phases since it does not require detailed information or calculations. The framework also takes away the discussions, which currently take place for each distinctive project, on what aspects circularity need to be assessed for one specific project. Application of the indicator framework results in scores for each indicator. The scores of the indicators provide insight in the circularity of a design. This allows comparison of different design alternatives as the scores of the indicators exposes differences and similarities between designs on the aspect of circularity.

The research outcome is an indicator framework with a scoring system that allows the comparison of design alternatives on the aspect of circularity. The indicators are divided in three categories: 'resource use', 'design characteristics', and 'end of life phase'. The categories comply with the lifecycle phases of an infrastructure object, respectively the production and construction phase, user phase, and end of life phase. The indicators represent different aspects of circularity. Examples of indicators are 'renewable energy use', 'lifespan' and 'reuse rate'. A brief explanation for each indicator is provided in the indicator framework.

Validation with the experts shows that, altogether, the indicators cover all the relevant aspects of circularity for civil engineering design alternatives. Most of the indicators are scored on a five-point

interval scale. The five scores are: ‘poor’, ‘fair’, ‘good’, ‘very good’, and ‘excellent’. The different scores are described for each indicator. If possible the different scores are described with percentage ranges. An example of an indicator and score is given.

Indicator	*Score*	*Scoring description*
Reuse of existing objects, components and materials	Fair	A small amount of the object (20-40%) consists of recycled materials or reuse components.

The indicator ‘reuse of existing objects, components and materials’ represents how much of the design alternative consists of existing objects, components and materials. Using existing objects, components and materials in a new object contributes to circularity by saving the use of new finite resources and by closing of the material cycle. The score fair indicates that the assessed design alternative consists for 20-40% of existing objects, components and materials, and for the other part of new resources.

The research objective is achieved by conducting a literature study and expert interviews. First a literature study was done into circular economy frameworks and indicators. A literature matrix was used to identify the indicators to measure circularity, used in multiple articles. This resulted in an indicator framework. Second, eight experts in the field of circularity were interviewed to find out if the indicator framework was complete and how a measurement instrument could be developed for the indicators. Seven respondents are active in the construction sector and one expert is active in product design. The transcriptions of the interviews were analysed by using the indicators from the literature study as labels that guided coding. If the majority of the experts agreed with an indicator the indicator was included in the final framework, otherwise the indicator was deleted.

The literature and experts agree on the set of indicators to measure the categories ‘resource use’ and ‘end of life phase’. This was not the case for the set of indicators for the category ‘design characteristics’. These indicators are not exactly defined in literature and were too complex for the experts, which make the set of indicators difficult to define. Additionally, the indicators consist of different factors (e.g. the fixing method of components) that together influence the score. The indicators can partially overlap each other, which makes it more complex to define them.

PREFACE

This report is written in partial fulfilment of the Msc. Civil Engineering & Management at the University of Twente and is developed in cooperation with the engineering consultancy firm Witteveen+Bos. During my study I developed a strong interest in sustainability and innovations in the construction sector. In my search for a topic for my thesis related to sustainability I came in contact with Maarten Schäffner, sustainability advisor at Witteveen+Bos. We looked for a topic that was interesting for both science and the company. He infected me with his enthusiasm about the concept of circular economy for the construction sector and we started looking for a research topic in this field.

The first idea for a research was about scoring the level of circular economy in a bridge, for example. Such a goal was too ambitious since the implementation of the concept of circular economy in the construction sector is in a(n) – very – early stage. The construction sector is still searching what the concept of circular economy means for the construction sector and how it should be implemented. The research goal was changed to a more abstract level, focussed on what circularity for the construction is and how to gain insight in the 'circularity' of infrastructure objects. The result can be found in this report and I hope the outcome contributes to the implementation of the concept of circular economy in the construction sector.

During this research I interviewed eight experts in the field of circular economy, most of them active in the construction sector. Through this way I want to thank all the experts for their time, willingness to help and interesting ideas. With your input I was able to make the link between theory and practice that lifted the outcome of the research to a higher level.

I would like to thank Maarten for his ideas during the initiation phase, and the feedback and discussions during my internship at Witteveen+Bos. Thereby, your enthusiasm for the subject was an extra motivation during the research. André Dorée, thank you for your feedback, especially to get the research proposal sharp and feasible. Finally, I would like to thank Léon olde Scholtenhuis and Silu Bhochhibhoya for all the valuable discussions, feedback and meetings. You always had time to provide me with feedback or ideas that helped me achieving the research goal and to write this report.

Lastly, I owe my thanks to my girlfriend, family and friends for their support throughout my academic career. Thank you for your help and advice. Without your supports I could not have finished my study.

Erik Meijer
Amsterdam, December 2018

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
CE	Circular economy
CO_2	Carbon dioxide
ECI	Environmental cost index
EMF	Ellen MacArthur Foundation
EoL	End of life
EU	European Union
LCA	Life cycle assessment
MFA	Material flow analysis
RWS	Rijkswaterstaat
WEF	World Economic Forum

DEFINITIONS

Assessment criterion: an aspect or characteristic used to compare or assess infrastructure objects.

Circularity: circularity comprises the closing of the material cycle and renewable energy use for all processes needed for the construction of an infrastructure object.

Circular economy: the concept of circular economy comprises a regenerative economic system in which materials and products are kept in use after their lifecyle or given back to the ecosystem and keep their value. In a circular economy there is no waste and use of new resources, since all materials are kept in use. It includes the transition towards renewable energy.

Design alternative: a possible function fulfiller for certain system requirements. An example is the different types of wall that could function as a dividing element to separate two rooms.

Infrastructure object: a physical object that is part of the facilities needed for the operation of a society or enterprise.

Lifecycle: the time an object or product fulfils it function.

Material cycle: the lifecycle of a material, from excavation till the end of its useful life.

LIST OF TABLES

1. INTRODUCTION

1.1. Background

It is expected the world population will grow from seven billion to nine billion people in 2050, thereby an increase of prosperity in many parts of the world is expected. This will lead to a bigger negative impact of human activities on the environment (United Nations, 2017; Zaman & Lehmann, 2013). The use of raw materials will keep growing, together with the global consumption and waste generation. If the extraction of raw materials continues at the current rate it is likely raw materials will become scarce and more expensive, or in the worst-case scenario they will even become unavailable (Behrens, Giljum, Kovanda, & Niza, 2007; Ecorys, 2014; McKinsey Global Institute, 2011). Furthermore energy related carbon dioxide (CO_2) emissions will more than double by 2050 without decisive action to reduce fossil energy demand (International Energy Agency, 2013). The construction sector and buildings have a big share in global CO_2 emissions and raw material extraction, as the world's largest raw material consumer (World Economic Forum [WEF], Khasreen, Banfill, & Menzies, 2009; 2016). This is why it is important to reduce the environmental impact of the construction sector (Behrens et al., 2007; International Energy Agency, 2013; Pomponi & Moncaster, 2017).

1.2. The concept of circular economy

The concept of circular economy (CE) emerged from the aim to minimize the depletion of the earth's resources by optimizing material flows and resource efficiency. CE has developed through the years as a new concept or business model with environmental, economic and - indirect - social aspects (Ghisellini, Cialani, & Ulgiati, 2016; Kirchherr, Reike, & Hekkert, 2017; Pomponi & Moncaster, 2017). CE is seen as a concept or business model that is a - partial - solution to minimize the environmental impact of human activities on the planet. The concept of CE could lead to a decrease in the extraction of raw materials, waste generation and CO_2-production (Ellen MacArthur Foundation [EMF], 2013; Ghisellini et al., 2016; Pomponi & Moncaster, 2017; Su, Heshmati, Geng, & Yu, 2013). The current economic system is linear, consisting of the steps "take-make-waste" (Figure 1). Raw materials are extracted and used to make products. The products are used and after their lifecycle they are disposed and become waste: the material cycle is open. In a CE the material cycle is closed: materials are prevented from becoming waste and the extraction of raw materials is minimized. This is done by reducing the production and consumption of materials, and by reusing and recycling materials after their lifecycle (Andersen, 2006; Behrens et al., 2007; EMF, 2013; Ghisellini et al., 2016; Kirchherr et al., 2017; Su et al., 2013).

Next to the closed material cycle the concept of CE comprises a transition towards the use of renewable energy for economic processes instead of fossil energy. If economic processes are fuelled by renewable energy the emissions of CO2 and other toxics will be minimized, and so the negative impact on the environment. Also the use of toxics, like chemicals, should be eliminated, so materials can be safely reused or recycled without danger for the environment or human health, and biodegradable materials can be safely returned to the ecosystem (EMF, 2013; Ghisellini et al., 2016; Korhonen, Honkasalo, & Seppälä, 2018).

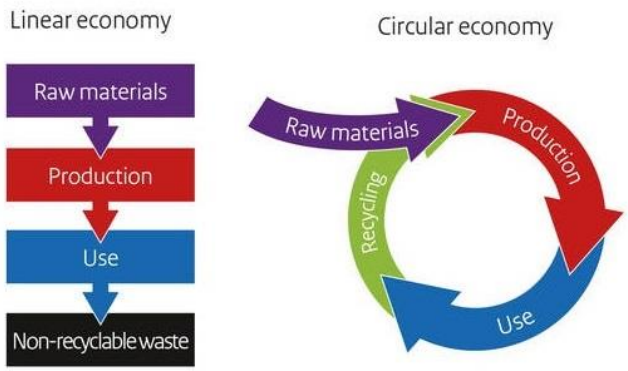

Figure 1. Linear economy vs. circular economy (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016).

The closed material cycle classifies two different material loops: biological and technical (Figure 2). The biological nutrients are materials that are non-toxic and can be returned to the biosphere safely, where they will be incorporated in natural systems. The biological nutrients are reprocessed after their lifespan by ecological processes and become nutrients for natural systems. The technical materials are man-made materials and are designed to be reused after their lifespan, so they are kept in the economic system and do not become waste. The reprocessing of materials maintains or generates new value for used materials and minimizes the extraction of raw materials from the earth (Braungart, McDonough, & Bollinger, 2007; EMF, 2013).

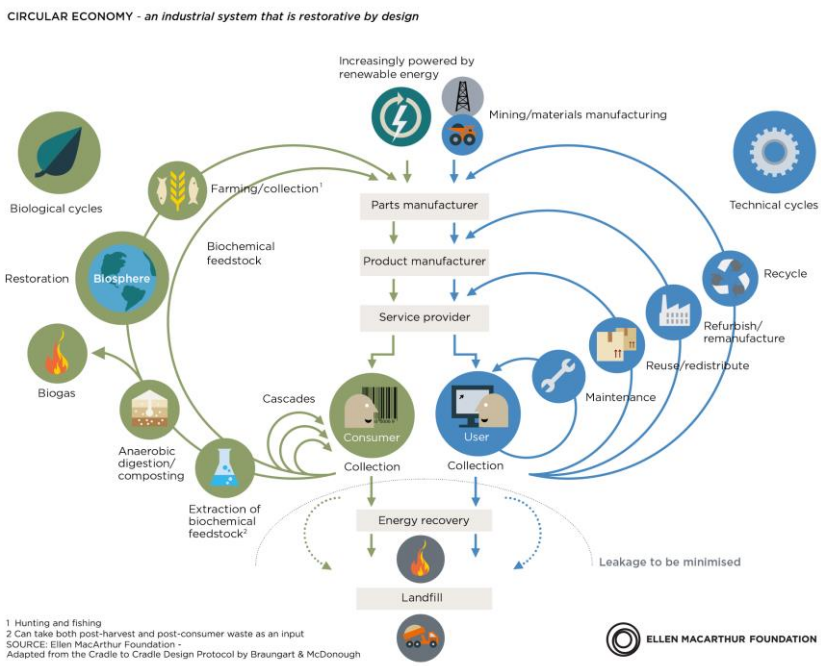

Figure 2. The biological and technical material cycle (EMF, 2013).

1.2.1.Circular Economy in the Dutch construction sector

The construction sector is world's largest consumer of raw materials and therefore responsible for the largest part of the global extraction of raw materials. Also, 25-40% of the global CO2 emission is coming from constructed objects and buildings and the construction sector generates 34% of all European waste (Eurostat, 2017; WEF, 2016). All together the construction sector has a high energy consumption/ is a large energy consumer and has a large environmental impact (Khasreen et al.,

2009). The transition to a CE could be a – partial – solution to these problems because it deals with material consumption and CO2 emissions.

In 2016 the Dutch government has pronounced the Dutch economy should be – for the most part – transformed to a CE in 2050. For 2030 the halfway goal is set to use 50% less raw materials in the economy (Ministry of Infrastructure and Environment & Ministry of Economic Affairs [MIE & MEA], 2016). This vision of the central government needs to be translated to specific visions and targets for different sectors of the economy, of which the construction sector is one. The construction sector can be divided in residential and non-residential construction sector and civil engineering sector. Rijkswaterstaat (RWS) is active in the civil engineering sector as executive government and is responsible for the design, construction, and management and maintenance of the main infrastructure of the Netherlands. Thereby they are responsible for the implementation of CE in the infrastructure, complying with the view of the central government. This means that RWS has to develop a policy with targets for a civil engineering sector in compliance with the concept of CE, for new projects and to be constructed infrastructure as well for existing infrastructure.

The – future – change of RWS of their policy and towards 'circular' projects concerns their contractors. Contractors will have to comply with the new requirements in projects to earn contracts. The fact the central vision is just presented in 2016 and the vision of RWS is still under development brings a challenge for their clients. As the vision of RWS on the concept of CE develops further the design evaluation criteria with regard to CE for future infrastructure projects are not precisely known yet. This makes it difficult for civil engineering firms to act towards the vision of RWS on CE.

1.2.2. The aspect of circularity

In this research the economic and social aspect are out of scope for circularity, although both are present the concept of CE (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Kirchherr et al., 2017). One reason is that there is a lack of direct social indicators and economic indicators that are applicable for CE. Thereby, no consensus exists about what social aspects should be included and to which extent the concept of CE could contribute to the – subjective – well-being (Geng, Fu, Sarkis, & Xue, 2012; Geissdoerfer et al., 2017; Ghisellini et al., 2016). This, in combination with the large consumption of raw materials and resources of the construction sector leads to the focus on the environmental or technical aspect. Circularity in this research comprises the closing of the material cycle and renewable energy use for (construction) processes. The material cycle consists of the biological and technical material cycle as explained in Paragraph 1.2.

1.3. Problem description

Witteveen+Bos, a civil engineering consultancy firm, is a client of RWS that has to adjust their projects to the vision of RWS. Motivated by the vision of the government Witteveen+Bos is developing a design strategy for civil engineering projects that leads to the embedding of circular design principles. A design strategy is the strategy for designing a civil engineering project or object. It concerns, among other things, the design principles which designers practice, how alternatives for a design are compared and how design decisions are made.

During the design of a civil object design decisions have to be made. Various design alternatives are possible as function fulfiller for certain system requirements. An example is a division element, like a

wall: possible design alternatives are concrete, wood, even more materials, and the exact place of the wall. The client defines the requirements the design will have to satisfy. In the design decision process different design alternatives are compared using various assessment criteria, to eventually choose a design alternative that satisfies the requirements. Examples of assessment criteria can be 'costs' and 'safety'. Yet CE or 'circularity' is not an assessment criterion yet.

Witteveen+Bos is looking to incorporate the assessment criterion 'circularity' in their design strategy. This can be seen in light of the aimed transition of the Dutch economy to a CE in 2050 and the according change of the design evaluation criteria of RWS. Although the precise design evaluation criteria are not known yet, it is clear they will include the assessment of - parts of - circularity. To take the assessment criterion 'circularity' into account for a design decision the designer or decision-maker must be able to assess the circularity of a design alternative. Existing methods such as Life Cycle Assessment (LCA) of materials and Environmental Cost Indicator (ECI) calculations need a certain level of detailed information, including the material choices and dimensions of the infrastructure object. During the early design phases design decisions are made that can impact the circularity of an infrastructure object (Gehin, Zwolinski, & Brissaud, 2008; Ghisellini et al., 2016; Ramani et al., 2010). But, during these phases - especially in the phases before the definitive design - the detailed information is not available (as it is too expensive and time intensive to make calculations for each design alternative). As a result it lacks Witteveen+Bos a systematic method to assess the circularity of design alternatives during the early design phases.

1.4. Research goal

The research goal is:

To develop an instrument that allows comparison of civil engineering design alternatives on the aspect of 'circularity'

Research scope: the aimed instrument will be developed for civil engineering - infrastructure - projects on land, with the focus on dry infrastructure, for example a bridge. It could be possible the method is applicable for wet infrastructure or constructions but specific requirements for wet infrastructure and constructions will not be researched and included. Wet infrastructure is infrastructure for water management and flood management, such as a dike or flood defence.

1.5. Research outline

The research method is described in Chapter 2. In Chapter 3 the literature review is explicated. Chapter 4 shows the results of the expert interviews. The results of Chapter 3 and Chapter 4 are combined into the final indicator framework in Chapter 5. After this the findings of the validation sessions are described in Chapter 6. The report ends with the conclusion (Chapter 7) and discussion (Chapter 8).

2. RESEARCH METHOD

In this chapter the research method is explained to develop the indicator framework. The indicator framework was developed based on a literature study and expert interviews. First, a literature study was done and the outcome, an indicator framework, was further developed with expert interviews. Synthesizing the literature study outcome and expert interview outcomes resulted in the final indicator framework that was validated by two sustainability experts. The research steps are explained in the next paragraphs.

2.1. Literature study

The goal of the literature study was 'develop an indicator framework to measure circularity based on literature'. The literature study started with the gathering of articles with or about CE frameworks and indicators. The search for articles included the gathering of peer-reviewed journal articles and articles that were not peer-reviewed, such as policy papers and reports, like (EMF, 2013). The non-peer-reviewed articles are included, since a part of the work on CE is done by non-academic players and research. This is reflected by the fact that literature reviewing articles, such as Ghisellini et al. (2016) include this kind of papers in their review.

The search was conducted in search engines such as Google (Scholar), Scopus, and Web of Science. The first search was for the term 'circular economy'. The results were scanned for articles about the concept of CE and frameworks. By reading articles that review and summarize literature about CE, such as Ghisellini et al. (2016), new articles and terms came up that were used to specify the search. For the next searches 'circular economy' was combined with terms as 'indicators' 'framework', 'construction sector', 'assessment', and 'measurement'. The articles that contained indicators or a framework to assess circularity were used for the research. The researcher is aware of the fact that the sample of articles used is not representative for all the CE frameworks and indicators described in literature. However, the researcher believes after the literature study that the sample is fairly comprehensive for the goal of this research.

For the development of the indicator framework to compare the circularity of civil engineering design alternatives CE frameworks with different spatial focuses were reviewed. Frameworks for meso (eco-industrial parks) and macro level (regions, nations) were included due the limited available CE frameworks with a focus on micro level (single product or process) and because frameworks designed for a specific product or process are not fully applicable on other products or processes. For example, a CE framework specifically designed for a train may not be – completely – applicable on a bridge. The indicators described in the articles or included in the CE frameworks were put in a literature matrix. After studying the articles the literature matrix showed which indicators are discussed in literature, specifying the references for each indicator. The literature review focused on the indicators (what they measure or indicate) and not on the calculation methods. The literature matrix showed how many articles included an indicator. Indicators that are addressed by five articles are more grounded to include in the indicator framework than an indicator that is addressed by one article. The selected indicators form the indicator framework.

2.2. Expert interviews

The indicator framework was further developed with eight expert interviews. The experts are all considered experts on CE, most of them in the construction sector. A mix of four academics (professors and researchers) and four professionals was interviewed. The academics work at the universities of Delft, Enschede and Eindhoven. The professionals work at contractors, engineering consultancy firms, and at RWS. The experts were asked about their view on circularity in the construction sector, specifically for infrastructure projects. First was asked if they agreed on the used definition of CE and circularity. After this, the experts were asked to explain what aspects of circularity should be measured to compare design alternatives on circularity. The indicators obtained from the literature review served as guideline for the interviews. The researcher made sure all the indicators from the developed indicator framework were discussed. The experts were also asked to explain the indicators and describe when a design alternative scores high and low on circularity, including examples.

The interviews were recorded and transliterated. The information of the transcriptions was analysed by coding the information. The indicators of the framework were used as labels that guided coding, and the label 'new indicator' was added. Secondly, the labelled information was specified by describing if the expert agreed or disagreed with the indicator. The information was put in a table which cumulatively showed how many experts agreed or disagreed with each indicator. An indicator was selected for the final framework if the majority of the experts agreed with it. With this analysis of the interviews the indicator framework was adjusted. Indicators were kept in the same way, adjusted, removed or added. For each indicator a descriptive scoring system was made according to the Rubrics method. Rubrics is a descriptive scoring methodology that describes the quality of a product, service or performance - or part of it - by addressing criteria and describing different levels of performance of criteria (Oakleaf, 2009). For each indicator was described when it scores 'high' or 'low' on circularity, including examples. The scoring was based on the information from the expert interviews.

2.3. Validation of the result

The outcome of the literature study and expert interviews is the final indicator framework that allows comparison of civil engineering objects on circularity. Final step in the research was a validation session with two sustainability experts from the University of Twente. During two individual sessions the indicator framework was shortly explained and the experts were asked to review the completeness of the indicator framework and to test the framework with an example the researcher provided. Main aspects that were reviewed were the completeness of the indicator framework, the usability and utility (if it produces the right outcome with regard to the research goal). Remarks about descriptions that were unclear to the experts or missing words were processed in the final framework.

3. LITERATURE REVIEW: INDICATORS FOR CIRCULARITY

In literature different frameworks are proposed that assess to what extent CE is incorporated in 'something'. That something can be a lot of things, from a product (e.g. a car) to a nation. The focus of the frameworks is on different spatial levels, namely macro, meso and micro level. Macro focuses on areas, such as nations, regions and cities. Meso is for eco-industrial parks and micro focuses on a single process or product, like the production process of a company, a car or bridge. The CE frameworks contain different indicators that measure an aspect of CE. All the indicators of a framework together measure circularity or to what extent CE is incorporated.

Different indicators can be used to measure an aspect of CE, depending on the spatial level focus of the framework and calculation methods for the indicators. Some indicators are specific for one spatial level, while others can be applied for multiple spatial levels. In general frameworks aimed for macro and meso level use more general indicator than frameworks for micro level. Frameworks for micro level have to address characteristics of a product or process that might be specific and not applicable for other products or processes. For example, the use of metal is relevant for the production process of a car, but not for the production of beer. Frameworks for macro and meso level have to assess multiple products and processes or areas and contain more general indicators (Geng et al., 2012; Ghisellini et al., 2016). In literature most of the CE frameworks focus on macro and meso level. For a focus on micro level the framework needs to incorporate specific indicators and characteristics of a product that are not relevant for other applications. This limits the applicability of such a framework (Geng, Sarkis, Ulgiati, & Zang, 2013; Pintér, 2006).

The indicator frameworks in literature contain different indicators that together measure the circularity of an area or product. Due the diversity of the aspects that the concept CE handles, for example 'resource use', it is difficult to represent the circularity of a product, for this research a civil engineering object, through one value. This results in CE frameworks that show the circularity through different indicators or frameworks that focus on a part of CE (Geng et al., 2013; Ghisellini et al., 2016).

For the development of the indicator framework to assess the circularity of a civil engineering design object frameworks with different spatial focus are reviewed. Frameworks for meso and macro level are reviewed due the lack of CE frameworks with a focus on micro level and because frameworks designed for a specific product or process are not fully applicable on other products or processes.

3.1. Indicator framework for circularity

In this paragraph the indicators are enumerated that are needed to measure circularity to be able to compare civil engineering design alternatives on circularity. Although at least 114 different definitions are used in literature for the concept of CE (Kirchherr et al., 2017) this literature review shows there is somehow consensus about what aspects of circularity should be measured. The indicators selected in for this research are applicable for infrastructure objects. Table 1 provides an overview of the selected indicators.

Category	Indicator
Resource use	Amount of used materials
	Environmental impact of used materials
	Emission of greenhouse gasses
	Energy use
	Toxicity
	Reuse of existing materials
	Refuse principle
Design characteristics	Modularity of the design alternative
	Disassembly possibilities of the design alternative
	Maintainability of the design alternative
	Reparability of the design alternative
	Lifespan
End of life phase	Reuse rate
	Recycle rate
	Waste generation & energy recovery rate
Economics	Economic costs

Table 1. Overview of indicators for comparison of design alternatives on circularity.

Different aspects of circularity are included or assessed in CE frameworks. The categories in Table 1 represent the different aspects of circularity. The categories resource use, design characteristics, and end of life phase comply with the three lifecycle phases of an infrastructure object. Resource use occurs mainly during the construction phase, the design characteristics influence mainly the user phase, and the end of life phase comprises the phase when an infrastructure object has fulfilled its lifespan. The categories are explained in Paragraph 3.2.

In Table 1 the indicators are shown that together measure the circularity of a design alternative. The indicators measure a part of the category they belong to. For example, the indicator 'lifespan' measures how long a design alternative fulfils its functions. The lifespan is a design characteristic and therefore the indicator 'lifespan' is divided in the category 'design characteristics'.

In literature different calculation methods are used for similar or highly similar indicators. For this research the calculation method is out of scope and only the indicator is used. Indicators that have the same purpose only with a different description or calculation method were merged into one indicator. Otherwise the list of indicators would become too comprehensive to be useful and indicators would overlap each other. The indicators that are selected for the indicator framework in this research are focussed on infrastructure objects, like a bridge or a road. The complete literature matrix can be found in Appendix A: Literature matrix. The selected indicators are described in Paragraph 3.3.

3.2. Categories for circularity indicators

Literature review revealed that CE frameworks and literature with CE indicators contain a number of categories in which indicators can be divided. The categories represent the different aspects of circularity and are listed in Table 2. The categories are explained after Table 2.

Indicator category	References
Resource use	Bakker, Wang, Huisman, and den Hollander (2014); Di Maio and Rem (2015); Elia, Gnoni, and Tornese (2017); Franklin-Johnson, Figge, and Canning (2016); Gehin et al. (2008); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Go, Wahab, and Hishamuddin (2015); Kirchherr et al. (2017); Leising, Quist, and Bocken (2018); Linder, Sarasini, and van Loon (2017); Niero and Hauschild (2017); Pintér (2006); Söderlund, Muench, Willoughby, Uhlmeyer, and Weston (2017); Wen and Li (2010); Yi and Liu (2016)
Design characteristics	Bakker et al. (2014); Franklin-Johnson et al. (2016); Gehin et al. (2008); Ghisellini et al. (2016); Go et al. (2015); Kirchherr et al. (2017); Leising et al. (2018); Linder et al. (2017); Pigosso, Zanette, Filho, Ometto, and Rozenfeld (2010); Singh, Murty, Gupta, and Dikshit (2012)
End of life phase	Bakker et al. (2014); Di Maio and Rem (2015); Elia et al. (2017); Franklin-Johnson et al. (2016); Gehin et al. (2008); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Kirchherr et al. (2017); Leising et al. (2018); Linder et al. (2017); Niero and Hauschild (2017); Pigosso et al. (2010); Pintér (2006); Söderlund et al. (2017); Wen and Li (2010); Yi and Liu (2016)
Economic costs	Elia et al. (2017); Franklin-Johnson et al. (2016); Geng et al. (2012); Ghisellini et al. (2016); Yi and Liu (2016)

Table 2. Indicator categories for circularity.

Resource use

One of the goals of the concept of CE is to reduce the material use to stop the depletion of resources by closing the material cycle. Closing the material cycle will prevent the need for new resources (Braungart et al., 2007; Ghisellini et al., 2016; Linder et al., 2017). As explained earlier the construction sector has a large share in the material use (EMF, 2013; Pomponi & Moncaster, 2017). Another aspect of the concept of CE is the energy used for the production of materials and the construction of infrastructure objects that is also part of the resource use (Geng et al., 2012; Wen & Li, 2010). The resource use focuses on the resources used for the production of needed materials, the materials of which an infrastructure object is made of and the resources that are needed to build the infrastructure object.

Design characteristics

During the design phase the characteristics of a product are determined on different levels of detail. Design characteristics describe how a product is constructed, how it can be used and what the possibilities are after its lifespan (Gehin et al., 2008; Ghisellini et al., 2016; Pigosso et al., 2010). Design characteristics are not incorporated in CE frameworks, but are mentioned as an aspect that has influence on the circularity in literature that reviews the concept of CE (Geissdoerfer et al., 2017; Ghisellini et al., 2016). Also in design studies design characteristics are described as an aspect that influences the circularity (Gehin et al., 2008; Go et al., 2015).

End of life phase

The end of life phase is the phase of an infrastructure object after one lifecycle. For example, if a bridge cannot be used anymore and needs to be replaced it is at its end of life phase. At the end of life phase will be determined if the materials are kept in the material cycle, and the material cycle is closed for the infrastructure object, or if the materials becomes waste. Therefore the end of life phase

needs to be included in the assessment of circularity (den Hollander, Bakker, & Hultink, 2017; Gehin et al., 2008; Pigosso et al., 2010).

Economic costs

The economic costs or value of a product is incorporated in CE frameworks to cover the economy part of CE. The economic costs can be included as a separate indicator or it is included in the calculation method of other indicators (Geng et al., 2012). An example is the Circular Economy Index proposed by Di Maio and Rem (2015) that is the ratio between the value of recycled material and value of the total amount of materials needed. Although it is not included in the definition of circularity the indicator is included in the indicator framework because multiple frameworks and articles include it directly or indirectly.

3.3. Indicators to measure circularity

To be able to compare two objects, for this research civil engineering design alternatives, it is necessary to measure information that is needed for the comparison. What the necessary information is depends on what aspect(s) the comparison is done. For example, if the size of two objects needs to be compared, the necessary information is the length, width and height of the object, while the colour is not useful. Indicators provide the needed information. A good indicator provides objective and useful information about the object, which can be used to reach the desired outcome (Pintér, 2006). Indicators can also function as a kind of guideline during the design of strategies or objects (Su et al., 2013). For this research this means an indicator should provide information about the aspect of circularity and should help to compare design alternatives on the aspect of circularity.

3.3.1. Resource use indicators

In this paragraph the indicator for the category resource use are explained. In Table 3 the indicators are listed with the references. After the table the indicators are explained.

Indicator	References
Amount of used materials	Bakker et al. (2014); Di Maio and Rem (2015); Elia et al. (2017); Franklin-Johnson et al. (2016); Gehin et al. (2008); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Leising et al. (2018); Linder et al. (2017); Niero and Hauschild (2017); Pintér (2006); Singh et al. (2012); Söderlund et al. (2017); Wen and Li (2010); Yi and Liu (2016)
Environmental impact of used materials	Bakker et al. (2014); Elia et al. (2017); Franklin-Johnson et al. (2016); Gehin et al. (2008); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Go et al. (2015); Kirchherr et al. (2017); Linder et al. (2017); Niero and Hauschild (2017); Pintér (2006); Singh et al. (2012); Söderlund et al. (2017); Wen and Li (2010)
Energy use	Elia et al. (2017); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Go et al. (2015); Linder et al. (2017); Niero and Hauschild (2017); Pintér (2006); Singh et al. (2012); Yi and Liu (2016)
Toxicity	Elia et al. (2017); Geng et al. (2012); Ghisellini et al. (2016); Go et al. (2015); Linder et al. (2017); Niero and Hauschild (2017); Pintér (2006); Singh et al. (2012); Wen and Li (2010)
Emission of greenhouse	Di Maio and Rem (2015); Elia et al. (2017); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Go et al. (2015); Linder et al. (2017); Niero and Hauschild

gasses	(2017); Singh et al. (2012)
Reuse of existing materials	Bakker et al. (2014); Franklin-Johnson et al. (2016); Ghisellini et al. (2016); Leising et al. (2018); Linder et al. (2017); Söderlund et al. (2017)
Refuse principle	Bakker et al. (2014); Elia et al. (2017); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Kirchherr et al. (2017); Leising et al. (2018); Söderlund et al. (2017); Wen and Li (2010)

Table 3. Indicators for the category resource use.

Amount of used materials

One of the goals of the concept of CE is to reduce the material use to stop the depletion of resources. Measuring the amount of used materials provides information for the reduction of material use (Elia et al., 2017; Ghisellini et al., 2016). In all the CE frameworks is resource use included with one or more indicators (Table 3). The Material Flow Analysis (MFA) is a widely used method to measure the input and output of material through a system and used in different frameworks, but the exact indicators can differ and can be chosen by the developer of the MFA (Elia et al., 2017; Pintér, 2006). Other articles that developed a single indicator also indicate the material use as an aspect of circularity, like Linder et al. (2017). Different indicators that measure the amount of materials are used in literature. Most of them are highly similar with only different calculation method. Examples are 'output of main mineral resource' (Geng et al., 2012) and 'direct material input' (Wen & Li, 2010). Different calculation methods while they both measure the amount of used materials.

Environmental impact of used materials

Besides the amount of used materials the impact of the materials on the environment plays a role in circularity. The material cycle needs to be closed to prevent the discarding of harmful materials to the ecosystem and should be measured, as described in Elia et al. (2017); Ghisellini et al. (2016); Niero and Hauschild (2017). Environmental impact is not directly incorporated in CE frameworks for macro or meso level, since the indicators in these frameworks focus mainly on amounts of resources (Geng et al., 2012; Pintér, 2006). The environmental impact covers the ecological impact of the used materials. Factors that are considered part of the environmental impact are, for instance, CO_2-emission, scarcity of a material, water use, and transportation distance (Bakker et al., 2014; Ghisellini et al., 2016; Pomponi & Moncaster, 2017). The factors that influence the environmental impact can differ per material. Also, a complete list of environmental factors would become too comprehensive for the framework. Therefore, one indicator, the 'environmental impact of used materials', covers these environmental factors.

Emission of greenhouse gasses

The emission of greenhouse gasses has a negative environmental impact and is one of the causes of climate change. Although the emission of greenhouse gasses is an environmental impact it is often included as a separate indicator. Most used and mentioned indicator is the CO_2-emission (Ghisellini et al., 2016; Niero & Hauschild, 2017). Since greenhouse gasses are explicitly mentioned as a separate indicator by eight articles it is included in the indicator framework.

Energy use

Another resource use indicator is the energy use. Energy is used for the construction of infrastructure objects. Energy is needed for all processes, such as the production of concrete or the transportation of

materials to a construction site. In frameworks the energy use is calculated through different methods, but all include the distinction between fossil energy use and renewable energy use (Elia et al., 2017; Linder et al., 2017; Singh et al., 2012). The use of fossil energy results in toxic emissions, such as CO_2-emissions, that are harmful for the ecosystem. Renewable energy, such as wind and solar energy, do not cause CO_2-emissions and do not deplete any resources and are therefore considered not harmful for the environment. The production process of the infrastructure needed for renewable energy is not considered in this research, since there is no consensus about how it should be included (Linder et al., 2017).

Toxicity

The emissions of pollutants and use of toxics during the production of a product or during a process have a negative environmental impact and should therefore be minimized. Toxics and pollutants are therefore taken into account for CE assessments. Although it can be allocated under environmental impact, 'toxicity' can also be addressed in one or more indicators. Toxics can have a negative impact on human health and the environment. They could cause sickness or death for humans and nature. Some articles name specific toxics or pollutants (e.g. Ghisellini et al., 2016; Wen & Li, 2010), but mostly toxics are mentioned as one indicator that measures the pollutants in a resource flow (e.g. Geng et al., 2012; Yi & Liu, 2016) or just as an aspect of CE (e.g. Linder et al., 2017). For this research the toxicity is included as one indicator, because a list of all possible toxics and pollutants is too comprehensive to include. For example, Wen and Li (2010) already identified ten pollutants and toxics that are common in resource use.

Reuse of existing materials

Closing the material cycle incorporates the use of materials that already exist and are used before to prevent them from becoming waste. In most articles the recycling is mentioned for the end of life phase, but during the design and production phase it should also be measured to ensure the use of existing materials in the new product, in this research an infrastructure object (Bakker et al., 2014; Franklin-Johnson et al., 2016; Söderlund et al., 2017).

Refuse principle

The refuse principle is not included in CE frameworks but is considered a main aspect of the concept of CE as nine articles cover it. The refuse principle comprises the thought that 'doing nothing' is the most environmental friendly thing to do (Ghisellini et al., 2016; Kirchherr et al., 2017). The refuse principle stimulates to prevent the construction of new objects that are not necessary or not the most circular solution. The idea is that designers rethink the goal of the project by thinking from the needed function, instead of a needed construction. When design for a function is the starting point other solutions can come up that could be more circular than when a certain construction from a standard solution is the starting point. For example, if there is always a traffic jam during rush hour on a road between point A and B the solution in line with the current infrastructure is to widen the road. But if it is possible to increase the intensity of trains between A and B during rush hour and people are willing to go by train, this could be the 'best' or most circular solution and prevents the need for new constructions.

3.3.2. Design characteristics

The design characteristics indicators are obtained from design research, including eco-design research and end of life (EoL) strategies. Table 4 shows the indicators for the design characteristics. After the table the indicators are briefly explained.

Indicator	References
Modularity	Bakker et al. (2014); Go et al. (2015)
Disassembly possibilities	Franklin-Johnson et al. (2016); Gehin et al. (2008); Ghisellini et al. (2016); Go et al. (2015); Leising et al. (2018); Pigosso et al. (2010)
Maintainability	Bakker et al. (2014); Gehin et al. (2008); Go et al. (2015); Pigosso et al. (2010)
Reparability	Bakker et al. (2014); Franklin-Johnson et al. (2016); Gehin et al. (2008); Kirchherr et al. (2017); Pigosso et al. (2010)
Lifespan	Bakker et al. (2014); Franklin-Johnson et al. (2016); Gehin et al. (2008); Ghisellini et al. (2016); Kirchherr et al. (2017); Leising et al. (2018); Linder et al. (2017); Singh et al. (2012)

Table 4. Indicators for the category design characteristics.

Modularity of the design alternative

An infrastructure object is modular if it consists of different components. This means that – some of the – components can be replaced if they are broken or need to be changed. Ideally components have functional independence, so they can be replaced more easily than if multiple components provide one function (Bakker et al., 2014; Go et al., 2015). For example, if a crash barrier is anchored in the soil next to the road it can be replaced without damaging the road itself. But if the crash barrier is anchored in the road itself the road might have to be closed and replaced to replace the crash barrier. Another example is prefabricated parts that are fixed together on the construction site. Ideally the components can also be used in new (infrastructure) objects (Go et al., 2015)

Disassembly possibilities of the design alternative

The disassembly possibilities describe how an infrastructure object can be disassembled and reassembled at a different place or with different components. Especially in the construction sector this could lead to savings of resources (Guy & Ciarimboli, 2005). An infrastructure object can be disassembled if it consists of different components. Disassembly includes the process to disassemble and reassemble an infrastructure object. Aspects are the time disassembly takes, the logistics and equipment needed for disassembly, and the quality of the components after disassembly (EMF, 2013; Go et al., 2015; Pigosso et al., 2010). Extensive guidelines exist to design for disassembly (Guy and Ciarimboli, 2005). According to Go et al. (2015) the three most important aspects are how different components are fixed together (e.g. screwed or glued), how the components are designed (e.g. size of the components), and the materials that are used.

Maintainability of the design alternative

Maintenance can preserve circularity by ensuring the functionality of an object over a longer period of time than without maintenance. So it saves the need for a new object and consequential effort and resources. Thereby maintenance preserves the quality of an object for its lifetime. The maintainbility depends on the frequency of maintenance that an object needs and the effort that comes with it, such as the ease of inspectation of the infrastructure object (Bakker et al., 2014; Gehin et al., 2008; Go et al., 2015)

Reparability of the design alternative

Reparations preserve circularity by bringing broken or faulty components, or the whole infrastructure object, back to usable state (Bakker et al., 2014). The lifespan is extended compared to a situation without reparations. Reparability indicates how easy an infrastructure object can be repaired if something is broken. It partly depends on the modularity of the infrastructure object, because that would make the replacement of components possible. It also depends on the accessibility of the broken component (Bakker et al., 2014; Gehin et al., 2008; Pigosso et al., 2010)

Lifespan

The lifespan indicates how long (years) an infrastructure object fulfils its function. Once an infrastructure object is constructed a long lifespan saves the need for a new infrastructure object compared to a short lifespan. This saves resources, such as materials and energy, which are needed for the construction of a new infrastructure object. On the other hand it is possible that an infrastructure object has to be designed more robust, which means in most cases more resource use and thus a larger environmental impact than a similar object with a shorter lifespan (Franklin-Johnson et al., 2016; Go et al., 2015).

3.3.3. End of life phase

At the end of life phase different strategies can be applied to process the infrastructure object at the end of its life. Comprehensive frameworks exist with possible strategies, but for infrastructure objects three main strategies are applicable. The strategies are: reuse, recycling, and waste generation & energy recovery (Gehin et al., 2008; Ghisellini et al., 2016; Kirchherr et al., 2017; Pigosso et al., 2010). Table 5 shows the references for the end of life indicators. The strategies are discussed below the table.

Indicator	References
Reuse rate	Bakker et al. (2014); Elia et al. (2017); Franklin-Johnson et al. (2016); Gehin et al. (2008); Ghisellini et al. (2016); Kirchherr et al. (2017); Leising et al. (2018); Linder et al. (2017); Pigosso et al. (2010); Wen and Li (2010)
Recycle rate	Bakker et al. (2014); Di Maio and Rem (2015); Elia et al. (2017); Franklin-Johnson et al. (2016); Gehin et al. (2008); Geng et al. (2012); Geng et al. (2013); Ghisellini et al. (2016); Kirchherr et al. (2017); Leising et al. (2018); Linder et al. (2017); Niero and Hauschild (2017); Pigosso et al. (2010); Pintér (2006); Singh et al. (2012); Söderlund et al. (2017); Wen and Li (2010); Yi and Liu (2016)
Waste generation & energy recovery rate	Bakker et al. (2014); Elia et al. (2017); Franklin-Johnson et al. (2016); Geng et al. (2012); Ghisellini et al. (2016); Kirchherr et al. (2017); Niero and Hauschild (2017); Pigosso et al. (2010); Pintér (2006); Singh et al. (2012); Wen and Li (2010); Yi and Liu (2016)

Table 5. Indicators for the end of life strategies.

Reuse rate

Reuse refers to any operation by which products or components are used again for the same or similar purpose or functionality as before, in its original form or with little enhancement or change. This can also include the repairing of products after their lifecycle by replacing components so they can be used for a new lifecycle (EU, 2008; Gehin et al., 2008; Go et al., 2015; Kirchherr et al., 2017). Reuse itself does not provide information about the circularity of an infrastructure object. Therefore the

reuse rate is included. The reuse rate is ratio between the reused parts of an infrastructure object and its total amount of materials.

Recycle rate

Recycling is using materials after their lifecycle in new materials or for new purposes without becoming waste. Combustion of waste or products for energy recovery is not considered recycling (EU, 2008). Recycling can be done in three ways. First, materials can be recovered and used as resource for the same or new purpose. An example is the melting of used steel of which products can be produced of the same quality. The second option is downcycling. Downcycling is the use of materials into new materials or products of a lesser quality or reduced functionality. An example is the recycling of concrete as granulate for the foundation of roads. The concrete is crushed after its lifecycle in granulate and cannot be used again as concrete, e.g. for the pillar of a bridge. The third option is upcycling where materials are used in materials of higher quality or with more functionality than before. Upcycling is rare in current practice, while a big share of recycling is downcycling, like the example of concrete that becomes granulate for road foundations (Braungart et al., 2007; EMF, 2013; Go et al., 2015).

Waste generation & energy recovery rate

The last strategy that is included for the end of life phase is waste generation and energy recovery. For circularity the material cycle needs to be closed. Materials should be kept in the material cycle and should not leave the material cycle as waste. Waste can be discarded at a landfill or combusted to generate energy (Ghisellini et al., 2016; Kirchherr et al., 2017; Wen & Li, 2010). Energy recovery is not considered recycling since the materials are lost after combustion. Different calculation methods are used in frameworks to include the waste generation, mainly in amount of waste, for example in tonnes. For this research the waste & energy recovery is indicated as the ratio between the part of the infrastructure object that becomes waste and is combusted and the total amount of materials of the infrastructure object.

3.3.4. Economic costs

The economic costs are included as a direct indicator that indicates the total cost of the design alternative, including the costs of the used materials, costs of the construction of the design alternative and costs during the lifespan of the design alternative.

3.4. Conclusion

In this chapter the categories and indicators from literature are described that are needed to compare the circularity of design alternatives. The four categories are: ‘resource use’, ‘design characteristics’, ‘end of life phase’, and ‘economic costs’. In literature sixteen indicators were found that together measure the circularity of design alternatives. The sixteen indicators are divided in the four categories and form the indicator framework, which can be found in Table 1.

4. RESULTS OF THE EXPERT INTERVIEWS

This chapter shows the results of the eight expert interviews. The interviews were analysed in four steps. The first step was transliterating the interviews, the transcriptions can be found in Appendix C (in Dutch). Then relevant information in the transcriptions was labelled. The indicators from the literature review (Table 6) served as labels. The label 'new indicator' was used for information about proposed indicators that did not come forward during the literature review. Information with the same label was put together to give an overview of the expert's sayings about the indicators. Per indicator the information was analysed whether it supported or rejected the indicator and, if supported, in what form the indicator should be incorporated.

4.1. Definition of circularity

At the start of all the interviews the researcher explained the definition of circularity that was used during the literature review to the expert. The experts were asked if this agrees with their definition of circularity.

The used definition of circularity focussed on the technical part of CE, the circularity of resources and objects, while CE is more considered a framework or business model by most experts. The experts agreed on the definition that was used for circularity. The experts also agreed with the focus on circularity without considering the economic and social aspects for this research. Economic and social aspects are part of the total concept of CE, but should be out of the scope of the developed indicator framework to keep the indicator framework manageable and concrete. The experts added that for circularity the finiteness of resources is important to consider. In practice minimization of resource use is often aimed for, but circularity focuses on the prevention of finite resources and use of infinite resources.

4.2. Indicators from the interviews

During the interviews the expert were asked on which aspects (indicators) of circularity design alternatives should be compared in the construction sector. Table 7 shows per indicator how many experts agreed or disagreed with the indicator. Under '# Experts disagree' are also the experts included that did not mention the indicator specifically. An indicator was selected for the framework if the majority of the experts agreed with it. One new indicator was proposed by the experts. After Table 7 the results from the interviews are elucidated per indicator. For each indicator is described why the experts agree or disagree with it and some explanation about scoring the indicator. Some indicators that were proposed after the literature review are combined into one indicator that encompasses the aspects of the merged indicators.

Category	*Indicator*	*# Experts agree*	*# Experts disagree*
Resource use	Amount of used materials	8	0
	Environmental impact of used materials	8	0
	Emission of greenhouse gasses	6	2
	Energy use	8	0
	Toxicity	0	8

	Reuse of existing objects, components, and materials	4/8*	4/0*
	Refuse principle	5	3
Design character-ristics	Modularity of the design alternative	6	2
	Disassembly possibilities of the design alternative	6	2
	Maintainability of the design alternative	8	0
	Reparability of the design alternative	8	0
	Lifespan	8	0
End of life	Reuse rate	8	0
	Recycle rate	8	0
	Waste generation & energy recovery	8	0
Economics	Economic costs	3	5
New	Transparency of the information of the used materials	6	2

Table 6. Number of experts that agree or disagree per indicator.

* The first number is the number of experts that explicitly explained this indicator. The second number is the number of experts that consider reuse of objects, components and materials as an indicator of circularity.

4.2.1.Resource use indicators

Amount of used materials

According to the experts the finiteness of resources is important to consider for circularity. The material use is an important aspect, since the construction sector is a big consumer of materials. The amount of used materials is especially useful when finite materials will be used. When similar materials are used in different design alternatives less material use is generally more circular than more material use. When different materials are compared the next indicator 'environmental impact of the used materials' should be combined with the 'amount of used materials' to compare the design alternatives.

Environmental impact of used materials

All experts explicitly mention the environmental impact of the used materials as an important indicator for the circularity of design alternatives. The environmental impact of materials exists of a combination of different environmental factors, such as CO_2-emission or scarcity. At the same time they indicate that the environmental impact is comprehensive and contains too many factors to include them separately in the framework. All experts mentioned the methods LCA and DuboCalc that are widely used to calculate the environmental impact in the construction sector. LCA shows the environmental impact through different factors, while DuboCalc shows it through one number, the ECI. Per material the most significant factors for the environmental impact can differ. DuboCalc shows for each material an ECI wherein all environmental factors are weighted, which allows direct comparison of different materials on environmental impact. For all materials go that a low environmental impact is preferable.

Emission of greenhouse gasses/CO_2-emission

Most experts mention the emission of CO_2 and not explicitly the emission of greenhouse gasses. The CO_2-emission is mostly mentioned in combination with energy use, since fossil energy use causes CO_2-

emission. CO_2-emission is an important factor in the environmental impact of materials and is thus already included in the framework. But, as several experts point out, clients and the Dutch government are currently asking for a separate CO_2-emission calculation for the CO_2 impact on the global warning, so it could be included as an optional indicator in case the client asks for it.

Toxicity

All experts agree that the toxicity of a design alternative (its materials or impact) should be taken into account. But the toxicity is already incorporated in the environmental impact of used materials, especially when methods like DuboCalc or LCA are used. Therefore the experts reject toxicity as indicator.

Renewable energy use

The energy use is considered an indicator in the framework to compare design alternatives on circularity, according to all the experts, but is renamed as 'renewable energy use'. In the ideal situation all the energy that is used for human activities and processes, like the construction of a bridge, is renewable. In that situation it does not matter how much energy is used for a process, since it does not exhaust resources, such as oil, and it does not cause any toxic emissions, like CO_2. In case no renewable energy is used the amount of energy used does matter, but is not considered circular anymore.

Reuse of existing materials

All experts consider reuse and recycling important actions for circularity. The reuse or recycling of existing materials is the first step in the design process where reuse or recycling can be incorporated in a design alternative. Besides materials, experts mention the reuse of objects and components. Multiple experts mentioned the fact that most part of our constructions already exist and should be used again after their lifecycle. Examples are the preserving of a bridge for a new road instead of demolishing it, the reuse of bridge decks from bridges that will be demolished or the recycling of the material of a demolished bridge into the new bridge. The reuse of an existing object is considered the most circular action, then the reuse of components, followed by the recycling of materials.

Refuse principle

Five of the eight experts mention the refuse principle as part of circularity explicitly, but as a principle that should be considered before a project for a specific infrastructure object is started. Before the client has specified what kind of infrastructure he wants the refuse principle can help considering different solutions that could prevent the need for new constructions. Therefore it is not an indicator for the comparison of design alternatives on circularity.

4.2.2.Design characteristics indicators

Modularity and disassembly possibilities

Modularity and disassembly possibilities are considered slightly different but are mostly used interchangeably. A very strict definition of both is not necessary for the purpose of comparing design alternatives on circularity, so the two aspects are merged into one: 'modularity'. The easiness of the disassembly of an object or component, such as the accessibility to reach it or effort needed to disassemble it influences the rate of modularity. The quality after disassembly should be the same as

before disassembly to be circular and is an aspect for this indicator. Generally objects that are made of components can be reused more easily after their lifecycle than objects that are made of one part.

Maintainability of the design alternative

All experts agreed on this indicator. Maintenance ensures a longer lifespan of an object and is therefore considered more circular than not maintaining an object. The maintainability is determined by the effort the maintenance takes and the corresponding nuisance for the users of the object, and the frequency of the maintenance needed. The effort is determined by the maintenance actions, such as the energy needed and the equipment. The nuisance for users is the usability of the object during maintenance, so if a road will be blocked or not. For the maintainability the combination of these factors determine the score.

Reparability of the design alternative

All experts mention reparability as an aspect of circularity, since it preserves a longer lifespan of an object than without reperations. But they consider it as a part of maintainability. The reparability is therefore included in the maintainability indicator. Thereby, the possibilities to replace components are incorporated in the indicator modularity.

Lifespan of the object

All experts mention the lifespan of the object as an indicator. The lifespan of an object on itself does not provide useful information about the circularity of object. The lifespan of an object is useful in combination with other indicators, such as the environmental impact of the used materials and maintainability. The combination of these indicators provides insight in the circularity of an object. For instance, a short lifespan in combination with a low environmental impact can score high on circularity. The same short lifespan in combination with a high environmental impact indicates a low score on circularity.

4.2.3.End of life phase indicators

All the experts mention the three end of life phase strategies as were found in the literature review: reuse, recycling, and waste generation and energy recovery. This is in order of most circular (reuse) to the least circular option (waste). Thereby, some experts say recycling of materials in their original form is just as circular as the reuse of an object. An example is the recovering of sand from concrete. Only requirements for full circularity are the use of renewable energy for the recycling process and that it can be used on the same quality as before it was used in the object. The experts acknowledge the fact that an end of life scenario of an object is a sort of predicting the future in light of the current technologies. Future changes and new technologies could make other end of life strategies possible that are currently not possible and therefore not considered.

4.2.4.Economic indicator

Economic costs

Economic costs are considered important in the context of infrastructure objects, but are not a part of the comparison of design alternatives on circularity. Only two experts mention the economic costs as part of the comparison, in light of the context an infrastructure object is designed in but not as an aspect of circularity. The indicator framework focuses on the technical circularity, the materials and the object as a whole, in which the economic costs are not an aspect. Thereby, the experts appoint the lack of ‘circular’ economic indicators that fit in a circular economy business model.

4.2.5. New indicators

Transparency of the information of the used materials

Six of the eight experts explicitly mentioned transparency of the information of the used materials as an aspect of circularity. The transparency indicates the reliability and availability of information about the materials and components that are used in an object. It concerns information about the origin and production process of materials and components, and the former use in other objects. The transparency itself does not influence the circularity of a product, but indicates the reliability of the information about the environmental impact of a certain material or component. The experts consider this as a helpful aspect towards more insight in the production process of materials and a better comparison. A material or component with a transparent production process is preferred over one without when two equal materials or components are compared. Examples and suggestions for databases of materials and used components that are available were made during the interviews.

4.3. Conclusion

All the indicators from the literature review were discussed with the experts during the interviews. If the majority of the experts agreed with an indicator it was selected for the final framework, otherwise the indicator was deleted. Table 8 shows the indicators that are selected and rejected by experts.

Category	Indicators selected by the experts	Indicators rejected by the experts
Resource use	Amount of used materials	Refuse principle
	Environmental impact of used materials	Toxicity
	CO_2-emission	
	Renewable energy use	
	Reuse of existing objects, components & materials	
	Transparency of the information of the used materials	
Design character-ristics	Modularity of the design alternative	Reparability
	Maintainability of the design alternative	
	Lifespan	
End of life	Reuse rate	
	Recycling rate	
	Waste generation & energy recovery rate	
Economics		Economic costs

Table 7. Accepted and rejected indicators.

5. THE FINAL INDICATOR FRAMEWORK

In this chapter the indicator framework is presented that is developed based on the literature study and expert interviews. First, the boundaries and focus of the indicator framework are explained. Secondly, the indicator framework is presented, including a brief explanation of the indicators. After that the scoring of the indicators is explained and the final paragraph presents the Environmental Costing Index of the most used construction materials from DuboCalc.

5.1. Boundaries and focus of the indicator framework

The indicator framework focuses on circularity aspects of design alternatives for civil engineering objects. Civil engineering objects are, for example, a road or a bridge. Design alternatives are possible solutions for parts of a civil engineering object. For example, for a bridge the design alternatives for the joists can be concrete joists or steel joists. Two or more design alternatives can be compared on circularity with the framework (circularity is defined below). The framework is developed for the generic use for dry and on land infrastructure. It may be applicable on wet infrastructure, such as dikes, but specific requirements or characteristics for wet infrastructure were not taken into account during the development of the framework.

The indicator framework focuses on the circularity of civil engineering objects. Although the motivation for this research comes from the rise of circular economy, the focus of the research is on circularity: the technical aspects of circular economy in relation to infrastructure. Circularity comprises the closing of the material cycle (Figure 2) and renewable energy use for all processes, such as the production and construction process.

The indicator framework can be used during the early phases in the design process of infrastructure projects after the initiation phase, when the choice to build something is made. The early design phases are considered the phases when no detailed information is known or detailed calculations can be made. During the early design phases, already design decisions have to be made that affect the circularity of an object.

The future users of the indicator framework are likely to be designers of infrastructure objects and decision-makers or project members that will use it during decision meetings for the design of a civil engineering object. Designers can use the indicator framework to compare different design solutions during the design process without losing much time or/with making calculations. It provides insight for the designer how to come to the most circular design for a civil engineering object with the possible design alternatives. For decision-makers or project members the indicator framework is useful for decision-making. It provides a systematic method to compare possible solutions on circularity. The indicator framework takes away discussion and miscommunication about what circularity is and on which aspects it should be compared. Depending on the assignment and requirement of the client decisions can be made based partially on the indicator framework.

<u>Context</u>

Since not all aspects that have influence on a design decision are covered by the framework, the framework cannot be used solely to ground design decisions on in practice. The framework can only be used to compare the circularity of design alternatives.

Economic costs

The economic costs are not part of circularity in the used definition of circularity for this research. The economic costs do play a role if the concept of CE is considered. For the comparison of design alternatives on circularity the economic costs are excluded to keep the focus of the comparison on circularity. Thereby, in practice the economic costs will always play a role in the decision making in infrastructure projects.

Refuse principle

An important principle in the circular economy is the 'refuse principle'. The refuse principle is discussed in literature and all the experts mentioned it as important. According to this principle before a construction project is started the question should be asked if the construction is really needed and if so, is the standard or chosen option the best fitting and circular option for the needed function. This principle let people rethink the possible solutions and let them find the best solution to fulfil the needed function. This could solve a problem with lesser materials or even without constructing something new. The refuse principle tries to prevent the construction of unnecessary objects. An example is to shift the transport modality from the car to the train instead of widening a highway when congestion occurs on the highway. Therefore, the refuse principle should be taken into account before the start of each construction project.

5.2. Final indicator framework

The next table shows the indicator framework with a short explanation for each indicator.

Category	*Indicator*	*Explanation*
Resource use	Amount of used materials	The weight or volume of the used materials
	Environmental impact of used materials	The environmental impact (pollution and ecosystem impact) of the used materials
	Renewable energy use	To what extent renewable energy is used. Renewable energy is: wind energy, solar energy, hydro energy, tidal energy, and geothermal heat use. Biofuels are not considered renewable because the current production process is often fuelled by fossil fuels (for machinery, transportation, etc.) and competes with agriculture.
	(CO_2-emission)*	CO2 is part of the environmental impact but can be shown as a separate indicator if desired by clients. * Can be scored by estimating the emission in the desired unit, e.g. CO_2-equivalent.
	Reuse of existing objects, components and materials	Are existing objects reused and in which form (object, components, materials)?
	Transparency of the information of the used materials	The transparency of information about the process of excavation and production of materials or components that are used in the design alternative.
Design characteristics	Modularity of the design alternative	The modularity indicator scores to what extent the design alternative consists of different components that can be disassembled and reassembled, or can be replaced if needed. The accessibility of the components and the quality of the reassembled construction are part of the score.
	Maintainability of the design alternative	The maintainability is a combination of the needed effort for the maintenance of the design alternative (frequency of maintenance and effort of maintenance operations) and corresponding nuisance for the users, and the easiness and possibilities to repair the object when something is broken.
	Lifespan	The expected useful lifespan of the object
End of Life	Reuse rate	How much of the object can be reused at the end of life
	Recycle rate	How much of the object can be recycled at the end of life
	Waste generation & energy recovery rate	How much of the object will become waste and/or will be recovered as energy at the end of life

Table 8. Final indicator framework.

5.3. Scoring system for the indicators

For each indicator the scoring method and categories are described. Some indicators are scored descriptively on a five point interval scale. The five scores are 'excellent', 'very good', 'good', 'fair', and 'poor'. For each indicator a description of the scores is given. In this chapter a 'user' means a user of the framework that scores a design alternative on circularity.

5.3.1. Resource use indicators scoring system

Amount of used materials: the amount can be estimated during the early design phase. The amount can be estimated in the weight of the amount of used materials or in volume, depending on the standards used for the material and in for what unit the ECI is determined (per unit of weight or per unit of volume). For the same materials goes: the lower the amount, the more circular it is. When different materials are compared the amount of used materials should be estimated and together with the environmental impact of the type of materials used the user can say something about the circularity of the material use.

Depending on the design alternatives the materials that have a significant weight in the design alternative should be scored, so small fractions of materials can be neglected.

Environmental impact of used materials: LCA and DuboCalc are two methods that are widely used in practice to compare or calculate the environmental impact of materials. DuboCalc shows the environmental impact of the materials in one score and is therefore used to compare materials on environmental impact. On page 28 the ECI scores from DuboCalc are shown for the most used construction materials. In combination with the estimated amount of materials needed a (rough) calculation can be made to compare different design alternatives on their environmental impact. The user can use LCA if the user prefers LCA for the calculation of the environmental impact.

Renewable energy use: two types of energy are distinguished, namely non-renewable energy, mainly known as fossil fuels, and renewable energy. The following energy types are considered renewable: solar, wind, geothermal, hydra and tidal. Biofuels are not considered renewable energy in the current situation, because the energy that is needed to produce the biofuels is often not renewable. Also the land used for biofuels competes with agricultural use of the land for food. No distinction is made between the types of renewable energy.

Score	*Description*
Excellent	80% or more of the construction process is fuelled by renewable energy. Also the production process of the components is for 80% or more fuelled by renewable energy.
Very good	60-80% of the construction process and production process of components is based on renewable energy
Good	40-60% of the construction process and the production process of components is based on renewable energy
Fair	20-40% of the construction process and the production process of components is based on renewable energy
Poor	0-20% of the construction process and the production process of components is based on renewable energy

Table 9. Scoring for the type of energy used.

Reuse of existing objects, components and materials in new object: for a new object existing objects, components and materials can be used to construct it. These existing parts can come from the demolished object that will be replaced by the new object, or from other places. The reuse of objects is more circular than the reuse of components, which is more circular than the reuse of materials (recycling). Also important is the transportation of the parts. Within the Netherlands it does not play a significant role, but it does when it comes from other countries. Reuse of parts for the same functionality (bridge deck as bridge deck) is more circular than reuse in a lower quality (concrete deck demolished to granulate for roads). The consideration between recycling of nearby materials and reuse of objects with a longer transportation distance can differ per case.

Score	*Description*
Excellent	Most or all parts of the object (80-100%) are made of reused components and/or objects; additionally a small part can be made of recycled materials.
Very good	A large part of the object (60-80%) is constructed with recycled materials and/or reused components.
Good	About half of the object (40-60%) is constructed with recycled materials and reused components.
Fair	A small amount of the object (20-40%) consists of recycled materials or reuse components.
Poor	No reuse or barely any reuse at all in the object (0-20%)

Table 10. Scoring of the reuse of existing objects, components and materials.

Example: if the existing bridgehead can be used again as bridgehead, this option would score 'excellent'. If only the foundation of the bridgehead can be used again, which is approximately 30% of the total of the bridgehead and 50% of the demolished part of the bridgehead can be recycled for the new one, the option would score 'very good'. With regard to the transportation distance the reuse of a bridge deck 100 kilometres away from its original place is more circular than the recycling of the materials of the bridge deck as foundation for the new highway at the same place.

Transparency of the information of the used materials: information about the history of the used materials for a design alternative. This includes where the material or resources were excavated, how it was processed to the current state, how old it is, etc. The scores are described in the next table.

Excellent	Information is known about 80% or more of the production process of the used materials and its environmental impact, including information about former used components.
Very good	Information is known about 60-80% of the production process of the used materials and their environmental impact, including information about former used components.
Good	Information is known about 40-60% of the production process of the used materials and their environmental impact, including information about former used components.
Fair	Information is known about 20-40% of the production process of the used materials and their environmental impact, including information about former used components.

Fair	Information is known about 0-20% of the production process of the used materials and their environmental impact, including information about former used components.

Table 11. Scoring of the transparency indicator.

5.3.2.Design characteristics indicators scoring system

Modularity of the design alternative: the first aspect is the components of an object. The best size of the components differs per case, but one should take into account the possibilities of transport and effort needed for dis- and reassembly. Ultimately the components are interchangeable with other constructions and components, like Lego pieces. Second part is the fixing or connection method: when components can be unfixed, like screwed connections, an object is more modular than when components cannot be unfixed, for example when components are glued together. Also the accessibility of the components plays a role: whether the different components are accessible for reparations or not. The quality of the components after disassembly is the last aspect of the modularity of an object. The quality at which the components can be reused after disassembly should be as high as possible, ideally at the same level of functionality as before disassembly. The scoring is a combination of these aspects.

Score	*Description*
Excellent	Most or all of the components are easy to disassemble and transport, and do not lose any quality after disassembly. They can be reused directly after disassembly and transport. Components can be used interchangeably, also in other constructions.
Very good	Large part of the components is quite easy to disassembly and transport, but can lose some quality and some maintenance is needed before reassembly.
Good	Most of the components can be disassembled and transported, but quite some effort is needed. Components can also lose some quality after disassembly.
Fair	It is hard to disassemble the components or only a small part of the components can be disassembled. Quite some effort is needed and a part of the components are difficult to access. Part of the construction cannot be disassembled.
Poor	None or almost none of the components can be disassembled, or the object does not contain components.

Table 12. Scoring of the modularity.

Example: to score 'excellent' a design alternative should be constructed like a Lego construction, so you can use the different parts multiple times without losing functional quality. For a bridge this means that the different parts can be disassembled relatively easy (e.g. with a mobile crane) and the different parts can be used in a new construction for the same function. A bridge scores 'fair' if it contains some components for reuse but they have to be disassembled with exceptional machinery and much effort, for example if a construction crane has to be set up for disassembly. 'Poor' modularity would mean a fixed bridge that does not exist of components that can be disassembled.

The maintainability of the design alternative: important aspects are the frequency of needed maintenance and how big the maintenance operations are in terms of effort and nuisance for the users of the object. The effort is determined by the energy needed for the maintenance operations and the equipment. Also the possibilities and effort required to repair broken parts of the object influence the maintainability.

Score	*Description*
Excellent	Little maintenance is needed to ensure the designed lifespan, and the maintenance operations can be considered as small, with hardly any nuisance for the users.
Very good	Not much maintenance is needed to ensure the designed lifespan, some maintenance operations take some effort and cause some nuisance, but most maintenance not.
Good	Some maintenance operations needed to ensure the lifespan, without much nuisance for the users and the operations does not take much effort to do.
Fair	Quite some maintenance is needed, although the effort and size of the maintenance operations differ from small to extensive. The small operations are easy, but the extensive operations cause nuisance for the users.
Poor	Very frequent maintenance is needed to ensure the quality and lifespan, causes quite some nuisance for the users. The maintenance operations take some effort to execute.

Table 13. Scoring of the maintainability.

Example: a road that needs small maintenance every six months to reach it designed lifespan while the road can be kept open for traffic during the maintenance could score 'very good', while a road that should be cleaned every month with special equipment to ensure its lifespan and quality will score 'fair'. Also, a bridge that needs inspection every six months but is easy to repair if needed would score 'excellent'.

Lifespan: the lifespan is scored in time and can be compared directly with each other.

5.3.3.End of life phase indicators scoring system

The end of life phase distinguishes three end of life strategies for an infrastructure object: reuse, recycling, and waste generation and energy recovery.

- Reuse is when an object or component is used again for the same or different purpose with little enhancement or change, or with some refurbishment so the component can be reused at the same functionality.
- Recycling is using materials after their lifecycle in new materials or for new purposes without becoming waste. For recycling materials can be recovered and used as resource for the same purpose or new purpose, but at the same quality as in their original form. An example is the recovering of sand out of used concrete. Materials can also be 'downcycled'. This means materials are used into new materials or objects of lesser quality or reduced functionality, such as concrete that is demolished into granulate for the foundation of highways.
- Energy recovery is the combustion of materials whereby the heat is transformed into energy. Waste generation is when products are discarded and 'thrown away', and usually end up at a landfill.

Scoring the end of life phase of an object is a sort of predicting the future. With current knowledge estimation can be made about the possibilities for the end of life phase of an object, although the user should keep in mind that it could be different at the actual end of life of an object. Especially when something is designed for thirty years or more new techniques could make end of life strategies possible that are not possible in the current situation. The estimation of the end of life possibilities is

done in percentages of the object. The reuse and recycling scores are shown in one table, followed by the waste generation and energy recovery scores.

Reuse and recycling scores (reuse is more circular than recycling)

Downcycling is specified in the recycling scores. The percentage downcycling indicates the part of the recycling score that is allowed to be downcycling. For example, if the recycling rate is 50%, the score would be 'good'. The downcycling <40% means that less than 40% of the recycled material may be downcycled. For the scores 'poor' and 'fair' the downcycling is not identified.

Score	% of the object	*Reuse description*	*Recycling description*
Excellent	80-100%	Can be reused	Can be recycled, downcycling <20% of the recycling rate
Very good	60-80%	Can be reused	Can be recycled, downcycling <30%
Good	40-60%	Can be reused	Can be recycled, downcycling <40%
Fair	20-40%	Can be reused	Can be recycled
Poor	0-20%	Can be reused	Can be recycled

Table 14. Scoring of the reuse and recycling rate.

Waste generation & energy recovery scores

Score	*Explanation*
Excellent	0-20% will become waste or will be incinerated
Very good	20-40% will become waste or will be incinerated
Good	40-60% will become waste or will be incinerated
Fair	60-80% will become waste or will be incinerated
Poor	80-100% will become waste or will be incinerated

Table 15. Scoring of the waste & energy recovery indicator.

* The indicators 'reuse' and 'recycling' and 'waste & energy recovery' should be looked at together. The 'waste & energy recovery' score of different design alternatives can be compared directly with each other. The 'reuse' and 'recycling' scores should be compared together, because a high score on one of these indicators causes a low score for the other indicator, while the overall score on 'reuse and recycling' can still be high. For example, if a bridge deck can be reused completely after its lifecycle it will score 'excellent' on reuse, but 'poor' on recycling. When only the recycling score is compared with another bridge deck it seems the reusable bridge deck is not circular, while it scores 'excellent' on reuse and is therefore more circular.

Example: when a bridge deck can be used again as bridge deck, that design alternative would score 'excellent' for reuse and 'poor' for recycling. If the deck itself can be reused and the top layer should be replaced and the top layer is about 30% of the total bridge deck, it would score 'very good' on reuse, and 'fair' on recycling if the top layer could be recycled.

5.4. Environmental impact of construction materials

The next two tables show the most used construction materials and their ECI (Environmental Cost Index) from DuboCalc. DuboCalc expresses the environmental impact in euros. DuboCalc allocates costs to each environmental factor, such as CO_2-emission during the production of a material. The

costs of all environmental impacts are combined for each material through a fixed method in the program into one score, the ECI in euros. A higher score means more environmental costs, thus a higher environmental impact. Innovative and new materials, such as composites are not covered by DuboCalc and are therefore not included in the overview. DuboCalc uses a cradle-to-grave approach that means the materials are considered to be used for one lifecycle and become waste afterwards. Although this can differ from the real situation the ECI can be used to compare the environmental impact of materials, since the end of life phase is scored through other indicators. The ECI includes all the phases from the production phase till the disposal of the material and an average transport distance is taken into account for each material. The user can make an estimation of the ECI for a specific project by multiplying the ECI-score with the estimated amount of a certain material that is used.

5.4.1.ECI construction materials

For the construction materials the ECI per lifespan of a material is shown and for a project time of 100 years. The lifespan for each material is fixed in DuboCalc. The project time is set at 100 years since RWS designs bridges for 100 years and the lifespan of concrete is 100 years. Thereby, a longer project time is not realistic since - almost - never a longer project time is required by the client. A sensitivity analysis for concrete C20/25 CEM I, concrete C20/25 20% recycled concrete, European hardwood and tropical hardwood can be found in Appendix B: Sensitivity analysis ECI.

Construction materials	*Unit*	*Lifespan (years)*	*ECI per lifespan (€)*	*ECI per 100 years (€)*
Concrete C20/25 CEM I	1 tonne	100	17.635	17.635
Concrete C20/25 20% recycled concrete	1 tonne	100	10.971	10.971
Concrete C20/25 100% recycled concrete	1 tonne	100	11.829	11.829
Concrete C20/25 CEMIII	1 tonne	100	11.537	11.537
Concrete C30/37 CEMI	1 tonne	100	18.129	18.129
Concrete C30/37 CEMIII	1 tonne	100	11.672	11.672
Concrete C35/45 CEMIII	1 tonne	100	11.677	11.677
Concrete reinforcing bars	1 tonne	100	106.238	106.238
Profile steel (galvanised)	1 tonne	100	109.547	109.547
Profile steel (ungalvanized)	1 tonne	100	97.913	97.913
European hardwood *	1 tonne	15	-10.901/0	-72.675/0
Tropical hardwood	1 tonne	40	38.265	95.662
Sand	1 tonne	Infinite	4.009	4.009
Concrete pile	1 tonne	100	12.400	12.400
Steel pile	1 tonne	100	78.682	78.682

Table 16. ECI data construction materials.

* DuboCalc allocates a negative ECI to European wood, which means that using more European wood in an object generates a lower environmental impact than using less European wood. DuboCalc argues that using European wood stores CO_2 for a period of time, so using European wood would help reduce the amount of CO_2 in the atmosphere. This reasoning is point of discussion and suggested is to calculate with an ECI of 0 when making ECI calculations for European wood.

Since the lifespan of concrete is 100 years, the type of concrete with the lowest ECI per unit (1 tonne) is also the most circular choice when the same amount of material is considered. For example, if a

design alternative requires 10 tonnes of concrete, no matter which type of concrete is used, the most circular option is concrete C20/25 20% recycled concrete.

5.4.2.ECI road construction materials

For the road construction materials also the ECI per lifespan is shown and for a project time of 50 years, because roads are usually more subjected to change than other civil constructions. Although the ECI for 50 years does not change for materials with a lifespan of 60 years, a longer project time is not considered since the project time for roads does not exceed the 50 years in practe. The sensitivity analysis for road construction materials can be found in Appendix B: Sensitivity analysis ECI.

Road construction materials	*Unit*	*Lifespan (years)*	*ECI per lifespan (€)*	*ECI per 50 years (€)*
Concrete granulate 250 mm thick	1 tonne	60	3.474	3.474
Steel slag 250 mm thick	1 tonne	60	2.750	2.750
Asphalt rubble	1 tonne	60	7.434	7.434
Asphalt rubble partial recycling 20%	1 tonne	60	7.652	7.652
Asphalt rubble partial recycling 50%	1 tonne	60	7.697	7.697
Asphalt (OAB) partial recycling 20%	1 tonne	35	10.812	15.446
Asphalt (ZOAB)	1 tonne	12	15.003	62.512
Asphalt (ZOAB+)	1 tonne	14	15.183	54.224
Asphalt low temperature	1 tonne	60	7.143	7.143
Paving stones (big size)	1 tonne	40	17.256	21.571

Table 17. ECI data road construction materials.

OAB = Open Asfalt Beton
ZOAB = Zeer Open Asfalt Beton

5.4.3.Other materials

Other resources, such as bio-degradable plastics or biocomposites, are not included in the database of DuboCalc or the Nationale Milieudatabase and are therefore not included in the scoring system for this indicator. If the ECI of such materials becomes available it can be included in the scoring system. Also, if the user has made own LCA calculations for such materials the calculated ECI can be used to score the environmental impact of materials in the indicator framework.

LCA or ECI information about new materials, such as biocomposites, is limited and not always available. In the current system companies or owners of new materials keep the LCA calculations secret or limited available, as it can be part of their profit strategy. This practice restraints the innovation and use of new materials that could have a lower environmental impact than the construction materials that are included in the database of DuboCalc.

In the end it is possible to calculate an ECI for new materials if all the outcomes of the environmental factors of the LCA are available and the exact considerations between the environmental factors is known. There are no standard calculation methods for the lifecycle impact of a material that limits the easiness of such calculations that can be widely used. Since there is no standardized method the impact factors that are selected to calculate the environmental impact can differ, which can have a significant impact on the outcome of the ECI (Korol, Burchart-Korol, & Pichlak, 2016).

6. VALIDATION OF THE INDICATOR FRAMEWORK

The indicator framework was validated by two experts in the field of sustainability and CE from the University of Twente: Mrs. Wilma Dierkes (Elastomer Technology & Engineering) and Mrs. Laura Franco Garcia (Governance & Technology for Sustainability). The validation sessions were conducted individually. The researcher presented briefly the background of the research, the research goal and how the indicator framework was developed. After this the context and boundaries of the framework were explained and the indicator framework was showed. The experts read the indicator framework and reviewed its completeness with regard to the research goal. After this the scoring system was shown to the experts along with an example to let them imaginary use the indicator framework and score the design alternative(s) from the example. The findings of both validation sessions are described below. In this chapter circularity means circularity for a civil engineering design alternative, unless explained otherwise.

6.1. Completeness of the indicator framework

The experts reviewed the completeness of the indicator framework. To be able to compare design alternatives on circularity the indicator framework should measure all aspects of circularity. This means all the indicators that are needed to measure all the aspects of circularity should be included in the indicator framework. Both experts recognized the different lifecycle phases of an infrastructure object in the categories. The four phases in a lifecycle of a product are the production and construction phase (resource use), the user phase (design characteristics), and the end of life phase. All these phases and their aspects are covered by the indicator framework.

The completeness of the indicators was reviewed per category. The indicators in the category resource use cover all the relevant aspects of circularity for the resource use, since the energy use is covered and the environmental impact indicator includes the production process of materials and components. The indicators 'transparency of the information of used materials' and 'reuse of existing objects, components and materials' provide a more in-depth look in the resource use of a design alternative. Both indicators could also stimulate designers to include these aspects in their designs.

Mrs. Dierkes agreed with the three indicators for the category design characteristics. Mrs. Franco Garcia compared it with circular design principles for a product. The three indicators are correct and cover the most important aspects for a design alternative. Yet she doubted if other aspects could be included in the framework. The first aspect was standardization and compatibility. Although partly covered by the indicator modularity it could be included as a separate indicator. The same goes for flexibility, but the measurement of flexibility is difficult and limits the use of flexibility as an indicator. Final remark was the resilience in time and for technology of an infrastructure object.

The end of life category includes the three strategies that are relevant for infrastructure objects. The combination of 'waste generation' and 'energy recovery' is in line with the used definition of circularity. Waste and energy recovery are both not closing the material cycle and should therefore be avoided.

6.2. Usability of the indicator framework

The experts used the indicator framework for the example provided by the researcher. After the use of the framework the usability was questioned. Both experts pointed out that the categorization provides structure for the user and the order of indicators is logic and in line with the chronological order of lifecycle phases.

On first sight, the framework does not make clear that the indicators 'amount of material used' and 'environmental impact of used indicators' should be combined together to get a useful score for the circularity. The individual indicators do not provide insight in the circularity of a design alternative on itself. Only the combination provides useful information and this relation should be clear when reading the indicator framework without the scoring system.

6.3. Scoring system of the indicators

The five point interval scale fits the goal of the framework. It allows users without precise knowledge about all the aspects and details of a design alternative to use the framework and compare design alternatives methodically. The scoring percentages in the descriptions make the scoring concrete for the user.

The scoring for 'renewable energy use' was ambiguous. The description made not clear if the energy use during the production process is part of the scoring percentage that is given for each score or not. Suggested was to include the energy use of the production process in the score, since it is needed for circularity.

It is unclear why the transparency indicator has three scoring levels instead of five. Five would make the scores more accurate. Thereby is the description not concrete. It uses value judgement terms as 'reliable' that can be interpret differently per person. The term should be omitted and replaced by percentages. Also the five point interval scale should be implemented.

The scoring descriptions for the indicators 'modularity' and 'maintainability' are complex. The scores are determined by different aspects that are not specified. Thereby, the weight of each aspect for the complete score is not given and has to be determined by the user him/herself. Defining a method with the aspects that should be considered for the scores of these indicators, including their importance and calculation method, would make the scoring systems of both indicators objective.

7. CONCLUSION

The construction sector has to comply with the concept of CE and is looking how to incorporate circularity into infrastructure objects. Currently, there is not a systematic method to compare design alternatives on the aspect of circularity. The goal of this research was *develop an instrument that allows comparison of civil engineering design alternatives on the aspect of circularity.* The research goal is achieved by conducting a literature study and conducting expert interviews. From literature an indicator framework was developed. Expert interviews were conducted to found out if the indicator framework was complete and how the indicators can be scored. The results were synthesized into one final framework with a scoring system for each indicator.

The research outcome is an indicator framework with a scoring system that makes design alternatives comparable on circularity (Table 8). An example of an indicator is 'renewable energy use'. A scoring system was developed with five different scores. The scores are described for each indicator and range from 'excellent' to 'poor'. For example, a design alternative scores 'very good' for the indicator 'reuse rate' if '60-80% of the object can be reused after its lifespan'. Validation with the experts showed that, altogether, the indicators cover the complete aspect of circularity, as all aspects of circularity are covered that are discussed in literature and during the expert interviews. Application of the indicator framework results in scores for each indicator. The scores of the indicators provide insight in the circularity of a design. This allows comparison of different design alternatives as the scores of the indicators exposes differences and similarities between designs on the aspect of circularity.

In the future the indicator framework might lead to more circularity in infrastructure objects. During the early design phase design decisions are made that could impact the circularity (Ghisellini et al., 2016; Ramani et al., 2010). During the early design phases detailed information is not available and detailed calculations cannot be made. The proposed descriptive scoring system allows designers to score the indicators already during the early design phases, since it does not require detailed information or calculations. The framework also takes away the discussions, which currently takes place for each distinctive project, on what indicators circularity of design alternatives need to be assessed for a specific project.

The indicator framework might impact the design philosophy when used for a certain period of time. It could be possible that designers and decision-makers will adjust their focus for design alternatives towards design alternatives that score high on circularity after using the indicator framework for a period of time. Through using the indicator framework in multiple projects it could become more standard to choose or think of circular design alternatives compared to the current practice: the aspect 'circularity' would become embedded in the design philosophy of designers.

A final impact of the indicator framework might be that clients will ask for more circularity in their assignments. Clients, such as RWS, are looking for a way to incorporate circularity in their assignments. So far there was a lack of a complete framework for the construction sector that covers all the aspects of circularity. The indicator framework provides indicators for the clients that can be included and specified in their assignments. Incorporating indicators for circularity in assignments will lead to more

circularity in future infrastructure objects, since the contractors will have to comply with the requirements of the client.

The results of the literature study and expert interviews show a division of the indicators in three categories, in line with the lifecycle phases of an infrastructure object. The categories are 'resource use' (construction phase), 'design characteristics' (user phase), and 'end of life phase'. The research shows agreement between literature and the experts about the indicators for the categories 'resource use' and 'end of life phase'. All the aspects that are covered in literature are also considered essential by the experts to compare design alternatives on circularity. This was not the case for the indicators in the category 'design characteristics'. These indicators are not exactly defined in literature and were too complex for the experts to exactly define them, which make the indicators difficult to score. Thereby, the indicators consist of different aspects that together influence the score. To make it more complex different indicators can partially overlap each other.

8. DISCUSSION

The goal of performing this study was developing an instrument that allows comparison of civil engineering design alternatives on the aspect of circularity. During the first part of the literature study it became evident that there does not exist consensus about the definition of CE, as Kirchherr et al. (2017) and Korhonen, Nuur, Feldmann, and Birkie (2018) showed. Thereby, there is a lack of CE research focussed on the micro level (Elia et al., 2017; Ghisellini et al., 2016) and on the construction sector (Pomponi & Moncaster, 2017). This research fills a part of this gap by proposing an indicator framework that allows comparison of civil engineering design alternatives on the aspect of circularity. The framework combines the research of different studies that developed indicators that assess a specific part of circularity, like Di Maio and Rem (2015) and Linder et al. (2017) or that assess a category, like the resource use (Geng et al., 2012), into one framework that covers all the aspects of circularity. This research combines the different studies with CE frameworks on different spatial levels and indicators for a part of circularity in one indicator framework and proposes a standard for the aspects of circularity that should be assessed for infrastructure objects. A standard for circularity would take away the discussion about the definition and stimulates research to the assessment and operationalization of circularity (Geissdoerfer et al., 2017). The indicator framework could function as foundation for future research to the assessment of circularity for infrastructure objects. The proposed scoring system of the indicator framework describes how to score the indicators. It defines when an indicator scores high or low on circularity. The scores are made concrete with percentages for each score. In a way this is also operationalization of circularity for infrastructure objects. In this light the indicator framework could stimulate the implementation of circularity in infrastructure objects.

The indicator framework could function as a tool to stimulate the implementation of more circularity in infrastructure objects. 'Companies only want to know what they can measure' according to Mr. Van de Worp (Appendix C: Expert interviews). This includes clients, who have a key role in the requirements for infrastructure objects (Leising et al., 2018) as also Mr. Ypma explained (Appendix C: Expert interviews). RWS by means of Mr. Crielaard explained that RWS is looking for a way to incorporate circularity in their design evaluation criteria. The indicator framework defines what should be measured (the indicators) and with the proposed scoring system a tool is provided that can be used during the early design phases to compare design alternatives on circularity. The indicator framework gives the client a tool to guide the measurement of circularity in their assignments. Incorporating indicators for circularity in assignments will lead to more circularity in future infrastructure objects, since the contractors will have to satisfy the requirements of the client.

CE is has gained the interest of researchers over the last decade (Kirchherr et al., 2017). Most studies focus on the business models or concept of CE (Korhonen, Nuur, et al., 2018). This results in a limited number of articles that focus on CE for the construction sector (Pomponi & Moncaster, 2017). To overcome this problem articles from other research fields, such as product design, or with a focus on the general concept of CE were used for the literature review. This may have influenced the outcome of the literature study towards an outcome that does not optimally connect with the construction sector. On the other hand the expert interviews made sure the outcome of the research is connected with the construction sector. Further, this exploratory research leads to the development of new

knowledge for the construction sector on which future research can be build. For the same reason articles with frameworks and indicators for different spatial levels were reviewed. The result is that indicators for macro level assessment are combined with indicators for meso and micro level assessment. The restrictions caused by this combination are limited since not the scoring methods were reviewed but only the indicators self.

The interviews were conducted with eight experts in the field of CE. Four experts are academics and four experts work for engineering consultancy firms or contractors. Indicators from the literature study were accepted if the majority of the experts were in favour of an indicator. Although this is a systematic approach the small number of interviews made the conclusions drawn from the interviews sensitive for deviating opinions. To minimize this the researcher discussed the definition of circularity with all the experts at the start of the interview, so the starting point was – more or less – the same for each expert. The results of this research could be verified by conducting a questionnaire among researchers and practitioners in the construction sector from which statistical conclusions can be drawn about the indicators. The second point of discussion is that the information obtained from interviews comes from individuals and represents their own opinion and thinking about CE and circularity. The eight experts do not represent the industry, although their opinion as expert is considered is important. CE as an expertise in the construction sector does not consist for a long time and therefore the expertise of the experts is young compared to other fields of expertise, such as structural engineering that exists for dozen of years. But, all fields of expertise started similarly and started from little research and expertise. This research contributes to the development of research and expertise of circularity in the construction sector.

8.1. Recommendations for future research

Although the indicator framework was validated by two sustainability experts, it is not tested in practice. No case studies are conducted or workshops with future users were held due the limited time. For future research the indicator framework could be tested and optimized for practical use. The indicator framework could be tested in workshops with designers or decision makers that would use the indicator framework during their work. During a workshop the indicator framework could be tested with an example or case from a real project. The participants of the workshop will use the indicator framework for the case. The results from the indicator framework and the user experience can be discussed to gain feedback. Another option is to test the indicator framework in case studies. Real infrastructure projects could function as cases. A researcher would use the indicator framework for the design decisions that were made during the cases. The researcher can critically look at the results of the indicator framework and the use of the framework. With the outcome the indicator framework could be further developed. This development can be focussed on the indicators or on the proposed scoring system. Future research can aim to find out if all the needed indicators are included in the framework to compare design alternatives on circularity. The second aim of future research can be on the proposed scoring system that can be tested in practice or further specified with specific knowledge for the indicators.

The indicator 'maintainability' is reviewed as complex during validation. The score of this indicator is based on multiple factors that have to be combined by the user of the framework. Thereby, the user of the framework has to make his/her own considerations between the importances of these factors. Both will lead to either vagueness or subjectivity in the scoring for design alternatives. To solve this

the maintainability as indicator could be studied more in-depth to develop a method to score the different factors and determine their importance.

Legislations are not considered during the research. This could limit the practical use of the indicator framework. It could be possible that some scores of the indicators are not legally possible (yet). For example, if legislation prescribes that asphalt must consist of 50% unused materials, asphalt will not score 'excellent' for 'the reuse of existing materials' in practice. The researcher did not consider the legislations because they change over time and to keep the focus of the research on circularity. Thereby, the indicator framework is not bounded by a nation's legislations.

8.2. Recommendations for Witteveen+Bos

The recommendations are based on the outcome and conclusions of this research.

- **Use the indicator framework for each design decision during early design phases:** during a design phase designers work on design alternatives for an infrastructure object. After the possible design alternatives are described and specified, the 'best' design alternative has to be chosen. The indicator method should be used to compare the circularity of each design alternative. The comparison of design alternatives on circularity can be included in the design decision process, next to existing assessment methods for other aspects.
- **Use the indicator framework during decision making meetings for infrastructure projects:** at the end of each design phase the decision makers of an infrastructure project come together in a decision making meeting. The decision makers consist usually of a mix of project members from the client and contractor. During these meetings the decision makers compare the possible design alternatives and decide which will be chosen for the project. The decision is based on different assessment criteria. During these meetings the indicator framework should be used to include circularity as an assessment criterion.
- **Use the indicator framework standard for each infrastructure project:** Witteveen+Bos aims to increase sustainability in their designs through a companywide design strategy with a focus on sustainability. The use of the indicator framework for each infrastructure project can help Witteveen+Bos embed circularity in their design strategy. To achieve the best result the indicator framework should be used for each design decision. If this is not feasible the indicator framework should at least be discussed at the start of each design phase and at the end of each design phase. At the start of a design phase the discussion of the framework makes the designers aware of the aspect of circularity. At the end of a design phase the outcome of that design phase can be assessed on circularity with the framework. The designers and project members become aware of the impact of design decisions on circularity of the designed object. After a certain time it will be part of their design strategy and they will automatically consider circularity aspects during the design of an infrastructure object. This will eventually lead to more sustainability in designs of Witteveen+Bos.
- **Specify the framework for different disciplines:** different disciplines work together on an infrastructure project to make a design. Examples of disciplines that are involved in infrastructure projects are 'landscape', 'structural engineering', and 'permits'. Usually the disciplines compare design alternatives from their own point of view. The indicator framework is developed for generic use but can be specified for each discipline to make the framework specifically useful for each discipline. Each discipline could use the specified framework for

their design decisions. This would make the indicator framework continuously useful for each discipline.

The final recommendation is made in light of the aimed transition to a circular economy by the Dutch government.

- Study the economic aspect of circularity: the economic aspect is important to make circularity attractive for companies, like Witteveen+Bos. If the company can develop a method to incorporate the economic aspect in circularity it has a framework that it can offer to clients, like RWS, that want to measure circular economy and the tool can be used more decisively.

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APPENDIX A: LITERATURE MATRIX

In this appendix the literature matrix is shown that was used for the literature review. The next table shows all the used articles. After this the literature matrix is shown.

Nr.	*Author(s)*	*Name*	*Year*
1	Elia, Gnoni & Tornese	Measuring circular economy strategies through index methods: A critical analysis	2017
2	Ghiselini, Cialani, & Ulgiati	A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems	2015
3	Linder, Sarasini, & van Loon	A metric for quantifying product-level circularity	2017
4	Kirchherr, Reike, Hekkert	Conceptualizing the circular economy: An analysis of 114 definitions	2017
5	Di Maio and Rem	A robust indicator for promoting circular economy through recycling	2015
6	Geng, Sarkis, Ulgiati, Zhang	Measuring China's circular economy	2013
7	Zongguo Wen and Ruijuan Li	Materials metabolism analysis of China's highway traffic system for promoting circular economy	2010
8	Singh, Murty, Gupta, Dikshit	An overview of sustainability assessment methodologies	2011
9	Lu Yi, Zhigang Liu	Establishment of evaluation index system on construction enterprise's circular economy and empirical study	2016
10	Pintér	International experience in establishing indicators for the circular economy and considerations for China	2006
11	Bakker, Wang, Huisman, Hollander, den	Products that go round: exploring life extension through design	2014
12	Franklin-Johnson, Figge, Canning	Resource duration as a managerial indicator for circular economy performance	2016
13	Geng, Jia Fu, Sarkis, Xue	Towards a national circular economy indicator system in China: an evaluation and critical analysis	2011
14	Soderlund, Muench, Willoughby, Uhlmeyer, Weston	Green roads: A sustainability rating system for roadways	2017
15	Leising, Quist, Bocken	Circular economy in the building sector: Three cases and a collaboration tool	2016
16	Niero and Hauschild	Closing the loop for packaging: Finding a framework to operationalize circular economy strategies	2017
17	Gehin, Zwolinski, & Brissaud	A tool to implement sustainable end-of-life strategies in the product development phase	2008
18	Go, Wahab, & Hishamuddin	Multiple generation life-cycles for product sustainability: The way forward	2015
19	Pigosso, Zanette, Filho, Ometto, & Rozenfeld	Ecodesign methods focused on remanufacturing	2009

Table 18. Literature list.

The next table shows the references for the indicators from the literature review. In the left column the indicators enumerated, and horizontally the numbers correspond with the numbers of the articles shown in Table 19. An X in table below indicates that the indicator was found in that article.

Indicator ↓ / Article number →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Amount of used materials	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		
Environmental impact used materials	X	X	X	X		X	X	X		X	X	X	X	X		X	X	X	
Energy use	X	X	X			X		X	X	X			X			X		X	
Toxicity	X	X	X				X	X		X			X			X			
Emission of greenhouse gasses	X	X	X		X	X		X					X			X			
Reuse of existing infrastructure/objects		X	X								X	X		X	X				
Refuse principle	X	X		X		X	X				X		X	X	X				
Modularity											X							X	
Disassembly		X										X			X		X	X	X
Maintainability											X						X	X	X
Reparability				X							X	X					X		X
Lifespan		X	X	X				X			X	X			X		X		
Reuse	X	X	X	X			X				X	X			X		X		X
Recycling	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Waste & energy recovery	X	X		X			X	X	X	X	X	X	X			X			
Economic costs	X	X							X			X	X						

Table 19. Literature matrix.

APPENDIX B: SENSITIVITY ANALYSIS ECI

The total ECI of a material in an infrastructure object depends on the ECI per unit per lifespan of the material, the project lifespan, and the total amount of materials used. In this appendix two sensitivity analysis are made: for four types of construction materials and five types of road construction materials.

Sensitivity analysis construction materials

A sensitivity analysis was made for three construction materials: concrete C20/25 CEM I (concrete I in Figure 3), concrete C20/25 20% recycled concrete (concrete II in Figure 3), European hardwood and tropical hardwood. The lifespan of concrete is 100 years, which is longer than the required lifespan for most assignments. RWS requires a lifespan of 100 years for bridges, a longer lifespan is - almost - never required. Therefore the sensitivity analysis is done till 100 years. Figure 3 shows the results of the sensitivity analysis.

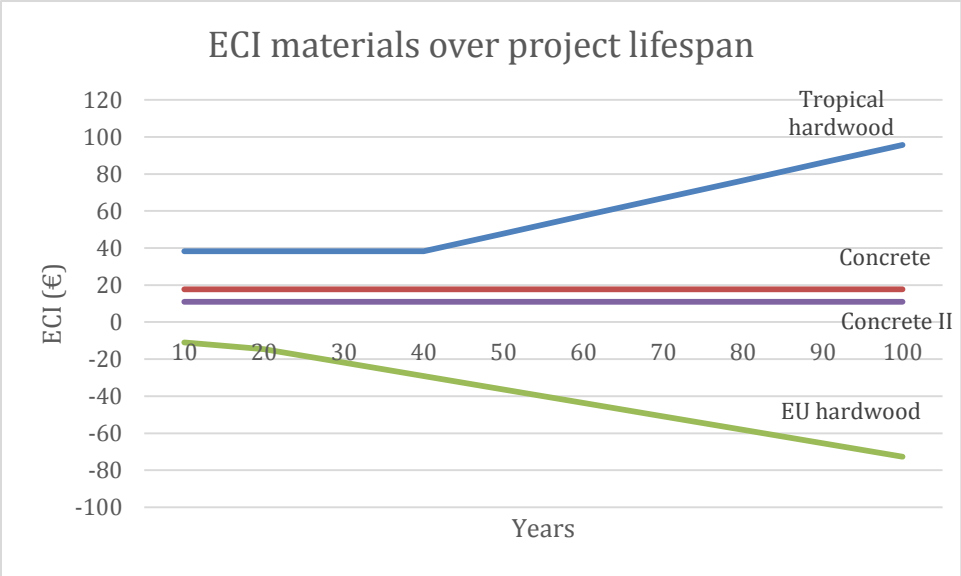

Figure 3. Sensitivity analysis construction materials.

Since the lifespan of concrete equals the project lifespan of 100 years the ECI does not change for the two types of concrete. The concrete C20/25 with 20% recycled concrete has a lower ECI per unit than concrete C20/25 CEM I and scores a lower ECI for the project time of 100 years. For concrete the type of concrete with the lowest ECI per unit will also result in the lowest ECI for the total amount of concrete used. The tropical hardwood has a higher ECI than concrete and the ECI increases after its lifespan of 40 years, since the used tropical hardwood needs to be replaced. The ECI of the EU hardwood is negative and decreases after its lifespan of 15 years. As explained in Paragraph 5.4.1. this is not considered realistic.

Sensitivity analysis road construction materials

Also for five road construction materials a sensitivity analysis was done. The compared materials are low temperature asphalt, OAB partial recycling 20%, ZOAB, ZOAB+, and paving stones (big size). The

project lifespan for the sensitivity analysis is set at 80 years. Figure 4 shows the sensitivity analysis for road construction materials.

Figure 4 shows that the ECI of low temperature asphalt and paving stones is low compared to the other asphalt types. Two factors clarify their low ECI. The ECI of low asphalt temperature and OAB is low per unit as can be seen in Table 18, and the lifespan of both materials is longer than the other materials. OAB is not a top layer, but a between layer under the top layer and foundation of the road. The lifespan of OAB is 35 years. After 35 years it has to be replaced to guarantee its quality and functioning. The top layer will have to be removed, also if the top layer did not reach its lifespan, as could be the case for low temperature asphalt (lifespan 60 years). Although the paving stones have a slightly higher ECI per unit per standard lifespan than ZOAB and ZOAB+, its ECI is lower than both (ZOAB and ZOAB+) when they reach their lifespan of respectively 12 and 14 years.

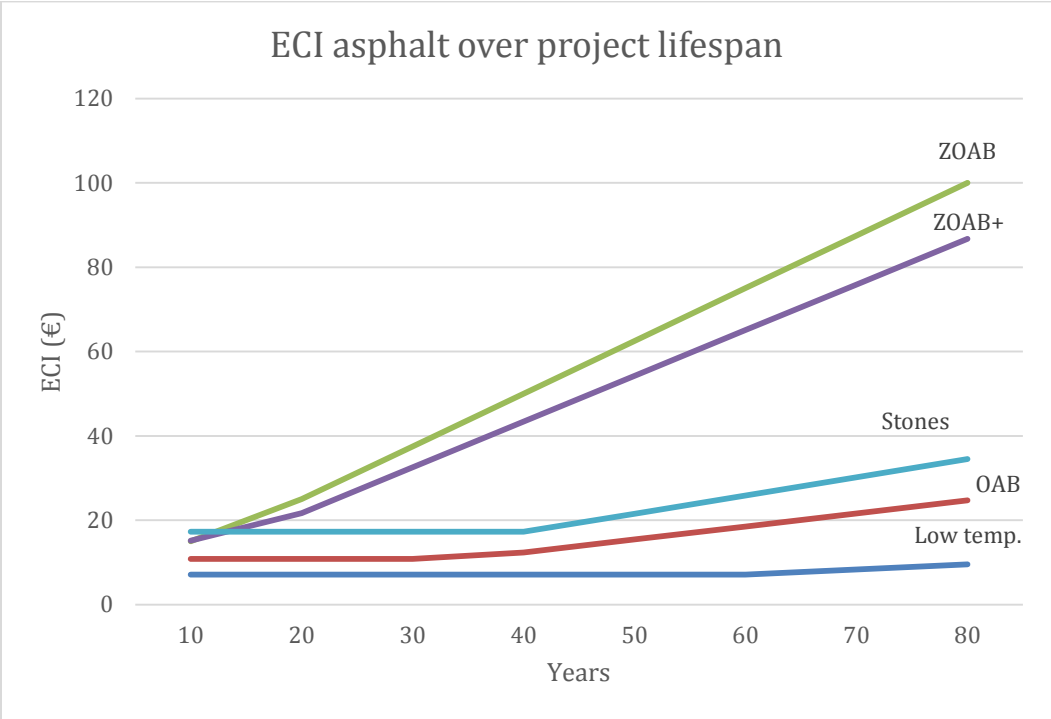

Figure 4. Sensitivity analysis road construction materials.

APPENDIX C: EXPERT INTERVIEWS

This appendix elaborates the selection of the experts and provides details about the selected experts.

Experts for the interviews

The next table contains all the experts that were interviewed, with their organisation, function and date of the interviews. The experts were selected based on their expertise: they all work with circularity or circular economy on a professional base. A group of experts was contacted by e-mail with a request for an interview. The group contained experts that were selected through research by the researcher, experts from the network of Mr. Schäffner and of the graduation committee. The selected experts responded positively to the request for an interview. Three experts responded that they did not have time; one of them suggested two other experts, of which one was selected for the interviews (Mr. Geldermans).

Name	Company	Function	Date
Erik van de Worp	Schagen Groep	Project manager Circularity	25-09, 10:00
Henne ter Huerne	UT/Prov. Overijssel	Ass. Prof./Cons. Circ. Infrastr.	25-09, 13:00
Bauke de Vries	TU Eindhoven	Prof. Built Environment	26-09, 10:30
Maarten Schäffner	Witteveen+Bos	Consultant CO2 reduction & Circ.	02-10, 09:30
Bob Geldermans	TU Delft	Sr. Res. Circular Built Environment	02-10, 13:00
Mink Jaap Ypma	Van Gelder	Director Integrated Projects	03-10, 09:30
Ruud Balkenende	TU Eindhoven	Prof. Circular Product Design	05-10, 11:00
Machiel Crielaard	Rijkswaterstaat	Consultant Circular Economy	08-10, 09:30

Table 20. The interviewed experts.

The academic researchers are all active within research about CE. They are not necessarily active in the field of civil engineering, since the research field of circularity in civil engineering is relatively new and the subject is complex that touches different research backgrounds. Two academic experts in circularity are active in 'architecture and built environment' and, one in 'civil engineering' and one in 'industrial design engineering'.

The professionals were selected based on their function and activities. They are all active in civil engineering projects and the subject of CE. A mix of young professionals and senior professionals was selected. Mr. Crielaard and Mr. Van de Worp are responsible for the implementation and measurement of circularity in infrastructure and constructions, at respectively RWS and Schagen Groep B.V. Mr. Schäffner is consultant for Witteveen+Bos for circularity and CO_2-reduction in mainly infrastructure projects. Mr. Ypma is director of integrated projects of infrastructure projects.