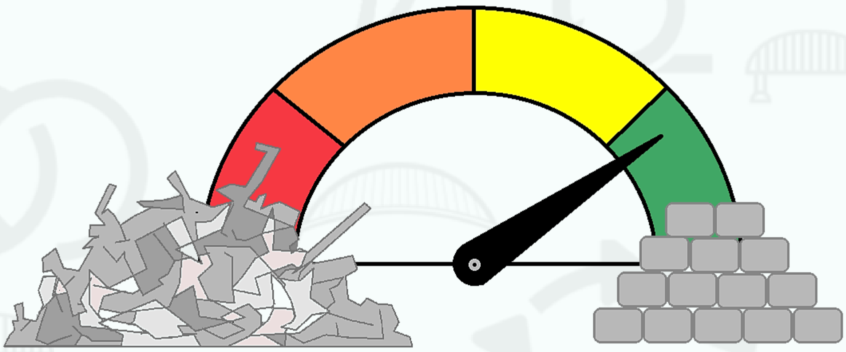
# Circular bridges and viaducts

## Development of a circularity assessment framework

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# Preface

Still today, bridges and viaducts are constructed with tons of virgin materials to eventually become waste. However, in the Circular Economy concept, this linear resource flow is curved into a looped one. The transition towards the Circular Economy is both desired and inevitable for Rijkswaterstaat, which is financing as well as hosting the design project. However, the most suitable way of achieving this transition is currently searched for. In this study, executed in the department of Construction Management and Engineering at the University of Twente, a bridge circularity assessment framework was developed to support the implementation of the Circular Economy within Rijkswaterstaat considering the design of bridges and viaducts. Although the client is Rijkswaterstaat, this publicly available thesis could be valuable for other public clients that aim to make bridges circular as well as to scholars who are studying the Circular Economy concept in the civil engineering domain.

This design report should be read as the backbone of the PDEng project. It includes the design methodology, theoretical background and the design process of the project. Although the end-product – the circularity assessment framework – along with its product-specific tool and support documents are presented in individual deliverables, the design outlines and major findings are discussed in this report.

Despite my name is the only one on the front cover, the results presented in this report would not have been half of what they are without the help and support of many others. Therefore, I take the opportunity here to thank these people. First of all, I would like to thank my supervisors for their support and advice these last two years. In particular, I would like to thank João Santos and Joop Halman at the University of Twente for providing me continuously with the confidence I needed on the one hand, and the careful balance between guidance and freedom on the other. This helped me to execute this design research project at its fullest, while exploring the field in many unforeseen ways. Moreover, I would like to thank Sonja Fennis and Sjoerd Wille for their outstanding supervision within Rijkswaterstaat. Even in busy times, they always found time to provide me with the input I needed and helped me to put the research in a broad perspective.

Moreover, an almost inexhaustible list of experts, both within and outside Rijkswaterstaat, have helped me to find the right directions, put lots of ideas in my head and provided me with the information and data I needed. Although the list is too long to present here in full, I am very grateful to each and every person that helped me during this journey. Furthermore, many thanks to all my colleagues from the department of Construction Management & Engineering, and particularly the ones in room Z-202, who kept the atmosphere at such heights that even in harder times, it was a pleasure to work on the project. Without such colleagues, it would have been impossible to keep the joy and enthusiasm I had in the work.

Finally, but above all, I want to express my deepest gratitude to my girlfriend Karina, my family and my friends. You both supported me throughout the two years and provided me with the distractions I needed to keep my mind clear. Thank you very, very much for all the love and support!

I wish you a pleasant reading.

Tom Coenen

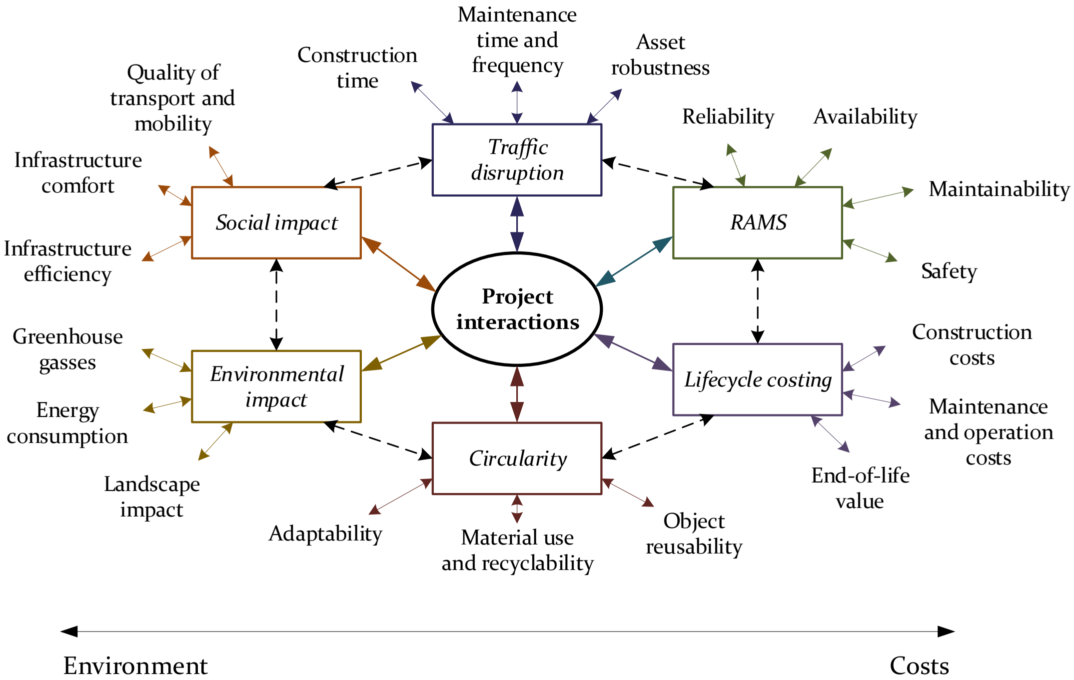
Enschede, November 13th, 2019

# Executive summary

The construction sector accounted in 2015 for around 40% of the total waste in the Netherlands and nearly 50% of the material flows are construction related. A large share in civil engineering structures in the construction infrastructure sector consist of bridges and viaducts. In these assets, the increasingly scarce materials are either “captured” in the assets or transformed after the asset end-of-life into waste. The Circular Economy (CE) is a concept that replaces this linear material flow model by loops. By means of lifetime extension, reuse and recycling, the maximum value is extracted from each virgin resource. Rijkswaterstaat has set the goal to be circular in 2050. Hence bridges and viaducts must be built and managed circular. In this project, an assessment framework is presented to reveal to what extent a bridge design decision is circular.

## Goal and approach

regarding various aspects, decisions have to be made before a bridge-related project can start, irrespective of the type, size or surroundings. Circularity is just one of the many aspects in this decision-making process (figure below). However, other aspects, such as investment costs, are currently outweighing circularity. This is largely because it is still unknown how to measure and value circularity. Yet, environmental impact plays more and more a part in infrastructure decisions. Circularity, which aims foremost at resource efficiency and effectivity, both exceeds and differs from the scope of the current ways to calculate environmental impact and related environmental costs, while indicators for these bridge-related circularity aspects are still lacking.




Circularity must become an essential aspect of the decision-making processes concerning bridge design to reach a circular practice. Therefore, it should be clear what decisions or design choices are circular and how bridge designs can be improved. In other words: What is circularity in relation to bridges and what aspects does it entail? The final deliverable of this project is a circularity assessment framework, which includes a set of indicators with respect to bridges and viaducts. This assessment framework is developed by using a Design Science Research (DSR) approach. DSR employs an iterative process to develop a suitable design that can be used to solve a specific type of practical problem or challenge. The intended outcome of DSR consists of both a practically applicable end-product and the creation of knowledge.

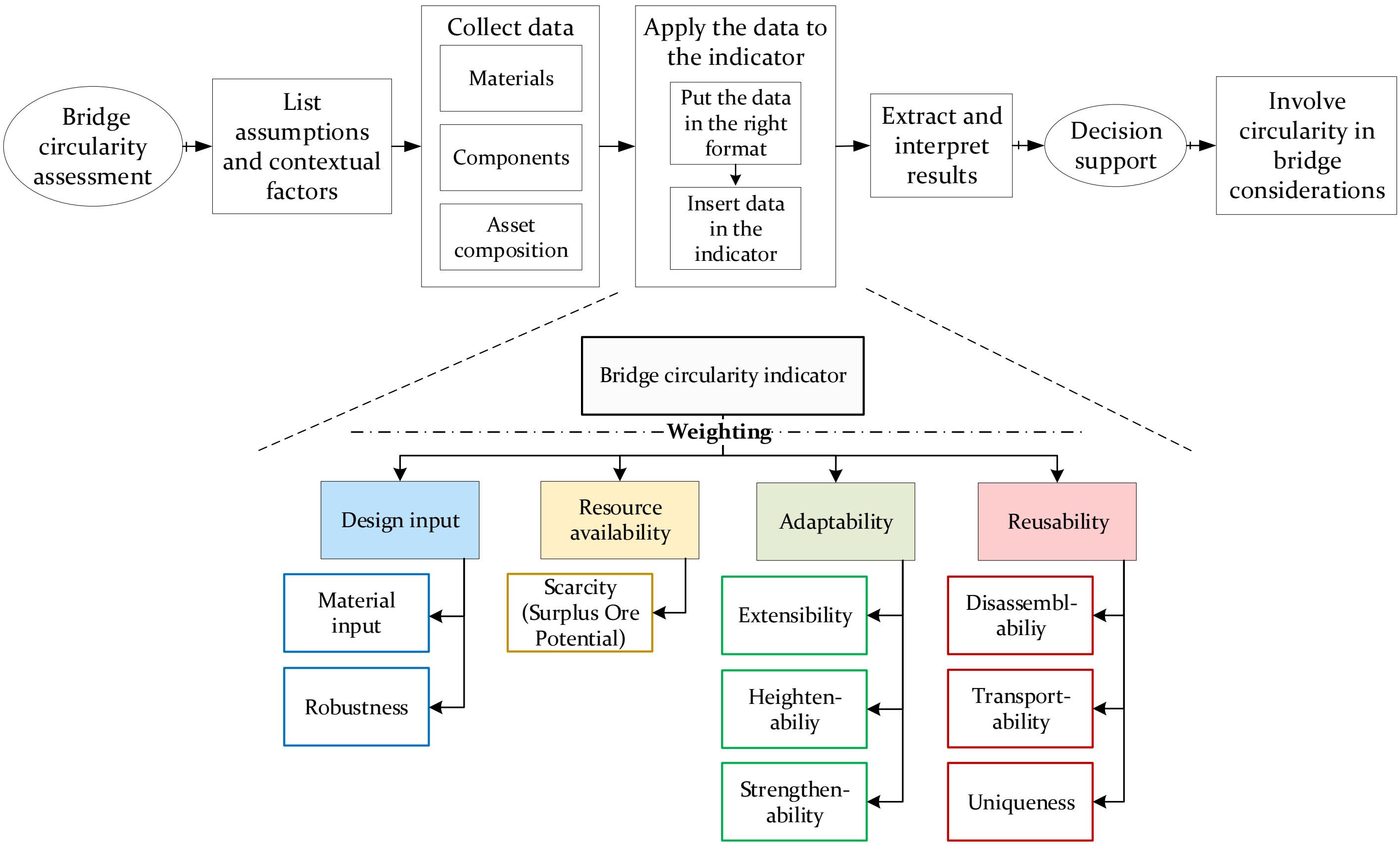
The goal of the bridge circularity assessment framework is to measure the extent to which a bridge is designed according to the principles of the CE. However, since this concept is still evolving, a fixed definition is presented in this study to which this framework is designed. This *Bridge circularity 2019* is defined as follows:

*The* Bridge Circularity 2019 *is the level to which a bridge or viaduct is designed in order to prevent resource depletion by minimizing input of virgin, scarce, unrenewable and unrecyclable materials while designing it in a way that considers evolving functional requirements.*

The first input for the design process is a gap analysis considering circularity indicator literature using the waste hierarchy as a basis. Together with a decomposition of the bridge lifecycle aspects, the first conceptual outline for the framework and circularity indicator is developed. By means of three case studies, the initial design was revised towards the final framework. These case studies are: (1) five design alternatives for a revised Daelderweg crossing of the A76 motorway within the Parkstad Limburg project; (2) the modular design of the Circulaire Viaduct compared to a conventional box-girder design; and (3) six design alternatives using various materials in the Balgzandbrug. The final framework is validated using the triangulation approach. The internal validity is tested by comparing to the gap analysis in literature, execution of user cases, and by means of expert sessions and interviews. Furthermore, the concurrent validity is tested by comparing the framework to various bridge circularity analyses executed or commissioned by Rijkswaterstaat.

## Results

The conceptual outlines of the final assessment framework, including the bridge circularity indicator, is presented in the figure below.



## The use of the framework

The framework and indicator are operationalized by means of a spreadsheet. By inserting the bridge design data in the spreadsheet, the level of bridge circularity can be determined on several levels. Consequently, the framework can be used for three main purposes in the design and procurement processes.

### As a design guide

The first type of use considers the framework as a guideline to design bridges and viaducts more circular. The four main indicators – *design input, resource availability, adaptability* and *reusability* – convey design principles that may broaden the designer's perspective on circularity. The designer can insert the design in the tool which results in insights into circularity aspects regarding materials, components and the sub-indicators. This potentially reveals flaws in the design with respect to circularity and offers opportunities for improvement. Moreover, by trying various design choices, effects on circularity can be tested. Transparency in underlying results is provided considering circularity aspects, materials, components and functional groups. This allows for using the tool as a design guide for identifying opportunities to circularize the design.

### As an assessment method

The second type of use considers the assessment of designs and comparison of design alternatives. By inserting various design alternatives for a similar bridge application, it becomes immediately clear what alternative has the highest score on (certain aspects of) circularity. This enables the client to apply circularity as a selection criterion in the procurement process. In this type of use, the tool is both used by the designers at the market side and by the client's project managers who are responsible for the selection of the contractor. The project managers can eventually determine in what way circularity contributes to awarding the project.

### For formulating circular requirements

The third and final type is to use the tool for partial assessment or in a prescriptive way. Sub-indicators might be translated into design criteria or requirements to strengthen the clout towards circularity in projects. The client might also require the contractor to, for example, reuse a certain amount of old asset parts in the new asset instead of scoring on the use of recycled and reused materials. As such, the tool is used to check minimum circularity requirements. The project manager at the client's side is for this type of use eventually the tool user and defines the circularity requirements based on the various sub-indicators in the tool. However, to increase impact, these requirements might be taken up to higher levels of decision-making for standardizing practices regarding circularity rather than applying these in specific projects.

## Implications for practice

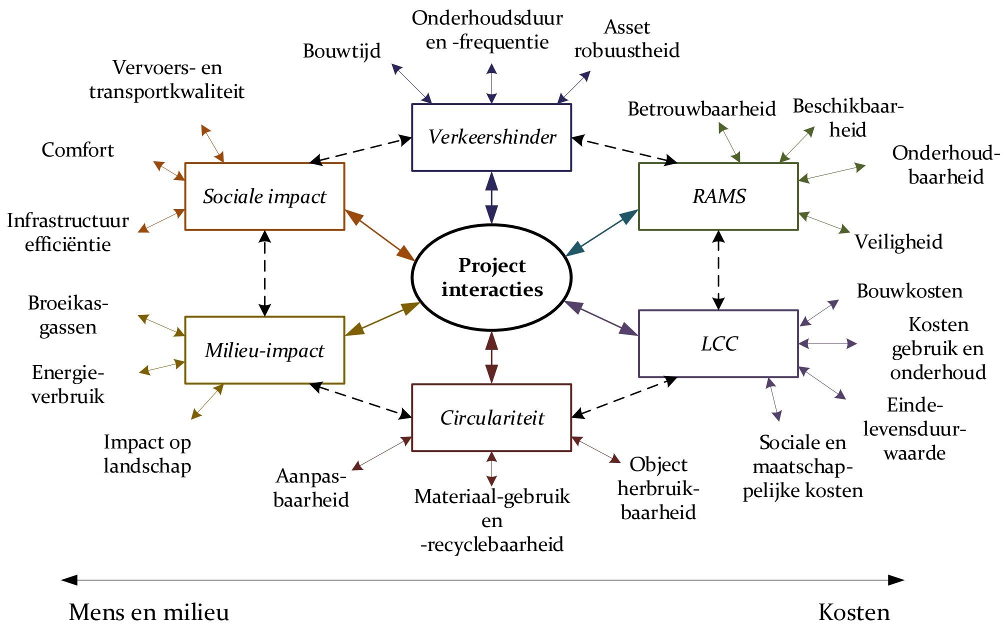
The framework represents a static set of attributes in an inevitably dynamical environment. Therefore, the framework must change with these dynamics to remain representative and up to date in relation to circularity. This means that the framework should be regularly maintained and updated in order to remain relevant. Furthermore, the framework outcomes provide insights into only the material circularity. For the sake of a more comprehensive decision-making process, the indicator should in projects always be used in combination with, for example, DuboCalc and lifecycle costing, following the interactions shown in the first figure in this summary. Finally, the framework just provides the opportunity to include circular principles in bridge and viaduct designs, while the whole system in which it operates is based on linear resource flows. To arrive at circular practices, changes at more fundamental levels, including the institutional, legislative, value chain and organizational ones, are required.

# Managementsamenvatting

De bouwsector was in 2015 verantwoordelijk voor grofweg 40% van het afval in Nederland. Daarnaast zijn in totaal bijna 50% van de materiaalstromen bouw-gerelateerd. De steeds schaarser wordende materialen zijn tijdens de levensduur “opgeslagen” in bruggen en worden na eindelevensduur verwerkt tot afval of in sterk gedegradeerde toepassingen. De Circulaire Economie (CE) is een concept dat dit lineaire model van materiaalstromen vervangt door een cirkelvormig model, waarin wordt gepoogd om door middel van levensduurverlening, hergebruik en recyclen, een maximale waarde te halen uit elk stukje nieuw materiaal. Rijkswaterstaat heeft zich tot doel gesteld in 2050 geheel circulair te zijn. Daarvoor moeten ook de bruggen en viaducten circulair gebouwd en gemanaged worden. In deze studie presenteren we een raamwerk om te bepalen hoe circulair een brugontwerp is.

## Doel en aanpak

Alvorens een project gestart kan worden, dienen beslissingen gemaakt te worden, ongeacht het type, de grootte of de omgeving. Circulariteit is hierin slechts één van de vele aspecten (zie figuur onder). Andere aspecten, zoals investeringskosten, zijn in de huidige praktijk doorgaans doorslaggevend in ontwerpbeslissingen. Dit komt grotendeels doordat men nog niet weet hoe circulariteit moet worden gemeten op brugniveau. Duurzaamheid speelt echter steeds vaker een rol in het besluitvormingsproces. Waar circulariteit zich voornamelijk richt op materiaal-efficiëntie en grondstofuitputting, richten de bestaande indicatoren zich doorgaans op andere milieueffecten en gerelateerde milieukosten. Door een gebrek aan een meetmethode is het tot op heden nog niet mogelijk om circulariteit systematisch in deze afwegingen mee te nemen.




Om de doelen voor 2050 te halen, dient circulariteit een kernaspect te worden van het besluitvormingsproces omtrent brugontwerpen. Het moet daarom duidelijk zijn welke beslissingen en ontwerpkeuzes circulair zijn en waar verbetermogelijkheden liggen. In andere woorden: wat is brugcirculariteit en welke aspecten vallen hieronder? Het eindproduct van dit project is een circulariteit-beoordelingsraamwerk welke een verzameling circulariteitsindicatoren bevat om de brugcirculariteit te bepalen. Met behulp van de *Design Science Research* (DSR) aanpak is dit raamwerk in iteratieve ontwerpcycli ontwikkeld. De uitkomst van deze studie draagt zodoende zowel bij aan een toepasbaar product als aan de ontwikkeling van wetenschappelijke kennis.

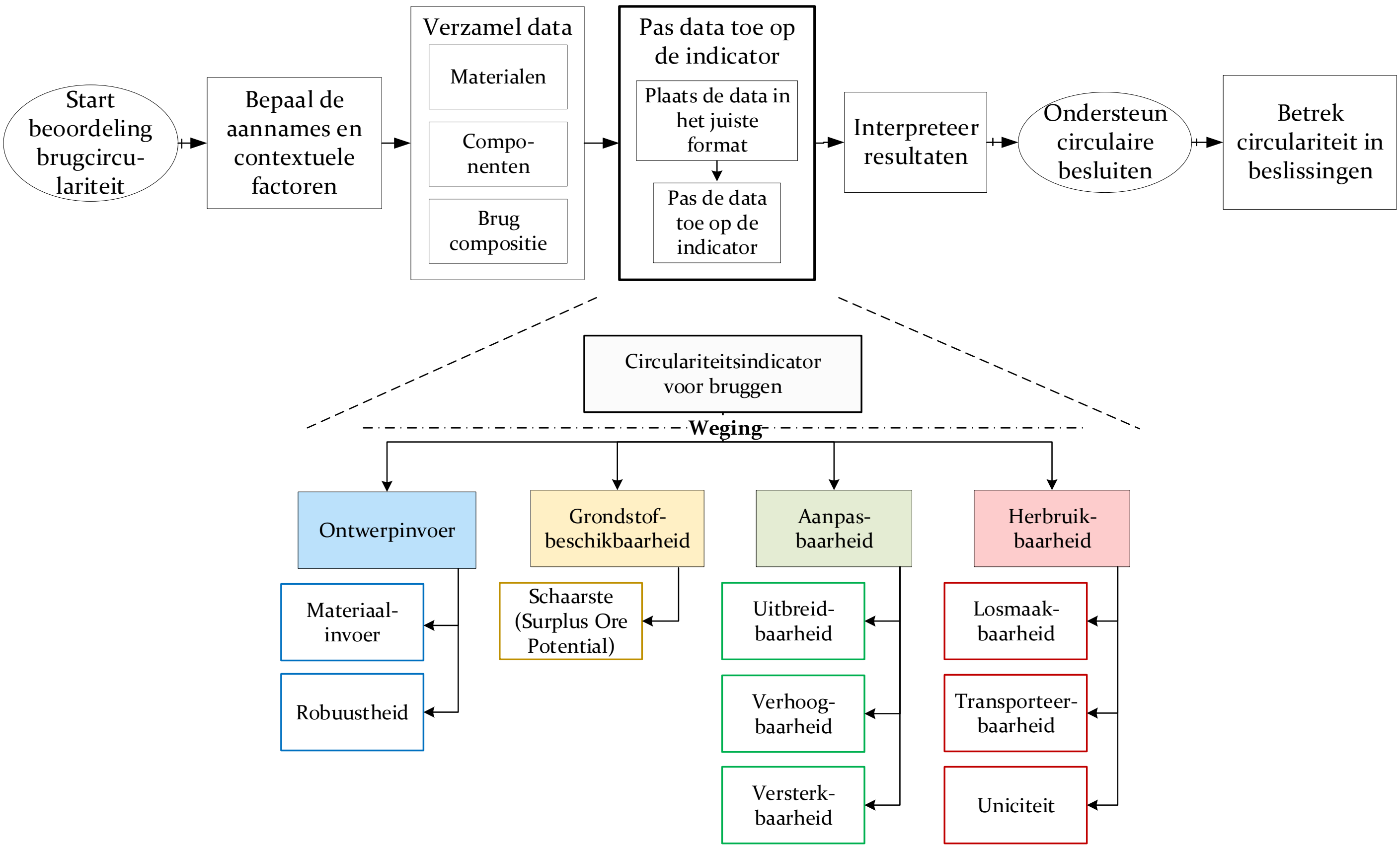
Het circulariteit-beoordelingsraamwerk voor bruggen meet de mate waarin een brug is ontworpen volgens de principes van een CE. Omdat het CE concept een evoluerend concept is, dient voor de ontwikkeling van het raamwerk een statische definitie gegeven te worden. De *Brugcirculariteit 2019* is daarom als volgt gedefinieerd:

*De "Brugcirculariteit 2019" is de mate waarin een brug of viaduct is ontworpen om grondstofuitputting te voorkomen door het minimaliseren van gebruik van primaire, schaarse, niet-hernieuwbare en niet-recyclebare grondstoffen alsmede zo te ontwerpen dat het brugontwerp bestand is tegen toekomstige veranderingen in functionele eisen.*

De eerste stap in het ontwerpproces was een onderzoek naar de hiaten in de huidige indicatoren waarbij de afvalhiërarchie als een startpunt heeft gediend. Samen met een decompositie van de levenscyclus van een brug heeft dit tot het eerste conceptuele ontwerp van het raamwerk geleid. Met behulp van drie casussen zijn deze eerdere versies van het ontwerp getest en verbeterd. Deze zijn: (1) vijf ontwerpalternatieven van het viaduct waarin de Daelderweg de A76 overspant binnen het Parkstad Limburg project; (2) het modulair ontworpen Circulaire Viaduct vergeleken met een conventioneel kokerliggerviaduct; en (3) zes ontwerpalternatieven met verschillende gebruikte materiaaltypen voor de Balgzandbrug. Het uiteindelijke raamwerk is gevalideerd door middel van de triangulatiemethode. De interne validiteit is allereerst getest door het raamwerk te spiegelen aan de literatuurstudie en de gevonden hiaten, ten tweede door toepassing van het raamwerk op meerdere casussen en gebruikerstests, en ten derde door middel van expertsessies. Verder is de concurrent validiteit getest door middel van vergelijkingen tussen uitkomsten van het raamwerk en andere onderzoeken naar brugcirculariteit binnen Rijkswaterstaat.

## Resultaten

Deze aanpak heeft tot het volgende ontwerp van het raamwerk en bijbehorende indicator geleid:



## Raamwerkgebruik

Het raamwerk en de indicator zijn geoperationaliseerd door middel van een spreadsheet. Door data van het brugontwerp in te voeren, wordt de mate van circulariteit op verschillende niveaus doorgerekend. Als zodanig kan het raamwerk op drie verschillende manieren gebruikt worden in het ontwerp- en aanbestedingsproces.

### Als ontwerpondersteuning

Het eerste type gebruik is als ontwerpondersteuning bij het circulair ontwerpen van bruggen en viaducten. De vier hoofdonderdelen – *ontwerpinvoer, grondstofbeschikbaarheid, aanpasbaarheid* en *herbruikbaarheid* – en de onderliggende sub-indicatoren geven de ontwerper inzicht in de verschillende ontwerpprincipes. Wanneer de ontwerper een brugontwerp ingevoerd heeft, geven de resultaten inzicht in de materialen, componenten, en sub-aspecten van brugcircylariteit. Dit biedt inzicht in de verbetermogelijkheden van het ontwerp met betrekking tot circulariteit. De onderliggende resultaten zijn in de spreadsheet inzichtelijk gemaakt om de verbetermogelijkheden aan het ontwerp voor circulariteit zo duidelijk mogelijk weer te geven.

### Als beoordelingsmethode

Het tweede gebruikstype beschouwt het raamwerk als beoordelingsmethode voor vergelijkingen tussen brugontwerpen. Naast de toekenning van een circulariteitsscore voor een ontwerp kunnen verschillende brugontwerpen ingevoerd en vergeleken worden om circulariteit mee te nemen als selectie of gunningscriterium. De gebruikers zijn in deze toepassing voornamelijk de ontwerpers om hun ontwerp in te voeren aan de marktzijde en de projectmanagers om de ontwerpen te testen en te beoordelen aan de opdrachtgeverszijde. Naast bijvoorbeeld de milieukostenindicator (MKI), esthetiek, hinder of levenscycluskosten (LCC) kan brugcircularitiet zo meegenomen worden als een *EMVI*-criterium.

### Ter formulering van circulariteitseisen

Het derde en laatste type is om de spreadsheet voor gedeeltelijk gebruik en formulering van eisen in te zetten. Zo kunnen sub-indicatoren omgezet worden in ontwerpcriteria of –eisen om de nadruk op circulariteit te vergroten. De opdrachtgever kan bijvoorbeeld eisen om een vastgesteld gedeelte van een brug her te gebruiken in het nieuwe ontwerp of bepaalde aanpasbaarheids-aspecten uit de indicator voor te schrijven en te sturen op minimale circulariteitseisen voor het nieuwe brugontwerp. In dit geval is de projectmanager aan de opdrachtgeverszijde de raamwerkgebruiker. Om de impact op de transitie naar een CE te vergroten, kunnen deze eisen op bijvoorbeeld programmaniveau ingezet worden. Bepaalde eisen kunnen binnen Rijkswaterstaat ook gestandaardiseerd worden in de eisen voor nieuwe bruggen.

## Implicaties voor de praktijk

Het raamwerk beschrijft een statische set aan attributen binnen een dynamische omgeving. Het raamwerk moet daarom onderhouden en geüpdatet blijven om de actuele perceptie van circulariteit te beschrijven. Verder geeft het raamwerk slechts inzicht in materiaal-georiënteerde circulariteit. Voor een brede ontwerpbeoordeling zullen deze resultaten dus altijd naast andere factoren gebruikt moeten worden, zoals de MKI, levenscyclus kosten (LCC) of RAMS aspecten als aangegeven in het eerste figuur in deze samenvatting. Tot slot biedt het raamwerk uitsluitend de mogelijkheid om brugontwerpen op circulariteit te beoordelen, terwijl het gehele systeem waarin het raamwerk ingezet wordt ingericht is op lineaire materiaalstromen. Om circulair te worden zal Rijkswaterstaat veranderingen op een fundamenteler niveau door moeten zetten, waaronder een herziening van onder andere de instituties, wetgeving, organisatie van de waardeketen, werkprocessen en organisatiestructuur.

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# List of abbreviations

| | |
|---|---|
| BVi | Rijkswaterstaat department of bridges and viaducts |
| CBA | Cost-benefit analysis |
| CE | Circular Economy |
| DSR | Design science research |
| EoL | End-of-life (stage) |
| GPO | Rijkswaterstaat department of large projects and maintenance |
| GUI | Graphical user interface |
| LCA | Environmental lifecycle assessment |
| LCC | Lifecycle costing |
| MCI | Material circularity indicator |
| MFA | Material flow analysis |
| MFCA | Material flow cost accounting |
| MKI | Milieu Kosten Indicator (environmental costs indicator) |
| PPO | Rijkswaterstaat department of programmes, small projects and maintenance |
| RWS | Rijkswaterstaat |
| V&R | Rijkswaterstaat programme Vervanging en Renovatie |

# 1 Introduction

Circular Economy (CE) has recently become a major topic regarding reducing environmental impact, especially in respect of the use of finite resources. Although there are several ideas and initiatives for a successful transition towards a CE, clear ways to fulfil these goals are currently lacking, in particular in the infrastructure domain. By developing a method for determining which of the many solutions is most circular, this PDEng report provides an assessment framework for stimulating circular solutions and making circular decisions on bridge and viaduct designs.

## 1.1 The project

This project is executed as part of a Professional Doctorate in Engineering programme (PDEng). A PDEng is a post-Master's programme in which an individual design-oriented project, aimed at solving a particular industrial or governmental problem, plays a central role. This design project is accompanied with both individual academic supervision and project-specific courses on a post-Master's level within the University of Twente. In addition, the project is commissioned and guided by the Dutch Rijkswaterstaat infrastructure agency.

### 1.1.1 Problem context

The increasingly scarce resources are either "captured" in assets or transformed into waste. In this respect, the Dutch construction sector was responsible for about 25 million tonnes of construction waste in 2012 (Schut, Crielaard, & Mesman, 2015). Moreover, nearly 50% of the material flows in the Netherlands are construction-oriented (Knopperts, 2018). Bridges and viaducts are an essential part of the transportation infrastructure system and when demolished, they end up as waste. Furthermore, while assets often meet the technical requirements, they may either be insufficient or superfluous from a functional perspective, resulting in demolition of technically valuable objects (Groeneweg, 2017). Moreover, a large share of the bridges and viaducts are expected to reach the end-of-life stage (EoL) between 2020 and 2040, which will expectedly be a very time-consuming exercise. Within Rijkswaterstaat, large-scale programmes were launched to cope with the challenges involved in asset renovations and renewals. Among the multiple initiatives, *Vervanging en Renovatie* (V&R) is the most notable example.

At the same time, the Dutch Government has set as a political goal to make the Netherlands circular in 2050. This requires a thorough change in current practices (Ministerie van Infrastructuur en Milieu & Ministerie van Economische zaken, 2016). Accordingly, Rijkswaterstaat formulated goals and ambitions for 2030 and 2050. The main circularity goals for 2030 are reducing material use and operating without waste. Although the concept of CE is firmly established, actual implementation remains difficult. Therefore, it is essential to structurally incorporate CE in the processes to meet the goals for 2030 and 2050.

### 1.1.2 Problem definition

Decisions have to be made before a bridge-related project can start irrespective of the type, size or surroundings. Circularity is just one of the many aspects in this decision-making process (Figure 1). Other aspects, such as investment costs, are currently outweighing circularity, largely because it is still unknown how to measure and value circularity. The leading aspects in a bridge replacement or renovation project are usually costs and related RAMS aspects (reliable, available, maintainable and safe). Increasingly, environmental impact plays a part in decision-making. Circularity, which aims foremost at resource efficiency, both exceeds and differs from the scope of the current ways to calculate environmental impact and related environmental costs, while measurements for these bridge-related circularity aspects do not yet exist.

The decisions regarding national bridges are made by Rijkswaterstaat and concern public funds. Therefore, financial consequences of decisions have to be demonstrated before budget is allocated to a specific project. Consequently, each criterion shown in Figure 1 has to be accounted for. However, circularity is currently not among the decision criteria in practice. On the one hand, there is ambiguity regarding the definition and scope of CE. On the other, clear ways of measuring the aspects of CE on an asset (micro) level are lacking. Only when circularity becomes a fundamental part of the project and asset considerations – and hence can be measured – the transition towards a CE within Rijkswaterstaat can be achieved. In the separate report *Barriers to diffusion of circularity regarding bridges and viaducts* (T. Coenen, 2018a), barriers were discussed regarding the CE transition in the bridge domain. Unsurprisingly, one of the barriers identified is a lack of structured methods for assessing circularity.

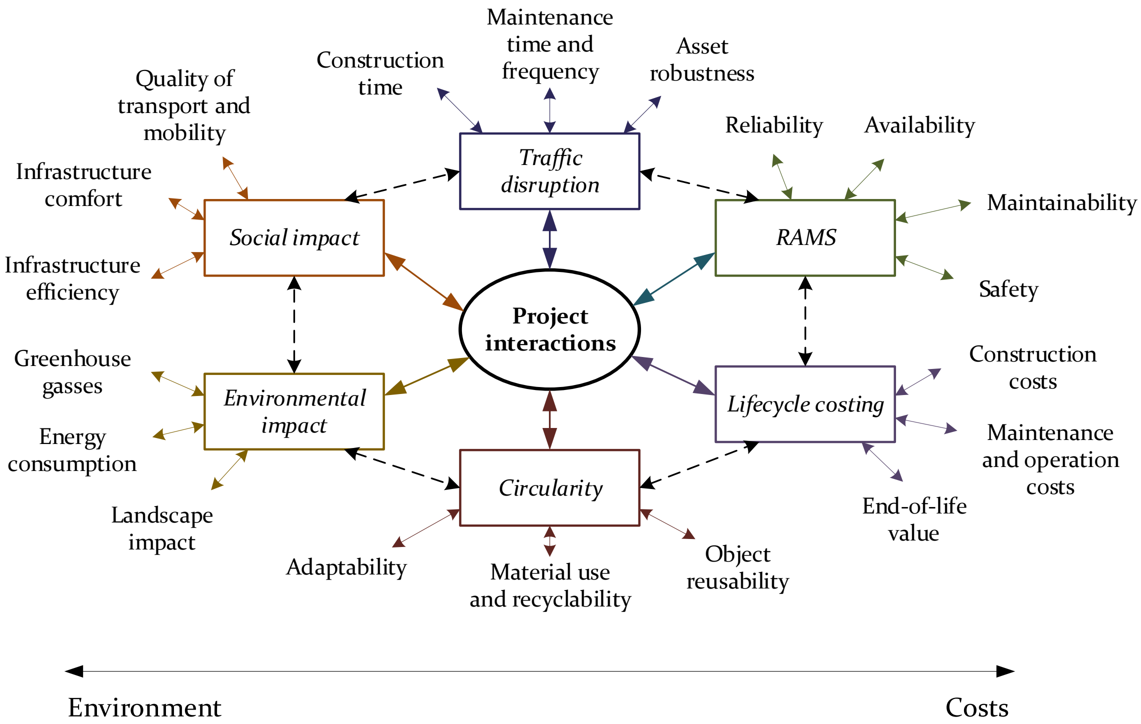



*Figure 1 – Main interactions in a regular bridge construction project*

### 1.1.3 Project goals

Circularity has to become an essential aspect of the decision-making processes concerning bridge design. Therefore, it should be clear what decisions or design choices are circular and what can be improved. In other words: What is circularity in relation to bridges and what aspects does it entail? For determining to what extent a design decision is circular, circularity must be measured. Consequently, the main goal of this project is to:

*Develop a framework to assess the level of circularity of bridge and viaduct designs within Rijkswaterstaat.*

The final deliverable of this project will be a circularity assessment framework, which includes a set of indicators with respect to bridges and viaducts. For making the framework applicable in practice, a tool is developed to determine the circularity scores for bridges. The circularity assessment framework will be developed using the Design Science Research (DSR) approach. The project will be executed using, scientific and practical literature, expert input, and case studies, both for data input and validation.

## 1.2 Deliverables and position of this document

The assessment framework is accompanied with several supporting documents. This report aims both to describe the design process and to provide background on the topics and domains addressed by the end-product. Moreover, it offers insights into the design choices made and the considerations of the end-product within the context. Although this document gives the most comprehensive account on the project, the contents are explained in greater detail in two other documents. Of course, these three documents act merely in support to the final deliverable: the spreadsheet tool *Bridge Circularity Indicator*. In Figure 2 the three following deliverables are described and related to each other:

1. Theoretical background: background on the concepts and theories used in this study
2. The indicators: Appendix with design choices and calculations steps per sub-indicator
3. Guideline: guideline on how to use and apply the assessment framework to cases

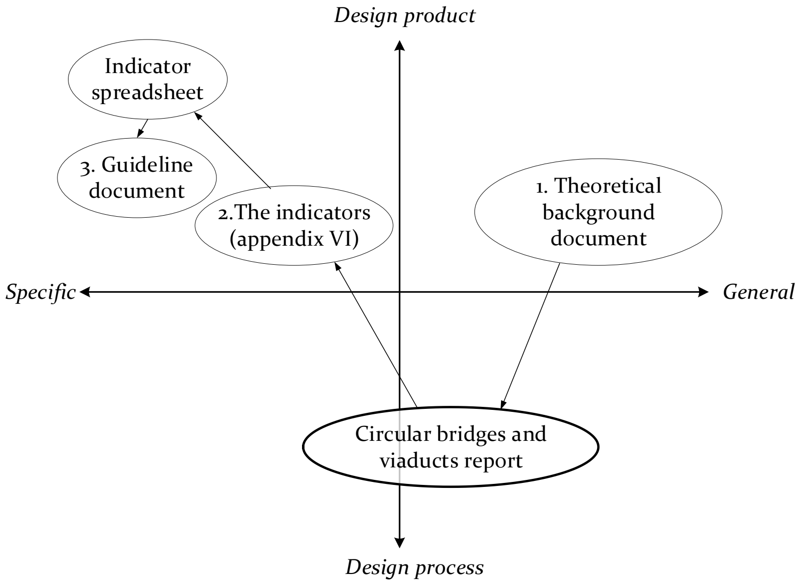



*Figure 2 – Place of the various documents relating to the project*

Further, two small side projects were executed parallel to this design project regarding circularity and bridges, which offered insights for this design project. These are:

- Barriers to diffusion of circularity regarding bridges and viaducts (T. Coenen, 2018a)
- Interfaces between the concept of circular economy and the domain of bridges (T. Coenen, 2018c)

## 1.3 Outline of the report

The outline of the report follows the structure of the methodology presented in Chapter 2, which also contains background on design science and the design steps. Chapter 3 offers insights into the theoretical background of the topics addressed in this study, including bridges and viaducts, the CE, and performance indicators. Moreover, this chapter addresses the gaps in literature addressed by this design project. In chapter 4, our approach to measuring bridge circularity is addressed. This design is in chapter 5 applied to three case studies, which offers ground for the validation of the framework in chapter 6 and subsequent design improvements. In chapter 7, the final version of the circularity assessment framework is discussed. Note that early design iterations used for the case studies are not presented as a chapter. Chapter 8 presents a discussion on implementation issues and further treatment, including maintenance and revision of the framework. Finally, in chapter 9 conclusions and future recommendations are presented.

# 2 Project methodology

The study will be executed in the shape of a design project following the DSR approach. This contains fixed steps for reaching a solution to a particular design problem in a structured way. The scope and methodology of the design project are explained below.

## 2.1 Project scope

The project considers bridge and viaduct assets with regard to circularity in the sustainability domain. Figure 3 shows that circular decisions require clear measurability which follows a concept definition which is a product of more abstract political goals. The relation to goals and ambitions, the domain considerations of this scope and the boundaries are discussed below.

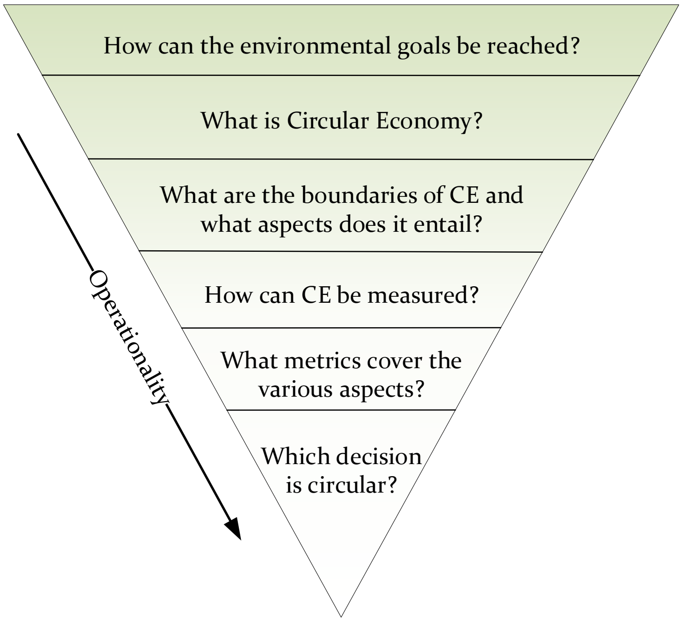



*Figure 3 – Scope of the project: from environmental goals to circular design decisions*

### 2.1.1 Relation to ambitions, goals and strategies within Rijkswaterstaat

The framework is developed according to the specific needs of Rijkswaterstaat. Therefore, it has to be clear how the framework fits within Rijkswaterstaat's current ambitions, goals and strategies. In the 2015 report on sustainability *Duurzaamheidsrapportage: Rijkswaterstaat en duurzaamheid* (Rijkswaterstaat, 2015), six focus areas were defined with regard to sustainability, being: (1) energy & climate; (2) Circular Economy; (3) sustainable area development; (4) health; (5) sustainable water management; and (6) sustainable accessibility. At the same time, a global coalition signed the Paris Agreement, including the Netherlands. The goals set in this agreement were translated by the government into national policy goals. Following these goals, Rijkswaterstaat formulated three spearheads for reaching the goals with respect to a sustainable living environment as shown in Figure 4.

Within these three spearheads, one of the pillars is CE, which, in this definition, deals with the use of (finite) materials. The policy goals towards a circular Rijkswaterstaat are: (1) a circular operation and a 50% reduction of using primary materials in 2030; and (2) a *wasteless* Rijkswaterstaat in 2050. In order to meet these ambitious goals, the *Impulse programme Circular Economy* was launched in 2016. By *learning by doing* and extensive annual evaluations, the progress and lessons learned are reported (Rijkswaterstaat, 2019b). Next to this programme, CB'23, exploratory studies and numerous pilot project have been launched. These initiatives cover largely the input need for the upper half of the reverse pyramid presented in Figure 3.

Milestones are set for 2030 – including: "Circular considerations are incorporated in the MIRT and V&R project stages and processes and CE is part of the service level agreement (SLA) directions for 2022-2025" (Rijkswaterstaat, 2019a) – which requires measurement. Also, to make circular decisions in a structural fashion, measuring circularity is essential. The framework developed in this project fills this gap with respect to bridges and viaducts (Figure 4). As such, it enables Rijkswaterstaat to make circular decisions regarding circularity in two ways. First, it guides designers in designing bridges in a circular way and identifying design flaws with regard to circularity. Second, it allows for assessing design alternatives and score on circularity. Especially regarding the latter, the relation with the existing environmental sustainability assessment tool DuboCalc should be closely managed. DuboCalc is not intended to measure some essential aspects regarding circularity, but offers instead a partial sustainability assessment (Figure 4). Hence, the framework is developed to offer a supplementary part to DuboCalc and may be used to score design according to their circularity performance for, when combined, a comprehensive assessment of the effects on the environmental impacts.

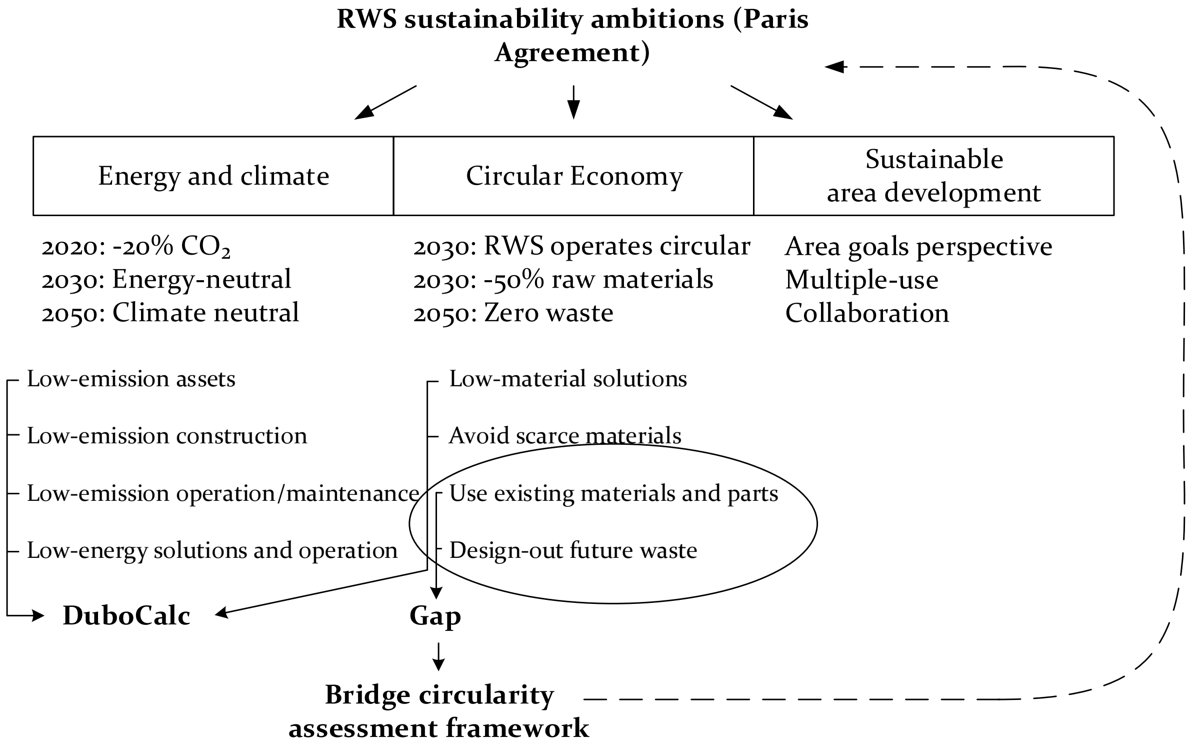



*Figure 4 – Relation of the framework to the political goals within Rijkswaterstaat*

### 2.1.2 Place within the domains

The framework considers the circularity of bridges. This indicates two domains: the infrastructure and environmental impact. Below, the position and scope of study within these domains is discussed.

#### *2.1.2.1 Infrastructure, bridges and viaducts*

In this project, we focus merely on bridges and viaducts as part of the public infrastructure sector. The assessment framework will be tailored to Rijkswaterstaat assets and practices. Consequently, the framework is firstly tailored to the specific project client and only later the generalizability to all fixed bridges and viaducts will be considered. Moreover, the possibility will be considered to generalize the used principles and calculation methods to other civil engineering structures.

#### *2.1.2.2 Environmental impact*
The need for reducing the environmental impact, often indicated as the sustainability paradigm, knows various directions. Our aim is not to measure the entire impact regarding bridges, but to deliver one of the significant pieces of the puzzle. The directions towards environmental sustainability are often divided into: (1) energy use; (2) air pollution; (3) water efficiency; and (4) material depletion. To a large degree, air pollution and clean water depend on polluting fossil energy use, while material depletion stands alone in this list. Surely, extraction and production of materials and products comes with energy use and polluting by-products. In this study, we only consider the fourth direction and, as such, only material flows are taken into consideration, since DuboCalc covers the former three (Figure 4). We regard each of the four directions equally important, but the other three directions are simply not covered by the scope of this project – even though the other directions are included in the concept of a CE in some literature.

### 2.1.3 Project boundaries
In line with the scope of this design project, the following boundaries and limitations are set:

- The project will limit itself to bridges and viaducts owned by Rijkswaterstaat.
- The project will focus on the bridge designs rather than existing bridges.
- Bridges and viaducts are considered at the object/asset level rather than project level.
- Circularity is only considered in terms of material and waste flows, since this is considered the most important to be assessed apart from the environmental impact already measured by DuboCalc. Unavoidable overlapping factors between DuboCalc and circularity will be made transparent to avoid double-counting. The term *Circularity* will be accordingly used following the *Bridge Circularity 2019* definition (section 3.2.11).

## 2.2 Design science and the design cycle
The project is executed following the DSR approach. According to Van Aken et al. (2016), "DSR is a domain-independent research strategy focused on developing knowledge on generic actions, processes and systems to address field problems or to exploit promising opportunities. It aims at improvements based on a thorough understanding of these problems or opportunities." DSR refers herein to an explicitly organized, rational, and wholly systematic approach to design. Rather than applying knowledge of products, design is considered as a scientific activity in itself (Cross, 2001). Below, the DSR methodology is explained in detail, including the approach in which it is tailored to the purpose of this project.

DSR employs an iterative process to develop a suitable design that can be used to solve a specific type of practical problem or challenge. The intended outcome of DSR consists of both a practically applicable end-product and the creation of scientific knowledge. Hevner (2007) stressed this duality of DSR outcomes by illustrating that the design cycle should seek both relevance in the application domain and rigor in the creation of theoretical knowledge. Figure 5 shows the place of design science within its context. It shows the interaction of a designed end-product (i.e. bridge circularity assessment framework) with the social context on one hand and the knowledge context (CE and bridges) on the other. It explains the clear link between the development of a design and the development of knowledge; something that is inextricably linked in this project. Moreover, measuring something requires understanding of the matter. Development of this circularity assessment framework will hence inherently contribute to the understanding of the circularity concept.

Approaching the project from the DSR perspective, a fixed, but iterative, succession of steps will be followed for developing the circularity assessment framework. This is done by following the design cycle theory (Wieringa, 2014). In the basis, this cycle runs from problem investigation to real-world implementation (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007; Wieringa, 2014). The design process involves three major steps: (1) real-world problem investigation; (2) design of the framework; and (3) real-world implementation. The actual project problem and goal are discussed in greater depth below.

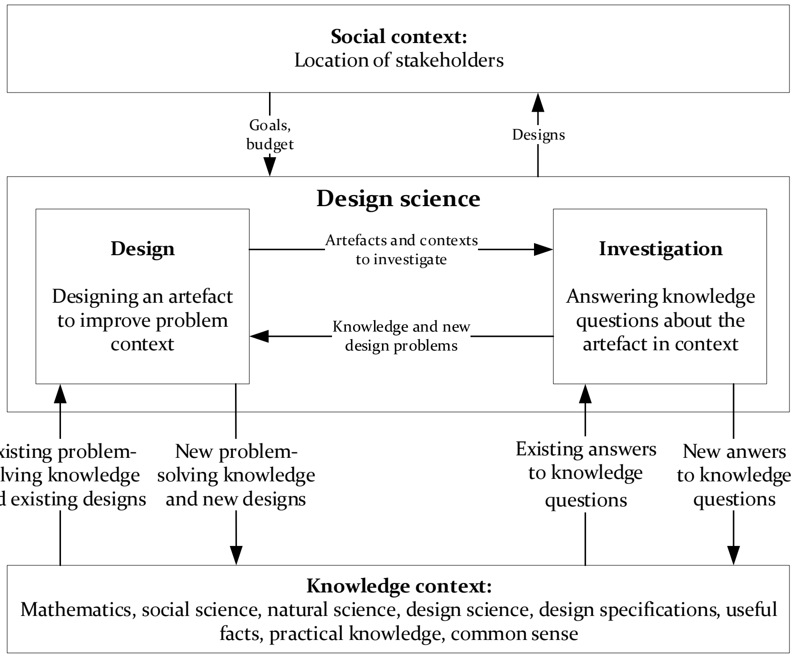



*Figure 5 – Design science framework (source: Wieringa, 2014)*

### 2.2.1 Design problems in the project context

The first step in the design cycle is to clearly define the problem for which the design should offer a solution. Guided by the seven questions proposed by Wieringa (2014), the design problems in their context and the transformation into design goals identified are as follows.

Within this context, a bridge circularity assessment framework will be developed, which includes of a set of performance indicators and guidelines on how to use, apply and interpret the indicators. This will be done based on literature, Rijkswaterstaat documents, case studies and expert consultation sessions. The framework interacts on the one hand with other assessment tools regarding, for example, lifecycle costs and environmental costs and on the other, it is shaped by input data from real-world projects. Therefore, it will affect designs and asset management decisions. These interactions should both aid decision makers in *circularizing* bridges and prove to designers that their solutions are more circular than others (i.e. both in guidance and assessment). The goals herein are similar to the current goals within Rijkswaterstaat, namely making *good* decisions and offering the best alternatives by market parties and their designers. The following requirements are extracted from Coenen (2018b).

F*irst*, the framework should cover all aspects of a CE that are not covered by DuboCalc. *Second*, it should express the circularity of the bridge as complete as possible. *Third*, the framework should be applicable and easily usable in practice and *fourth*, it should effectively supplement existing assessment methods and frameworks within Rijkswaterstaat. It is important to note that regarding models, there is always an inevitable trade-off between complexity and accuracy: user-friendliness requires low complexity, which reduces model accuracy. Domain boundaries and scope are explained in section 2.1. Indicator-related requirements are discussed in section 3.3.

### 2.2.2 Knowledge questions
For developing the assessment framework, specific knowledge is collected using knowledge questions. Depending on the question, these are answered in four different ways, being through: (1) scientific literature; (2) internal Rijkswaterstaat documentation; (3) expert interviews and sessions; and (4) case studies. The knowledge questions follow the main design question, which is: *How can the level of circularity of bridges and viaducts, and their components be measured in such a way that it can be used in the decision-making process?* The knowledge questions below help to address the main design question.

1. What does CE and circularity mean and which aspects do they entail?
2. What is circularity with respect to bridges and viaducts?
3. What part of circularity regarding bridges and viaducts can be measured or determined and how is this currently measured in literature?
4. Which input data is required for measuring the circularity of a bridge or viaduct?
5. How can this data be used to make decisions on circularity?
6. What aspects indicate the level of circularity in bridges, how can performance indicators be defined and how do they fill the gaps in literature?

## 2.3 Design methodology
In the previous section, a conceptual framework (DSR) was defined for executing the design project within its context. The concrete design steps in this project are discussed in this section.

### 2.3.1 Design steps
The design cycle method is introduced to design the assessment framework (Figure 6). The cyclical process of is shown in the *Design cycle* box in Figure 6. The design results are all based on the final iteration, but the preliminary iterations are shown in appendix III.

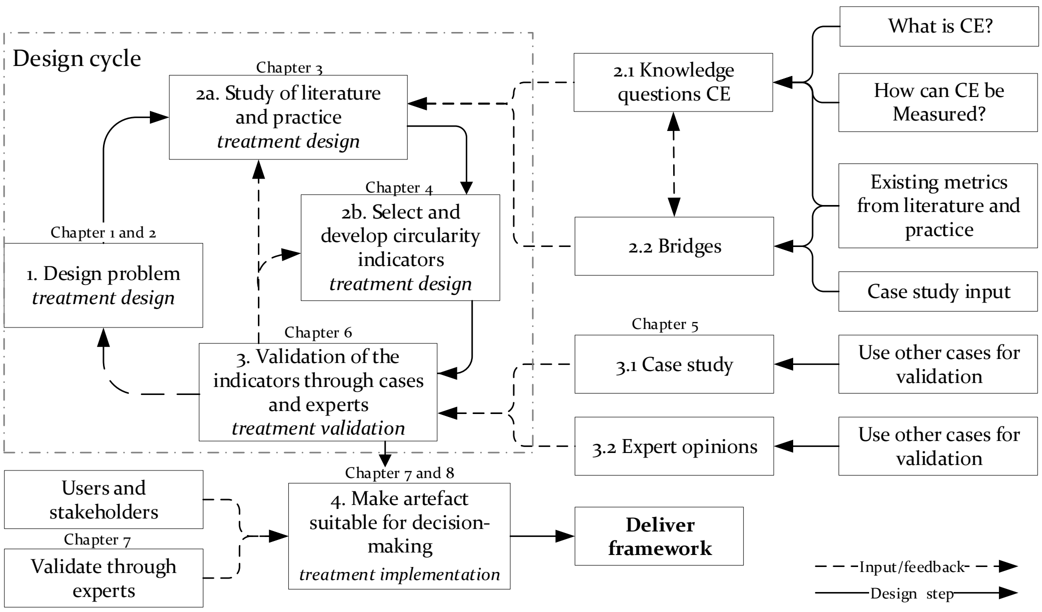



*Figure 6 – Design methodology bridge circularity assessment framework*

The various ways of measuring bridge circularity and current gaps are both studied. The set of indicators should both fill the gaps and fit within existing indicators used by Rijkswaterstaat. This is done by analysing literature and using actual bridge elements from cases selected within Rijkswaterstaat. This step also includes the case study input. Next, the set of indicators is validated through expert and stakeholder interviews and applied to other cases in practice.

This validation will provide new input for step 1 and 2. This cyclical process is conceptualized by the *Vee model* in systems engineering (Figure 7). Each iteration adds detail to the design, until it is fine-tuned up to the smallest detail for each sub-indicator. When a full set of sub-indicators is developed, they are weighted and shaped into a usable circularity assessment framework which is suitable for decision-making support. This usability is guaranteed by offering a user interface by means of a spreadsheet. Concurrently, in the validation stages, each (sub-)indicator is validated and integrated into the composite indicator, until the assessment framework is made fully operational on a systems level. The *Vee model* approach is particularly applicable to this design, since the circularity assessment framework has a composite structure.

Depending on the use, the outcomes are aggregated. If the indicator is used to support designers in making circular design choices, full transparency in the results is required. Yet, when it is used to assess design alternatives, aggregation allows for comparison of the overall circularity. The aggregation of these indicators into a composite indicator is conducted by following the *Handbook on Constructing Composite Indicators* (OECD, 2008). This widely-adopted handbook provides a ten-step guideline from data collection to communication of the composite indicator. This methodology is used as a narrative to aggregate the various sub-indicators discussed in chapter 4. Thereafter, validation and iterations are being executed through expert interviews and framework application to various case studies. Finally, the final framework is validated by means of the triangulation approach and, if valid, delivered and communicated to the client.

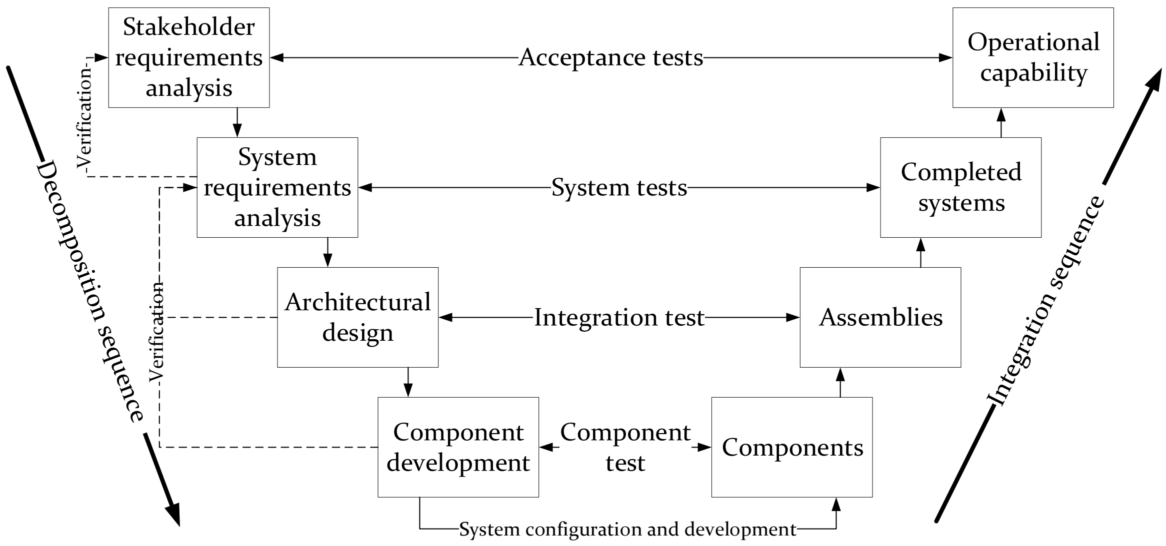



*Figure 7 – Vee model System Engineering (Source: Blanchard & Fabrycky, 2014)*

### 2.3.2 Design verification

As discussed above, the design process is both concurrent and cyclical. Moreover, the design problem in this PDEng project can be categorized as a *wicked problem*, which means that, as a result of complexity, the design will not solve the entire CE matter, but merely contributes to making steps forward (Figure 4). As a result, it is impossible to exactly know when the end-product is finished and hence when the design cycle has been completed. Therefore, design criteria must be formulated to indicate when the project goal has been met. The nature of the model prevents us from developing strict SMART criteria, but qualitative criteria contribute to controlling the design process. The first set of criteria is formulated as part of the PDEng programme. Further, a second set of project-specific criteria is formulated to measure the design product successfulness in a qualitative fashion. These criteria are reflected upon in section 6.3.

#### 2.3.2.1 PDEng criteria

The PDEng programme is guided by and assessed on a specific set of criteria, which are specific to the nature of a design project. Apart from the fulfilment of a pre-determined part of process- and content-related courses, two sets of criteria are formulated in the *Study Guide – PDEng programme in Civil Engineering*: one regarding the design product and another considering the design process. Not only are these criteria used to assess the project, they are also used during the design process to guide to validate the product and guide the process. Moreover, the criteria are used as an integral part of the project methodology. The criteria are the following:

***Design process assessment criteria:***

1. <u>Organization and planning,</u> indicated by project planning, compliance to the plan and conducting meetings.
2. <u>Problem analysis and solution,</u> indicated by analysis, understanding of impact, creativity and genericity.
3. <u>Communication and social skills,</u> indicated by oral and written reporting, knowledge management, stakeholder motivation and working atmosphere.
4. <u>Structure and attitude,</u> indicated by structure and constancy, self-reflection and critical attitude, and independency.

***PDEng product and project assessment criteria:***

1. <u>Functionality</u>, including product satisfaction, ease-of-use and reusability.
2. <u>Construction</u>, indicated by product structure, originality and convincingness.
3. <u>Feasibility</u>, (or realizability) including technical and financial feasibility.
4. <u>Impact</u>, including societal impact and product risks.
5. <u>Presentation</u>, indicated by completeness and correctness of the product and supporting documents.

#### 2.3.2.2 Project-specific product criteria

To each Civil Engineering PDEng project, the abovementioned criteria apply in both guidance and assessment. However, the circularity assessment framework – i.e. the envisioned end-product in this study – has a particular nature that requires additional criteria. As mentioned before, only few criteria are measurable due to the nature of the end-product, but qualitative criteria are used to monitor the qualities of the framework. If, during the design process, one of these criteria do not apply to the product, another design iteration is required.

***Specific product assessment criteria:***

1. <u>Completeness:</u> indicated by construct validity regarding CE.
2. <u>Compliance</u>: including suitability and appropriateness of the framework within current practices and systems within Rijkswaterstaat.
3. <u>Awareness</u>: including to what extent the framework is known within Rijkswaterstaat and to what extent the tools aids in conceptualizing the CE for employees of Rijkswaterstaat.

### 2.3.3 Design validation

It should also be assessed whether the framework is able to perform to the extent it is intended to perform: internal validity. To validate the assessment framework, in three ways is tested whether the design does what it should do, following the triangulation principle. This use of three perspectives to test validity ensures a encompassing validity (Leedy & Ormrod, 2014). Furthermore, the concurrent validity is tested for checking the appropriateness of use as part of the processes within Rijkswaterstaat and the relation with other assessment methods.

#### 2.3.3.1 Triangulation for testing content validity

Whether the assessment framework does what it should do is tested in three different ways. A positive result in the three tests provides input for design improvement and eventually checks the workings of the assessment framework. The following three methods are applied:

- Two theoretical approaches to circularity are used to check whether the indicator covers all relevant aspects, one considering the "9Rs" and the other reasoning from bridge and viaduct lifecycles (section 3.2.10).
- The assessment framework is commented by means of sessions, a conference and interviews by a diverse group of scholars and Rijkswaterstaat's experts regarding bridges, circularity, research design methods and other adjacent domains.
- The framework is applied to case studies to check whether the data is appropriate and whether the output of the framework offers insights regarding circularity. Also, by letting others execute assessments of additional cases, the tool usability is validated.

#### 2.3.3.2 Concurrent validity

To test the concurrent validity of the assessment framework in relation to CE principles, the results of framework application are compared with other cases of circularity assessment executed or commissioned by Rijkswaterstaat. These will be selected to find the appropriateness of the design and fitness to the political goals within Rijkswaterstaat in respect to CE presented in Figure 4. There are several bridges and viaducts within Rijkswaterstaat that are assessed on circularity from a broader view through other methods and studies. By using these cases to test the indicator overlap in results would test the concurrent validity of the indicator. Moreover, discrepancies would indicate either the need for further research and design improvements of this model or inadequacies in the other methods used.

# 3 Theoretical framework

A subject can only be measured if it is clearly defined and framed, as shown in Figure 3. Therefore, the definitions and boundaries of the various concepts used regarding bridge circularity are discussed in this chapter. First, the domain of bridges and viaducts is explained to clarify in what perspective CE is considered. Second, a brief literature review is presented on the definition and boundaries of CE, measuring circularity and *Bridge Circularity 2019* (section 3.2.11). For a more elaborate review of CE, performance measurement and bridge practices, a separate document *Theoretical background on circular design of bridges and viaducts* is written, which is used as a referencing work. This gives the basis for the third and final section considering indicators, metrics and assessment methods related to circular bridges.

## 3.1 Bridges in a project lifecycle perspective

Sets of performance indicators regarding bridges play both a vertical and a horizontal role: one regarding the course of the asset lifecycle decision-making process throughout time and another for each individual decision moment. Accordingly, the decision-making moments before, during and after a bridge lifespan are taken as a basis for determining the set of performance indicators. This will also reveal spots where circularity indicators can contribute to circular decision-making. This will provide a basis for the processes and definitions used in the case studies.

### 3.1.1 Bridge and viaduct assets

Bridges and viaducts are the group of assets that physically carry a road over another area, mostly roads, railways or waterways. Although these assets easily spark one's imagination, some classifications require additional attention.

#### *3.1.1.1 General classification*

A general classification within Rijkswaterstaat is made in the *Object Type Library* (OTL) regarding bridging. These are: (1) bridge; (2) bridge span; (2.1) land bridge span (2.2); movable bridge span; (2.3) fixed bridge span; (3) ecoduct; (3.1) tree bridge; (4) aqueduct; (5) viaduct; (5.1) fly-over. However, this classification does not tell us anything about the physical or technical characteristics of the bridge, but only about the function. Therefore, some additional classifications and clarifications are needed.

#### *3.1.1.2 Bridges versus viaducts*

Although different contexts result in different definitions, clear boundaries are set in this study; it only considers the Dutch situation. Herein, the definitions between a bridge and a viaduct differ on the basis of the type of area they cross. Although some definitions include particular span lengths, in this study, a bridge crosses waterways and a viaduct crosses traffic, rail or land. This difference in crossing results in a difference in span, since it is often unwanted to place support in water – generally speaking – resulting in bridges spanning a longer distance than viaducts. The span largely determines the suitable construction techniques and applied construction materials.

#### *3.1.1.3 Steel versus concrete*

Another major difference is related to the main construction material. Within Rijkswaterstaat, a clear distinction is made between steel and concrete superstructures. These two materials are by far the most important materials for bridges and viaducts. Both materials have their particular characteristics and failure modes. Furthermore, in relation to CE, those materials find completely different next-lifespan applications. For short spans, cheaper concrete is often preferred over expensive steel, while the tensile and sheer force qualities of steel make the material outstanding for long spans and slim designs. On the other hand, well-maintained steel structures are easily disassembled for reuse, while fatigue is often a reason that renders this fate impossible. Concrete is heavier, but requires less maintenance and – with proper maintenance – degrades very slowly. Recently, other materials have been tested and introduced in bridges and viaducts, such as bio-based composites, but in comparison to steel and concrete these materials are still unorthodox.

### 3.1.2 Lifecycle processes

In the light of circularity, and as such the multi-lifecycle approach, it is essential to distinguish different construction processes during the stages of the asset lifecycle. There are several ways of contracting and procuring, but the following description is based on a regular Design & Construct (DC) project. For a new bridge or viaduct, the lifecycle from a Rijkswaterstaat perspective is usually the following:

1. In a case of a complete new infrastructure plan, the first step is the pre-project phase in which the Minister decides on a new connection between two locations, often as part of a route decision (tracébesluit). The route decision will be captured in one or more projects in which Rijkswaterstaat gets the executional lead. The new bridge or viaduct is consequently part of, or entails, a new construction project.
2. Next, the project planning and design phase will start. Rijkswaterstaat formulates goals and requirements for the new bridge or viaduct. This goes hand in hand with the feasibility study in which a project brief is developed. The requirements are formulated regarding all kinds of aspects: from safety, to aesthetics, and from environmental impact, to traffic obstruction. Also, a preliminary design is often made by Rijkswaterstaat to make a cost estimation and to develop a point of reference.
3. Thereafter, the procurement phase starts in a tender process to execute the construction project. Based on several selection criteria fitting the requirements (e.g. environmental impact or circularity), the *best* bid is selected for execution of the design and construction activities. In most cases, this is done within one contract and sometimes even financing and maintaining the asset is included (in a DBFM contract).
4. Based on the set of requirements and the contractor's preliminary design, different design stages are executed in order to come to a final design. This design is often made in cooperation between (several) consultancy and architectural firms and the contractor. All parties involved must comply with the agreements and requirements set in the contract.
5. Thereafter, the actual construction phase takes off. The main contractor looks for subcontractors and suppliers to execute the different parts of the construction process, although this can also be done in earlier stages. One subcontractor may, for example, take care of the excavation, while another supplier delivers the pre-stressed girders. Rijkswaterstaat's role consists in this executional phase mainly of checking whether the contractor is working in accordance with the contract and agreements, and fulfils in particular cases more extensive roles regarding project management.
6. When the completed work is delivered, the service life of the bridge starts. In most cases, the asset is owned by one of the regional departments of Rijkswaterstaat, which is also responsible for monitoring the structural safety and maintenance. Often, care of the monitoring and maintaining practices are also contracted. When the structural safety or a contextual factor indicates that the functionality is in jeopardy, a decision must be made regarding the follow-up steps. These can vary from preventive maintenance, such as painting, to renovation or replacement of the entire structure. Regarding larger interventions, new projects with new procurement procedures and contracts follow.

7. The previous step is repeated until a given factor leads the regional department of Rijkswaterstaat to decide on EoL steps, including renovation, replacement or removal. This is also the place where an asset is eligible to the V&R programme (section 3.1.3). In practice, maintenance becomes increasingly expensive for older structures, up to the point lifetime extension is no longer considered beneficial. In many cases, a new demolition project is issued in which often only the current structure is removed. The materials released from the demolished structure revert generally to the demolition contractor, who has often no direct stake in reuse or recycling of materials or components.
8. New lifecycle. In many cases the route is still in place, which urges for a new asset, meeting new functional requirements. This means that the entire process starts over again, while skipping step 1, depending on the infrastructure plan.

The process described above is strongly simplified and varies in reality per project. The decision moments for Rijkswaterstaat take largely place in step 2 (design and issuing of the project) and step 6 (asset management). Also, step 7 largely affects the material flow of the structure, while the most effective CE choices are made in step 2. Moreover, the extent to which CE can be applied depends on the stage in which the decisions are made: the earlier the decision the larger the opportunities for circularity. Circularity as a *most economically advantageous tender* (EMVI) criterion plays a role in steps 3 and 4 after the decision to do so has been made in step 2.

### 3.1.3 *Programme: Vervanging en Renovatie*

The steps in a replacement or renovation project are different from those of a construction project of a new bridge, since it concerns a transition between two bridge lifecycles. It is only eligible for V&R after it has been constructed and delivered. According to Klatter, Roebers, Van der Hark and Brandsen (2016), an EoL asset is eligible for three types of intervention (Figure 8). After step 6 in the process described above has been reached, the procurement phase can start.

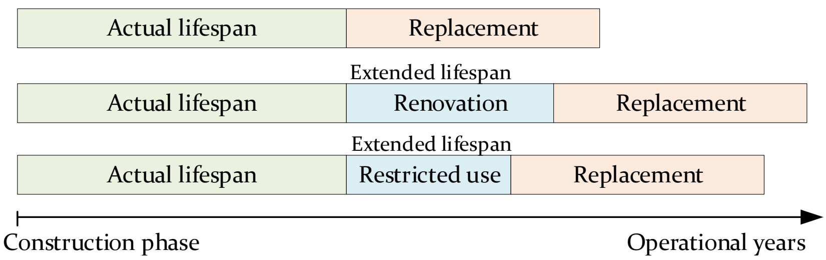



*Figure 8 – Basic choices of EoL intervention within V&R (source: Rijkswaterstaat, 2016)*

To determine in what moment a project can be influenced with regard to CE, the decision moments need to be revealed. Since the moments and corresponding decisions vary per project, the V&R decision moments are studied. These processes concern a vast majority of the existing bridges and viaducts. The V&R procedure consists of an exploration phase, planning phase and execution phase. New bridges, however, have a much more varying route of decision-making. Within V&R, there is a systematic road of decision-making, although not all steps are thoroughly considered in practice and the procedure does not always follow the indicated way. However, this decision-making process provides clarity on the instances where circularity can be affected.

Generally speaking, the steps from initiative to project execution run as described next (Figure 9). First, a district of a regional department requests an asset to be included in the V&R process of the department of large projects (GPO). It develops a problem definition and receives counsel from the national GPO, department of small projects and maintenance (PPO) or the information department (CIV). These latter departments manage the V&R programme and consider the multi-annual budget. Up to this step, content-related decisions and priorities were not made. Thereafter, within step 3, the boundaries and counsel from the national departments are considered and the regional department determines the scope of the intervention. Although the regional departments make the decision, the input from the national departments plays an important role. When the scope is set, the actual project and its place within V&R can be set following step 4.

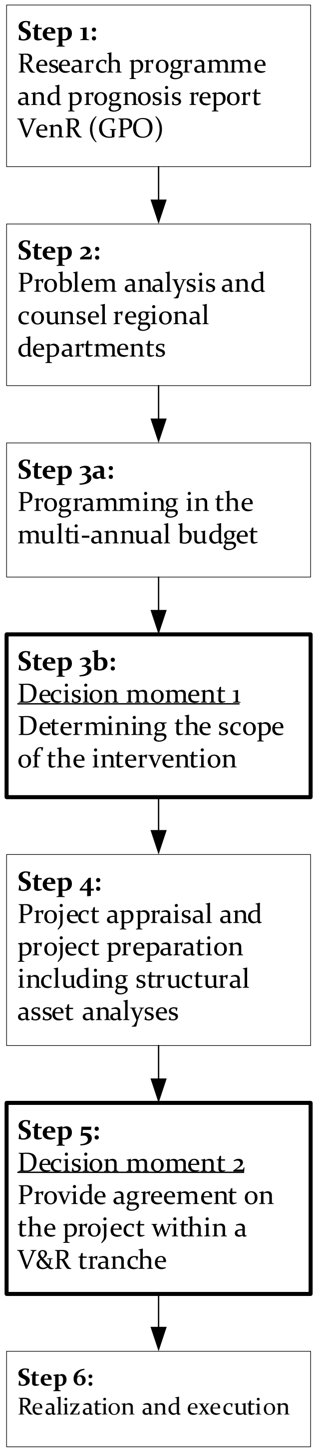



*Figure 9 – Decision-making path in V&R*

Firstly, it is examined whether the project or parts of it can be coupled or clustered with other projects. After this has been determined, the capacity demands are submitted and an *Integral Project Management* (IPM) team is assembled. This IPM team develops together with experts an action plan including the investigation plan and procurement strategy. Formally, this plan is assessed by a group of experts, but this step is often skipped, which can result in mistakes in later phases. Once each party involved has agreed on the action plan, a time schedule, communication plan, risk management plan, inspections and client requirements are developed. This is followed by several assessments, counselling sessions and process evaluations. This forms the basis of the actual scope of execution and shape of the intervention.

In the final step, the project assignment document (POF) is formulated and the capacity and roles are filled, including environmental manager, project manager and asset manager. After the final IPM team has been determined, the final POF is drawn and the project is executed as a regular project within its tranche, following the predetermined scope and shape of the intervention. This includes the priorities and type of intervention, which strongly narrows down the opportunities for CE.

### 3.1.4 Current bridges, their condition and prognosis

The bridges and viaducts discussed above are scattered throughout the country in varying amounts, conditions and technical specifications. One of the main challenges in CE is to connect lifecycles in order to facilitate reuse. Therefore, we need to reveal what and how many bridges are expected to be revised or replaced on the one hand, and how many are required on the other. This is integrally reviewed in the V&R process. Rijkswaterstaat has presented a study in the *Prognoserapport 2019: Vervanging en Renovatie*, in which – based on quantitative research on inspection reports, expected and planned projects and programmes, and statistical analysis – is estimated what projects can be expected, ultimately in order to allocate long-term budgets (Klatter, Roebers, Slager, & Hooimeijer, 2019). This information, however, is also important in the light of circularity, since this provides clarity on the necessity of reusable and adaptable design measures, as well as the shares of technical and functional demolition.

The prognosis report shows that a vast majority of these bridges and viaducts was built between 1960 and 1980. It also reveals that within the coming 20 years, roughly 140 concrete bridges are expected to be in need for renovation and approximately 40 for replacement, while for steel bridges, this amount is predicted to be considerably lower. Regarding fixed water-crossing bridges, the average lifespan is 92 years, while for viaducts this lifespan amounts 81 years. However, the designed technical norms prescribe design parameters for 100 years. Furthermore, an internal Rijkswaterstaat memo shows that of all 271 removed concrete bridges, 215 are demolished due to functional reasons rather than technical ones and when only demolitions prompted by technical reasons are considered, the average lifespan reaches 101 years. Another finding was that the average lifespan in the Randstad, which is considered a highly dynamic and urban area, is slightly lower, albeit less than 3 years. Furthermore, bridges that are part of large intersections have a lifespan of approximately 10 years lower than stand-alone structures, which indicates the extra need for adaptability and reusability in these situations. Given these numbers, both the average lifespan, which is considerably lower than the technical lifespan, and the prognoses for replacement and in particular revision provides opportunities for large-scale reuse, which indicates value for adaptable and reusable design.

#### 3.1.5 The assessment framework within the construction processes

The assessment framework developed in this study can be deployed in two stages of the lifecycle processes (section 3.1.2), being in supporting the client to develop a circular reference design in step 2, or in selecting the contractor in step 3. This takes place during the second decision moment in step 5 and 6 (section 3.1.3) in the V&R decision-making path. This indicates both the limited scope of the assessment framework and the place within the V&R processes.

### 3.2 The Circular Economy

In this section, the CE concept is explored in order to provide clear boundaries in relation to this study. This forms the basis for the design activities with regard to the framework and its resulting tools. Moreover, the link between CE, construction and bridges is addressed in this section, combining the input of both the CE conceptualization and bridge and viaduct practices.

#### 3.2.1 Why a circular economy?

The current economic system thrives on production and sales of goods and services: buying products leads to an increased demand, which stimulates production, which creates jobs and businesses. This induces creation of value (and hence money), which increases capacity to buy. In theory, this cycle is endless, leading to a never-ending growth and increase of wealth, were it not that mineral resources are exhaustible and some are, according to various studies, even running out within the coming few decades (Henckens, 2016; Vieira, Ponsioen, Goedkoop, & Huijbregts, 2017). At the same time, the world's population is expected to continue to grow and the growth of the middle class people is exponentially (Statista, 2016), while humanity is gradually running out of minable materials (Allwood, Ashby, Gutowski, & Worrell, 2011). On top of this, the pollution of the air, oceans and land has never been as high as it is now (UNEP, 2018).

These two trends promise a worrisome increase in both scarcity of resources and pollution of the planet and hence urge for a new approach that promotes consistent and equal wealth (Henckens, 2016). A solution is sought in bending this linear economic approach (from raw materials extraction to landfill) into a looped one: the CE. This approach aims both at ecological impact reduction and sustainable economic welfare. In this report, value is considered to be the economic worth of a resource. Next to the worth of the mere materials, the value of an object consists of the labour put into the manufacturing and maintaining processes that make an entity fulfil its function. Eventually, the value depends on what something is worth to people. As a result, the value of a component, material or asset is after its EoL not zero, as it is presumed to be the case with waste. Instead, it retains a certain value, since it can always fulfil a certain function, regardless of how high (or low) this function might be.

This new approach contradicts the current finance and accounting methods. In CE, the value depends on the product or asset state and might be (almost) equal to is acquisition worth, depending on several aspects, such as, construction quality, maintenance quality, disassemblability, transportability, toxic material contamination, material scarcity, etcetera. By thoughtful design, this EoL value can be increased by increasing the EoL potential of entities or its parts with lower use of virgin materials and less creation of waste. As a result, rethinking a certain process will result in considerable value creation and value retention. Next to these intrinsic motivations for circularization, political goals (section 2.1.1), largely following the *Paris Agreement*, demand Dutch public organizations to take action to make practices more circular.

### 3.2.2 The Circular Economy concept

The CE concept as we know it today was introduced in 2012 by the Ellen MacArthur Foundation (2013), but the idea elaborates on earlier sustainability initiatives such as, among others, sustainable development, cradle-to-cradle (C2C), Sharing Economy and Green Economy (Braungart & McDonough, 2002; Jacobs, 1992; Pauli, 2015; World Commission on Environment and Development, 1987). Eventually, these initiatives result from the analogy that considers the earth as a floating, closed-loop spaceship (Boulding, 1966). Contrasting the mere sustainability concept, CE involves broader EoL considerations, such as lifespan extension, revised business models and revolutions in data management (Guldager Jensen & Sommer, 2016), all, eventually, in order to *close the loop*. The definition of a CE issued by both practitioners and academics vary considerably across literature. Yet, all consider the resource outputs from products and processes to be input for new products and processes (Kirchherr, Reike, & Hekkert, 2017). Nevertheless, the extensiveness varies from mere recycling to a systemic revolution. An extensive review of the concept and its definitions is provided in the separate document *Theoretical background – Circularity assessment of bridges and viaducts* (Coenen, 2019).

An essential note is that CE is a *way of thinking* rather than a clear-cut definition. Consequently, it aims at acting according to certain principles or towards certain goals rather than fulfilling strict requirements. This is one of the reasons that complicates the development of indicators and prevents us from using the waste hierarchy as a measuring framework. Below, we aim to sketch the principles rather than setting strict criteria. As means for operationalization, we use the waste hierarchy framework. The consideration of the waste hierarchy, captured by the "Rs" principle, as proposed in a lot of scientific literature, is considered to be essential for a meaningful definition (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). This hierarchy was extended and elaborated by the Dutch government agency PBL into the "9R" waste hierarchy. It is based on the *Lansink's Ladder*, introduced in 1979, which is the first form of a waste hierarchy. Furthermore, its applicability as an operationalization of circularity has been largely acknowledged (Lansink, 2017; Potting, Hekkert, Worrell, & Hanemaaijer, 2017).

The CE concept fits the criteria of an *umbrella concept* (Blomsma & Brennan, 2017). As such, it can be considered as a paradigm which involves the entire societal system. *Circularity*, on the other hand, merely connotes that something follows certain rules or principles that fit the CE paradigm. In that sense, circularity is both more limited and more specific than the CE concept, but, as a result, more suitable for measuring. Hence, in this study, we do not measure how the bridge contributes to the CE, but merely how well it follows certain principles that fit the CE concept – and thus circularity. A separate definition is provided in section 3.2.11.

### 3.2.3 Conceptual limitations

The CE is not a single solution to all problems related to resource depletion. Six limitations to the concept have been identified by Korhonen et al., (2018), considering both economic and social aspects. The *first* group consists of thermodynamic limits, describing the exchange value between physical flows of matter and energy, and abstract monetary flows. It explains that a cyclical flow does not necessarily secure a sustainable project outcome (Potting et al., 2017). The *second* group inheres spatial and temporal system boundaries, which addresses the fact that the impact of a single product or project should be viewed as a part of the whole world, which urges adequate considerations regarding for example the human-mobilized material flows. Long lifespans may, for example, result in lower sustainability on the long term because of unknown negative impacts in the future, which is particularly relevant to civil engineering structures.

*Thirdly,* a group of physical economic growth limitations is suggested. This includes the question whether profits from CE can be ensured to be directed towards sustainable consumption instead of enlarging the world's consumption and increasing sustainability problems in that light (also known as the *rebound effect*). *Fourthly*, path dependencies and lock-in mechanisms are identified as a group which entails *survival of the first* instead of the *survival of the fittest*. This may result in easy or profiting recycling innovations prevailing the more complex and integral CE-type innovations. *Fifth*ly, CE products go through various levels of administration, which requires several layers of networking. This results in complexities related to responsibility, risk, financing and control. *Sixthly*, the definition itself brings along limitations. Culture, history and community decide on what is good and bad. This includes definitions of waste and economic value – especially introducing the terms of reuse, remanufacturing and refurbishment – resulting in dynamics in and evolution of understanding. This is accounted for in section 3.2.11. Other than being boundaries, these are considered to be areas of concern while developing the model.

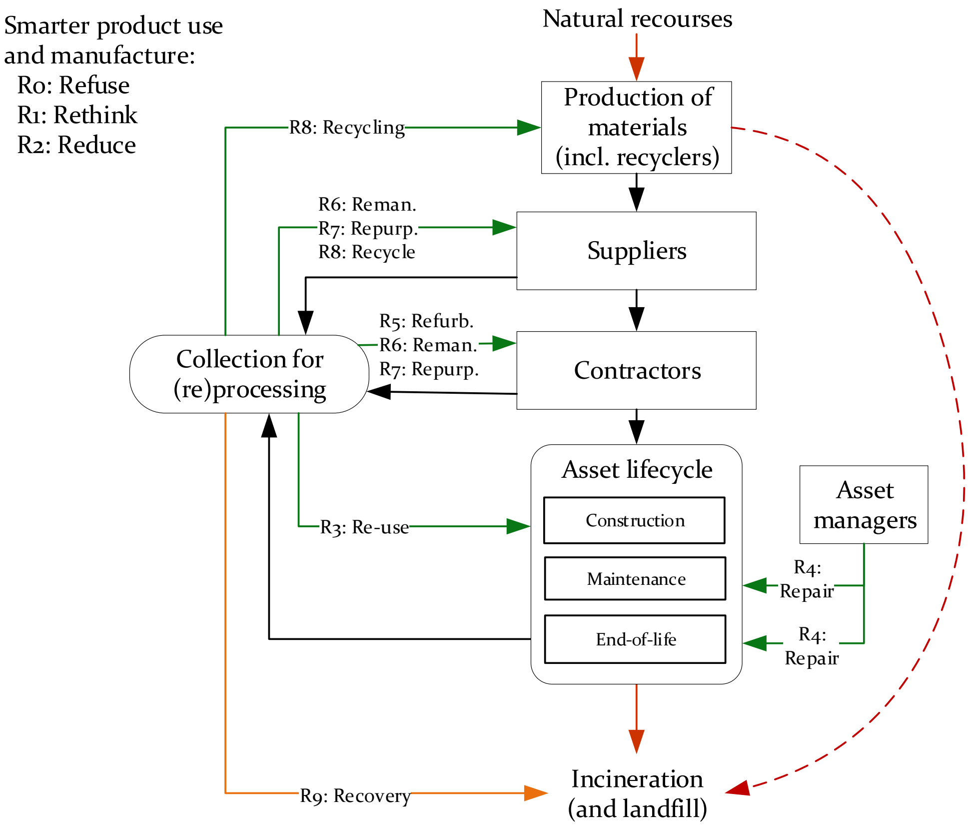



*Figure 10 – Various "R" strategies within the product chain (source: Potting et al., 2017)*

### 3.2.4 The supply chain

The way these "Rs" fit into the construction supply chain is demonstrated in Figure 10. The model makes clear that R0-R3 encompass the whole system, while R8 and R9 affect the outer stages, i.e. material input and incineration. Within the system, extension of the life spans affects the industry. This reveals the opportunities for circularity within the product chain of bridges and viaducts. The model is based on a typical configuration of a traditional supply chain as discussed by Vrijhoef and Koskela (2000). This figure shows the various actors within a construction supply chain, which immediately points out essential differences with the manufacturing industry. Furthermore, integral implementation of CE requires supply chain integration and close cooperation, which will result in horizontal compression of the model as presented below.

The construction supply chain is considerably more linear than the manufacturing industry, since the sector is both demand-oriented and tailored to one-of-a-kind projects. This project-structure results in linear material flows. Figure 10 presents the opportunities for circularity strategies in bridges and viaducts. The opportunities lay most notably between contractors, consisting of main contractor and sub-contractors, and the client who owns the project. Moreover, suppliers can use the higher tiers of the R-model. Ultimately, the arrow between "client/project" and "incineration (and landfill)" is shortened, which is equal to a waste reduction. The lack in circularity appears from the material inputs and waste outputs. These are highlighted in red. A noteworthy aspect is that the model discussed in Figure 10 may suggest the existence of an entity that collects and (re)processes the EoL components, but in reality, this is merely a process. However, in the future this process block may be replaced by an actual entity or (virtual) *market place*, of which the *Bruggenbank* is an example.

### 3.2.5 The asset cycles

An important note to be made concerns the meaning of recycling and reuse. Of course, when reusing components, elements or products, a new cycle is also started, but in order to make clear distinctions, reuse is differentiated from recycling. Hereafter in this report, the word reuse is a general term that includes repair before reuse, refurbish before reuse, remanufacture before reuse and repurpose. Recovery, often denoted as incineration, is, although some sustainability literature suggests otherwise, not considered to be recycling, since the materials are not used in the new life cycle and therefore, there is no circular way of material use. Instead, it is regarded as energy recycling. The essential difference between reuse and recycling is clarified in Figure 11. After the tighter cycle (reuse) has been completed so often that it cannot be reused in this application, the remaining possibility is recycling. When recycling is no longer possible, the remaining material turns inevitably into waste. However, in the case of renewable materials, this might result in closing the biological loop and hence not in the creation of waste.

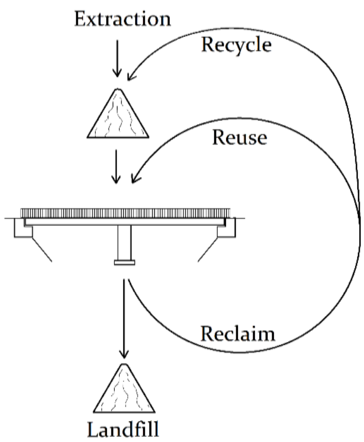



*Figure 11 – Reuse vs. recycling*

### 3.2.6 Layers and levels of bridges and circularity

Constructions should be *built for change* in order to survive the ravages of time. However, as Brand (1994) pointed out: "Buildings don't adapt well. They're designed not to adapt; also budgeted and financed not to, constructed not to, administered not to, maintained not to, regulated and taxed not to, even remodelled not to. But all buildings adapt anyway, however poorly, because the usages in and around them are changing constantly." Building constructions consist, as Brand (1994) argued, of six layers of change, each with its own variable life span (*shearing layers*). As such, for a future-proof design it is essential keep layers with a shorter lifespan accessible without touching the layers with a higher lifespan. This idea can be applied just as easy to bridges as to buildings, although the properties of the particular layers differ. Important in the shearing layers theory is to consider the functional layers rather than the technical ones. Various rates of change occur, all as a result of various reasons, from aesthetical trends to natural disasters. For building construction, Brand distinguished the "six S's", being Site, Structure, Skin, Services, Space plan, and Stuff. Stuff is hardly applicable to bridges, as there is no movable interior that is inherently part of the construction. The remaining "five S's" and their application to bridges and viaducts are shown in Figure 12.

| "S" | Examples in bridges |
|---|---|
| Space plan | Pavement, road marks |
| Services | Smart mobility, lightning |
| Skin | Decorative panels, paint |
| Structure | Abutment, beams and pillars |
| Site | Geographical setting |

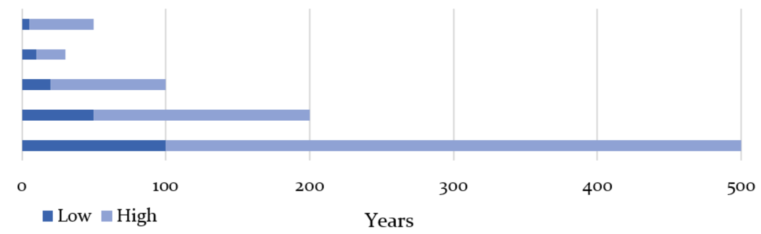



*Figure 12 – Expected bridge lifetime per layer (inspired by Brand, 1994)*

Each "S" layer represents an individual functional group of elements with largely comparable lifespans, although the lifespan of each element within the groups can vary as well. However, bridges as a whole are usually designed as an integral construction with a technical lifetime of 100 years, without actively considering shearing layers. In Figure 12, life span estimations of the different layers are shown, presenting the minimum and maximum estimated lifespan. However, in specific cases, the values may be different. For example, there are still Roman bridges that have barely changed in the past 2000 years. Also, it varies in approach per country, which makes the figure not generalizable. The figure does show the design life spans. Functional life spans may be considerably shorter, depending on the context. From a circular asset management perspective, it is essential to keep lower-lifespan layers accessible without damaging higher-lifespan layers. This is an essential principle of *Design-for-Disassembly*, modular and adaptable designs, which are crucial principles for circular design.

*Table 1 – Functional groups*

| **Functional group** | **Subgroup** | **Clarification** |
|---|---|---|
| **Substructure** | ***Foundation*** | Lowest support |
| | ***Abutments*** | Deck support at the bridge ends |
| | ***Piers*** | Compression-based support between bridge ends |
| **Superstructure** | ***Non-substructure deck support*** | Tensile-based support between bridge ends |
| | ***Deck*** | Support of the pavement |
| | ***Pavement*** | Layer to support traffic |
| | ***Fencing and barriers*** | All physical barriers to protect traffic |
| **Finishing** | ***Edging elements*** | All parts that finish the structure, often contributing to bridge aesthetics |
| | ***Lines and signs*** | Parts that guide traffic |
| | ***Transition parts*** | Parts that support transitions between roads |
| | ***Street lightning*** | Streetlights |
| **Servicing** | ***(Rainwater) drainage*** | Parts to support drainage of rainwater |
| | ***Cables and pipes*** | Cables, pipes, tubes that transport resources (water, energy, digital information) |
| | ***Electronics*** | Sensors, chips, tags and computers that support infrastructure management |

### 3.2.7 Functional separation of bridges

Following the various functional layers, proper maintenance, reuse and particularly disassemblability must be considered in the design phase. That is, connections of the various function groups need to be defined clearly to determine the mutual dependencies of the design. As a basis, the functional groups presented by Durmisevic (2006) are used. For non-moveable bridges, the functions are quite standard. The various functional system groups and their subgroups are shown in Table 1. These are used for further analysis in the assessment framework.

### 3.2.8 Rijkswaterstaat approach to circularity design principles

All Rijkswaterstaat programmes and project regarding infrastructure fall under the umbrella of the *Multiannual programme Infrastructure, Spatial planning and Transport* (MIRT). Also the investments made in the V&R are included in the scope of the MIRT (Rijksoverheid, 2017). Together with Witteveen+Bos engineering firm, Rijkswaterstaat developed design principles to circularity on an object level for the MIRT process (W+B & Rijkswaterstaat, 2017). This scheme is presented in Figure 13. This guideline is applicable from the earliest pre-design phases (especially regarding prevention) to concrete design solutions (e.g. materials) and functions.

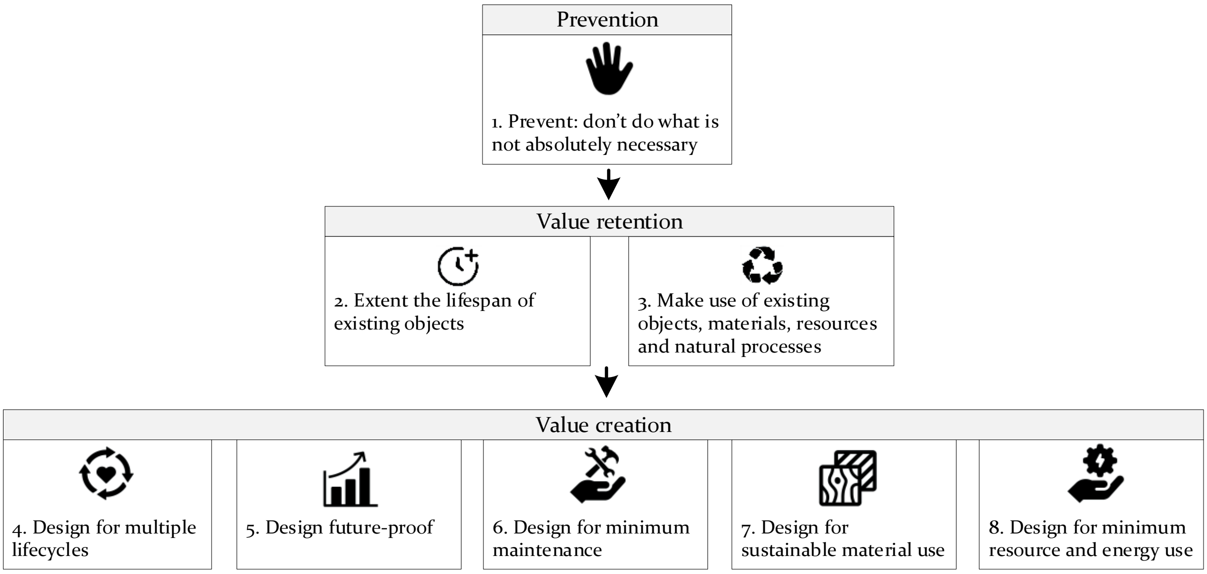



*Figure 13 – Circular design principles (source: W+B & Rijkswaterstaat, 2017)*

These principles come very close to the waste hierarchy discussed in section 3.2.2, although these focus on civil engineering practices. However, it is still quite abstract and does not offer concrete activities to make circular designs. Nevertheless, it is used in most recent documents within Rijkswaterstaat concerning circularity and it is also used for several case studies. Although the construct validity does not stand out, the most essential principles of CE are covered by the scheme. Examples of aspects that are at least not strongly emphasized by the scheme are material toxicity, regenerative systems and business models. However, they may be put under one or more principles and are often not applicable to bridge or viaduct projects.

### 3.2.9 Connecting Circular Economy with bridges and viaducts

In a separate study, *Interfaces between the concept of a circular economy and the domain of bridges,* the interfaces between the transition towards a CE and bridges were studied using intermediate categorization. Reasoned from the waste hierarchy (9Rs), actions to increasing circularity were developed, following the CEIMA framework developed by Coenen et al. (2019). These actions were categorized into groups regarding applicable phase (pre-design, design, construction, operation and EoL), domain (economic, political, process and material) and level of the scope (macro, meso and micro). Further, a general bridge within the V&R programme was studied and anatomized in an object, process and project level. The overlap in categorizations between each CE action was studied with each bridge aspect. This resulted in an extensive table that revealed the strength of the interfaces and aided in identifying relevant bridge aspects.

#### 3.2.10 Structuring of the concept

As discussed in section 3.2.2, the structuring of the CE concept is done by using the waste hierarchy as a starting point. The decomposition of the concept is done in considerable detail, but aspects may be grouped when developing indicators. CE is structured through three main categories, which are subdivided into the "9Rs" (Figure 14). To each "R", practical actions are linked that contribute to circularization. The composite indicators should proportionally reward the actions coupled to the CE strategies in designs and should also indicate presence of actions in existing designs. These actions are principles that urge for activities, and are thus process-oriented, while the eventual indicator assesses on the basis of an object.

#### 3.2.11 Definition: Bridge Circularity 2019

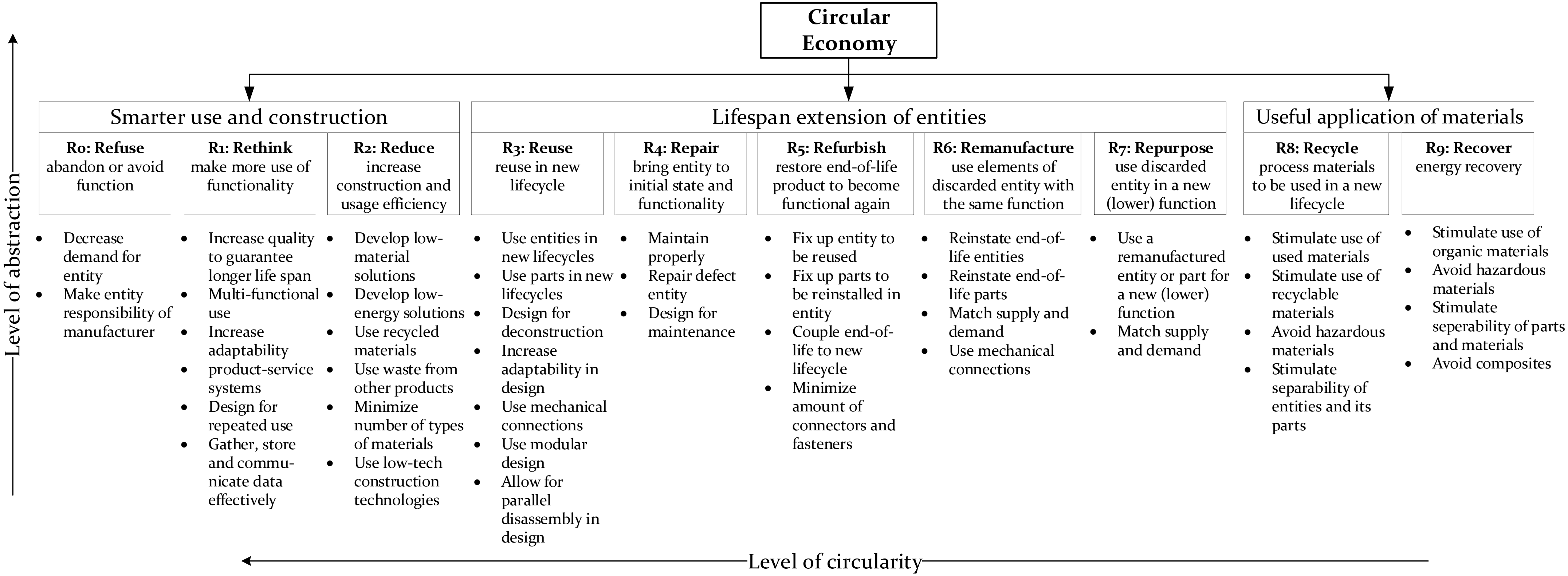
Both the dynamicity of the concept and the fact that it is a way of thinking rather than a clear-cut definition make it likely that the CE concept will evolve and adapt in the future. To make sure that the basis of the assessment framework is grounded on a uniform and unambiguous definition, we present, based on the theory presented in this chapter, a labelled definition below. Developments in the CE concept, and therefore a change in definition, lead automatically to the need of revision of the assessment framework presented in this study. Sections 3.2.1 to 3.2.10, considering CE, construction and application to bridges resulted in the following definition of *Bridge Circularity 2019:*

> *The* Bridge Circularity 2019 *is the level to which a bridge or viaduct is designed in order to prevent resource depletion by minimizing input of virgin, scarce, unrenewable and unrecyclable materials while designing it in a way that considers evolving functional requirements.*

This definition will be used to design the framework on as well as to test its construct validity. After implementation of the assessment framework, the definition needs to be updated regularly to fit the present-day meaning of CE. For example, by introducing the updated definition *Bridge Circularity 2022* three years from the presentation of this definition.

### 3.3 Performance indicators

In current procurement practices, rewarding circular bridge designs can only be done if it can be quantitatively and objectively demonstrated that a design is more circular than another. This demonstration requires objective measurement and therefore indicators. Whereas, for example, economic indicators are mostly used to predict future trends on the basis of single aspects that represent certain complex phenomena (Yamarone, 2012), indicators in this study are used in the other way around. Contractors will design to score highest on aspects that are indicated to enlarge the changes on winning the tender. Consequently, the indicators should possess a prescriptive and evaluative nature. Moreover, the indicator should be usable as a circularity guideline for designers. This section captures both the indicators literature and methods of analysis regarding bridges and circularity reviewed in sections 3.1 and 3.2. This is discussed in detail in appendix I.


Circular Economy
Smarter use and construction
Lifespan extension of entities
Useful application of materials
R0: Refuse
abandon or avoid function
R1: Rethink
make more use of functionality
R2: Reduce
increase construction and usage efficiency
R3: Reuse
reuse in new lifecycle
R4: Repair
bring entity to initial state and functionality
R5: Refurbish
restore end-of-life product to become functional again
R6: Remanufacture
use elements of discarded entity with the same function
R7: Repurpose
use discarded entity in a new (lower) function
R8: Recycle
process materials to be used in a new lifecycle
R9: Recover
energy recovery
• Decrease demand for entity
• Make entity responsibility of manufacturer
• Increase quality to guarantee longer life span
• Multi-functional use
• Increase adaptability
• product-service systems
• Design for repeated use
• Gather, store and commu-nicate data effectively
• Develop low-material solutions
• Develop low-energy solutions
• Use recycled materials
• Use waste from other products
• Minimize number of types of materials
• Use low-tech construction technologies
• Use entities in new lifecycles
• Use parts in new lifecycles
• Design for deconstruction
• Increase adaptability in design
• Use mechanical connections
• Use modular design
• Allow for parallel disassembly in design
• Maintain properly
• Repair defect entity
• Design for maintenance
• Fix up entity to be reused
• Fix up parts to be reinstalled in entity
• Couple end-of-life to new lifecycle
• Minimize amount of connectors and fasteners
• Reinstate end-of-life entities
• Reinstate end-of-life parts
• Match supply and demand
• Use mechanical connections
• Use a remanufactured entity or part for a new (lower) function
• Match supply and demand
• Stimulate use of used materials
• Stimulate use of recyclable materials
• Avoid hazardous materials
• Stimulate separability of entities and its parts
• Stimulate use of organic materials
• Avoid hazardous materials
• Stimulate seperability of parts and materials
• Avoid composites
Level of abstraction
Level of circularity

### 3.3.1 Circularity indicator frameworks and classifications

Between 2015 and 2019, the literature on measurement of resource efficiency and circularity experienced a massive growth. Various studies, including Elia et al. (2017), Iacovidou et al. (2017), Linder et al. (2017), Parchomenko et al. (2019), Pauliuk (2018) and Figge et al. (2018), show the plurality of approaches for measuring circularity, either at a product or at an asset level. In addition to these studies, Saidani et al. (2019) developed the "Circularity Indicators Advisor" tool, in which the existing indicators in literature are systematically ordered in line with a structured taxonomy. Further, Moraga et al. (2019) tried to capture and classify the existing CE indicators in a framework. Nevertheless, their focus on resource output makes it, for the same reasons as the studies above, not directly applicable to our study – also indicated by the strategies in Figure 14 that are not covered by resource output. However, considering the long lifecycle of a bridge and the unpredictability of the bridge management context, adoption of these indicators as a means to promote the circular design, construction and management of bridges is infeasible without making shaky assumptions on the later asset lifecycle stages.

This is compensated by introducing design strategies that cope with future uncertainties. In the past two decades, *Design-for-Disassembly* and transformable design have become important ways to reduce waste in the construction industry. However, metrics and indicators that measure disassemblability, transformability and adaptability are either barely addressed or disregarded by the aforementioned studies on circularity indicators. However, given the large similarities in techniques, materials and conditions, the CE principles from the building construction do broadly apply to civil engineering structures, for which a more consolidated literature base exists (e.g Addis and Schouten, 2004; Brand, 1994; Crowther, 2015; Durmisevic, 2006; Kibert, 2016; Schmidt, 2014). The bottom line in all these studies is that by making assets transformable or disassemblable, the potential to adapt or reuse decreases the future likelihood of unsuitability or obsolescence and hence contributes to resource efficiency.

### 3.3.2 Characteristics of the indicator

What should the framework and indicator assess? Following the taxonomy proposed by Saidani et al. (2019), the indicator's characteristics depend on the scope and the objectives of the study. Using the categories presented in that study, the characteristics of the indicator are:

1. The indicator developed in this study aims at a micro level, as it considers single assets.
2. Further, it includes all "Rs" that are applicable after the decision is made that the asset should be designed, thus leaving out *rethink*, without valuing or ranking particular "Rs".
3. Since CE largely aims at resource efficiency, the indicator should measure intrinsic performance of the bridge system.
4. Moreover, bridge designs are measured, resulting in an estimation of the potential circularity. Consequently, the circularity is presented as an *ex ante* resource efficiency.
5. Furthermore, the purpose of the indicator is to support decision-making in the procurement process of bridges.
6. Therefore, the indicator is sector- and bridge-specific.
7. The broadness of the approach to CE urges for a multi-metric composite indicator.
8. To ensure objectivity in the procurement process, the indicator is based on quantitative methods. The unit of measurement is not relevant, since it is merely used relatively to other designs (comparative). However, it should be consistent to allow for comparison.
9. To make this indicator usable for various locations while ensuring up-to-date databases, the assessment framework will be automated by means of a spreadsheet. This guarantees a consistent and maintainable graphical user interface (GUI).

### 3.3.3 Qualities of circularity indicators

Circularity indicators can be found and developed to measure various circularity aspects. However, there are several qualities that make an indicator appropriate for the design goals. First, (1) it should measure only material circularity, and no other aspects such as energy use, since this is already covered by other indicators. Moreover, it should be compatible with other indicators within Rijkswaterstaat, thereby considering both overlapping and gaps. Further, (2) since the selection of contractors can be highly reliant on this study, the assessment framework should be robust against opportunistic behaviour of contractors. Moreover, (3) the set of indicators should represent the level of circularity and should hence be reliable. Also, (4) indicators often include assumptions and (expert) judgements. Although judgemental input is inevitable, it should be minimized, since these judgements add subjectivity to the assessment. Further, (5) the set of indicators should be applicable to all types of bridges and corresponding processes, irrespective of the type, material or lifespan. Finally, (6) the indicators should be aggregated into a composite indicator without decreasing representability. These six qualities are ensured by developing the composite indicator according to a strictly structured approach presented in Table 5 (section 4.3). Furthermore, the data required is collected both from scientific literature and internal data within Rijkswaterstaat, documentation and expertise. The general procedure of a project within the V&R programme is taken as a guide to determine other metrics and indicators. The set of performance indicators in this study should act independently, but supplementary to these existing ones. The overall assessment framework should furthermore be in line with the PDEng design criteria as discussed in section 2.3.2.

### 3.3.4 Strengths and weaknesses of existing indicators and assessment methods

To select existing indicators and find the gaps to develop new ones, existing indicators and assessment methods are analysed with regard to sustainability and CE. Whereas a method, as part of a methodology, is used as a comprehensive approach to assess certain characteristics (Moraga et al., 2019), an indicator is a measuring instrument that represents a singular aspect of an entity. Consequently, a method is a way to do things and an indicator an explicit quantification of a certain characteristic. In Table 2, the strengths and weaknesses as of the existing circularity assessment methods are presented. Table 3 shows the weaknesses of the existing circularity indicators, although several of the characteristics are outside the scope of this study. These are based on the analysis presented in appendix I. In the two tables below, only the indicators that match the characteristics discussed section 3.3 are presented.

### 3.3.5 Gaps in existing indicators and Rijkswaterstaat indicators

Table 3 shows the existing circularity indicators initially considered in this study. A widespread weakness of these indicators is the lack of construct validity. This tells us that a particular indicator or metric does not comprehend the entire CE concept. However, the variety in approaches shows the plurality in perspectives. In the study that analysed the interfaces between CE and bridges (section 3.2.9), the concept of CE was completely anatomized and allocated to 27 actions. Measurement of each of these actions should be either binary (B) or continuous (C) by the final set of indicators. Verifiable actions can be measured through binary indicators. The remaining actions should be covered by the indicator which are true to a certain degree. Furthermore, several of the aspects are already covered by the Rijkswaterstaat sustainability and asset management indicators (first section of appendix I). Therefore, these do not need to be covered by the set of indicators developed in this study. Table 4 shows the link between CE measures available and an existing indicator within Rijkswaterstaat. CE measures that are measurable and not covered by either or both the existing CE indicators and Rijkswaterstaat indicators need to be developed in this study.

*Table 2 – Strengths and weaknesses of existing circularity assessment methods*

| Method | | Strengths | Weaknesses |
|---|---|---|---|
| **LCA** | *Impact on the environment of materials and processes of a product along all its life stages.* | • Considers entire lifecycle<br>• Considers broad externalities<br>• Identifies drivers for environmental impact<br>• Highly mature technique | • Low construct validity<br>• Laborious exercise<br>• Difficult quantification of renewable and recyclable resources<br>• Strong reliance on lifecycle assumptions |
| **MFA** | *Analysis of material flows in and out of a system in terms of material mass.* | • Considers both system inputs and outputs<br>• Measures inputs of material types | • Different materials into a single number<br>• Not all environmental impacts are specifically accounted for<br>• Mass quantity-oriented<br>• Does not include emissions |
| **MFCA** | *Analysis of material flows in systems in terms of monetary values.* | • Provides an output in monetary terms<br>• Strong categorizations of elements | • Different materials into a single number<br>• Less generalizable than MFA |

*Table 3 – Strengths and weaknesses of existing circularity indicators*

| Indicator | | Strengths | Weaknesses |
|---|---|---|---|
| **CEI** | *Considers share of recycled materials.* | • Considers material application<br>• Focus on EoL | • Doesn't consider all forms of material recovery<br>• Does not include material value loss<br>• Does not consider value durability |
| **Ecological footprint (EF)** | *Considers the environmental impact human behaviour.* | • Well-established techniques<br>• Broad incorporation of aspects | • Barely incorporates material value<br>• Not aimed at products |
| **MCI** | *Analyses circularity on large number of aspects, including reuse, recycle, toxicity and environmental impact.* | • Comprehensive<br>• Different materials usage compensated for in efficiency index<br>• Considers resource duration | • Dependency on judgement lead to optimistic estimations<br>• Requires extensive data input<br>• Does not include emissions |
| **Recycling potential** | *Recyclability of a material, component or product.* | • Considers design choices | • Low construct validity<br>• Prone to judgement |
| **Recycling rate** | *Percentage of recycled materials used.* | • Focus on value retention<br>• Easy to calculate | • Low construct validity |
| **Resource duration** | *Longevity of resources used over its lifecycle.* | • Focus on value retention<br>• Considers levels of | • Low construct validity<br>• Major aspects are lacking |
| **Reuse potential** | *Reusability of a material, component or product.* | • Focus on waste output reduction<br>• Considers design choices | • Low construct validity<br>• Prone to judgement |
| **RISE circularity indicator** | *Considers degree of recirculated economic value.* | • Focus on value of product parts | • Strong focus on macro level<br>• Low construct validity |

The information presented in Table 4 shows that each action is covered by literature in one way or another, except for the focus on maintainability. This aspect was not found in any of the existing metrics. However, some aspects are covered, but are considered in a general way rather than accurate measurement. The metrics used by Rijkswaterstaat, and especially the MKI show large gaps in the coverage of bridge circularity (Figure 4, section 2.1). Table 4 shows clearly that the largest gaps are in measurability of aspects related to *design-for-circularity*, since no existing indicators or methods cover these aspects, while this is essential according our definition *Bridge Circularity 2019* (section 3.2.11). Material input and measuring reuse of products is largely covered by the existing MKI. This gap analysis used as a validation instrument for the composite indicator development as discussed in chapter 4 and based on the lifecycle transformation discussed in section 4.1.

*Table 4 – Coupling of CE aspects to CE indicators and identification of gaps*

| No. | Action | B/C | Covered by existing method | Covered by existing indicator | Covered in current RWS indicators |
|---|---|---|---|---|---|
| 1. | Decrease demand for entity | *B* | *n/a* | *n/a* | *n/a* |
| 2. | Make entity responsibility of manufacturer | *B* | *n/a* | *n/a* | *n/a* |
| 3. | Increase quality to guarantee longer life span | *C* | - | Resource duration, MCI | SLAs |
| 4. | **Multi-functional use** | *C* | - | MCI (partly) | - |
| 5. | **Increase adaptability** | *C* | - | Reuse potential | - |
| 6. | Product-service systems | *B* | - | *n/a* | *n/a* |
| 7. | Develop low-material solutions | *C* | LCA, MFA, MFCA | EF, MCI | MKI |
| 8. | Develop low-energy solutions | *C* | LCA | EF | MKI |
| 9. | Use recycled materials | *C* | MFA, MFCA, LCA | CEI, MCI, Resource duration, RISE, Recycling Rate | MKI |
| 10. | Use waste from other products | *C* | LCA, MFA | EF, LCA, MCI, MFA, RISE | MKI |
| 11. | **Use entities in new lifecycles** | *C* | MFA, MFCA | Reuse potential, MCI, RISE, recycling potential | - |
| 12. | Use parts in new lifecycles | *C* | MFA, MFCA | Reuse potential, MCI, recycling potential | MKI |
| 13. | **Design for deconstruction** | *C* | - | Reuse potential | - |
| 14. | Maintain properly | *C* | - | MCI | SLAs |
| 15. | Repair defect entity | *C* | LCA | MCI | SLAs |
| 16. | Design for maintenance | *C* | - | - | ROK |
| 17. | Fix up entity to be reused | *C* | LCA, MFA | MCI, Recycling potential | MKI |
| 18. | Fix up parts to be reinstalled in entity | *C* | LCA, MFA | MCI, Recycling potential | MKI |
| 19. | Couple end-of-life to new lifecycle | *B* | *n/a* | *n/a* | *n/a* |
| 20. | Reinstate end-of-life entities | *C* | LCA, MFA, MFCA | MCI, Recycling potential, resource duration, reuse potential | MKI |
| 21. | Reinstate end-of-life parts | *C* | LCA, MFA, MFCA | MCI, Recycling potential, resource duration, reuse potential | MKI |
| 22. | Use a remanufactured entity or part for a new (lower) function | *C* | MFA, MFCA | MCI, Resource duration, reuse potential | MKI |
| 23. | Match supply and demand | *B* | *n/a* | *n/a* | *n/a* |
| 24. | Stimulate use of recyclable materials | *C* | LCA, MFA , MFCA | EF, MCI, RISE | MKI |
| 25. | Avoid hazardous materials | *C* | LCA | EF, MCI, Recycling potential, RISE | MKI |
| 26. | **Stimulate separability of entities, its parts and materials** | *C* | - | Reuse potential | - |
| 27. | Stimulate use of bio-degradable materials | *C* | LCA | EF, MCI | MKI |

# 4 Measuring circularity

The background on circularity and measurement of circularity is discussed in chapter 3. This provides the basis for developing circularity indicators for bridges. Following step 2 of the design methodology (Figure 6), the conceptual indicators identified as gaps in section 3.3.5 are developed below according to step 3 – *treatment design* – in the methodology (chapter 2). Next to the design, the bridge circularity assessment framework principles are presented, including the aggregation. Although conceptual outlines of the framework, indicators and tool are discussed below, only the validated and final version is presented in this report in chapter 7.

## 4.1 Multi-dimensional assessment of circularity

CE and our definition *Bridge Circularity 2019* (section 3.2) relies on value retention as a means to prevent resources from being depleted in the (near) future. The level of circularity is mainly based on the resources used and potentially required over the bridge's entire lifecycle and the potential for reuse in a next one. Therefore, the analysis must be value-based rather than mass-based. As an illustration, a ton of crushed concrete has a value of approximately 50 times lower than the same amount of newly produced concrete element (Guldager Jensen & Sommer, 2016). Consequently, there is not one single formula for circularity and the assessment framework should be multi-dimensional (Kalmykova, Sadagopan, & Rosado, 2018; Moraga et al., 2019; Saidani et al., 2019). Moreover – and this might be either a trade-off or a complementary attribute – the functional adaptability towards future changes determines to what extent materials used are likely to be kept in use on a high-value level.

These factors affect the level circularity and may either reinforce each other, work independently or act as a trade-off (e.g. robustness vs. flexibility). These considerations are included in the definition *Bridge Circularity 2019* presented in section 3.2.11. The weighing of the factors vary for each project, asset and lifecycle phase and are moreover dependent on the priorities determined in relation to other project characteristics (Figure 1, section 1.1). The transformation from the conceptualization of the CE with respect to bridges and viaducts into indicators is shown in Figure 15. This transformation is established following the Vee-model shown in Figure 7 (section 2.2.1). This is validated through the CE principles resulting from the waste hierarchy presented in Figure 14 (section 3.2.10).

## 4.2 Selection of circularity indicators

The indicators should cover the gaps between what should be measured in terms of CE and what is measured within Rijkswaterstaat (section 3.3.5). Literature was studied to reveal the circularity indicators as developed by scholars and a gap analysis was conducted between CE aspects and those existing indicators in section 3.3.5. By developing indicators that fill those gaps and by selecting useful indicators from literature, the set of indicators is determined below. In Figure 15 the indicator is shaped following a structured CE decomposition regarding a bridge lifecycle as discussed in section 3.1, while taking into account the *Bridge Circularity 2019* definition.

The circularity indicator analysis in section 3.3.5 shows the gaps in literature and in existing Rijkswaterstaat indicators, resulting in the parts that must be included in the composite indicator. Existing indicators, both in scientific and professional literature, are discussed in appendix I and in more detail in the separate report *Theoretical background on circular design of bridges and viaducts*. The selection of indicators, including the newly designed indicators, is discussed below per sub-indicator and in greater depth in appendix VI. In the following sections, these indicators and sub-indicators are briefly discussed.

### 4.2.1 Design input

The existing MCI is found to be suitable for assessing and guiding particular aspects of designs of products or assets (EMF & Granta, 2015). It focuses on four major points:

1. Using feedstock from reused or recycled resources
2. Reusing or recycling materials after product use
3. Keeping products in used longer (e.g. reuse or redistribution)
4. Making more intensive use of products

All four points aim at increasing material value. Although applying one or more of these principles will not cause a systemic revolution, the widespread use will slowly tilt the current system. However, the applicability of the MCI is more suitable for consumer products than public assets and focuses on the material flows rather than the reusability of components or products. Therefore, the existing MCI should be tailored to the civil engineering domain and only the suitable parts can be used. This part is incorporated in the *Material input* indicator. The existing MCI does not take biological cycles (materials in original state back to nature) into account, but in our approach, the use of renewable materials is stimulated. Moreover, in the *Material input* indicator, EoL recovery is not distinguished, as it assumes same-quality reuse in an uncertain future. However, this EoL part is compensated by the reusability indicator (section 0). The other EoL consideration used in the *Material input* is the recyclability of components, which depends both on the materials used and the separability of materials, which should be indicated by the designer.

Within the *Design input*, material use is included in the *Material input* indicator. This sub-indicator includes, next to the fractions reused and recycled materials, the recyclability of the components and the fraction of renewable materials used. Next to this *Material input*, extended use is included as *Robustness* as a potential for lifetime extension. Together, the *Material input* and *Robustness* compose the *Design input.* An important note is that all calculations in this *material input* merely consider mass of materials, while this does not reflect the effect on resource depletion. This is compensated by introducing materials scarcity.

### 4.2.2 Resource availability indicator

Only including material weight as unit of input does not reflect the impact of the *resource availability* on the planet. Therefore, resource scarcity is often promoted as an essential part of lifecycle considerations (Mancini, Benini, & Sala, 2018). Because resource scarcity – also called criticality – is a relative concept, it involves the question *Critical to whom?* (Mancini et al., 2018). In this study, only depletion of raw materials is considered, rather than supply risks and geopolitics involved in the material criticality considerations. We acknowledge the weakness of both the Abiotic Depletion Potential (ADP) and Surplus Ore Potential (SOP) in the sense that the data used to calculate these indices are neither able to reflect the actual global material availability, nor are they empirically verifiable. This results in deriving the scarcity from the price elasticity of materials, even though Henckens (2016) demonstrated a limited representation.

However, no reasonable alternative has been developed yet with respect to the reflection of resource depletion (Van Oers & Guinée, 2016). Since the SOP, in contrast to the ADP, not only considers the materials available in the earth's crust, but in particular focusses at the feasibility to obtain the materials from it, we consider the SOP a more appropriate indicator to reflect the material scarcity. The SOP data are mainly retrieved from Vieira et al. (2017), including the database with SOP scarcity in which each material is compared to the scarcity of copper (SOP copper = 1,00). Scarcity is included in the indicator positively as *resource availability*.

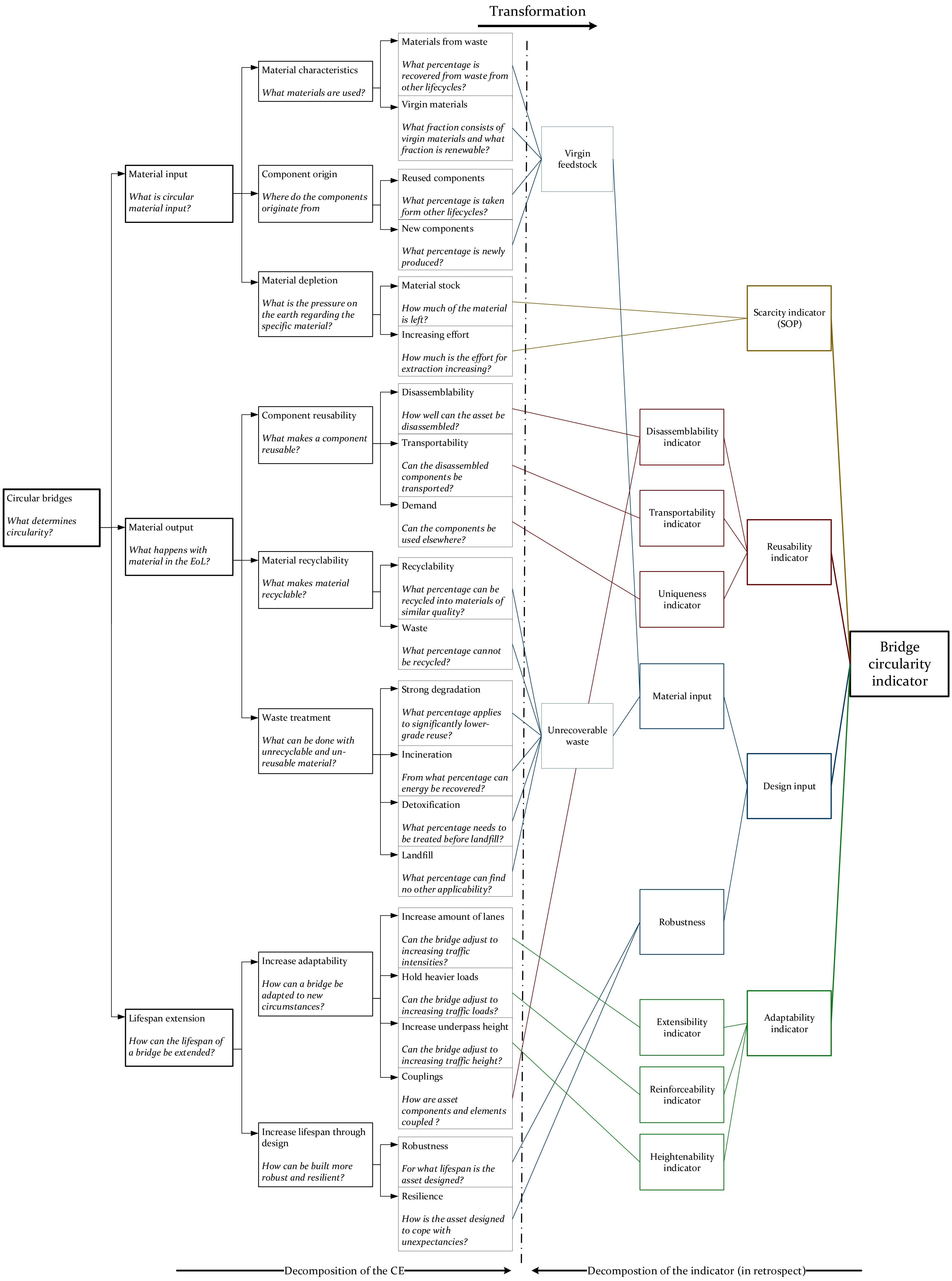



*Figure 15 – From CE concept to composite bridge circularity indicator*

### 4.2.3 Reusability and adaptability

The *Design input* lacks the ability to account for design decisions that increase responsiveness to changing functional requirements during and after the service life. In our composite indicator, this is accounted for by introducing the *Reusability* (EoL) and *Adaptability* (service life) indicators. Despite their low individual construct validity regarding CE, they fill the gaps regarding components and compositions in the *design input* indicator (Table 4). The main sub-indicators of these two indicators are *disassemblability, uniqueness* and *transportability* for the former and *extensibility, heightenability* and *strengthenability* for the latter. González (2018) provided a list with factors that indicate functional performance, which is used to determine the last three *adaptability* factors. The structural *disassemblability*-oriented indicators are largely based on the theory developed by Durmisevic (2006) and subsequent literature. It considers the structural composition of assets, considering the amount, arrangement and types of connections and distinguishes various functional groups.

Considering the *adaptability* of the asset, *extensibility, reinforceability* and *heightenability*, can be achieved in numerous ways and often require innovations. Therefore, clear-cut technical measurement is impossible. As a result, these sub-indicators involve mere preconditions which are either true or false. This should be indicated by the designer. Finally, component *uniqueness* is measured by indicating whether a component complies with reference standard designs to be developed by Rijkswaterstaat. This applies only to components with reference standard designs (and are hence standardizable). The three sub-indicators (sections 4.2.2 and 0) which complement the shortcomings of the fourth *Design input* sub-indicator (section 4.2.1) are at the heart of measuring bridge circularity. These are described in detail in appendix VI. How to aggregate those into a sub-indicator and further details on the sub-indicators are described below. This section provides ground for the design, the application and the validation of the assessment framework, which will be discussed in greater depth in chapters 5 to 8.

## 4.3 Aggregation of the indicators

Considering a multi-dimensional concept, such as the CE, several metrics measure multiple circularity aspects of the entity. Indicators provide a specific piece of information about the performance of a particular part of the asset with regard to a given objective and goal. Often the units used are inconsistent and furthermore, they are not relatively scaled and weighted. Uncomplimentary indicators may result in information overload and unclear representation of reality (Galar, Berges, Sandborn, & Kumar, 2014). A collection of indicators aggregated into one single indicator, also called composite indicator, provides a consolidated perspective that aims to represents reality as well as usefulness in practice. This composite indicator will be at the heart of the circularity assessment framework. Since the circularity aspects might be conflicting (trade-offs), finding balance is difficult and hence aggregation should be done with care.

Using aggregation of partly conflicting parts has several drawbacks. By definition, a composite indicator is built up from underlying sub-indicators, which are weighted, and thus valued. However, the *thing* it measures – in our case circularity – is multidimensional and as a result, an indicator is always subject to assumptions and subjectivities regarding importance of sub-aspects of circularity. However, by not aggregating the sub-indicators, the usability within the procurement process (section 3.1.2) is degraded. Nevertheless, through a proper tool design, the composition and sub-results of the performance indicator are kept as transparent as possible to all users and system maintainers. This results in the possibility to use the tool for a one-number circularity score for procurement purposes, as well as for design support using the transparent underlying results.

*Table 5 – Steps for developing composite indicators (source: OECD, 2008)*

| Step | Why it is needed |
|---|---|
| **1. Theoretical framework**<br>Provides the basis for the selection and combination of variables into a meaningful composite indicator under a fitness-for-purpose principle. | • To get a clear understanding and definition of the multidimensional phenomenon to be measured.<br>• To structure the various sub-groups of the phenomenon (if needed).<br>• To compile a list of selection criteria for the underlying variables, *e.g.*, input, output, process. |
| **2. Data selection**<br>Should be based on the analytical soundness, measurability, country coverage, and relevance of the indicators to the phenomenon being measured and relationship to each other. | • To check the quality of the available indicators.<br>• To discuss the strengths and weaknesses of each selected indicator.<br>• To create a summary table on data characteristics, *e.g.*, availability (across country, time), source, type (hard, soft or input, output, process). |
| **3. Imputation of missing data**<br>Is needed in order to provide a complete dataset (*e.g.* by means of single or multiple imputation). | • To estimate missing values.<br>• To provide a measure of the reliability of each imputed value, to assess the impact of the imputation on the results.<br>• To discuss the presence of outliers in the dataset. |
| **4. Multivariate analysis**<br>Should be used to study the overall structure of the dataset, assess its suitability, and guide subsequent methodological choices (*e.g.*, weighting, aggregation). | • To check the underlying structure of the data along the two main dimensions, namely individual indicators and countries (by means of suitable multivariate methods, *e.g.*, principal components analysis, cluster analysis).<br>• To identify groups of indicators or groups of countries that are statistically “similar” and provide an interpretation of the results.<br>• To compare the statistically determined structure of the data set to the theoretical framework and discuss possible differences. |
| **5. Normalization**<br>Should be carried out to render the variables comparable. | • To select suitable normalization procedure(s) that respect both the theoretical framework and the data properties.<br>• To discuss the presence of outliers in the dataset as they may become unintended benchmarks.<br>• To make scale adjustments, if necessary.<br>• To transform highly skewed indicators, if necessary. |
| **6. Weighting and aggregation**<br>Should be done along the lines of the underlying theoretical framework. | • To select appropriate weighting and aggregation procedure(s) that respect both the theoretical framework and the data properties.<br>• To discuss whether correlation issues among indicators should be accounted for.<br>• To discuss whether compensability among indicators should be allowed. |
| **7. Uncertainty and sensitivity analysis**<br>Should be undertaken to assess the robustness of the composite indicator in terms of mechanism for including or excluding an indicator, normalization scheme, data imputation, choice of weights and the aggregation method. | • To consider a multi-modelling approach to build the composite indicator, and if available, alternative conceptual scenarios for the selection of the underlying indicators.<br>• To identify all possible sources of uncertainty in the development of the composite indicator and accompany the composite scores and ranks with uncertainty bounds.<br>• To conduct sensitivity analysis of the inference and determine what sources of uncertainty are influential in the scores and/or ranks. |
| **8. Back to the data**<br>Is needed to reveal the main drivers for an overall good or bad performance. Transparency is primordial to good analysis and policymaking. | • To profile country performance at the indicator level so as to reveal what is driving the composite indicator results.<br>• To check for correlation and causality (if possible).<br>• To identify if the composite indicator results are overly dominated by few indicators and to explain the relative importance of the sub-components of the composite indicator. |
| **9. Links to other indicators**<br>Should be made to correlate the composite indicator (or its dimensions) with existing (simple or composite) indicators. | • To correlate the composite indicator with other relevant measures, taking into consideration the results of sensitivity analysis.<br>• To develop data-driven narratives based on the results. |
| **10. Visualization of the results**<br>Should receive proper attention, given that the visualization can influence (or help to enhance) interpretability | • To identify a coherent set of presentational tools for the targeted audience.<br>• To select the visualization technique which communicates the most information.<br>• To present the composite indicator results in a clear and accurate manner. |

The methodology for aggregating composite indicators consists usually of the following steps: (1) data enquiry; (2) data normalization; and (3) data aggregation (El Gibari, Gómez, & Ruiz, 2018). The OECD (2008) has published an extensive and instructive manual on how to structurally develop composite indicators using these three steps. They formulated ten steps to guarantee a transparent, easy-to-interpret, reality-representing and comprehensive composite circularity indicator that is suitable among the existing indicators (Table 5). Below, each step in the OECD framework is discussed with respect to the particular bridge circularity indicator.

#### 4.3.1 Missing data and data imputation

If essential empirical data is missing to measure circularity, other data has to be assigned to account for these gaps, also called imputation. The selected indicators cover the aspects of the *Bridge Circularity 2019*. The indicators are selected on the basis of available data and rely merely on design data, which is fully known to the designing or executing stakeholders. Considering unknown future – i.e. EoL – only abilities to increase the potential of increasing resource efficiency are used. Therefore, data imputation is not needed, but the proper use of the tool requires full insights in the design data, including material quantities and origins.

#### 4.3.2 Multivariate analysis / sensitivity analysis

The composite indicator is based on various indicators, which might be correlated. However, interrelationships between these indicators should be studied to ensure a representative composite indicator. These analyses will aid in assessing suitability of the data and provide an understanding of the implications of methodological choices, as well as revealing correlated indicators that may be changed or excluded by means of a multivariate analysis (OECD, 2008). Although the lack of large amounts of case studies prevent us from executing a large-scale multivariate analysis, the effect of the weightings on the outcomes are studied in section 4.3.4.

#### 4.3.3 Normalization of data

The collection of indicators has resulted in a multidimensional set with various scales and units of measurement. Normalization is hence needed to allow for the aggregation of the indicators. There are several ways to normalize, but each way results in a commensurate dataset. Nevertheless, this step deserves special attention because of the possibility of false scale adjustments. Each sub-indicator will be expressed in a number between 0 and 1, in which 0 is either "lacking" or "very bad" and 1 is either "fully present" or "very good". Any value in between is scaled accordingly, using a continuous scale between minimum (0) and maximum (1). Based on case studies, these minimum and maximum values that correspond to respectively 0 and 1 are determined. The resulting formulas for each sub-indicator are presented in appendix VI.

#### 4.3.4 Weighting of the indicators

Both the applicability and importance of sub-indicators depend on the bridge characteristics and design context. Weights are set based on the expected influence of a certain aspect of CE in relation to the context in which the bridge is situated. Assigning weights to the individual parts, given an individual situation, offers opportunities for stressing particular aspects on the one hand and providing a legitimate representation of the reality on the other. The way various individual indicators are weighted is presented next. An expert session has revealed that the use of scenarios would be difficult to determine due to the many different situations. Instead, using the bridge context to formulate weighting parameters allows for a context-specific weighting without losing subjectivity. On the one hand, this prevents the necessity of a project team to manually determine the importance of each sub-indicator for each particular bridge while risking biases, and on the other hand, it allows for specifying the weights to the particular situation of the asset. The weighting set is developed based on three factors. These are as follows.

1. Type of spanned area: What does the asset cross?
2. Dynamicity of the area: To what extent is the bridge prone to change?
3. Expected lifetime of the asset in the current state: What is the design lifespan?

The three factors all consider a certain likelihood for the bridge to remain in place during a certain period without the need for either adaption or disassembly at a certain moment of time. These three variables tell us to what degree we should either aim at flexibility or at robustness. The relations between the indicators and the depending variables were set using expert insights.

#### 4.3.4.1 Type of spanned area

Depending on the area that is crossed, various characteristics apply to the situation. These characteristics affect the expected unchanged lifespan and hence the *design input, adaptability* and *reusability indicators*. Table 6 shows the corresponding values determined according to expert judgement and are indicated on a scale from 0.0 (non-corresponding) to 1.0 (fully corresponding).

*Table 6 – Relation between spanned area and sub-indicators*

| *Type of spanned area* | *Design input/robustness* | *Adaptability* | *Reusability* |
|---|---|---|---|
| Roads | 0,6 | 0,8 | 0,8 |
| Railroad | 0,8 | 0,4 | 0,6 |
| Land | 0,8 | 0,6 | 0,4 |
| Water <10 m | 0,6 | 0,8 | 0,8 |
| Water >10 m, <30 m | 0,8 | 0,6 | 0,6 |
| Water >30 m | 1,0 | 0,6 | 0,6 |

#### 4.3.4.2 Dynamicity of the area

For a highly dynamic area, strong emphasis should be put on *adaptability* and *reusability*, while, in a low-dynamic area, *robustness* is more important (Table 7). This is determined by examining the context rather than the design goals or the scope of the particular asset design. Dynamicity is indicated on a scale from 0.0 (fully static) to 1.0 (extremely dynamic).

*Table 7 – Relation between the dynamicity and the sub-indicators*

| *Dynamicity* | *Design input/robustness* | *Adaptability* | *Reusability* |
|---|---|---|---|
| 1 | 1,0 | 0,2 | 0,2 |
| 2 | 0,8 | 0,6 | 0,2 |
| 3 | 0,6 | 0,8 | 0,4 |
| 4 | 0,4 | 1,0 | 0,6 |
| 5 | 0,2 | 1,0 | 0,8 |

#### 4.3.4.3 Expected lifetime

The expected lifetime deals mainly with the controlled expected lifetime. That is, the designer's intention to keep the asset on a certain place in a certain condition. Figure 16 shows the relations between the importance of the sub-indicators and the expected lifetime according to expert insights. The relations are plotted from 0.0 (non-applicable) to 1.0 (fully applicable). The remarkable shape of the curve for *adaptability* (i.e. skewed bell curve) results from the fact that the longer the life, the more likely are the functional requirements are to require change. However, for a very long service life, *adaptability* starts losing ground as an option due to an decrease in structural safety and remaining technical lifespan.

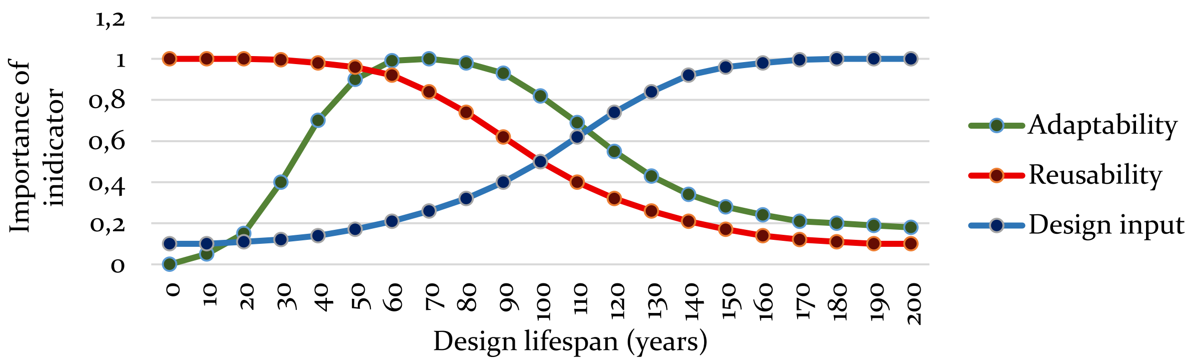



*Figure 16 – Relations between expected design lifespan and importance of indicators*

#### *4.3.4.4 Weighting based on the three criteria*

Depending of the context and scope of the assessment, either the moderator of the assessment or the tool user should indicate the parameters of each of the three criteria. That is, it can be indicated in the tool what area the bridge crosses, how dynamic the area is and for how long the bridge is aimed to serve at the particular location. Then, based on equal relevance between the three aspects, the final weighting is determined. In this weighting, the *Resource availability* indicator is linked to the *design input* and robustness and is weighted as 70% of the *Design input* indicator. This is done because the reason to focus on *material input* will, from a circularity perspective, only be done to prevent resource depletion, which is directly related to the *Resource availability*. The weighting works for an imaginary case as follows. Consider that the spanned area is railroad, the area is estimated moderately dynamic (dynamicity 3) and the designed bridge is aimed to serve for 80 years, the weights are calculated as follows. The factors are, respectively, 0.8, 0.6 and 0.32 (average = 0.57) for *Design input;* 0.4, 0.8 and 0.98 (average = 0.73) for *Adaptability*; 0.6, 0.4 and 0.74 (average = 0.58) for *Reusability* and 70% of 0.57 is 0.40 for *Resource availability.* This would result in the following weighting of the indicators: 16% for *Design input*, 36% for *Adaptability*, 29% for *Reusability* and 20% for *Resource availability.*

For an average viaduct (i.e. lifespan of 100 years, dynamicity of 3/5 and *road crossing*), the *Design input* and *Resource availability* together weigh for 41%, *Adaptability* for 35% and *Reusability* for 24%. When taking a bridge in its most rigid circumstances (i.e. lifespan of 200 years, dynamicity of 1/5 and *>30 meter water crossing*), the *Design input* and *Resource availability* account for approximately 73%, *Adaptability* for 14% and *Reusability* for 13%. In contrast, when considering a bridge in its most dynamic and uncertain circumstances (i.e. lifespan of 10 years, dynamicity of 5/5 and *road crossing*), the *Design input* and *Resource availability* account for 26%, *Adaptability* 31% and *Reusability* 43%. This demonstration shows that the indicator stimulates, depending on the scope and uncertainty, certain design features to promote circularity.

#### *4.3.4.5 Behaviour of the weights*

An important question to consider is what the effect of the different weighting settings is on the final circularity score. To answer this, the weighting parameters of the framework are applied to the bridge case studies in chapter 5. By tweaking the parameters in all possible directions, the range and variance of the circularity results are established and plotted. These plots show the CE outcomes as a result of changing the design lifespan and dynamicity given a fixed type of type of span.

For the road crossing viaduct Parkstad Limburg, the results, depending on the weights, are shown in Figure 17. For this box girder viaduct, with a rather average design for viaducts in the Netherlands, the lowest circularity score is established by setting the weighting parameters of a highly dynamical area with a lifespan of approximately 60 years (0.61). The highest circularity score is found with a weighting with a dynamicity of 2 and a lifespan of more than 130 years (0.71). This results in a range of 0.10 on a scale of 0 to 1, which is 10% of the tot bridge circularity score. The variance of all CE scores as a result of tweaking the weightings is 0.000733, which shows that the numbers are on average rather close. However, the 10% difference between minimum and maximum indicate a significant impact of the weightings on the score.

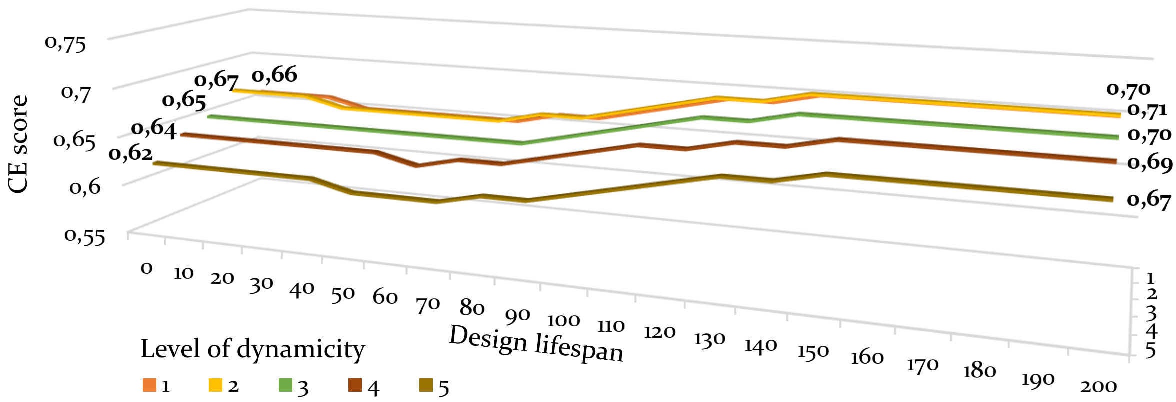



*Figure 17 – CE scores dependent on weighting settings for Parkstad Limburg Viaduct*

In the same way, this analysis is done for the 3D concrete printed cycling bridge, in which a "Water >10 m, <30 m" crossing is assessed. This bridge is considered to have a low circularity due to rigid, oversized and uncommonly shaped segments. For demonstration purposes, we only took a dynamicity of 1 and subdivided the results per indicator. Figure 18 shows that, due to the weighting, the *reusability* decreases, while this is strongly compensated by an increase in *scarcity* and *design input*. Indeed, the range in scores varies from 0.25 in a highly dynamical area with short lifespan to 0.47 for a long lifespan in a low-dynamical area. These results show a range of 22 and a variance of 0.003221; four times larger than in Figure 17. This can be explained by the fact that the score of this bridge scores particularly low on *adaptability,* which has the largest applicability in dynamical areas on the short term. Interestingly, the overall score is increasing after 80 years, while the reusability is decreasing as a result of the weighting.

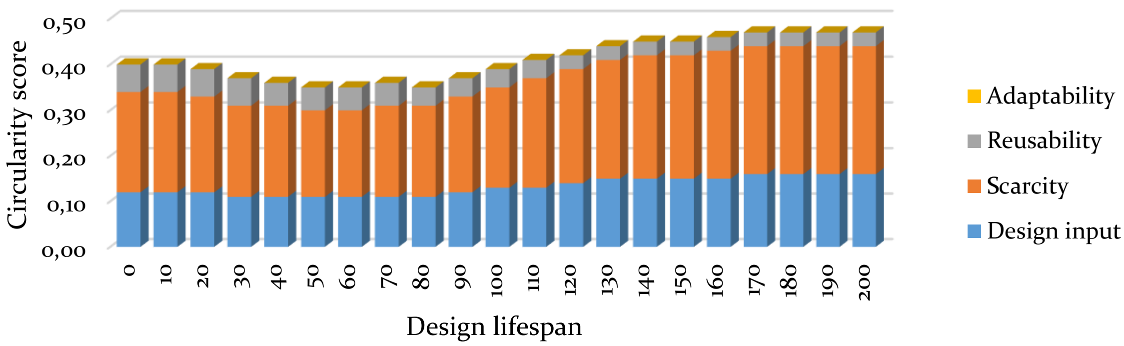



*Figure 18 – CE scores 3D concrete printed cycling bridge Nijmegen per indicator*

However, what is the variation for a viaduct that is considered highly circular? This is shown in Figure 19 for a road crossing, modular viaduct. For this *Circulaire Viaduct* (section 5.2), the scores range from 0.79 to 0.83 with a variance of only 0.000087, which is more than 8 times lower than the Parkstad Limburg viaduct. This can be explained by the fact that the scores of the sub-indicators are all high, and hence close to each other. All in all, the impact of the weighting – and, therefore, the context – is highly influential on the final CE results, ranging up to 30%.

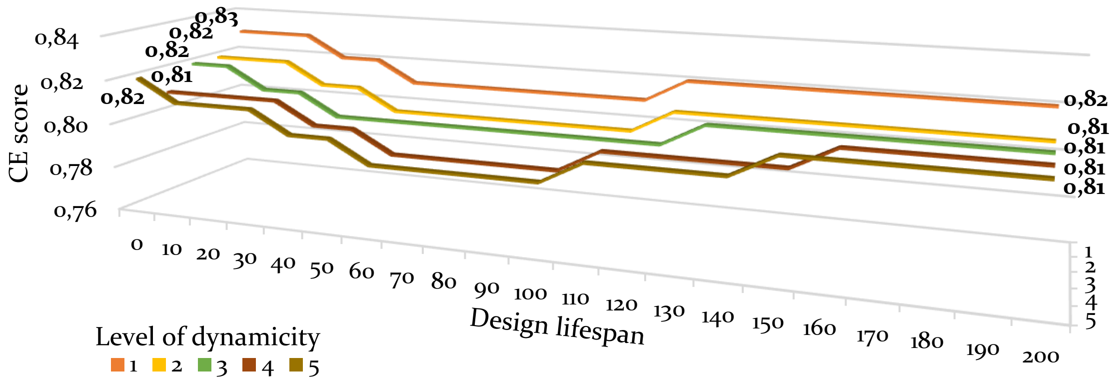



*Figure 19 – CE scores dependent on weighting settings road crossing Circulaire Viaduct*

### 4.3.5 Aggregating the indicators

The various indicators are all converted to commensurate units of measurement and received a degree of importance. Following this, weights express the individual interactions between the indicators. Next, the results of the indicators can be aggregated into a composite indicator. An important note to this aggregation is that the individual results of the sub-indicators should be transparent in order to allow for comprehensive decision-making. This transparency is guaranteed by showing not only the overall and aggregated results but also the underlying scores. By offering insights into the results per sub-indicator, bridge component, material used, functional groups discussed in section 3.2.6 and by presenting a visualization of resource flows during the bridge lifecycle, the results also show the weak and strong spots of the design. This allows for identifying design weaknesses during the bridge design process by means of the assessment framework, which indicates opportunities for circularizing the design. This application is discussed in greater depth in section 7.4.

# 5 Case study

Bridge-specific case studies are selected for demonstration, testing and validation purposes. The selection took place on the basis of four criteria: (1) the case studies should be significantly different from each other; (2) there should be sufficient data; and (3) they should be recent. Moreover, each selected case study consists of specific features that make it particularly interesting. The execution of the individual case studies is presented in appendix II. In this chapter, these case studies are briefly discussed along with the indicator results on an individual basis. The input from these case studies is used for the discussion on the validity in chapter 6.

## 5.1 Case study 1: Daelderweg – Parkstad Limburg

As part of the project Buitenring Parkstad Limburg, the viaduct in which the Daelderweg crosses the A76 motorway is eligible for revision in the V&R programme. The current structure comprises two parts: the southern part constructed in 1938, consisting of a cast-in-situ deck and a northern part built in 2005, which consists of a box girder deck. The 1938 structure needs to be replaced due to structural reasons and, furthermore, the current situation does not allow for extension of the A76 motorway with additional lanes (functional reason). Several alternatives have been developed, of which four have been considered feasible. These are: (1a) replace the old part and keep the new part; (1b) replace the old part by extending the new part; (2a) full replacement with middle support; and (2b) full replacement without middle support.

This is the first case study conducted in its full extent in my study and, next to case analysis, aims at finding and fixing errors in the framework and tool. Furthermore, particular emphasis is put on the differences between the four alternatives, since this enables to check whether the indicator outcomes meet the expectations regarding circularity. The analysis is executed with version 8 of the tool (appendix II). The main outcomes for the four design alternatives over the four main indicators and weighted total scores are shown in Figure 20.

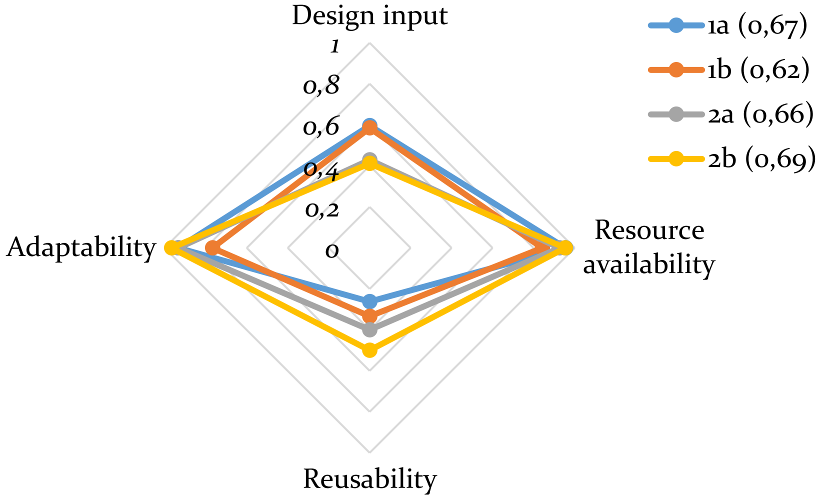



*Figure 20 – Comparison of the four alternatives on main indicator level*

Although the total circularity scores are quite similar, the comparison on underlying indicators show considerable differences. An interesting outcome is that the higher the *design input* score, the lower the reusability. This is related to the fact that the old parts are not reusable, while using old parts contributes strongly to the *design input*. Another striking fact is that alternative 1b scores considerably lower on *adaptability* than the other alternatives. That is, because the extended viaduct (partly consisting of the old viaduct) does not allow for additional lanes in the underpassing A27 motorway. The largely similar use of materials – concrete and steel – results in comparable and well-scoring numbers for *resource availability*.

All in all, this first analysis has led both to interesting case study results and new insights and errors in the model, which has proven to be an important validation step. Since this case study was the first complete execution of the model, the process of filling in the data in the tool has both led to many insights regarding usability and identification of various errors in the model. In turn, these insights led to several improvements, namely the repair of errors in links and calculation steps, transparency of results, improved colour coding, and extension of options in the *material input* part. The indicator outcomes contradict some of the expectations discussed in the start of this section, but these differences are in retrospect perfectly intelligible. This perceived discrepancy between expectations and model outcomes is a positive model outcome and shows that this analysis provides new insights considering circularity in a wider perspective than initial material use, which is often decisive in many circularity decisions.

### 5.2 Case study 2: Circulaire Viaduct

The *Circulaire Viaduct* is the Dutch name for a pilot-project modular viaduct designed for flexibility and multiple-lifecycle use. The central idea was to construct the viaduct from small segments that can be put together by reinforcement strings and bars and hence assembled and re-assembled in any desired configuration. The viaduct is currently located at a construction site of project Isala Delta close to the Reevesluis between Dronten and Kampen. Furthermore, it is planned to be moved to any other site when the construction project is finished.

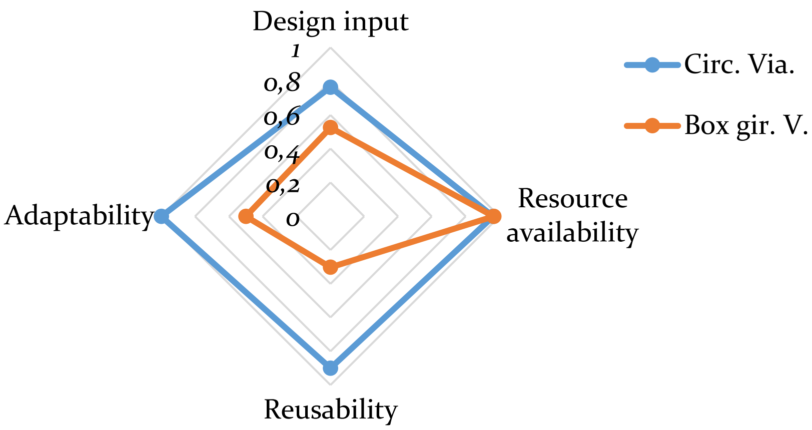



*Figure 21 – Comparison on main indicator level between Circulaire Viaduct and box girder viaduct*

For the same types of materials are used, the materials input and scarcity are quite comparable in the two alternatives (Figure 21). Given de modular and deconstructable nature of the design and the oversizing of the elements, the Circulaire Viaduct scores considerably higher on the *adaptability* and *reusability*. Given the ability to be extended, heightened and strengthened by increasing longitudinal reinforcement bars, the Circulaire Viaduct has an overall circularity score of 0.93 while the conventional alternative scores 0.49. Although the weighting is set at a road-crossing, highly dynamical area and a lifespan of 80 years, which perfectly suits the adaptable design, different weighting settings would only slightly affect the final results of the comparison (section 4.3.4).

Altogether, the designers' claim of a circular viaduct is confirmed by this analysis. However, the underlying results show room for improvement on several design aspects. First of all, the *design input* could be improved by replacing virgin materials by reused, recycled or even renewable materials. Secondly, the girder segments contain various elements that are pre-cast in the concrete and may result to pre-EoL destructive methods. By functionally separating these parts, the *disassemblability* and *reusability* could be improved.

This case study was important for both internal validity and concurrent validity of the indicator (chapter 6). Although the results above show that the indicator, indeed, measures circularity principles, it is not clear yet whether it fully measures circularity. Therefore, this anlaysis is compared to a sustainability analysis by NIBE (Van Beijnum et al. 2019a), to test the concurrent validity, which is discussed in section 6.2. An extensive analysis can be found in Coenen (2019) and is available online at the *Leeromgeving Circulair Viaduct*. However, following Figure 1, circularity is just one of the many relevant decision criteria, and a more extensive approach is required to determine whether this design approach is indeed better on the long term.

## 5.3 Case study 3: Balgzandbrug

The *Balgzandbrug* bridges the Balgzand canal by means of both a movable construction and a fixed truss span. It is located in Noord-Holland and a large part of the bridge has almost reached its EoL stage. Therefore, the bridge will be replaced within the V&R programme. The Balgzand case is used as an example in the *RWS ontwerpt* team and various design alternatives have been developed and tested using various types of materials and loadbearing techniques which are included in a separate sustainability analysis executed by NIBE consultancy and includes MKI, MCI and carbon footprint analysis, of which particularly the latter analysis is interesting to this case study (Van Beijnum et al., 2019b). The design alternatives are: (1) a truss span; (2) a steel slab bridge; a pre-stressed concrete span with (3) a concrete cover and (4) a syndiotactic poly-styrene (SPS) cover; (5) a composite alternative; and (6) in a separate study a wooden arc bridge.

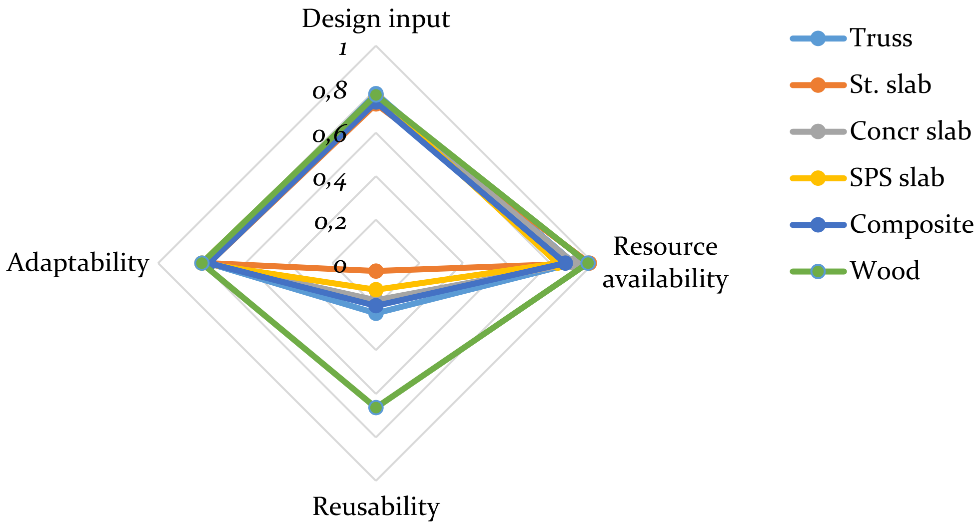



*Figure 22 – Result comparison Balgzand alternatives*

The framework is applied to these alternatives. Given the use of similar construction techniques of the slab bridges (standard, concrete top layer, SPS top layer and composite), the *adaptability* and *reusability* are in a very comparable range (Figure 22). However, the fact that also the *design input* and *resource availability* are equal is rather surprising, given the different materials used. However, for the *design input*, the underlying results show that there is a compensation between virgin, non-virgin and renewable going on. Regarding scarcity, on the other hand, the results show that, even when materials with entirely different scores are used, the *resource availability* remains above the 0.9. This indicates that the scarcity indicator is not properly scaled, resulting in a situation in which the design cannot distinguish itself by using non-scarce materials. This has led to the revision of the scaling of the *resource availability* indicator (appendix III).

Furthermore, the use of wood as a construction material in an arc bridge construction seems to have positive effect on circularity with a bridge circularity score of approximately 15% higher than the other alternatives. The fact that the wooden parts consist of fully new and non-recyclable materials is compensated for by the renewability of the material. Furthermore, the wooden parts itself can be disassembled relatively easily, which allows for reuse. Also the fact that wood is renewable and hence non-scarce contributes to the high circularity, despite the observation that all scarcity values are too close to make a difference.

All in all, the results are fairly comparable to MKI analysis of the NIBE report. However, the appliance on MCI shows entirely different results. This can be explained by the fact that the MCI neglects the types of materials used and the structural composition of products or assets. Consequently, the only way that the MCI could increase is by using reused and recycled materials, while the use of reusable, largely available or renewables materials is ignored. This is the main reason why the MCI aspects play only a very minor role in our indicator (elaborated on in appendix I and appendix VI). Therefore, it is positive that, even though completely other aspects of the design and materials are assessed, our circularity tool is largely in line with the broader sustainability assessment, while the MCI provides contra-intuitive results with a low construct validity and proves its unsuitability for circularity assessment for infrastructure assets.

# 6 Validation

The structured approach of selecting and developing indicators provides a solid basis for assessing circularity of bridges as demonstrated in the previous chapter. Yet, the internal validity of the indicators must be ensured. This step represents the *treatment validation* in the design cycle discussed in chapter 2. Also, since the case studies (chapter 5) do not cover all bridges, the generalizability is not guaranteed yet. This is ensured by means of additional case studies. Moreover, the usability of the framework is verified through expert interviews. Each improvement as a result of a validation effort can be regarded as a design iteration, following steps 1, 2 and 3 in Figure 6 in chapter 2. These iterations are discussed in appendix III.

## 6.1 Internal validity

Does the framework accomplish its purpose? This internal validity question is answered by using the triangulation approach discussed in section 2.3.3.1. First, the construct validity regarding circularity is analysed. This is followed by the analysis of the application of the framework to case studies and third, the expert involvement is discussed regarding validation purposes.

### 6.1.1 Construct validity using a gap analysis

Whether the framework grasps the concept of circularity in its broad and abstract sense is validated by using the gap analysis executed in section 3.3.5. First, the literature is studied regarding the concept of circularity. As discussed in the gap analysis, the existing indicators used by Rijkswaterstaat show various gaps with respect to circularity. The assessment framework as presented in this report should fully cover these gaps. Moreover, for some aspects regarding circularity, no indicators were presented in the literature to support bridge and viaduct designs. These sub-indicators have either been tailored from existing indicators or developed from scratch, as discussed in chapter 4. Analysing the indicator in retrospect, it fully covers both the gaps indicated by the gap analysis and the literature on circularity. Finally, Rijkswaterstaat has commissioned a report by Royal HaskoningDHV (2019), based on expert sessions in which design principles on circular bridge design have been discussed. Together with a circularity expert from Rijkswaterstaat, the indicator was compared with those principles. This comparison revealed that the proposed framework covers all circular design principles.

### 6.1.2 Content validity by means of user cases

The case studies presented in chapter 5 have provided insights into indicator improvements and allowed for determining the question whether the indicator measures what it should measure. Below, validation outcomes of these case studies are discussed in greater depth, while preliminary insights that led to design iterations are presented in appendix III.

The indicator (V10) was used by Rijkswaterstaat technical consultant Nienke Venema on a viaduct in the InnovA58 project in July 2019. She managed to fill in the tool with only making use of the *guideline* document. Apart from the fact that the tool seemed to be usable autonomously, this user case led to several suggestions to improve the usability (Appendix III). This was the first step in testing the usability of the indicator tool. Secondly, Felix Laumann, an intern at Rijkswaterstaat, applied the indicator to a 3D-concrete printed pedestrian bridge in Nijmegen, in which the printed bridge was compared to a conventional design. Apart from the results on the level of circularity, which were not surprising, on the one hand, the usability of the tool was, on the other hand, confirmed, given that he had only basic previous knowledge on circularity and civil engineering. The fact that he could use this indicator with only using the draft version of the written guideline indicates that the tool is usable for non-experts.

Thirdly, validity has been tested by means of a Master's thesis executed by Tim van Pelt. Van Pelt (2019) developed a circular design framework for bridges. In a final workshop, designers within consultancy firm Wagemaker designed bridges in a way they thought to be circular. In a second stage, the designers redesigned their bridges by making use of Van Pelt's (2019) framework. Both designs were posteriorly inserted in the Bridge Circularity Indicator tool. The results showed that the bridge circularity score increased considerably by using Van Pelt's framework. As such, the indicator validated Van Pelt's (2019) framework and, in turn, the assessment framework, which confirms the construct validity regarding circular bridge design.

#### 6.1.3 Expert interviews and expert session

Firstly, during the two years of PDEng project, various professionals, in particular within Rijkswaterstaat, were interviewed for a lot of different purposes with regard to the indicator. Some of these meetings or interviews have led to substantial improvements of the indicators, while others have provided me with certain insights on specific topics that only indirectly contributed to the indicator. However, in the end, each of these experts have strongly contributed to the development and validation process. Since in this report it is not possible to go into detail regarding each particular meeting or interview, in appendix IV a table with the experts, dates of the meetings and general topics discussed is presented. If a meeting resulted in a direct update of the assessment framework, this is shown in appendix III.

Secondly, I presented a poster on the main outlines of the framework in the CIRP conference. Although this did not result in specific input for indicator improvement, both the poster and presentation session resulted in insights into the way the CE is interpreted in the world. These differences in interpretation moved me to sharpen and reframe the formulation of circularity and its relation to infrastructure and measurement.

Thirdly, in the expert session the preliminary framework design was presented and critical aspects of this design were debated with a group of nine experts – both from the academic and professional perspectives. This has led to major framework improvement, considering most importantly the sub-indicators, the weighting, and the relation with the sustainability, the MKI and circularity goals within Rijkswaterstaat. The most important improvements are included in the list of iterations presented in appendix III.

Fourthly, I presented the outlines of the indicator at the IALCCE Lifecycle Management workshop in Rotterdam. This resulted in very interesting discussions, both on the indicator and on stimulating circular infrastructure in general. The attendees seemed to agree with the overall indicators in the framework. A main point of discussion, however, remained whether circularity has to be promoted in procurement, prescribed in contracts or even stimulated from a political level by, for example, introduce taxing on virgin materials. Despite the societal relevance of these discussions, an analysis of these considerations falls outside the scope of this study.

### 6.2 Concurrent validity

To test the concurrent validity of the assessment framework in relation to extant perceptions on the circularity concept, the framework assessment results are compared with other circularity assessment studies executed or commissioned by Rijkswaterstaat. Deviant outcomes are not necessarily wrong, but the causes of potential differences need to be analysed. Most importantly, an environmental sustainability analysis has been executed on the *Circulaire Viaduct* by NIBE. These results are shown in section 5.2. The LCA study shows that the "environmental costs" calculated by the MKI method are approximately 1.5 times higher for the Circulaire Viaduct when both structures are assumed to have a life span of 80 years. However, when a period of 200 years is considered and assuming that the Circulaire Viaduct is being reused after 80 years, in contrast to the box girder viaduct in the case study, the environmental costs of the Circulaire Viaduct over a 200 year period are only 0,75 times the environmental costs of the conventional viaduct. However, the MKI considers completely different environmental impact categories.

These conclusions are in line the circularity outcomes of the bridge circularity indicator. Indeed, oversizing of the elements results in additional environmental costs in material supply, transport, manufacturing and assembly during the acquisition phase, but, given that these costs are partly saved in a reuse scenario, both the overall environmental impact and bridge circularity is lower. Therefore, the bridge circularity indicator proves valuable, not only for potential material savings (resource efficiently-related CE), but also in contributing to wider sustainability goals. Therefore, the indicator has at least a fair concurrent validity towards CE. On the other hand, the MCI study of the Balgzand bridge (section 5.3), in which particularly material circularity was studied (Van Beijnum et al., 2019b), shows completely different results. However, given the indifference in material types, asset configuration and adaptability, it proves the unsuitability of calculating bridge circularity rather than the unsuitability of the bridge circularity indicator.

## 6.3 Personal perspective on design criteria and process reflection

One last verification check is done regarding the design criteria set in section 2.3.2. These criteria are individually reflected upon in appendix V. These contain both the criteria considering the product criteria and the PDEng design process. The discussion in appendix V reflects my point of view and may be perceived differently by other stakeholders and assessors.

# 7 A circularity assessment framework for bridges

The final tested and validated circularity assessment framework for bridges is presented in this chapter. It is based on the validated and aggregated indicators discussed in the previous three chapters. First, the framework is presented and second, the bridge circularity indicator is presented and discussed. Finally, the relation with the supporting documents is explained.

## 7.1 Circularity assessment framework

The development of the composite indicator was presented in chapter 4 and the validation process was discussed in chapters 5 and 6. However, the usability of the indicator in practice is still not guaranteed. To accomplish this, a framework to guide the entire circularity assessment process was developed and presented in Figure 23. First, both the purpose and scope of the analysis and the bridge context need to be clarified. second, the relevant data can be collected. For a full-scope analysis, data needs to be collected on the material input, the components and finally on the configuration and relations between the comments. Third, the data can be fed to the indicator in the spreadsheet. After all steps described in *Guideline to the bridge circularity assessment tool* are completed, the outcomes can be extracted and analysed. These offer ground for circular decisions in bridge design and the identification of potential improvements.

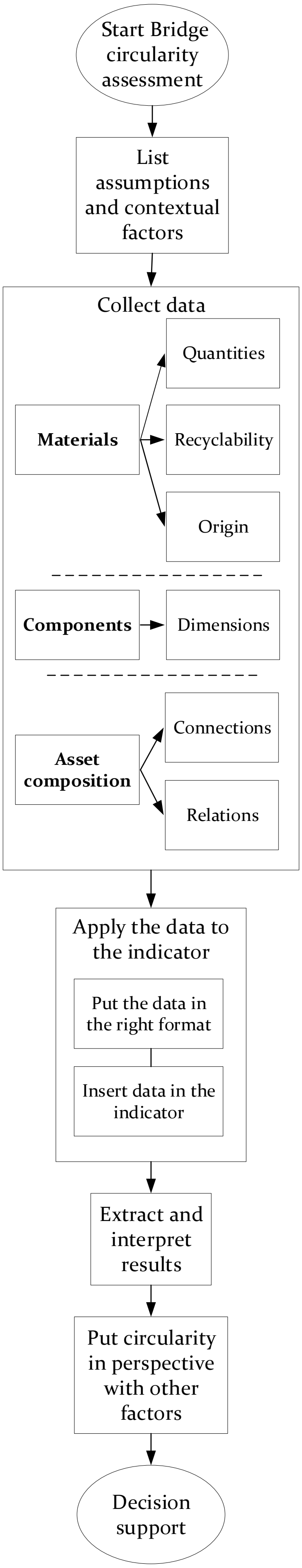



*Figure 23 – Bridge circularity assessment framework*

## 7.2 The indicator

The most crucial step towards circular decisions is the application of the composite indicator. This indicator comprises the core of the design project and consists of several design parameters, i.e. sub-indicators (appendix VI). The outline of the indicator is presented in Figure 24. However, in order to ease the data entry, an additional sheet is included in the tool in which all components, materials and material origins are collected. As such, this tab is the backbone of the circularity analysis. Furthermore, where possible, the tool is automatized in order to prevent errors and inconsistencies in data entry, which, also speeds up the tool application. When data is correctly filled in, the results appear automatically in the dashboard. Here, both the individual sub-indicator outcomes and the aggregated bridge circularity is presented. In a separate result tab, the intermediary results are clarified, including underlying indicators, distinction in components, materials, functional groups and levels of analysis. This provides both direct input for bridge design improvement and also puts the results into perspective with respect to the interactions presented in Figure 1.

## 7.3 Link with DuboCalc and other indicators within Rijkswaterstaat

Other (composite) indicators within Rijkswaterstaat are discussed in section 3.3 and appendix I. These indicators are often used in similar projects and situation as the indicator developed in this study, albeit for different purposes. Therefore, the indicator should fit within the existing landscape of indicators within Rijkswaterstaat. Most notably, DuboCalc calculates the degree of environmental sustainability of any infrastructure asset by means of the environmental cost indicator (MKI). This is largely calculated on the basis of environmental costs in an LCA-based method following EN 15804. Its final aim is to capture all issues that relate to environmental sustainability into one indicator in order to make sustainability an integral part of the procurement process within Rijkswaterstaat.

Eleven environmental impact categories are considered in the MKI. Although these environmental costs are calculated by using other databases than those considered in the bridge circularity indicator and consider generalized assumptions on construction products regarding various environmental effects, the data input regarding the asset characteristics is generally the same on the materials level. Furthermore, as shown in Figure 4 in section 2.1, the bridge circularity indicator complements the MKI by covering both the first two sustainable development spearheads: greenhouse gas reduction and resource use & waste reduction.

Next to the MKI, there is also overlap between circularity and financial aspects. Currently, LCCs – and in some projects CBAs – are executed to estimate the costs from a lifecycle perspective. For circularity, it is essential to consider these financial aspects from a multi-lifecycle perspective. That is, the residual value of asset components is not necessarily zero when the technical lifespan is reached, let alone the functional lifespan. Although various principles of the LCC and CBA can be used, current methods of accounting are unsuitable for circular investment decision-making (Korse, Ruitenburg, Toxopeus, & Braaksma, 2016). However, the principles from the proposed indicator can be used to account for circularity investment. This goes hand in hand with design-for-reuse.

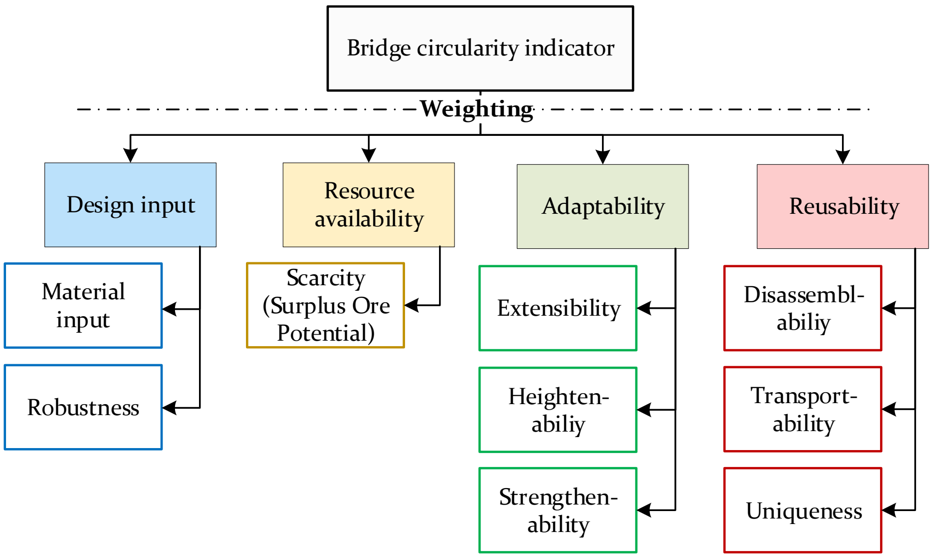



*Figure 24 – Outline of the bridge circularity indicator*

As such, the framework (Figure 23) shows the data acquisition step. This step may be combined with the processes regarding the MKI and financial aspects. As shown above, these decisions require largely the same input regarding the asset characteristics. As discussed in the separate literature review *Theoretical background on circular design of bridges and viaducts*, there are huge opportunities in the application of Building Information Modelling (BIM) and *Material Passports*. On this subject, it is worth mentioning that there are various ongoing initiatives within Rijkswaterstaat, regarding alignment of data and data structures which could benefit the indicators in sustainability, circularity and financial aspects during the entire asset lifecycle, and potentially the next one.

## 7.4 Usage types and the user

Following the applications of the framework and the connections to other indicators within Rijkswaterstaat, the various applications and target users are specified below. Particular attention is paid to the place within the decision-making processes the indicator can fulfil a role and the way weighting and aggregation is dealt with.

### 7.4.1 The framework as a design guide

The first type of use considers the framework as a guideline to design bridges and viaducts more circular. The four main parts – *design input, resource availability, adaptability* and *reusability* – indicate design principles that may broaden the designer's perspective on lifecycle thinking. Next, the designer can insert the design in the tool and will be provided with insights in materials, individual components and the various sub-indicators. This reveals flaws in the design with respect to circularity and offers opportunities for improvement regarding resource efficiency. In the case mentioned before, the user will be the designer, especially in and early stage of the project, and can both represent the client side regarding exploring opportunities for bridge circularity and also represent a contractor in a later stage with a more detailed bridge design. In this case, the aggregation of indicators is undesirable, since that may cover up the underlying design flaws and allows for compensation between sub-indicators. Therefore, transparency in the results is essential to use it as a design guide tool for identifying opportunities for circularize the design.

### 7.4.2 The framework as an assessment method

The second type of use considers the assessment of designs and comparison of design alternatives. For individual assessment, first, various case studies need to be done to give the numbers meaning. Only then, a certain score may explicitly indicate the circularity of a bridge. However, for comparative purpose, the tool is immediately valuable. By inserting various design alternatives for a similar bridge application, it becomes immediately clear what bridge scores best on (certain aspects of) circularity, which enables the client to apply circularity as a selection criterion in the procurement process. In this case, aggregation is required, since that provides a comparative outcome of the indicator. The framework users will be the designers of the draft and final designs as well as client's project managers who are responsible the selection of the contractor and determine the way the results contribute to the final scores to award the project.

### 7.4.3 The framework for formulating design requirements

The third and final way is to use the tool only for partial assessment. Sub-indicators might be translated into design criteria to strengthen the clout towards circularity in projects. For example, the project manager can decide to exclude adaptability from the tool and require the design to be extensible, heightenable and strengthenable. In that case, future adaptability of the asset is safeguarded, while merely scoring these aspects might results in compensation by "easier" measures (also known as greenwashing). It might also be the case that the client requires the contractor to reuse a certain amount of old asset parts in the new asset instead of scoring on the use of recycled and reused materials. This way of tool use should be done in the definition stage of the project and the earlier in the process these criteria are defined, the larger are the opportunities to increase circularity. The user that defines these circularity criteria or requirements is eventually the project manager. However, to increase impact, this might be taken up to higher levels of decision-making for standardizing practices regarding circularity rather than applying these in specific projects. A suitable place for this might be the *Directive: Design of Civil Engineering Structures* (ROK). However, this requires extensive research on consequences on other factors, including social aspects, LCC aspects and sustainability aspects.

## 7.5 Generalizability

It is discussed in the project scope (section 2.1) that the framework should be applicable to all fixed Rijkswaterstaat bridges. The variation in the selected case studies shows that this goal is met, but two questions arise: To what extent can the framework be applied to other bridges in the world? And to what extent can it be applied to other (civil) engineering structures?

Next to Rijkswaterstaat, the provinces and municipalities in the Netherlands own a large amount of bridges to which the same characteristics apply as to Rijkswaterstaat. Application of the framework by provinces and (large) municipalities might also give these public bodies the opportunities to procure bridges designs in a circular fashion. Even from a wider perspective, given the fact that bridges worldwide serve all the same purpose, their properties are also largely similar, as are the *Bridge Circularity 2019* aspects (section 3.2.11). Therefore, the indicator is expected to be applicable to a wide range of bridges in the world. However, several elements, such as the material mixtures and the corresponding scarcity values, might require manual entry in other parts of the world if these differ from the values applicable in the Netherlands. Regarding indicator use, it would be advisable to initially only use it in other countries in a comparative fashion, since functional requirements, technical requirements and contextual aspects are likely to differ, thereby leading to other design principles and consequently incomparable (sub-)indicator outputs.

Considering it even broader, the framework principles are expected to be applicable to other civil engineering structures with similarities in construction techniques, materials and lifecycle properties on the one hand and circularity principles for long-lifespan structures on the other. The main indicators – *design input, resource availability, adaptability* and *reusability* – are likewise applicable to, for instance, waterway locks. However, the sub-indicators might differ. For example, in order to make bridges adaptable to future requirements, they should be extensible, heightenable and strengthenable, but for locks, change in future requirements is likely to depend on other aspects – e.g. lock chamber length or water height. It could be worthwhile to study the framework applicability to other specific civil engineering structures. Expectedly, with few changes in the sub-indicators, the framework could be applied to a large variety of civil engineering structures.

The requirements for a wider range of applicable assets are the following. Firstly, the tool is most effective when the asset has clear and measurable system boundaries, both in spatial and time dimensions. These boundaries determine largely the input variables for the *adaptability* and *reusability* indicators. Secondly, the asset should be static in the sense that it does not use or produce resources during its operational stage, since this might require additional indicators that are not included in the framework.

## 7.6 Documents on framework use

Most importantly, the framework consists of the assessment tool which is a spreadsheet translation of the Figure 24. Although the structure of the underlying indicator is discussed in this report, the actual usage of the tool deservers some additional attention, both for facilitating usability and for avoiding its improper use. This is done by the guideline offered in separate report *Guideline to the bridge circularity assessment tool*. This additional document is relevant to all kinds of uses discussed in section 7.4. Moreover, each tab of the assessment tool contains a brief explanation of the steps to be taken. Furthermore, the design decisions regarding each of the sub-indicators are too extensive to be included in this chapter. Appendix VI discusses these design choices in greater depth. Also the data required for execution of the assessment is discussed in Appendix VI and is made more concrete in the *Guideline*.

# 8 Aftercare of the framework

The framework represents a static set of attributes in an inevitably dynamical environment. Therefore, the framework must capture as much as possible these dynamics to remain representative and up-to-date. As such, it needs to evolve with the concept it describes. Furthermore, as the tool developer, the author is the main expert on tool. However, after delivery, it would be important to establish a central group of experts that will be in charge of updating the framework and provide assistance to the users. Although implementation itself is not within the scope of this project, as the framework designer, the author has the most detailed view on the challenges for implementation. This chapter presents a starting point for the *treatment implementation* of Wieringa's (2014) design cycle.

## 8.1 Outlook on the impact of the framework

It is essential to consider the consequences of implementing the framework before doing so. Therefore, the impact of the framework needs to be analysed. Currently, the Rijkswaterstaat processes and practices are being reviewed to circularize linearity. The hierarchy in this process – from abstract political ambitions to clear-cut operation – is shown in Figure 3. Understanding the measurability is one of the pieces to circular decisions. Therefore, if the design is successful, the potential impact increases bridge circularity and hence contributes to Rijkswaterstaat's sustainability goals and assists in decreasing the contribution to resource depletion.

More directly, the use of the framework has some implications in practice. The framework, and in particular the indicator tool, aims to give insights into strengths and weaknesses of a design regarding circularity with respect to bridges. However, inevitable limitations on generalizability will lead to unforeseen outcomes, regardless of the amounts of tests before implementation. These unforeseen outcomes, which can be either unexpected results regarding circularity aspects or errors in the model, must be fixed in the early use phase. Lastly, the framework outcomes provide merely insights into material circularity. For the sake of a more comprehensive decision-making process, the indicator should always be used in combination with, for example, DuboCalc and LCC, following the interactions shown in Figure 1.

## 8.2 Implementation steps

To actually contribute to bridge circularity, the design should be implemented. Although implementation is outside the scope of this project, the recommendations to support a successful implementation are presented below. Meier, Ben and Schuppan (2013) explained that for adoption of such a software tool, there are various aspects that potentially cause decrease in acceptance of an innovation. Applied to the tool, the following aspects should be kept in mind.

Following Oreg (2003), lack of adequate communication of information regarding the tool might largely cause resistance to adoption of the tool. Furthermore, the information should be considered positive regarding the outcomes of the goals – in the case of this project to stimulate the transition towards a CE. Championing of the tool by both (higher) management and imployees can have a positive effect on stimulating diffusion within the organization (Meier et al., 2013). A high usability of the assessment tool might have a large impact on eventual adoption.

Furthermore, knowledge on the workings and applicability of the tool should be safeguarded. This is particularly important to the first stages of implementation. Therefore, a fixed group of Rijkswaterstaat experts will be joined into a steering group in order to: (1) act as a first point of contact for potential tool users; (2) steer the application of the tool in existing projects; and (3) fixing the errors, maintaining and updating the tool. This is an essential step in the first implementation processes after the delivery of this project.

## 8.3 Operation and maintenance

After the framework is put into service, both the dynamic nature of circularity and potential errors in the framework require adjustments to the system. Therefore, the tool must be maintainable. As the owner of the tool, its maintenance should be performed by Rijkswaterstaat. Both aspects are further discussed below.

### 8.3.1 Maintainability of the framework

Maintainability of the framework includes most notably the ability to be changed and updated. This concerns the sub-indicators as part of the composite indicators and the adjustability of individual indicators. This is guaranteed by the following measures:

- The separate document *A guideline to the bridge circularity assessment tool* provides a step-by-step guideline on the working mechanisms of the indicator.
- The calculation steps are explained carefully in appendix VI of this report
- The tool is made in Microsoft Excel, which is an easily adjustable software tool.
- Fixed and updatable definition of circularity in *Bridge Circularity 2019* (section 3.2.11).
- Consistent formatting is used to ease its use and maintainability.
- Launch of a steering group to safeguard the first implementation processes (section 8.2).

### 8.3.2 Framework maintenance strategy

The framework, composite indicator and sub-indicators consider circularity aspects as currently perceived. Since the CE concept and processes within Rijkswaterstaat are dynamic, the indicator must be kept up-to-date. To this end, a general maintenance strategy is proposed. Maintenance should be executed at least 3 months after delivery, 6 months after delivery, one year after delivery, and annually from that moment on. The higher frequency in the first year of delivery is because of the potential teething problems of the new framework. During each inspection, at least the following aspects need to be checked, and fixed if needed:

- The indicator structure must be checked and it should be considered whether each indicator still fits the current perception on circularity (and if necessary an updated version of *Bridge Circularity 2019*).
- For each sub-indicator it should be checked whether the data used, especially regarding existing databases, is still up to date. Also, the sub-indicator *disassemblability* is only partly prescribed, while extensive methods are currently being developed. If there is consensus on a most suitable method, it could be added to the spreadsheet. Furthermore, for the *uniqueness* sub-indicator to work properly, an extensive set of reference standard designs needs to be developed by Rijkswaterstaat.
- The coherence of the framework with other indicators within Rijkswaterstaat should be checked. Developments in for example DuboCalc or SLAs might require changes in the indicator. This includes changes in Rijkswaterstaat databases and data structures.

Furthermore, a final validation step by applying it to multiple user cases is only possible after the first implementation phases. Therefore, it would be highly recommendable to execute statistical analyses on indicator outcomes within the first implementation year. These analyses might generate insights that might, for example: (1) improve the weightings, (2) urge for the exclusion of largely overlapping or correlating sub-indicators; (3) urge for other data sources; or (4) indicate a need for inclusion of new or revised indicators. On the one hand, this might lead to valuable input for improvement and on the other, it might strengthen the validity and reliability. Moreover, this helps in solving the generalizability issues that inevitably result from the limited case study application in this study.

# 9 Conclusion and recommendations

In this chapter, the conclusion and recommendations of the project are presented and discussed. More specifically, the conclusion of the design product, recommendations for use and design limitations are presented below.

## 9.1 Conclusion

Rijkswaterstaat aims at a transition to a CE. The CE can be seen as a means to ban waste before 2050. The main goal of this project is to reduce the impact of bridges and viaducts on the resource depletion in order to contribute to this transition. To make these circular decisions, it is crucial to know *what* design choice is most circular. To this end, a framework is developed to assess how circular a bridge or viaduct design is in terms of material use. In contrast to existing circularity assessment methods, the framework does not only consider material flows, but also future change of functional requirements.

A composite indicator was presented in this report that measures circularity following the definition of *Bridge Circularity 2019* (section 3.2.11). The composite indicator measures circularity of a bridge or viaduct design on four major aspects: (1) *design input*: the types and origins of the materials used to construct the bridge and the robustness of the design; (2) *resource availability*: the scarcity of the materials used; (3) *adaptability*: the extent to which the bridge or viaduct is able to adjust to changed functional requirements; and (4) *reusability*: the extent to which the bridge or viaduct is able to be reused in a new situation. These four indicators, including various sub-indicators lead to an aggregated level of circularity. The assessment framework was developed by means of the DSR approach and its design was tested and validated by means of case studies and expert sessions. Next to revealing opportunities for design improvement, these case studies showed that the tool is able to generate a level of circularity of the bridge design and reveals clear insights in the differences in circularity in bridge design alternatives.

The composite indicator is operationalized by means of a spreadsheet in which the design parameters can be defined. To help making bridges and viaduct more circular, the resulting outcomes can be used in three different ways. *First*, the indicator can be used as a design guide. In various ways, the spreadsheet tool represents the underlying results and helps the designer to identify weak spots of the design with regard to circularity. *Second*, the framework can be used to compare and assess designs and design alternatives. This enables decision makers to include circularity as a selection criterion in the procurement process. *Third*, the indicator makes the various aspects of bridge circularity transparent. This can support clients to define circular design requirements. The client can also use the tool for setting requirement to prescribe a minimum circularity score for a particular circularity parameter or bridge aspect. In these three ways, this project contributes to the goal of creating the possibility to consider circularity principles in the bridge design and procurement process.

## 9.2 Recommendations for use

From the conclusions presented above, various recommendations can be made with regard to the use and conservation of the framework in practice. *First*, the framework should only be used for the purpose of quantifying the level of material-related bridge circularity in order to decrease the depletion of non-fuel resources. If a project team aims at considering circularity as a part of the sustainability domain, the framework should be used next to other sustainability indicators. *Second*, the framework should initially be used by the client in the pre-contracting phase to learn and further validate the framework and tool. Using it in this phase as a design guide will offer insights into both the indicator use and circular bridge design. Only then, the framework can be used for assessment and selection purposes. *Third*, CE is an evolving concept. By using the *Bridge Circularity 2019* definition, we made it specific, but it is strongly advised to update and maintain the framework regularly to keep the framework aligned with the principles of CE.

### 9.3 Limitations and future work

The foremost limitations of the framework and resulting suggestions for future research are inherent to the scope of the project. These include both the focus on material-related CE aspects and the mere inclusion of bridges and viaducts owned by Rijkswaterstaat. Yet, several limitations relate to the way how this project was executed.

*First*, using case studies for feedback, the final version of the framework design was developed through various design iterations. However, only three major case studies were executed alongside four smaller ones. Therefore, not all possible bridge designs were tested, which might result in surprising results when applying the framework to new cases regarding, for example, material types, connection types or contextual factors. Although each validation step supported the choice of the four main indicators, the underlying sub-indicators and weightings might leave room for improvement. Therefore, it is recommended to increase the amount of case studies and include bridge types that were not studied yet. Above all, implementation in practice would effectively reveal flaws or impracticalities of the framework.

*Second*, various sub-indicators consist of statements that have to be proven by design to enable the designer to score on circularity. Despite a bridge might be designed, for example, to be extensible or disassemblable, it is hard to prove that the bridge will be extensible or disassemblable several decades from now. For example, rust or structural degradation can lead to a loss of properties regarding adaption or reuse. Therefore, additional research is needed on a technical level to improve the assessment of technical specifications in relation to those indicators.

*Third*, the proposed indicator was only tested by designers that genuinely aim to assess the level of circularity. However, in procurement practices, the main goal for market parties is to win the tender. This goal might conflict with the circular intentions of the client and can, if not managed well, result in greenwashing. Several measures are taken to present misuse of the indicator, such as, a two-layered protection of the spreadsheet, the application of widely-acknowledged databases and the required design-based proof that has to be delivered by the designer with the circularity statements. However, additional work is required to test whether the assessment framework is able to withstand opportunistic behaviour.

*Fourth*, the framework assesses the circularity of the design on the basis of currently available techniques. However, the rate of innovation regarding recycling and reuse techniques is high and, therefore, the actual design choices might have different impacts on the future reuse and recycling of materials from those initially anticipated. Although this is, by principle, inevitable, additional foresight and innovation studies might reveal trends that could be included in adaption, recycling and reuse potentials considered by the framework.

*Fifth*, a more general limitation to the framework is that it just provides the opportunity to include circular principles in bridge and viaduct designs. However, the whole system in which it operates is based on linear resource flows. To achieve circular practices, changes at more fundamental levels, including institutional, legislative and organizational, are required. Although the framework presented in this report provides a good start for circular design practices, additional research is required to conceive circular practices that leverage the transition towards a circular infrastructure sector.

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# Appendices

# Appendix I: Discussion of existing performance indicators

Performance indicators are used for both assessing bridges within Rijkswaterstaat and in literature for indicating a degree of circularity. Below, these two groups of indicators are discussed. This elaboration is used as input for section 3.3.

## Bridge performance indicators within Rijkswaterstaat

Currently, indicators are used in several stages regarding bridges. Since one of the preconditions of the outcomes of this project is that it should fit within existing indicators (section 2.1), the existing indicators within Rijkswaterstaat should be listed and analysed. For existing structures, there are several indicators that determine maintenance and operation measures. When it has been decided that an asset has reached its EoL stage, a new set of indicators plays a role. If the asset is to be replaced, new, design-oriented aspects are measured through a new set of indicators. Since bridges are considered from a multi-lifecycle perspective, the design indicators are placed after the EoL phase, rather than before the operational phase. These three phases are distinguished below. Bridge lifecycle processes are discussed in more depth in section 3.1.2.

Within Rijkswaterstaat, several indicators are used for the other aspect to be used in, for example, design, asset management practices and contractor selection procedures. Lifecycle costs are considered by applying LCC and environmental are considered by means of an applied and simplified way of lifecycle assessment (LCA) in the software tool DuboCalc with environmental cost indicator (MKI) values. Both methods present a monetary output. As part of asset management practices regarding V&R, there are several performance indicators that currently are used for prioritizing and decision support. First of all, monitoring and inspection methods are used for determining the asset state and expected remaining state of the asset. Moreover LCC is used for determining the most cost-efficient solution over the lifecycle. Further, environmental impact of design choices is calculated through the MKI.

### Asset management indicators

Regarding asset management, Rijkswaterstaat has developed several service level agreements (SLAs). These include all input factors for decision-makers in asset management processes, among which the indicators (Van der Werf & Bosman, 2015). Since it is aimed at the entire road network rather than specific assets, technical aspects, such as, structural safety and asset maintainability are not included in this indicator. Also, costs and environmental impact are not included in the SLA list. These are aimed at the entire network of main roads and includes bridges and viaducts. Indicators used in the SLA are:

- Availability
    - Asset availability — Time/share
    - Asset availability rush hour — Time/share
    - Loss of hours for road users — Time
    - Traffic disruptions due to asset management activities — Share
- Safety
    - Road friction, rutting and ice control — Test-specific
    - Fatalities and severe injuries — Number
- Data availability and predictability
    - Availability of data for external stakeholders — Share
    - Predictability of travel times on the national routes — Standard deviation
- Sustainability and social aspects
    - Excessing noise standards — dB

### End-of-life indicators

Whether or not an asset is considered to have reached its EoL depends on several factors. These factors are revealed by indicators. Traffic-related, the *Hoofdwegennet indicator* (road network indicator) was developed (Van Mourik & Schaap, 2016). The indicators allows for prioritizing based on traffic flow. Since bridges are part of the network, decisions on revising a road often results in functional removal of existing infrastructure assets. Bridge-related, structural safety plays a major role. Internal Rijkswaterstaat guideline assessment of assets (RBK) provides, next to European and Dutch legislation, rules to which every bridge should comply. Often, the decision to remove or maintain the bridge is financially motivated: if it becomes too expensive to maintain the bridge in line with the standards renewal is requested.

### Design indicators

Designs are usually focussed on cost-effectivity. The leading criterion is to fulfil its function given its specific boundaries and requirements. Based on these boundaries and requirements, Rijkswaterstaat develops project-specific requirements and low-detail reference designs. Market parties can make their offer by providing a design with its costs. Usually, the most cost-effective alternative wins the tender. As such, the decision is merely a financially motivated. Often, this is based on lifecycle costing (LCC) methods. Depending on the extensiveness of the LCC, also social and environmental factors can be monetarized and included.

Recently, design indicators are developed that provide market parties with opportunities to distinguish themselves with designs on for example aesthetics and environmental impact by offering discounts for outstanding proposals. The leading set of indicators to calculate environmental impact within Rijkswaterstaat is captured in the MKI. This enables a market party to score with an environmental-friendly alternative. Nevertheless, many circularity aspects are still lacking. Further, the construction time and accompanying traffic disruption is considered in most cases, resulting in significant fines for time overruns. As a result, a market party can score on fast and cheap construction techniques. These can work counterproductive to the lifecycle-oriented circularity appraoch.

## Difficulties in measuring circularity

Circular Economy (CE) assessment literature is mainly concerned with the macro level and performance indicators are often aimed at this level (e.g. Di Maio, Rem, Baldé and Polder (2017), Smol, Kulczycka and Avdiushchenko (2017) and Ellen MacArthur Foundation and Granta (2015)). Therefore, performance indicators should be developed to allow for assessment on an object/asset level, specifically regarding bridges. However, macro-level indicators can be used as a starting point for prioritizations and also project indicators – mostly related to other fields – will be studied to be tuned towards measuring circularity.

It has been argued by Ellen MacArthur Foundation and Granta (2015) that "[...] there is no recognised way of estimating how effective a product or company is in making the transition from a linear to a circular mode of operation, nor are there any tools supporting such measurements." Moreover, Haupt, Vadenbo and Hellweg (2017) argued that currently used rates are still not suitable as circularity indicators, since secondary resources and information on eventual destination are not included. Nevertheless, since 2015, several researches have attempted to develop methods to overcome this issue. Linder, Sarasini and van Loon (2017) have developed a method that calculates the fraction of recirculated materials and products. However, it does not distinguish between the levels in the waste hierarchy, nor does it include other circularity-related topics, such as toxic materials and environmental impact.

The main difficulty in measuring circularity of bridges and viaducts is that it should be placed into perspective to other factors, as it is merely one of the criteria for the asset to its qualitative assessment as discussed in the introduction chapter. Therefore, it should be set up as a metric of low dimensionality, i.e. translating circularity into a single output parameter (Linder et al., 2017b). Therefore, CE aspects should not overlap with environmental impact in general and lifecycle costing, while it entails some large common divisors. Moreover, micro-level indicators must be developed (sub)sector-specific. There is not one perfect indicator for all entities in the world. For finding suitable bridge-specific (or more general infrastructure asset-related) indicators, the interfaces between bridges and CE are taken as a starting point (section 3.2.9)

## Existing circular material metrics and indicators

Despite the lack of comprehensive circularity indicators that are suitable for bridges, there are several methods of varying extensiveness that are studied for assessing the level of circularity. These are discussed in this section.

### Lifecycle assessment-based circularity assessment

Lifecycle assessment-based (LCA) techniques are also used for measuring circularity. However, these attempts often consider circularity as a part of sustainability and have consequently a poor construct validity towards CE. An example is Scheepens, Vogtländer and Brezet (2016) who used the LCA-based Eco-cost Value Ratio (EVR) to analyse potential negative environmental effects of system-level business initiatives. It considers, costs, eco costs and market value. Next to the EVR, it includes the so-called Circular Transition Framework, which describes stakeholder activities required for the transition towards sustainable business models. Major drawbacks of this approach are the labour intensity and the construct validity regarding CE. Moreover, it considers products as its smallest units, rather than its components and materials. Finally, LCAs make assumptions on the lifecycle stages, while a bridge lifespan exceeds the foreseeable future.

### Material flow analysis

A system with its boundaries has an input and output of materials while the system takes or adds value to the input. Since a CE is all about closing material loops – and hence reducing material input and output – one of the most self-evident circularity measurement methods is material flow analysis (MFA). In terms of material mass (often not considering specific qualities of the materials), the flows and stocks of the various materials within the defined system are analysed and quantified (Brunner & Helmut, 2005). Although the MFA approach is close to the LCA approach, the focus of MFA is mostly on particular materials, from raw extraction to waste instead of single products. As such it is more suitable for addressing, for example, remanufacturing activities where materials are reused in varying (types of) products than an LCA. However, LCA and MFA may be used complementary. While LCA strives for complete insights in flows of substances regarding a product and considers impact categories, MFA strives for transparency and manageability of material flows (Gregory & Kirchain, 2006).

### Material flow cost accounting

Close to the MFA, the material flow cost accounting (MFCA) considers material flows, albeit in monetary values rather than mass values (Christ & Burritt, 2016; Guenther, Jasch, Schmidt, Wagner, & Ilg, 2015; Nakajima, Kimura, & Wagner, 2015; Zhou, Zhao, Chen, & Zeng, 2017). Bierer, Götze, Meynerts and Sygulla (2015) proposed to use integrated LCC and LCA on the basis of MFCA. Zhou et al. (2017) argued to use this MFCA method as a basis for measuring circularity. Since LCC and LCA are already applied within Rijkswaterstaat, an option could be to develop a suitable application of MFCA to bridges and viaducts and their elements.

One of the solutions is to purely consider the material flows in the MFCA. MFCA originates from the process industry and is in that industry widely used for cost calculation (Zhou et al., 2017). MFCA includes materials, energy and system costs, which are classified into positive and negative products. This gives insights in relative improvements on a material flow level. Unlike traditional accounting systems, monetary and physical units are linked in the analysis. The method considers the relationships between accounting, environment and information management. As a result, value is assigned to by-products and waste. This principle can be used in order to value recycled and recyclable, and reused and reusable materials in assets.

Rieckhof and Guenther (2018) see this MFCA as "[…] a tie between LCA and LCC", which offers an integrated evaluation over both the lifecycle and supply chain. Therefore, combination of LCA and MFCA might be suitable for gaining insight of resource-related aspects in perspective to costs (integrated LCC). In the basis, MFCA consists of three main steps: (1) modelling the flow structure; (2) quantifying the flows in physical units; and (3) monetarily appraising the flow system (Bierer et al., 2015).

### Resource duration

Another perspective put forward in literature is from resource retention through the longevity indicator (Franklin-Johnson, Figge, & Canning, 2016). They stated that "if current practices focus on the reduction of negative burdens and not the comprehensive vision of material and product use (independent of their burden), then they are perhaps inadequate for guiding decisions that are at the very heart of Circular Economy, and which centre on retaining materials in productive use and thus their ability to create value for as long as possible. Hence, any measure to evaluate corporate actions with respect to Circular Economy should be based on material and/or product longevity. Such a measure is important to allow practical application at a corporate, as opposed to an industry level, so as to enable managers to visualise their contribution to a Circular Economy. […] Existing measures do not lend themselves to this task and one of the aims here is to close this gap".

Longevity and circularity are in this measure in a means-ends relationship. Circularity does not have any intrinsic value, but its goal is to increase the duration of which a resource provides value (Franklin-Johnson et al., 2016). The asset consists of various of which a part is unchanged from construction to end-of-life and a part changes during its lifecycle. Three temporal calculations to establish lifetime lengths between two events and two directional calculations (to establish the flow of the product and/or materials) allow the longevity to be calculated. These calculations follow a systems model of the assets and, thus, is design-specific. For every systems element, split-up in resources, the indicator delivers an outcome. As such, it overlaps MFA, but it moreover entails value retention of components with its materials.

### Material Circularity Indicator

One of the most comprehensive micro-level circularity indicators is the Material Circularity Indicator (MCI), which consists of the linear flow index in combination with additional use intensity indicators (Ellen MacArthur Foundation and Granta, 2015). The following inputs are used, being: (1) input in the production process; (2) utility during use phase; (3) destination after use; and (4) efficiency of recycling. The linear flow index is a variation on the MFA. It merges the different materials and components into a single numbers. For compensating for material recovery, it uses an efficiency index. Moreover, the utility factor is applied, which is an expert judgement-based estimation of average lifespans.

Further, complementary risk and impact indicators for products are offered alongside the MCI to determine other impacts of interest next to circularity and further insights into potential risks in relation to business priorities. It offers to assess circularity both on product and company level. The MCI is moreover operationalized in a web tool. A major drawback, however, is that knowledge on EoL destinations is required, while this is often lacking regarding bridges.

#### Circular Economy Index

The Circular Economy Index (CEI) is a macro-oriented metric for measuring circularity, which considers the share of recycled EoL products in relation to the material value (Di Maio & Rem, 2015). It compares material value of recycle processes to new versions of the same product and focusses merely on recyclability. Consequently, the largest drawback is the neglect of other possibilities in the waste hierarchy, such as refurbishment and reuse. Moreover, this index focusses largely on company level and uses information from financial reports and national statistics agencies for calculating the level of circularity on meso and macro levels. Di Maio and Rem (2015) argue that the largest benefit of this method is the simplicity and costs of use in relation to, for example, LCA and MFA studies. Of course, in each measurement method a trade-off exists between complexity and construct validity.

#### RISE product-level circularity metric

The RISE Swedish research institute has developed a product-level circularity measure. It uses the ratio of recirculated economic value to the total product value. It uses value chain costs as an estimator of the value. As such, it makes largely use of the MFA method. However, this circularity metric fails to include the circularity for future circularity, including *reusability* and *adaptability*. Considering bridges, these aspects determine largely the future waste generation.

### Measuring circularity beyond material usage

By determining the material flows and resource duration in the previous sections, only the material use side is covered. However, circularity includes more aspects that determine to which extent a design is future-proof in relation to recourse use. Two major aspects are adaptability, and reuse and recycle potential. Those are not clearly covered by most of the methods presented in the previous section, but are considering long-lifespan assets equally important for closing material loops.

#### Asset adaptability

Material flow calculations are largely dependent on future predictions regarding, for example, lifespans and traffic intensities. For bridges and viaducts, the future is highly unpredictable from a functional perspective and, as a result, a change in for example traffic density, structural safety regulations or connected infrastructure, can lead to demolition of an asset before its technical EoL. The degree to which a civil engineering asset is able to adapt or transform according to future changes largely determines the extent to which resources can be retained in their current value within an asset. Measuring this resilience to future changes is a largely undiscovered field and scientific literature on the topic is still largely lacking. However, indicating the assets' ability to absorb future functional change is essential to determine circularity of an infrastructure asset.

#### Reuse potential

From a resource perspective, it is measurable to which extent recycled materials or reused elements are used in an asset. However, when the circularity of an asset is considered, it is also essential to consider the assets, elements and materials to re-enter a next lifecycle according to the "9Rs" described in section 3.2.2. The degree to which this is possible depends largely on the use of the materials and the construction methods (Schwede & Störl, 2016). This is largely embedded in the idea of design-for-disassembly (DfD) and design-for-deconstruction as applied broadly in the building and utility construction sector (Sanchez & Haas, 2018). Kibert, Chini and Languell (2001) argued that besides material durability, desirability and longevity, retrievability – largely consisting of *disassemblability* – is the key to using materials in construction as future source of raw materials. As a result, reuse of construction materials will increase through design-for-deconstruction and design-for-disassemblability.

Next to these technical aspects, other factors are essential to enable efficient reuse. Rios, Chong and Grau (2015) define principles to DfD, being: (1) proper documentation on materials and methods regarding deconstruction; (2) design accessible connections and jointing methods and minimize e.g. chemical and welding connections; (3) separate non-recyclable, non-reusable and none-disposable items; (4) avoid constructional complexity and encourage simplicity and standardization ; and (5) design that considers labour, safety and productivity. Turning these principles into criteria, these five points, and especially the first four points can be used as indicators for *reusability* of a designed construction.

This "deconstructability" (in some literature referred to as disassemblability) determines to a large extent to which degree elements can be reused and the easiness of recycling. This is closely related to the adaptability: an easily disassemblable construction is adaptable. Moreover, it is related to the type of connections (mechanical vs. chemical) and it also indicates degree of modularity. Essential to this deconstructability is a well-thought design including materials that can be disassembled and used on another project. This principle can be applied by using reuse potential and recycling potential for the several elements (Beurskens & Durvisevic, 2017). These potentials depend on several factors, such as, but not limited to, material use, element couplings and links, element dimensions and level of standardization.

Reuse potential is also proposed to be used as indicator for managing wastes as resources. Park and Chertow (2014) argued that the reuse potential indicator can be seen as an effective communication tool to share information about technical quality or maximum *reusability* of a waste material. However, the laborious calculations of this potential remains a large pitfall for large-scale implementation. Yet, simplified versions may be implemented complementary. The reuse potential of construction and demolition waste was also studied by Iacovidou and Purnell (2016), who listed reuse potentials of specific materials and analysed the benefits of DfD in relation to reuse. Furthermore, they provided strategies for implementing DfD and reuse of materials in construction. However, actual calculation of a reuse potential is not being found in scholarly literature on infrastructure or civil engineering structures.

### Recycling potential

Other than in reuse, recycling does not require careful deconstruction, as long as the recyclable materials are separable. The most important requirement for recycling is therefore the choice of materials. The materials must therefore be non-toxic and easily processable. Furthermore, there should be a demand for the materials and the materials should be well-produced in the first place. Recyclability of materials broadly studied in literature and databases and industry averages are available in literature and practice.

## Units of measurement

Although there are, as presented in the previous sections, various ways of determining level of circularity, the units are often comparable. The most prominent units of measurement are mass (of materials and components), time (lifespans), watts (i.e. total lifecycle chain of direct and indirect energy consumption [also emergy]) and money (value and lifecycle costs). These units are measurable in quite straight-forward ways, although detailed calculations can become very laborious. However, one of the largest challenges is how to aggregate these values into a single value. Moreover, these units are not suitable for considering the hierarchy of waste treatment. Linder et al. (2017) argued that the "[…] economic value of recirculated elements is a reasonable unit upon which to base a robust and theoretically consistent aggregation principle." Use of this unit for aggregation accounts for price changes as result of scarcity, material price increases as result of added value when being part of products and feasibility of reliable estimations of shadow prices.

A large shortcoming of the units used is that it mostly considers merely the input side. As a result, most existing indicators and metrics merely consider the input side towards products. Although this is legitimate for many consumer products, for bridges this renders insufficient. Especially since the client is in most cases also asset manager and financer, it is equally important that assets can be managed, maintained, operated and removed in a circular way. Suitable metrics include therefore lifespan extensibility, deconstructability, material separability, material recyclability and reuse potential. Suitable units for these metrics are mostly mass, although a quality component should always be included. When these metrics are aggregated with the input-side metrics, the mass should be translated to material value, especially since remaining metrics and indicators within Rijkswaterstaat give also a monetary value as output. Nevertheless, also mass as a unit of measurement has a major drawback, since it does not differentiate between the impact of the material on world-wide resource depletion. Section 3.3 in the report shows a detailed gap analysis using the considerations discussed in this appendix.

# Appendix II: Case analyses

Below, the application of the indicators to the cases is discussed for each case individually. The cases and case contexts are summarized in chapter 5 in the main report, which is used for design iterations and validation of the assessment framework.

## Daelderweg – Parkstad Limburg

As part of the project *Buitenring Parkstad Limburg*, the viaduct in which the *Daelderweg* crosses the A76 motorway will be revised. The current structure exists of two parts: the southern part constructed in 1938, consisting of a cast-in-situ deck and a northern part built in 2005, which consists of a box girder deck. The 1938 structure needs to be replaced for structural reasons and, furthermore, the current situation does not allow for extension of the A76 motorway with additional lanes. Therefore, the whole situation is in need for revision. The availability of design alternatives makes it interesting as a validation case, since it allows for relative comparison of indicator outcomes. Six alternatives have been developed in a preliminary study, which are:

- 0: Fix up current structure – no replacement
- 1a: Replace the old part and keep the new part
- 1b: Replace the old part by extending the new part
- 2a: Full replacement with middle support
- 2b: Full replacement without middle support
- 3: Remove current assets and built a new one on another location

Four of the six alternatives have been considered in our analysis for the new situation and in the actual project, the final choice is picked based on costs, sustainability, safety, future-proofness, traffic disruption, feasibility and maintainability. A feasibility study has revealed that options 0 and 3 are not worth considering because of both reasons of structural safety and procedural feasibility. Therefore, also in this case study, only alternatives 1a, 1b, 2a and 2b are analysed on the aspect of circularity.

### Goal of this case study

This is the first case study in which the indicator is fully employed. This case study is, next to case analysis, aimed at finding and fixing errors. Furthermore, particular emphasis is put on the differences between the four alternatives, since this enables to check whether the indicator outcomes meet the circularity expectations. The nature of the asset, a motorway-crossing viaduct, covers a major share of the bridging structures in the Netherlands. The goal of this case study is to improve the indicator design and to gain understanding of the indicator outcomes.

### Case study characteristics

In the table below, the characteristics of the case study execution are shown.

| | |
|---|---|
| *Name viaduct* | KW06 |
| *Project* | Buitenring Parkstad Limburg |
| *Project stage* | Preliminary design stage at moment of analysis |
| *Type of analysis* | Comparison between design alternatives |
| *Data source* | Aannemerscombinatie BPL and Rijkswaterstaat |
| *Data quality* | Reliable, but in an early design stage (low level of detail) |
| *Data retrieval* | June 25th, 2019 |
| *Start analysis* | July 8th, 2019 |
| *Finalization analysis* | August 9th, 2019 |
| *Version of the indicator* | Executed with version 8 of the tool (V8) |

## Case study results

In this section, the case study results are discussed. Both the process of execution and model outcomes are shown.

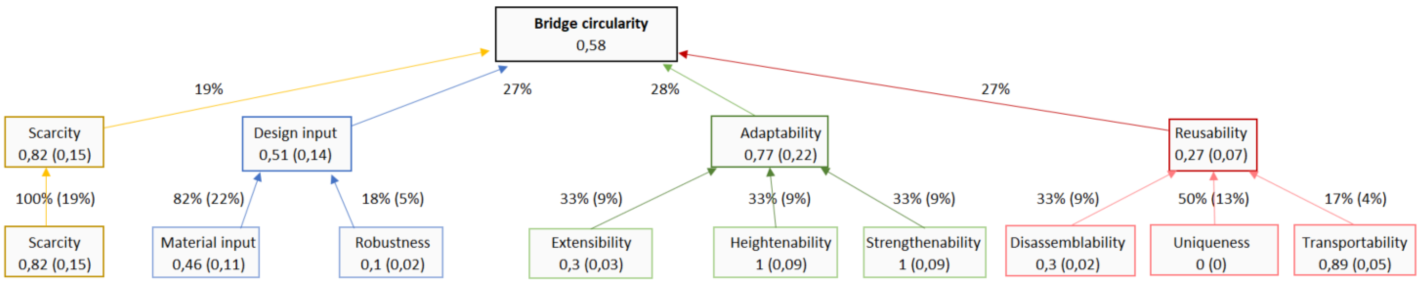
Process of execution

The first step has been the data collection. For the project is still in an early design stage, little detail on the small components and materials has been available. Therefore, estimations have been made based on industry averages, which have been used equally for all design alternatives. Next, the quantities and materials have been determined for all individual components. Due to a lack of information, origin of materials has been based on industry averages. In the alternatives where the 2005 bridge is reused, the old bridge is also inserted in the indicator, while *material input* is fully set on *reused*. Parts of the 2005 structure that do not meet legislation, such as the railing, have been considered equal to fully new components in terms of materials and origin.

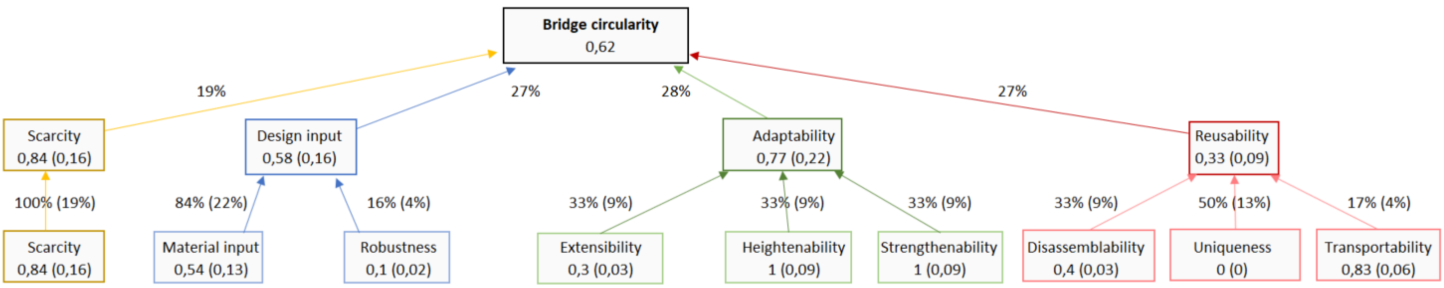
Predicted results and actual outcomes of the model

Next to the usefulness of the exercise of filling in the model, the model outcomes need to be studied. My CE expectations of the four alternatives are discussed and these are compared to the actual outcomes. Firstly, I expected that alternatives 1a and 1b would most circular because of the large amount of reuse. Nevertheless, the adaptability of alternatives 2a and 2b is expected to be higher, which results in a higher circularity. Yet, I expect this slightly higher adaptability not to compensate for the large amount of reuse. However, since alternatives 2a and 2b reuse a large part as well, such as abutments and foundation, these benefits might not be decisive. Between alternatives 1a and 1b, I expect that there will be nearly no difference in circularity, since the rates of reuse are quite comparable as well as the possibilities to adapt and reuse. Below, the actual indicator outcomes are shown for the four design alternatives.

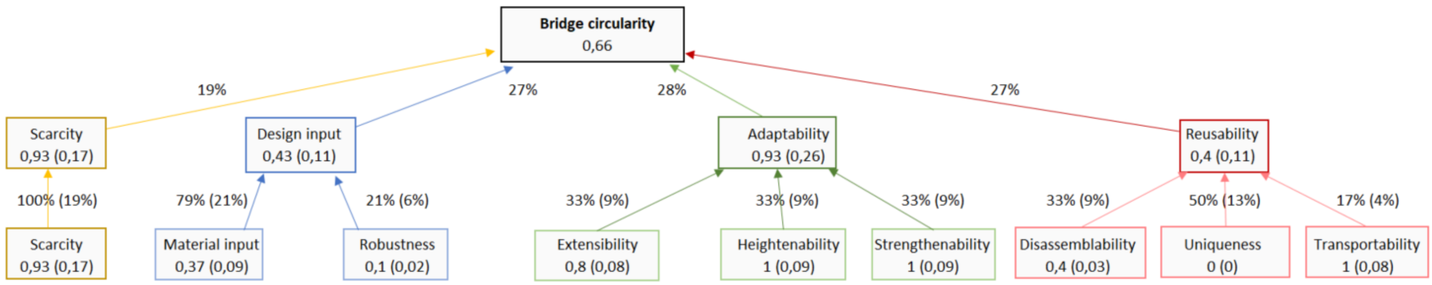
1a – Replacement of the 1938 part by new viaduct and retain the 2005 part



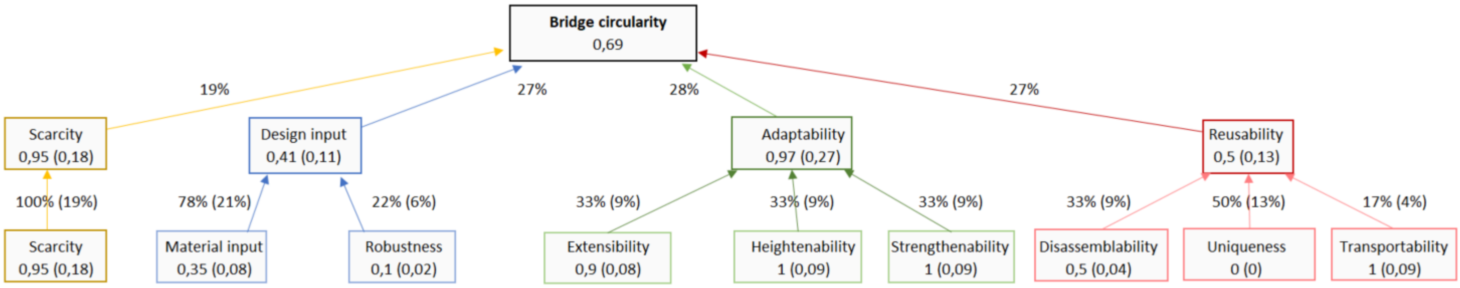

1b – Replacement of the 1938 part by extending the 2005 part



<u>2a – Full replacement with middle support</u>




<u>2b – Full replacement without middle support</u>




The results show that – although *design input* is lower in alternatives 1a and 1b – alternatives 2a and 2b have a higher circularity score. The largest differences are visible in the fact that a completely new viaduct allows for extension of both the viaduct and underpassing road, while alternatives 1a and 1b are restricted to the span of the current 2005 part. Furthermore, the 1938 part contains more steel than the new part, which leads to a slightly higher scarcity and therefore lower *resource availability*.

## Evaluation

Since this case study has been the first full execution of the model, the process of filling in the tool has both led to many insights regarding usability and the identification of various errors in the model. In turn, these insights led to the improvements discussed in the paragraph below. The indicator outcomes contradict some of my expectations discussed in the start of this section, but these differences are in retrospect perfectly intelligible. This perceived discrepancy between expectations and model outcomes is a positive model outcome and shows that this analysis provides new insights considering circularity. It puts the results in a wider perspective than material use, which is often decisive in circularity decisions. Note that the actual material savings are only known after the lifespan of the viaduct has ended. With no change in functional demand in 100 years, the reuse option (1b) would have been more resource-efficient after all. Yet, this indicators stimulates future-proof designs without excessively using scarce and virgin materials.

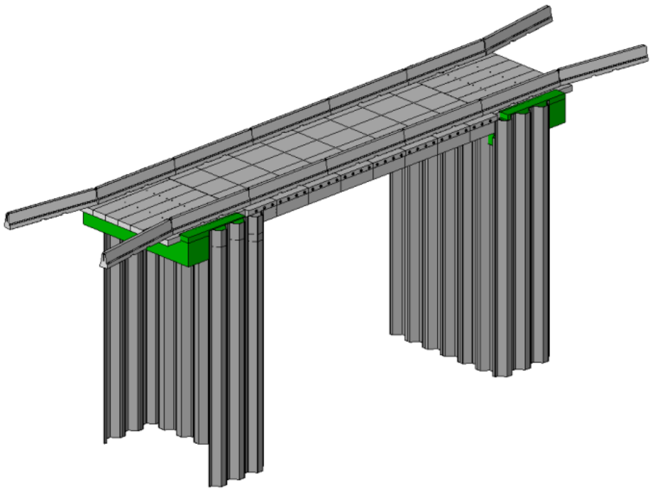
## Updates and improvements on the assessment framework

The case study has been applied to V8 of the tool and has delivered various insights that led to V9 and eventually to V10. These improvements are the following. First of all, mistakes in formulas, links and calculation steps were identified and fixed. Secondly, the case study showed that the results are still not transparent. Therefore, insights are provided in the circularity scores of individual components, materials and functional groups. This allows for identifying the weak spots of the design. Thirdly, colour coding in the *Materials* tab has been automated more consistently to improve user friendliness. Fourthly, the option has been included to indicate renewable virgin materials so that use of bio-composites, wood and other materials that do not affect depletion of finite resources are preferred over finite virgin materials.

## Circulaire Viaduct

The *Circulaire Viaduct* is the Dutch name of a viaduct which is designed for flexibility and multiple-lifecycle use. The central idea was to construct the viaduct from small segments that can be put together by reinforcement strings and bars and hence can be assembled in any desired configuration. The viaduct is currently located at a construction site of project *Isala Delta* close to the Reevesluis between Dronten and Kampen, and is planned to be moved to any other construction site when the construction project is finished. It has been designed and constructed in the shape of a pilot project by engineering firms (Van Hattum en Blankevoort), suppliers (Spanbeton) and in cooperation with Rijkswaterstaat. Furthermore, several other parties, such as TU Delft and Diana, have been consulted on the testing, calculations and modelling exercises. Currently the viaduct is monitored and analysed for evaluation and potential wider adoption.

The configuration of the Circulaire Viaduct is the following. The abutments are made of sand which is held together by sheet pile walls. Furthermore, the viaduct consists of five girders which are each built up from seven pre-cast segments. External longitudinal pre-tension cables keep those seven segments together. The five girders are kept together by transverse reinforcement bars which are applied on site. Each segment is designed such that it includes the necessary installation techniques, sensors and standardized interfaces and the interfaces are filled with removable concrete mixture.



### Goal of the case study

The Circulaire Viaduct is being extensively analysed on its level of sustainability by consultancy firm NIBE, which also included circularity aspects in the MCI and the LCA-based MKI. To test the indicator's concurrent validity, it is an excellent case to compare the indicator outcomes with the findings of sustainability consultancy firm NIBE. This analysis is discussed in section 6.2. Moreover, the claim of the designers and developers of the viaduct to be circular is interesting to study by means of the assessment framework. Finally, this analysis is another exercise to find and eliminate errors in the indicator tool.

### Case study characteristics

In the table below, the characteristics of the case study execution are shown.

| | |
|---|---|
| *Name viaduct* | Circulaire Viaduct |
| *Project* | L202801 |
| *Project stage* | Operational - viaduct half a year in use |
| *Type of analysis* | Comparison of assessment methods (study of NIBE) |
| *Data source* | Van Hattum en Blankevoort and Spanbeton |
| *Data quality* | Reliable and complete |
| *Data retrieval* | September 3$^{rd}$ |
| *Start analysis* | September 5$^{th}$ |
| *Finalization analysis* | October 8$^{th}$ |
| *Version of the indicator* | Executed with version 11 of the tool (V11) |

## Case study results

Below, the case study results are discussed. Both the process of execution and model outcomes are elaborated on.

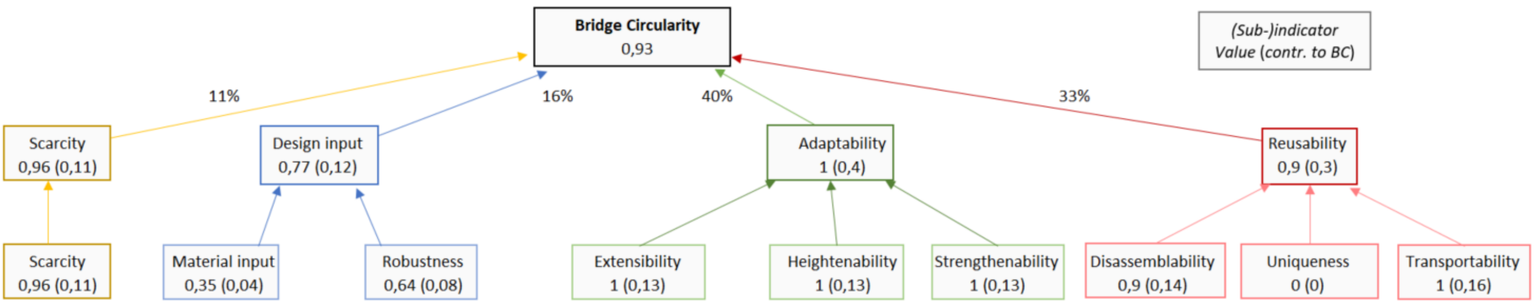
Process of execution

In close collaboration with Rob Valk – Rijkswaterstaat advisor in CE and closely involved in the *Circulaire Viaduct* project – the scope of the analysis was determined. The data was retrieved from a set of design drawings of the deck by Spanbeton. The assumptions on the project and the used information was aligned with NIBE in order to make the two analyses comparable. Apart from the alignment of the input data, the analysis with the bridge circularity indicator has been executed independently. The analysis was focused on the bridge deck, since this was also the focus of the NIBE study. Also, the finishing of the deck (pavement, road signs etc.) are not included in this analysis. The same is done for a reference deck, which is a standard box-girder deck of equal capacity and structural safety requirements (type SKK700). These numbers on the design were also retrieved from Spanbeton.

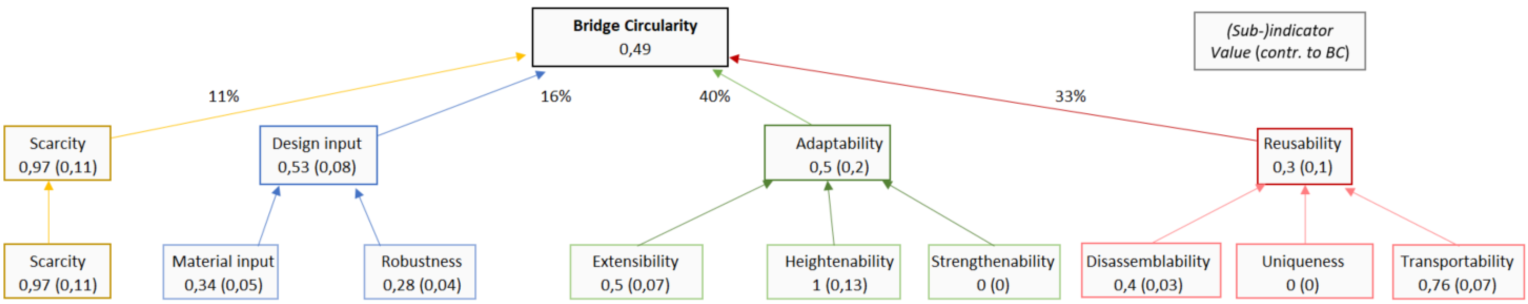
Predicted results and actual outcomes of the model

Below, first the level of circularity is predicted, followed by the actual model outcomes. My first expectation was that the circular deck would be, indeed, more circular, because of the used design-for-disassembly design principles and the oversized elements leading to more robustness. The larger amount of materials used as a result of the oversizing would not result from the circularity indicator, but only from NIBE's LCA-based sustainability measuring approach. The actual outcomes of the analysis are the following.

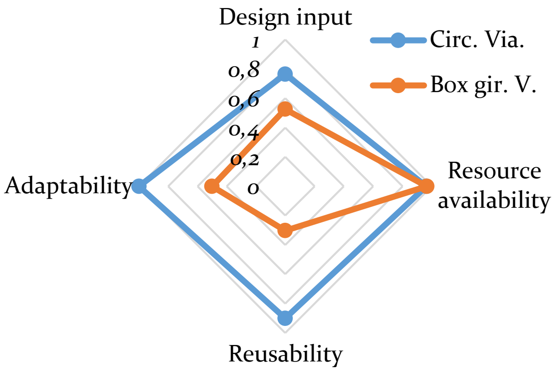
Circulaire Viaduct




Conventional box girder deck of equal dimensions




Indeed, as predicted, the Circulaire Viaduct is far more circular. Although the scarcity is very comparable in both designs due to the use of equal materials in the bridge deck (see figure below), as well as the *material input*, the robustness of the Circulaire Viaduct is higher due to the design lifespan of 200 years of the individual girder segments. However, the largest differences are in the latter two indicators. De Circulaire Viaduct can be adjusted both in width and girder length without creating waste and also additional reinforcement can strengthen the Circulaire Viaduct girders, while the reinforcement in the conventional alternative is cast into the concrete and is hence unchangeable. Due to the modular structure of the girders, the entire deck of the Circulaire Viaduct is deconstructable without creating waste and due to the small size entirely transportable. Only some elements belonging to the "services" layer of Brand (1994), section 3.2.6, are cast into the segments, resulting in that these elements are not replaceable during the service life, which would result in demolition. Therefore, the score for *reusability* is not perfect. However, in comparison to the filled-up box girder deck, the *reusability* is largely increased.




## Evaluation

The analysis of the two design alternatives has proved very valuable to this study, since it has given the opportunity to test a case that is claimed to be very circular. Indeed, the outcomes of the indicator show that the score is very high, but still offers room for improvement which matches perfectly the CE theory discussed in section 3.2.2. Therefore, this case provides evidence that the indicator indeed measures circularity in a broad sense and that the lack of the use of circular principles (the conventional box girder deck) scores considerably worse. Moreover, the options for improving the Circulaire Viaduct are largely feasible, including using more recycled and reused materials and increasing the modularity of the segments. Therefore, the scaling of the sub-indicators is done in the right fashion.

## Concurrent validity

The results of the broad LCA-based sustainability analysis is executed by NIBE (Van Beijnum, Van der Velde, et al., 2019). The LCA study shows that the "environmental costs" calculated by the MKI method are approximately 1.5 times higher for the Circulaire Viaduct when both structures are assumed to have a life span of 80 years. However, when a period of 200 years is considered, assumed that the Circulaire Viaduct is, in contrast to the box girder viaduct, being reused after 80 years, the environmental costs of the Circulaire Viaduct over 200 years are only 75% of the environmental costs of the conventional viaduct.

These conclusions fit the circularity outcomes of the bridge circularity indicator. Indeed, the oversizing of the elements results in additional environmental costs in material supply, transport, manufacturing and assembly, given that these costs are partly saved in a reuse scenario, the overall environmental impact is lower. Therefore, the circularity indicator proves valuable not only for potential material savings, but also in contributing to the wider sustainability goals.

## Updates and improvements on the assessment framework

The most important updates of the tool are related to additional materials mixtures in the scarcity database and the repair of various minor errors in the formulas and links in the spreadsheet.

## Balgzandbrug

The Balgzandbrug bridges the Balgzand canal by means of both a movable construction and a fixed truss span. It is located in Noord-Holland and the newer parts reach a lifespan of nearly 35 years while the older parts date from ~1930. Currently, a large part of the bridge has nearly reached its EoL stage. As such, it is included in the V&R programme and will be renovated or replaced in the coming years. To this case, there is already a CE-related study done regarding exploring possibilities for reuse and refurbishment. Also, various design alternatives are developed using various types of materials and loadbearing techniques which are included in a separate sustainability analysis executed by NIBE consultancy. These alternatives are: (1) a new steel truss span; (2) a steel slab bridge; a pre-stressed concrete span with (3) a concrete cover and (4) a syndiotactic polystyrene (SPS) cover; (5) a composite alternative; and (6), in a separate study, a wooden arc bridge.

### Goal of the case study

After having executed the previous two case studies, this final case study, which includes various design alternatives and externally executed sustainability analyses, is chosen to make the results more meaningful and fine-tune the scaling of the (sub-)indicators. Given that the major errors are already solved during and before the previous two case studies, it is expected that tool use itself will not be of any issue here.

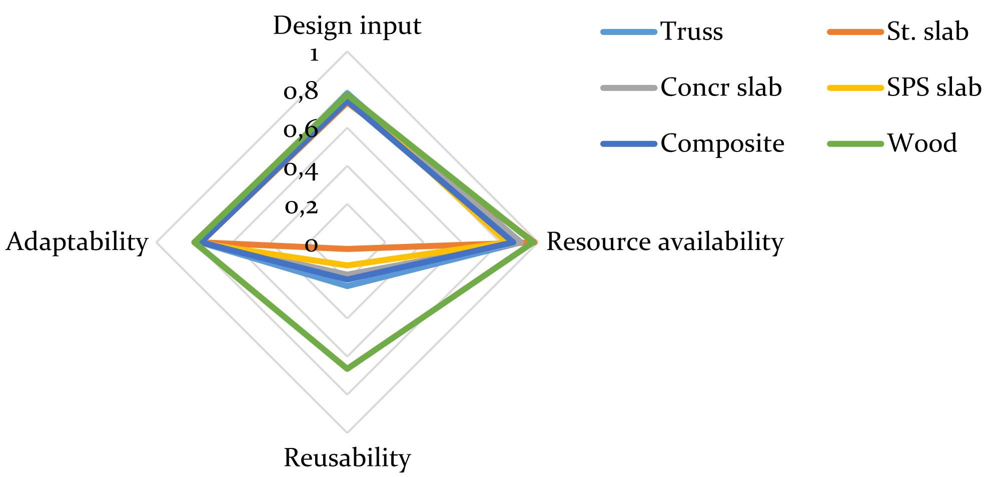
### Case study characteristics

In the table below, the characteristics of the case study execution are shown.

| | |
|---|---|
| *Name viaduct* | Balgzandbrug |
| *Project stage* | Planning stage |
| *Type of analysis* | Comparison of design alternatives and assessment methods |
| *Data source* | NIBE, Rijkswaterstaat and Lüning BV |
| *Data quality* | Reliable and varying level of detail |
| *Data retrieval* | October 10th 2019 |
| *Finalization analysis* | October 16th 2019 |
| *Version of the indicator* | Executed with version 13 of the tool (V13) |

### Case study results

The six design alternatives are applied to the tool, which results in the graph (figure below). On the next page, these results are discussed.



Given the similar construction techniques of the slab bridges (standard, concrete top layer, SPS top layer and composite deck) use the same construction techniques, it is self-evident that the adaptability and *reusability* are in a very comparable range. However, the fact that also the *design input* and *resource availability* are equal is rather surprising, given the different materials used. However, for the *design input*, the underlying results show that there is a compensation between virgin, non-virgin and renewable going on, while the same assumptions are used regarding origin of similar materials. Regarding scarcity, on the other hand, the results show that, even when materials with entirely different scores are used, the *resource availability* remains above the 0.9. This indicates that the scarcity indicator is not properly scaled, resulting in the situation in which the design cannot distinguish itself by using non-scarce materials. This has led to the design iteration below.

Furthermore, the use of wood as a construction material in an arc bridge construction seems to have a positive effect on circularity and scores approximately 15% higher than the other alternatives. The fact that the wooden parts consist of fully new and non-recyclable materials is compensated for by the renewability of the material. Furthermore, the wooden parts itself can be disassembled relatively easily, which allows for reuse. Also the fact that wood is renewable and hence non-scarce contributes, despite the observation that all scarcity values are too close to make a difference.

### Concurrent validity

The results of the broad LCA-based sustainability analysis and MCI analysis executed by NIBE can be found in the report *CE/VE verkenning Balgzandbrug voor verschillende material-varianten* (Van Beijnum, Schippers, et al., 2019). The LCA study shows that the *environmental costs* calculated by the MKI are lowest for the wooden alternative, if Azobé wood is used. Accoya scores way worse because this results in more material use. Also, in the circularity assessment framework, the wooden alternative has the highest score. Although in our analysis the remaining alternatives score quite comparable, in the MKI and $CO_2$ footprint calculations, the use of composite, and to a lesser degree SPS, has a large impact on the environment. However, if we merely consider the MCI in the report, the order is completely shuffled, since the MCI only considers material input origins and EoL destination. This is the main reason why the MCI aspects play only a very minor role in our indicator (elaborated on in appendix VI). Therefore, it is a positive result that, even though other aspects of the design and materials are assessed, the circularity tool is largely in line with the broader sustainability assessment, while the MCI provides contra-intuitive results with a low construct validity.

### Updates and improvements on the assessment framework

This case study has confirmed the usability of the tool for circularity assessment. However, it also led to an important lesson regarding the *resource availability* indicator. The range of a very scarce and very non-scarce bridge appeared to be very small in the final *resource availability* outcomes, so this indicator needed to be rescaled. By multiplying the scarcity scores by 7 in order to calculate *resource availability*, the most scarce alternative in this case study scored around 0.3, while the most non-scarce alternative scored a little above 0.9 after implementation of this design iteration. Seven turned out to be most suitable to enable bridge designers to distinguish their designs by using non-scarce materials. The scarcest alternative was the steel truss bridge in this study. However, given that there are construction techniques that use more scarce materials (e.g. zinc in galvanized beams and tubes) 0.3 turned out to be an appropriate number. On the other hand, for example, an entirely wooden bridge (thus without steel and concrete), made from a renewable material, results in a scarcity of 0 and *resource availability* of 1.

# Appendix III: Design iterations

Design is a cyclical process as shown in the methodology in Figure 6 in section 2.2 of the main report. Since this report draws mainly on the final design, the iterations are barely visible. This appendix offers a log of the iterations made in the design process. It includes a list with incentives for revision on this page and change logs for both the spreadsheet tool and support documents on the next. Each iteration is made as a reaction on feedback, using the validation techniques discussed in chapter 6. Below, in Table 8 and Table 9, iterations are divided into design iterations and writing/documentation iterations. Pre-design preparations are not considered design iterations. Moreover, general supervisor feedback is not included in the changelog, unless the feedback led to a structural revision of the design or document(s).

*Table 8 – Design iterations on framework and indicator*

| No. | Incentive/feedback | Iteration result | Date |
|---|---|---|---|
| 1 | General impression of literature, supervisors' and experts' views, and domain characteristics | First design (document) – no iteration | November '18 |
| 2 | Meetings with Sjoerd Wille, Sonja Fennis and meeting with Evert Schut | Better coverage of bridge aspects in indicator | December '18 |
| 3 | | Inclusion of scarcity | |
| 4 | Approval of João, Sonja and Sjoerd about outlines indicator | Spreadsheet-based indicator | December '18 |
| 5 | Meeting with Pieter Beurskens | Incorporation of Disassemblability tool | January '19 |
| 6 | Meeting with Sonja Fennis | Incorporation of Standardization | February '19 |
| 7 | Application of first and partial case data | Fine-tuning and removing errors from spreadsheet | February '19 |
| 8 | Presentation for CE group, WVL | Simplification and renaming sub-indicators | March '19 |
| 9 | Meeting with Sonja Fennis | Utility "X" in MCI consists of the difference in required lifespan and design lifespan | March '19 |
| 10 | Barbara van Offenbeek (RWS, WVL), Study for circular design principles RHDHV | Incorporation of recyclability degree | April '19 |
| 11 | Expert session at RWS | Revise name MCI | May '19 |
| 12 | | Robustness instead of Utility | |
| 13 | | Revised Heightenability | |
| 14 | | Revised transparency of outcomes | |
| 15 | Results CB'23 guidelines for measuring circularity in construction | An option to score on renewable materials has been included in design input | July '19 |
| 16 | Case studies Parkstad Limburg, Circular Viaduct | Improved tool usability and elimination of errors | July and August '19 |
| 17 | | Improved transparency of the results | |
| 18 | Model testing by Nienke Venema | Increase usability by protection of cells | August '19 |
| 19 | Presentation at Rijkswaterstaat | Scarcity positively described as resource availability | September '19 |
| 20 | Extensive case study on Balgzandbrug | Scarcity rescaled to increase impact on final results | October '19 |

*Table 9 – Change log PDEng report and supportive documents*

| No. | Incentive/feedback | Iteration result | Date |
|---|---|---|---|
| 1 | Literature review and meetings with various experts | First proposal | May '18 |
| 2 | Completion of Design Methodology course | Incorporation of Design Science in proposal | June '18 |
| 3 | Qualifier, narrowing down the project scope | Proposal rewritten into PDEng report | June '18 |
| 4 | Meeting with Sonja Fennis, meeting with João | Introduction of cases in PDEng report | July '18 |
| 5 | Completion of Systems Engineering course | Incorporation of SE theory in PDEng report | October '18 |
| 6 | First design document | Incorporation of indicator in PDEng report | November '18 |
| 7 | Report too extensive on background on topic | PDEng report literature study in separate report Theoretical Background | November '18 |
| 8 | Feedback from João | PDEng report extensively rewritten following DM | December '18 |
| 9 | Perceived ambiguity in expert meetings | Separate report for design choices indicators report | December '18 |
| 10 | Case study with three old cases | Cases unsuitable, PDEng report rewritten new cases | January '19 |
| 11 | New expert insights and insights from courses | PDEng report extended with new insights | February '19 |
| 12 | Tool was hard to grasp without clarification | Separate user guideline for indicator use | February '19 |
| 13 | Literature update | PDEng report and Theoretical background report was updated with scientific literature | March '19 |
| 14 | Planned expert and committee session at RWS | Integral revision of all documents | April '19 |
| 15 | Tool updates and user feedback | Major revision of guideline | August '19 |
| 14 | Tool updates, case study results and condensing text | Major revision and increasing conciseness of PDEng report | September '19 |
| 15 | Rijkswaterstaat users prefer Dutch documents over English | Translation guideline into Dutch for increasing usability | October '19 |
| 16 | A large final feedback round on the documents by João and Sonja | Full revision of all documents to increase readability and usability | November '19 |
| 17 | Meticulous analysis of written work | Polishing of all documents | November '19 |

*Table 10 – Tool updates*

| Version | Main updates and changes in the excel tool | Date |
|---|---|---|
| V1 | Conceptual version | January '19 |
| V2 | Inclusion Heightenability and solving errors in materials tab | February '19 |
| V3 | Crucial errors fixed in formulas and links | February '19 |
| V4 | Inclusion of a "project info" tab and "Client entries" tab in which all context can be filled out in one tab | March '19 |
| V5 | Errors fixed and improved usability through automation | April '19 |
| V6 | Made it a VBA Macro file (.xlsm) to extend the functionalities | May '19 |
| V7 | Refined "disassemblability" tab and removed "DSM" tab. Further automation of calculations. Inclusion of separate "results" tab for transparency | June '19 |
| V8 | Fixed errors and extension of the results tab to increase transparency. Weighting method updated | June '19 |
| V9 | Included renewable materials as insert option and included in material input | July '19 |
| V10 | Included functional groups in material tab and results and fixed major errors. | August '19 |
| V11 | Included material flow diagram in results. Fixed some calculation errors. | September '19 |
| V12 | Weighting of adaptability was changed to less importance in the first 30 years and emphasis between 60 and 90 | September '19 |
| V13 | Results presentation improved in fixing various errors | October '19 |
| V14 | Scarcity and resource availability rescaled and revision of the disassemblability tab | October '19 |
| V15 | Polishing the text, layout and particular attention paid to onsistencies in terms and colour coding | November '19 |

# Appendix IV: Interviewed experts

List of all experts interviewed and meetings, not including the main supervisors.

*Table 11 – Interviewed experts*

| | Name | Org. – dept. | Main topic | Date(s) |
|---|---|---|---|---|
| 1 | André Dorée | UT – CME | Put circularity into perspective | 11-1-'18 |
| 2 | Anne Jongkind | WBL – Sustainability | Implementation of sustainability and circularity in public organizations | 2-10-'18, 9-4-'18 |
| 3 | Arjen Ros | Copernicos | Databases and data management for managing circularity | 19-3-'19, 12-4-'19, 25-5-'19, 6-6-'19, 27-7-'19 |
| 4 | Baptiste Korff | RWS – GPO (BVi) | Circularity of Hoog Burel case study | 10-9-'18 |
| 5 | Barbara van Offenbeek | RWS – WVL | Circulaire projects Rijkswaterstaat and design principles | 25-6-'18, 9-4-'19, 4-7-'19 |
| 6 | Dick Schaafsma | RWS – GPO (BVi) | Future of circularity and sustainability in bridges | 21-12-'17 |
| 7 | Eize Drenth | RWS – GPO | Implementation circular databases and relation with indicator | 19-3-'19, 11-9-'19 |
| 8 | Evert Schut | RWS – WVL | Circularity within Rijkswaterstaat, CB'23 and CE measurability | 12-2-'18, 1-10-'18, 20-2-'19, 27-5-'19, 15-7-'19 |
| 9 | Gerwin Schweitzer | RWS – GPO | Circularity and DuboCalc | 10-1-'18, 3-5-'18, 3-12-'18, 17-5-'19, 15-7-'19 |
| 10 | Gilbert Westdorp | RWS – ZD | Predictive maintenance within Vital Assets | 10-9-'18 |
| 11 | Hans Boes | UT – CME | Circular procurement in construction teams | 18-2-'19 |
| 12 | Henny ter Huerne | UT – CME/Overijssel Prov. | Circular infrastructure, application in Province, doing instead of thinking | 6-12-'17, 17-9-'18, 21-5-'19 |
| 13 | Ingrid Jansen | RWS – CIV | Data and IT system management within Rijkswaterstaat | 23-8-'18 |
| 14 | Jaap Bakker | RWS – GPO | BIM and data management within Rijkswaterstaat | 12-2-'18 |
| 15 | Jaap Hoefman | RWS – GPO (BVi) | Reuse possibilities steel bridges | 30-4-'18 |
| 16 | Jan Willem Spruit | RWS – GPO | Experiences in project "Circulair Viaduct" with circularity | 27-5-'19 |
| 17 | Jeroen Nagel | RWS – WVL | Material passports and circular data management | 1-11-'18, 29-4-'19, 6-8-'19 |
| 18 | Jessica Reis-Leffers | RWS – WVL | Possible collaboration and working on tool | 4-7-'19 |
| 19 | Joost Gulikers | RWS – GPO (BVi) | Concrete reuse in projects (Badhoevedorp) | 17-8-'18 |
| 20 | Jur Niewold | RWS – GPO | Contract management with concrete reuse case study | 3-9-'18 |
| 21 | Leo Klatter | RWS – GPO | Data systems and DISK and V&R prognosis | 10-9-'18, 12-8-'19 |
| 22 | Maaike Snijder | RWS – CIV | Data and IT system management within Rijkswaterstaat | 23-8-'18 |
| 23 | Machiel Crielaerd | RWS – WVL | Measurement and principles of CE within Rijkswaterstaat | 21-12-'17, 4-6-'18, 10-9-'18, 1-11-'18 |
| 24 | Maria Angenent | RWS – CIV | V&R procedures and vital assets with future challenges | 26-6-'18 |
| 25 | Marjolein van der Klauw | RWS – GPO | Circularity, DuboCalc and circular purchasing | 3-5-'18 |
| 26 | Milicia de Kok | Witteveen+Bos | Model for measuring circularity from a macro perspective | 17-9-'18 |
| 27 | Nienke Venema | RWS – GPO (BVi) | InnovA58 and circular infrastructure, circular design principles | 4-12-'17, 25-6-'18, 10-11-'18, 27-6-'19, 12-8-'19 |
| 28 | Olga Paletaeva | Copernicos | Modelling of asset management and CE processes | 12-4-'19, 27-6-'19 |
| 29 | Ostar Joostensz | RWS – GPO (BVi) | Suurhoffbrug case study | 10-9-'19 |
| 30 | Pieter Beurskens | UT – OPM | Reuse potential of buildings | 7-5-'18, 12-11-'18, 8-1-'19, 18-2-'19, 11-3-'19, 4-7-'19 |
| 31 | Rob Valk | RWS – WVL | Circulair Viaduct case study | 27-6-'19, 10-9-'19, 20-9-'19 |
| 32 | Sanne van der Mijl | RWS – WVL | Circular Rijkswaterstaat initiatives in the EU | 24-11-'18 |
| 33 | Silu Bhochhibhoya | UT – CME | Academic approach towards CE | 22-1-'19 |
| 34 | Sjoerd Knippenberg | TUe / RWS | PhD project on standardization of lock configurations | 5-9-'19 |
| 35 | Tim van Pelt | UT – CME | Using the indicator to validate circular design framework of Tim | 7-8-'19, 11-10-'19 |
| 36 | Valerie Diemel | RWS – GPO (BVi) | Circular bridges and viaducts, CE documentary, standardization | 4-12-'17, 30-4-'18, 10-9-'18, 1-11-'18 |

# Appendix V: Reflection on the PDEng criteria

Below, the PDEng criteria are reflected upon based on section 2.3.2. This is split up in product-related PDEng criteria, process-related PDEng criteria and product-specific criteria. It complements section 6.3 regarding the design validation through verification of requirements.

## Product-related PDEng criteria

The criteria below follow the *PDEng study guide* and are related to the end-product.

*Functionality*

The design requirements have been presented in the proposal and in more detail in the final report of the course *Design Methodology for PDEng* (Coenen, 2018b). These requirements developed during the project and in the final delivery of the course *System Engineering for PDEng* (Coenen, 2018d), a mature set of requirements has been presented. These requirements tell what the end-product should do and to be considered successful. These requirements are kept in mind during the design process and as such, the framework has been designed according to the requirements. Consequently, the design functions as intended.

Furthermore, during the PDEng project, several opportunities emerged regarding linking the framework to other initiatives within and around Rijkswaterstaat. These have led to other functionalities that have initially not been included in the set of functional requirements. Most notably, those initiatives are the involvement in *Circulair Bouwen '23* (CB'23), resulting in adoption of several approaches towards circularity measurement. Although the framework has initially been developed for assessment purposes, extended functionalities emerged from presenting the results transparently on various dimensions, including sub-indicators, component, materials and functional groups.

Whether the framework is usable in practice is tested by letting experts and non-experts using the tool. In three cases described in section 6.1.2, the framework has been used without assistance by three people. In each case, the user was able to obtain the desired results, even with the preliminary versions of the indicator. Although the generalizability with bridge cases is safeguarded by the case studies, further generalizations towards other civil engineering structures has not been tested, as discussed in section 7.5.

*Construction*

The construction of both the broader assessment framework and the indicator is initially designed by systematically following the DSR methodology, resulting in various design iterations (appendix III). The indicator tool follows as much as possible the processes applied in Rijkswaterstaat with particular attention to DuboCalc. Where those are not aligned, the reasons are explained.

Furthermore, the composite indicator is composed such that each sub-indicator acts largely independently and the structure of the tool allows for easy adaption of sub-indicators and potential additions of new sub-indicators. The architecture of the framework including its indicator follows the *Vee model* as explained in section 2.3.1. Furthermore, as discussed in the validation part (section 6.1), the triangulation has been applied to test the validity. Finally, the special attention on implementability in chapter 8 shows that Wieringa's (2014) design cycle is followed through as much as possible.

*Feasibility*

The feasibility, also called *realizability*, has been guaranteed by identifying a clear and narrow scope. The project boundaries have been chosen such that the framework is developed in great detail instead of a broad scope with a low validity and a long road to implementation. Next to ensuring feasibility by a narrow scope, a lot of effort has been put into aligning the design with Rijkswaterstaat practices and experts within Rijkswaterstaat in order to create support and awareness within the organization for the purpose of implementation. This open Microsoft Excel-driven framework requires no additional investment costs, except for the working hours that are required to execute the analysis. It merely supports decision-making regarding circular design. Financial consequences of circular design falls outside the scope of this project and is covered within lifecycle cost analyses of individual construction projects.

*Impact*
The apparent contribution of the circularity principles to the environmental goals indicates a positive societal impact of the framework. Since increasing circularity was the main goal of the project, this, however, cannot be considered as an additional project characteristic. However, by getting involved in various circularity initiatives, such as the *Open Leeromgeving Circulair Viaduct*, organizing a session, presenting preliminary results and letting Rijkswaterstaat employees use the draft versions of the tool, the chances of implementation increase, which would results in an increase in impact.

Potential project risks have been analysed in the project proposal stage and were discussed in during the *Qualifier*. The foremost risk identified was project delay due to troublesome data acquisition and stakeholder cooperation. This risk has been mitigated by starting with the first design steps as soon as possible and devoting a considerable period to design validation (9 of the 24 months in the PDEng). This has enabled me to plan meetings, milestones and data collection well on time, and hence to finish the PDEng project within the two years. The risks of the end-product related to implementation of the framework are discussed in great depth in chapter 8.

*Presentation*
The design and accompanying documentation has been kept up-to-date during the entire design process. This has allowed for an accurate account of events. In total, the circularity indicator is supported by 3 documents (see section 1.2), being: (1) this report describing the design process; (2) a guideline to framework use; and (3) a report covering the theoretical background on the subject. Furthermore, iterations, changes and preliminary versions are clearly noted in appendices III and IV. Results have furthermore been exposed by means of participations in aforementioned conferences, workshops and writings. The end-product itself is the spreadsheet in which a lot of attention is paid to user-friendliness by means of consistent colour coding, supporting clarifications and a high degree of automation.

## Product-specific criteria

In addition to the *PDEng study guide* criteria, several product-specific criteria were formulated in the early project stages. These are reflected upon below.

*Completeness*
The product is considered *complete* if it covers the entire concept of *Bridge Circularity 2019*, which has been based on the most recent advancements in circularity literature. The gap analysis and comparison to Rijkswaterstaat's circular design principles (section 6.1.1) have shown that the current design covers the voids regarding measuring circularity within Rijkswaterstaat, while uncovered parts are part of the existing MKI. This is also part of the scope and the requirements set in the *Design Methodology* report and section 2.1.

*Compliance*
An important design criterion was that the design fits the existing practices within Rijkswaterstaat. This has been ensured by involving Rijkswaterstaat experts on various fields during the design process and by attending the various initiatives regarding measuring circularity within Rijkswaterstaat as well as organizing an expert session. Collecting the support for the design from these experts aided in aligning the design with existing processes.

*Awareness*
The awareness of the framework has been promoted by both involving the experts and by presenting the (preliminary) design results where possible – especially considering Rijkswaterstaat, but also at the University of Twente. This includes presenting at the BVi group and at the *Taskforce Circularity* at WVL. Furthermore, the framework has been published at an international conference as well as a Dutch conference and collaboration has been sought inside and outside Rijkswaterstaat as noted in Appendix III on, for instance, circular data management, other PhD students, innovation management and V&R experts.

## Process-related PDEng criteria
Apart from product criteria, the *PDEng study guide* addresses several process criteria.

*Organization and planning*
The project was carefully planned. This contained two approaches: one rough planning to manage the entire planning and for each academic quartile a separate, more detailed planning was made, including milestones. This provided flexibility and enabled to include unforeseen opportunities. The overarching milestones where mainly regarding prototype designs and validation sessions. Also in the preparation phase, several milestones were indicated and met. For each quartile deadlines and milestones were set. In the overarching planning a very extensive time was reserved for validation and implementation. This has created space for applying feedback and improving the design through design iterations.

Furthermore, both formal and informal meetings were organized both within Rijkswaterstaat and the University of Twente to keep the project on the right track. Regarding the planning of meetings, no fixed dates or periods were set, but the help or input of both supervisors and experts was proactively sought when needed. All meetings where documented in an extensive excel sheet, including time date, place, goal of the meeting and outcomes of the meeting. In total, between December 1st 2017 and November 17th 2019, 182 meetings were registered with both supervisors and the experts registered in appendix IV.

*Problem analysis and solution*
As elaborately discussed in chapter 2, the project has been executed following the design cycle proposed by Wieringa (2014). By following this methodology consistently, the problem analysis and solution development has been executed in a structured manner. During this process, a lot of emphasis has been put on creating a high likelihood of implementation and contributing to the circularization processes within Rijkswaterstaat. Furthermore, each design iteration has been documented (appendix III) in order to structurally arrive at the final version presented in chapter 7.

*Communication and social skills*
For increasing potential for implementation of the framework, preliminary results have been documented and the three reports as explained in section 1.2 have been kept up-to-date during the entire project. Meanwhile, preliminary results have been shared – in particularly with task force Circularity in WVL – in order to keep the results aligned. Furthermore knowledge has been

shared through scientific channels in the 26th CIRP lifecycle engineering conference, the IALCCE LCM conference in Rotterdam, and currently exposition by means of a scientific journal paper is being worked on.

*Structure and attitude*
Equal to the design iterations, the reporting has been updated as a result of feedback and new insights in various cycles. This has resulted in a structured approach of reporting. Regarding use of the definitions, terms and colours consistency is sought. Especially in the indicator tool, colour coding has been used to clarify and highlight the various parts of the indicator. The many iterations as a result of expert feedback and the organization of meetings and sessions indicate a search for receiving and processing feedback and expert opinions. Although my general attitude in those meetings is to assess about myself, the large variety of expert opinions resulted in a new and useful end-product which proved to be useful in practice and resulted in new knowledge in the field of CE in construction.

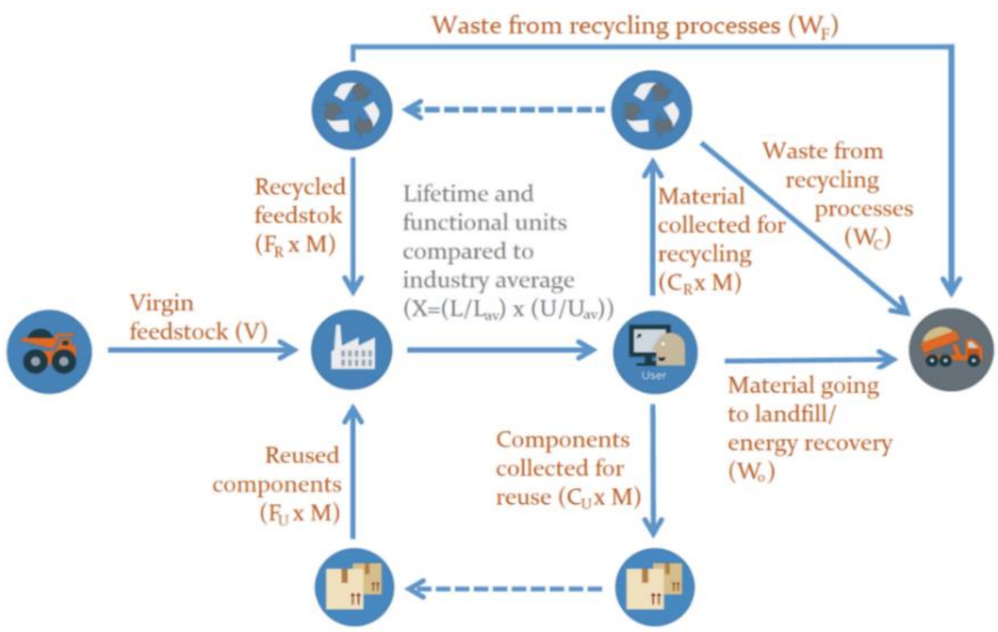
# Appendix VI: The indicators

This appendix provides the background on the selection, development, calculations and fine-tuning of the existing, tailored and new indicators which constitute the bridge circularity indicator. This appendix follows the structure of the decomposition tree as shown in chapter 7 of the report. The calculations presented in this appendix are also used in the spreadsheet to calculate the concerned (sub-)indicators. First, the *design input* is elaborated on, since this is based on an existing indicator (MCI). Subsequently, the *resource availability* indicator, *reusability* indicator and adaptability indicator are discussed. The sub-indicators developed in this document are used for aggregation of the composite indicator and act as a basis for the circularity assessment framework. The sub-indicators are developed following the DSR method as discussed in chapter 2 of the *Circular bridges and viaducts* report. As such, the development followed several rounds of designing, testing and feedback, resulting in the validated design presented in this report.

## 1. Design input indicator

The existing Material Circularity Indicator (MCI) is widely considered for assessing and guiding designs of products or assets (EMF & Granta, 2015). It focuses on four major points:

1. Using feedstock from reused or recycled resources;
2. Reusing or recycling materials after product use;
3. Keeping products longer in use (e.g. increased lifespan or direct reuse);
4. Making more intensive use of products.




| | | | |
|---|---|---|---|
| V | Virgin feedstock (kg) | $C_U$ | Share of reusable collected waste |
| $F_R$ | Share of recycled resources | $E_F$ | Recycling efficiency of feedstock |
| $F_U$ | Share of reused resources | $E_C$ | Recycling efficiency of collected materials |
| M | Mass of the asset/product (kg) | L | Design lifespan (years) |
| $W_C$ | Generated waste in collected materials (kg) | $L_{av}$ | Average/required lifespan (years) |
| $W_F$ | Generated waste in feedstock materials (kg) | U | Design functional utility (traffic load) |
| $W_o$ | Directly generated waste from product (kg) | $U_{av}$ | Average/required utility (traffic load) |
| $C_R$ | Share of recyclable collected materials | | |

### Tailoring the existing MCI to Design input

All four points result in increased material value. The MCI is in application more aimed at consumer products than public assets, but largely resembles the construction value chain. Therefore, the existing MCI should be tuned to our case of bridges and viaducts resulting in the *Design input* indicator. In general, the MCI considers the material flows as presented in the figure on the previous page. Roughly, the MCI distinguishes two parts: (1) the Linear Flow Index (LFI) aims at material use and recycling and (2) Utility (U) aims at the product use. The LFI considers both *material input* and EoL output.

### Material input indicator

In this whole-asset approach, firstly, the basic part of the *Material input* indicator is constructed by computing the virgin, recycled and reused feedstock and by calculating the renewable fraction and recyclability of the asset. The former parts in terms of mass are calculated by considering the fraction of used recycled resources ($F_{rec}$) and reused resources ($F_{reu}$) on the input side. First, it should be determined how recycling is valued in comparison to reuse. The main arguments – both for and against differentiation – on which this weight should be determined are the following:

<u>Equalize reuse and recycling:</u>

- Recycling may find a more suitable application than reuse – and the other way around.
- Recycled materials can be processed into all desired shapes and forms, while reused components remain largely as they were designed. Bridges exist in an ever-changing socio-technical regime.
- If recycling is lower valued, how much lower? An objective number is difficult to assign.

<u>Devalue recycling to reuse:</u>

- A component that is recycled underwent always more processing steps than a directly reused component.
- Something that can be reused can also be recycled. Hence, *reusability* increases EoL possibilities.
- All potential disadvantages of reuse in comparison to recycling (additional transport distance, oversized material use, etc.) are accounted for in other (sub-)indicators.

We propose to value recycling of materials 0.8 times reuse of components. This is shown in formula 1.1 by the multiplications of $F_{rec}$ and $F_{reu}$. This devaluating weight is mainly chosen due to the argument that feedstock that is used in a design which is recycled has required more steps than a reused material. The fact that potential oversizing and other additionalities are compensated for in the other indicators has moved us to value recycling slightly lower – 4/5 – in comparison to reuse. Moreover, unlike EoL potentials, in feedstock it is clear whether the actual materials are virgin, recycled or reused.

For the inability of determining the EoL destinations of the materials in bridge designs due to the long lifespan, the unrecoverable waste at the end of the use phase as deployed in the MCI is not adopted in this study. Instead, it is replaced by the EoL *reusability* sub-indicator discussed following sections. However, the ability of a component to be recycled should be assessed. This depends mostly on the materials used and the mixture of materials. This should be indicated by the designer of each of the components. This recyclability is a mere potential and only indicates the possibility according to current recycling techniques. Since components consists of multiple elements with each multiple materials, the component recyclability should be scaled from 1 (non-recyclable) to 5 (fully recyclable).

Next, for stimulating the use of renewable materials and as such contributing to the *biological cycle*, use of sustainably processed renewable materials can be included as subtraction to the virgin fraction of the *Material input*. Renewable materials are by definition biotic, since there origin is in biological organisms and can be used as a substitution for abiotic materials. The most notable application is wood, but also certain bio-based plastics or fibre applications may be eligible to fall within this category. Note that only certified materials may be used in order to be considered renewable, since the portion depleted by usage must be replenished through natural reproduction or recurring processes within a human time scale (CB'23, 2019). For example, using wood types that take hundreds of years to grow, will in the end contribute to resource depletion, resulting it to be considered non-renewable in this study.

This calculation of the generated waste forms the basis for the *material input*. The letter "F" in formula 1.1 is a fraction, and can be obtained by the mass of the fraction divided by the total bridge mass. An important note should be made that, in contrast to the original MCI, the material linearity is not equal to the share of linear products. Instead, it is here considered lower because of the correction in value differences between reuse and recycling. Moreover, the recyclability plays also a role in the formula. The *material input* is calculated as follows:

$$Linear\ fraction = 1 - (k * F_{rec} + F_{reu}) - F_{ren,v} \tag{1.1}$$

$$k = reducing\ factor\ for\ recycling\ (recommended\ 0{,}8)$$

$$F_{rec} = Fraction\ of\ used\ recycled\ materials$$

$$F_{reu} = Fraction\ used\ materials\ of\ reused\ source$$

$$F_{ren,v} = Sustainably\ produced\ renewable\ virgin$$

$$resources\ as\ fraction\ of\ total\ materials$$

Secondly, the *recyclability* is calculated. Each component is rated from 1 to 5, from non-recyclable to outstandingly recyclable, and the sum of all components of this number times the mass of each component, divided by the total mass indicates the recyclability (fraction recyclable). Together, these two parts form the linear fraction, which is calculated as follows:

$$Material\ input = \frac{Linear\ fraction + (1 - recyclable)}{2} \tag{1.2}$$

### Robustness

Next to the *material input*, the *robustness* is introduced that considers the asset's designed strength to determine the actual lifetime value of a product or element. In the initial MCI, it is compared to the average industry's resource duration and considers, in case of reuse or recycling, multiple lifecycles. However, since the robustness of bridges is very much dependent on the context and regulations, rather than technical capabilities, comparison with industry's averages does not make sense. However, the degree of use is important in the light of circularity. Next to the *adaptability*, which involves flexibility, the *robustness* determines the technical ability to withstand external stress. For bridges, this ability leads to lifespan extension and reduction of maintenance. The *robustness* is as such compared to the client's structural base line (formula 1.3). Usually, the base line is just set at 1, but every other measure may be applied by the client of the assessment. If the contractor can prove that the design is more robust than required, future technical bridge removal may be prevented. However, this will always be a trade-off with material use and flexibility. The weighting of the sub-indicators will eventually regulate this balance within the trade-off.

$$Robustness = \frac{Design\ robustness}{Minimum\ robustness} \tag{1.3}$$

### Calculating the Design input

Consequently, designs can score both by using recycled, reused and recyclable materials and by increasing the robustness. EMF and Granta (2015) expressed the *material input* in mass, but mass depends in bridges mainly on the main material used (most significantly concrete and steel). However, this is compensated for by the *resource availability* indicator. The total *design input*, giving a number between 0 and 1, is calculated as follows:

$$Design\ input = 1 - Material\ input \times Robustness \tag{1.4}$$

Products with both a robust design are awarded in the robustness sub-indicator. On the other hand, a high share of restorative flows decreases the influence of the robustness. The *design input* should, even with a fully linear material flow, not be zero if the robustness, expressed as F(Robustness), is strongly positive. Therefore, $F(Robustness)$ is expressed as $F(Robustness) = \frac{a}{Robustness}$, for which $a$ is a constant. EMF and Granta (2015) suggested a = 0.9 to be a reasonable number, since it places a fully linear product (k=1) with *Robustness* = 1 to a *Design input* of 0.1. However, this number remains arbitrary and can be updated if usage gives cause for revision. This is derived from formula 1.5:

$$Design\ input = 0.1 = 1 - 1 \times \frac{F(1)}{k} \rightarrow F(1) = 0{,}9 \tag{1.5}$$

### Input data required

For calculating the material circularity, various data is required for the bridges. In this section the data required is discussed following the formulas presented in this section. All Linear fraction-related parameters are measured in material weight and robustness-related parameters in undefined quantities.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1.1 | $F_{rec}$ | Mass of all materials Material origin (new/ reused) (kg) | Designers and contractors | The contractor should offer verifiable numbers on the mass and whether it is recycled or not |
| 1.2 | $F_{reu}$ | Mass of all materials Material origin (new/ reused) (kg) | Designers and contractors | The contractor should offer verifiable numbers on the mass and whether it is reused or not |
| 1.3 | *Recyclability* | Mass of components, recyclability per component | Designers and contractors | By using existing guidelines, the contractor your determine for each component the recyclability |
| 2.1 | *Design robustness* | Measure of robustness | Designers and contractors | Statistically determined on the basis of structural safety |
| 2.2 | *Base line* | Measure of robustness in the same quantity as design robustness | Client | Client's robustness requirement |

## 2. Resource availability indicator

A ton of gold is more valuable than a ton of gravel. Consequently, just adding material mass as done in the *Design input* does not represent the value of reuse or depletion of resources. This difference in value is largely explainable in the relation between demand and supply: *scarcity*. Nevertheless, the market value does not represent the actual earth's reserves of the material, as was discussed by Henckens (2016), so the classic price mechanisms will neither fully compensate for the scarcity in the procurement process. Only covering the mass part is compensated for by introducing a material scarcity indicator. This sub-indicator addresses the limitedness of the supply in relation to its demand regarding abiotic materials. Existing databases are used and applied to material quantities in bridges. Important to note is that material scarcity is used independently of the material sources; reusing a scarce material is considered as bad as virgin use of a scarce materials, because it contributes equally to the global resource depletion.

Many Life Cycle Impact Assessment (LCIA) methods take resource depletion into consideration. The most frequently used methods, such as the "Abiotic Depletion Potential" (ADP), rely on a distance-to-target approach (e.g. years of extraction given an expected availability of a resource), but this does not take the inherent decrease in grade into account (Vieira et al., 2017). The grade – kg material per kg mined ore – decreases when the mining continues: getting the material becomes increasingly difficult when more of the material is mined. This factor is compensated for in the relatively new, but well-embedded, Surplus Ore Potential (SOP). This is proposed as an indicator for scarcity for abiotic resources (Vieira et al., 2017). Moreover, this indicator is used for the so-called ReCiPe method, which is a widely-adopted LCIA method in the Netherlands (RIVM, 2017).

Since the ADP is already being used within Rijkswaterstaat, using this indicator would require less changes than introducing the SOP. For this reason, the ADP will be used when the SOP has no significantly different outcomes than the ADP. Despite both ADP and SOP relate for many materials to the price elasticity of demand for estimations of availability, while Henckens (2016) showed that this comes with flaws because price fall can occur while sustaining rates of extraction, usable alternatives are not yet available that cover all abiotic materials in bridges and viaducts. Therefore, despite this drawback, we use this method to determine mineral and metal scarcity. Another difference between the ADP and SOP is that the ADP takes antimony as a base line (1.00), while copper is set as the base line in the SOP. This, however, has no consequences for the calculations, since the differences are merely relative. In this indicator, biotic materials are considered to be non-scarce, in order to avoid too much complexity. This can be done, since the negative environmental impact of unwanted biotic materials are largely covered in the MKI.

The SOP is calculated as follows (Vieira et al., 2017). The extra amount of ore mined per unit of resource extracted is calculated by dividing the ore mined for a certain amount of resource extracted by the global reserve of the resource. This is shown in formula 2.1.

$$SOP_x = \frac{\int_{CRE_{x,total}}^{MRE_x} OM_x(RE_x)\, dRE_x}{MRE_x - CRE_{x,total}} \tag{2.1}$$

$SOP_x = Everage\ surplus\ ore\ potential\ of\ x$

$MRE_x = Maximum\ amount\ to\ be\ extracted$

$CRE_{x,total} = Total\ amount\ already\ extracted$

$OM_x = Ore\ mined$

$RE_x = Amount\ of\ resource\ extracted$

These numbers are not calculated in this study, but are already provided in other studies. Those studies show that in particular the $MRE_x$ for a material is a difficult number to quantify and requires extensive research. However, this has already been done on many metals and minerals for three scenarios as shown by the RIVM (2017). These scenarios are individualist (short term and acknowledging innovation and technological progress), hierarchist (a weighted average) and egalitarian (precautious and long term). Since the second alternative is considered to be the base line, we use the hierarchist scenario for the quantification of SOP. The database as presented by the ReCiPe method is used as a basis for the calculations. For calculating the bridge scarcity, the SOP of the mass of all materials used should be determined. This is calculating by multiplying the SOP of each material with the total mass of the material and divide this product by the total asset mass. This gives a weighted average of the material scarcity (formula 2.2).

$$S_{total} = \frac{\sum_{i=1}^{n} SOP_i * M_i * 10}{M_{total}} \tag{2.2}$$

$S_{total} = Asset\ scarcity$

$n = total\ amount\ of\ materials\ used$

$SOP_i = SOP\ of\ material\ i$

$M_i = Mass\ of\ material\ i\ (kg)$

$M_{total} = Mass\ of\ the\ asset\ (kg)$

However, this would result in the following. An entirely copper bridge would have a scarcity of 1, which is approximately 100 times the scarcity of an entirely clay bridge. A largely majority of the materials used in a bridge have such a low scarcity compared to copper that minor material changes would not result in changes in scarcity. Therefore, we scale this indicator as follows to result in a number between 0 and 1. As the highest factor, we take 0.1 times the scarcity of copper, which will result in a most scarce bridge with a scarcity number of 1. This means theoretically that a bridge that is made for 10% of copper and for 90% of an infinite abundantly available material would result in a scarcity of 1, while a bridge of 100% infinite abundantly available materials in a scarcity of 0. Because a non-scarce material is most circular, given its minor effect on resource depletion, this scarcity weights negatively on the bridge circularity. Therefore, in the final indicator, the negative scarcity is expressed as *resource availability*.

Case studies have provided insights into the impact of material choices in the scarcity. After various iterations, the negative scarcity turned out to provide a narrow range for designers to distinguish their designs on *resource availability*. Case studies have provided the insights that the negative scarcity times 7 results in a very scarce bridge with a *resource availability* score around 0,2 and a very non-scarce above 0,9. This reflects the circularity in a similar fashion as the other indicators. The total *resource availability* is hence calculated as:

$$Resource\ availability = 1 - S_{total} * 7 \tag{2.3}$$

$S_{total} = Asset\ scarcity$

To determine the *resource availability* of the materials used and hence the asset scarcity, the weight of all materials used and the SOP need to be collected. The design and contractor can provide the mass of the materials used and the SOP is calculated by researchers and presented in available databases.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1 | SOP | SOP | Scientific literature | Extract from existing databases |
| 2 | - | Insight in material mixtures | Suppliers and contractors | Documents and experts |
| 3 | M | Mass of all used materials | Designer/contractor | Retrieved from design |

## 3. Reusability indicator

*Reusability* is the ability to be reused and as such close to a reuse potential. It is considered on an asset and component level, depending on the aspect measured. It describes a suitability for reuse. Due to future uncertainty, it does not say anything on the event of actual reuse. *Reusability* of a component is determined as the sum of all components' *reusability* aspects as part of the total weight. For each component, it involves the *disassemblability, uniqueness* and *transportability*, of which the *disassemblability* is on asset level and the latter two on component level. These are discussed below in more detail. As explained in the previous section, the weight is compensated for by *resource availability*. Finally, the calculation of asset *reusability* is presented.

### Disassemblability indicator

The *disassemblability* of a (civil engineering) structure depends mostly on its internal component connections. Using the decomposition as defined by Durmisevic (2006), several aspects are used to calculate the *disassemblability* of a bridge. Various determining factors are related to bridges with respect to *disassemblability*. First, a relational pattern is constructed. A separate calculation method will present the asset *disassemblability* on several levels and generate a *disassemblability* plan based on the relations between the elements and the connection types.

*Relational patterns and disassemblability calculations*

Following the method based on Durmisevic (2006), we adapt this method to bridges and viaducts. By giving insights in mutual dependency and relations of the components and the used types of connections, the possibilities, arrangement and ease of deconstruction are revealed. First, the interfaces between all components visualized. Thereafter, the used connections between the interfaces are shown and each connection has another value in relation to the easiness of deconstruction. Various methods are either used or currently developed, such as Alba Concepts (2019), BAMB (2019) and Durmisevic (2006).

*Connections*

For defining the relations between components, the types of connections are defined. Beurskens (2019) has defined the connections for utility construction and defined four main groups:

A) Position-based connections;
B) Geometry-based connections;
C) Fastener-based connections;
D) Material-based connections (chemical).

These four groups are divided into various connection types. However, for bridges and viaducts, some connections are slightly different. By interviews with experts within Rijkswaterstaat a list is complemented with application in bridges and viaducts, from the perspective of both concrete and steel assets.

*Relational pattern diagram*

The relation of entities is visualized by drawing lines between connecting elements. By clustering groups of elements that together form a component, assembly or chunk, the various levels of decomposition is shown. As a result, a relational pattern is established, indicating the decomposition of the asset. For the application to a bridge analysis we do not consider the material level in the decomposition.

*Data required for determining bridge disassemblability*
The data required to determine the *disassemblability* is shown below. Most importantly, the structural composition and types of connections need to be extracted from the design.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1 | - | Pre-set connections | Report | Use the pre-set functional connections |
| 2 | - | Composition and subsystems of the bridge | Designer | Use the design to compose relational pattern |
| 3 | - | Various levels of analysis | Designer and drawings | Analyse the structure and identify the various levels of analysis |

## Uniqueness indicator

A component will only be reused when there is a demand for it. Within Rijkswaterstaat, this demand can often be coupled to internal projects, but also municipalities and provinces may, as large bridge owners, be potential buyers. This goes mainly for one-to-one replacement of components or assemblies, which is particularly applicable to short-span viaducts of which there are several thousand present in the Netherlands.

A very unique design is made up out of a specific geometry, materials and additional features. This specificity results in a decreased likelihood for fit at a new location and moreover decreased opportunities for applying another component in case of replacement – as a result, a decreased demand. Moreover, unique components require unique production processes, while larger-scale production in usually more resource-efficient. Therefore, the higher the *uniqueness* of a component, the lower the potential demand. The design *uniqueness* forms a part that is regarded as an aspect that should be measured in order to assess *reusability*. In the calculations the *uniqueness* is a number between 0 and 1 and because of the negative impact of *uniqueness* on *reusability*, it is used negatively in formula 3.2. This *uniqueness* is only considered with respect to attributes that affect the quality of being interchangeable in a certain situation. This concerns most importantly the dimensions and interfaces with other elements, while for example type of material is of no importance in this standardization effort.

*Uniqueness and standardization*
Measuring *uniqueness* is in an absolute sense close to impossible, since there is no reference available to which a degree of *uniqueness* can be measured. Therefore, reference standard designs should be developed to which the designed components can be compared. Here, the level of standardization of the asset indicates the *uniqueness*. Standard designs should only be developed for commonly used elements, such as pre-cast concrete girders, piers and connections, since it is a laborious activity and the design freedom will be called into question if standardization is applied to elements that highly dependent on the design context.

If a standardizable (i.e. common) component is designed conform the reference standard design, it is considered standardized and in any other case it is not. For each component's materials the mass is determined and listed (formula 3.1). To determine the asset *uniqueness*, the sum of the mass of the standard components is divided by the sum of the mass of all standardizable components. Components for which no standard design exists do, consequently, not negatively affect the asset *uniqueness*.

$$U_{total} = \frac{\sum_{i=1}^{n} M_i}{M} \tag{3.1}$$

$U_{total} = Asset\ uniqueness$

$n = total\ amount\ of\ standardizable\ components\ in\ the\ asset$

$M_i = Mass\ of\ a\ standardized\ component\ i$

$M = Mass\ of\ total\ standardizable\ components$

*The standardized components*
At the moment of publishing this report, within Rijkswaterstaat, no standard designs for components in bridges and viaducts have been developed. Therefore, it should be studied what components are eligible for standardization. In particular highly common components with manifold, nearly-similar designs should be considered for standardization.

*Data required for determining the bridge uniqueness*
The data required for determining the bridge *uniqueness* is shown below. This data should mainly be provided by Rijkswaterstaat.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1 | - | List of standardized components | RWS documents | Use list to determine whether components are eligible for |
| 2 | - | Design of the bridge components | Designer/contractor | Use the geometric data of components for comparison |

## Transportability indicator

If a component is not transportable after use, it will not be reused on another location. As such, *transportability* is treated as a precondition for reuse in the *reusability* indicator: the disassembled components should be transportable in line with the rules and legislation for transportation to be considered for reuse. Since the new asset or component destination is impossible to anticipate beforehand, these aspects cannot be included in the indicator on a continuous scale. Accordingly, considering only transport modes (e.g. water, rail or road), it is a binary expression, indicating simply true or false and are as such preconditions for reuse. Considerations regarding environmental impact in relation to transport distance are not included in this part, for these are included in the MKI.

Whether a component is transportable after disassembly, giving the available transport modes, depends mainly on two factors: (1) the component's dimensions; and (2) the weight of the component. Regarding bridge components, the weight results often in the application of the laws regarding oversized load. However, in the Netherlands, these laws result in extra requirements according to "Regeling Voertuigen 2009" and "Algemene Voorwaarden Exceptioneel Transport (AVET)", rather than prohibition of the transport. Consequently, the component's dimensions form the main limitations regarding *transportability*. Nevertheless, this oversize load transport may involve considerable additional costs, which are not included in this indicator, but must be considered in the overarching lifecycle cost (LCC) considerations. For each component, *transportability* should be assessed for various transport modes (either true or false). Non-*transportability* results immediately in non-*reusability* for the component; it is therefore a precondition rather than a measure.

*Transportability* of a certain dimension is not generalizable, since every location has its own barriers with regard to transportation. Where river crossings offer opportunities regarding water transport, possibilities in highly urbanized areas are limited. Inevitably, the available transport infrastructure are considered to not change over time. That is, it is not possible to know the actual surrounding infrastructure in 2100.

1. Available transportation modes: road (one or more lanes)/water/rail.
2. Maximum dimensions and weight according to the available transportation modes.
3. Valuation of the alternatives by determining the highest rated possibility.

Considering these steps, the modes must be weighted. The more desirable the mode, the higher the number (between 0 and 1). A suggested valuation of the transport infrastructure is provided below. For each situation (bridge and viaduct), these numbers should be divided by the highest possible score. For example, if rail is not available, water and 1-lane road obtains a valuation of 1. The 2,3-lane road gets a new valuation of 0.6/0.9=0.67. The possibilities of the modes are determined by the client before designs are procured. If no transport is possible, the transport mode is valued 0, resulting in immediate non-*reusability*.

| **Transport infrastructure** | **Valuation** | **Transport infrastructure** | **Valuation** |
|---|---|---|---|
| Water, rail, 1-lane road | 1,0 | Water, 2,3-lane road | 0,7 |
| Water, 1-lane road | 0,9 | Rail, 2,3-lane road | 0,7 |
| Rail, 1-lane road | 0,9 | 2,3-lane road | 0,6 |
| 1-lane road | 0,8 | Water | 0,4 |
| Water, rail, 2,3-lane road | 0,8 | Rail | 0,3 |

For determining the *transportability* of a component, the framework user requires various data sets. The data on which the indicator user should base the decision are presented below.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1 | - | Transport rules | Regulation | Determines the possibility for transportation |
| 2 | - | Available transport infrastructure | Bridge context | Determine the infrastructure connections in and near the place of construction |
| 3 | - | Component geometry | Designer/contractor | Retrieve data from design |
| 4 | - | Component weight | Designer/contractor | Retrieve data from design |

### Calculating reusability

The *reusability* of the whole asset is calculated as described in formula 3.2. It is the weighted sum of the *disassemblability* (D) between 0 and 1 times the average bridge *transportability* and sum of the negative *uniqueness* (U) between 0 and 1 times the *transportability* for each individual component. To find the *reusability*, weighting should take place between *disassemblability* and *uniqueness*. We propose an aspect ratio of k = 0.667, meaning that 66.7% of the weight is put on *disassemblability* and 33.3% (100% - k) on *uniqueness*. This is because the former has a larger effect on the eventual reuse, since well-disassemblable but very unique components are more likely to be reused than non-disassemblable standard components.

$$Ru_i = \sum_{i=1}^{n} (\underbrace{[1-k] \times -U_i}_{\text{Uniqueness}} \times \underbrace{T_i}_{\text{Transp.}}) + \underbrace{k \times D}_{\text{Disassembl.}} \times \underbrace{T}_{\text{Transp.}} \tag{3.2}$$

$Ru_i = Reusability\ of\ component\ i$

$D = Total\ bridge\ disassemblability$

$U_i = Uniqueness\ of\ the\ component\ i$

$T = Total\ bridge\ transportability$

$T_i = Transportability\ of\ component\ i$

$k = Relative\ importance\ of\ D\ in\ relation\ to\ U$

## 4. Adaptability indicator

Although *adaptability* is strictly speaking a mechanism for resilience – a diversity of states in which it is able to fulfil its function makes the bridge resilient to changing circumstances – here, we separate resilience or agility as quality to adapt to changing circumstances (e.g. through variety or redundancy) from adaptable design. These two require in the light of bridges two entirely different design philosophies. The Robustness accounts for the former resilience-related *adaptability*, while the latter is elaborated in this chapter.

*Adaptability* knows many interpretations and applications, yet Schmidt (2014) found four characteristics that apply to *adaptability* in general. These are: (1) capacity for change; (2) sustaining *fit-for-purpose*; (3) value retention; and (4) through-life (and hence future) changes. This led to the following definition (Schmidt, 2014): “[Adaptability is] the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising its value through life.” By applying this to bridges and viaducts, various possible changes are identified.

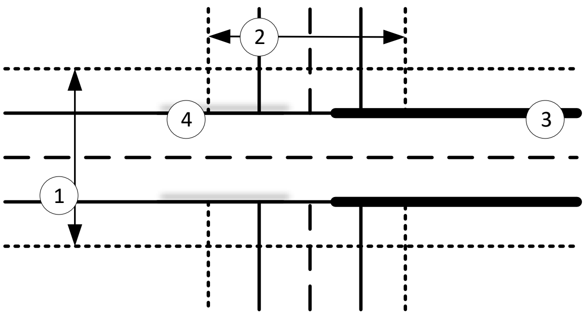



*Figure 25 – Four main possibilities of bridge adaptability*

A structure can be transformed if its elements can be defined as independent parts of the system and if its interfaces are exchangeable (Durmisevic, 2006). Rather than a comprehensive transformability, bridges are assessed on *adaptability*, since functional transformations are unlikely to be required. In this study, *adaptability* stands for the quality of a bridge to be adjusted to new traffic intensities, dimensions and loads. For bridges, we identified four main possibilities of adaption: (1) broadening of the crossing; (2) broadening of the underpass; (3) strengthening of the crossing; and (4) increasing the overhead clearance of the underpass. The easiness to which one of these adjustments can be made is captured in to concept of *adaptability* of the designed bridge.

On the one hand, this is described by the oversizing of the substructure, also called robustness. This allows for increasing resistance to future need for strengthening and allows furthermore for the possibilities of extending the structure with, for example, a bike lane. On the other, the possibilities in design-for-adaption needs to be assessed. This *adaptability* determines for a large part the future-proofness of a bridge or viaduct. In many respects, *adaptability* is related to *reusability*, since both need low levels of coupling. A combination of high *adaptability* and *reusability* increases the opportunities for both prolonging and closing the loops.

### Extensibility indicator

*Extensibility* describes the ease of adaption of the two crossing roads (number 1 and 2 in Figure 25). First, the *extensibility* in widening the upper (crossing) road is discussed, followed by the *extensibility* concerning widening the underpassing (crossed) road.

<u>Widening the crossing road</u>
The *adaptability* of the widening of the bridging road is closely related to the edging elements used as possibilities for connecting other components on a component level and space left in the asset's surroundings. For widening the crossing road, the possibilities of disassembling or adapting the side elements is essential in order to avoid creating waste to the existing structure.

Moreover, full *extensibility* requires the structural ability to carry the weight of the extended part – especially regarding the substructure of the bridge. However, in order to avoid overlap, this is a hard requirement, while the extent of oversizing is covered by the overdesigning indicator. Because the way that bridges can be extended is mostly limited to the addition of a lane, the indicator measures the share of interfaces that have to be constructed afterwards if a lane of similar capacity as the existing lanes is added. Since a limited amount of components play a role in the *extensibility*, while the solution for making structures extensible is manifold, no fixed measurement can be developed. Consequently, for a design being extensible, the designer should prove one of the following criteria:

1. On both sides of the bridge or viaduct, a lane with equal functionality could be attached to the existing structure without making the existing structure create waste.
2. On both sides of the bridge or viaduct, a lane with equal functionality could be attached to the existing structure with the existing structure creating maximum 5 mass% waste.
3. On both sides of the bridge or viaduct, a lane with lower functionality could be attached to the existing structure without making the existing structure creating waste without the need for additional substructure.
4. On one side of the bridge or viaduct, a lane with equal functionality could be attached to the existing structure without making the existing structure create waste.
5. On one side of the bridge or viaduct, a lane with equal functionality could be attached to the existing structure with the existing structure creating maximum 5 mass% waste.
6. On one side of the bridge or viaduct, a lane with lower functionality could be attached to the existing structure without making the existing structure creating waste without the need for additional substructure.
7. The crossing is not extensible.

Each number gets a certain weighting which are determined together with RWS experts. These weights show the contribution to the overall *extensibility*. If for example at one side a driving lane can be added and on the other a bike lane, those numbers can be added up to each other. For example, this would be 0.5 plus 0.3 which equal 0.8. The designer should prove which of the *extensibility* options apply to the design. Of course, the better the *extensibility*, the higher the circularity (formula 4.1). The weights are as follows:

| No. | Rationale | Weight |
|---|---|---|
| **1** | Both sides without waste | 1,0 |
| **2** | Both sides with <5% waste without support | 0,8 |
| **3** | Both sides with support | 0,6 |
| **4** | Both sides bike lane | 0,4 |
| **5** | One side without waste | 0,5 |
| **6** | One side with <5% waste without support | 0,4 |
| **7** | One side with support | 0,3 |
| **8** | One side bike lane | 0,2 |

<u>Widening the crossed road</u>
Also possibilities regarding *extensibility* of the crossed road (option 2 in Figure 25) are included for determining viaduct *extensibility*. The only criterion is that the designer should prove that on one or both sides, a lane can be added without creating waste to the bridging structure. This is only applicable to road-crossing viaducts, since these might be eligible for extension.

| *No.* | *Data required* | *Source* | *Method* |
|---|---|---|---|
| 1 | Estimation of the bridge that needs to be revised for extension | Designer/contractor | The designer should design and prove an extended design for the extension of either or both the crossed or crossing road |

### Strengthenability indicator
Often, oversizing is unwanted because of *material input*. To make the bridge resilient to future increasing loads and lifespan extension, the bridge could be designed *strengthenable*. These reinforcement techniques vary for each situation and therefore, no general sub-indicator can be developed. However, this can be approached by binary criteria. In order for the bridge of viaduct to be strengthenable, the designer should prove that the construction meets the following criteria:

1) The elements to which strengthening measures are applied are accessible for workers.
2) The reinforcing measures must be applicable to the geometry of the designed structure.
3) The reinforcing measures may not result in crease of functionality of other system elements.

If the designer can prove by design that the design fits the three abovementioned criteria, the asset is considered strengthenable.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1 | - | Design configuration | Designer | The designer should use the existing design to make a prove of strengthenability |

### Heightenability indicator
Under certain circumstances there is a possibility that the height of the underpass does not meet the required functionality. Especially with regard to bridges over water this *heightenability* scenario is relevant. Therefore, it might by desirable for the designed bridge to be increasable in height. Heightening the underpass can be done twofold: by lowering the underpass (in case of viaducts) or by lifting the cross-over (both bridges and viaducts). Either way, without a suitable design, additional material is used and waste created.

Piers and abutments are in many cases easily heightenable, so a liftable deck contributes largely to *heightenability*. If the deck is connected to the substructure such that it only requires non-destructive design methods to take the deck apart from the substructure, it is considered heightenable. The other way around, if the design allows for lowering the underpass without creating waste, the overhead clearance is increased without creating additional waste. Equal to *strengthenability* and *extensibility*, the designer must prove by design whether the asset is *heightenable*.

An important note is that the adjacent infrastructure should be such that it does not require extensive revisions and hence waste creation to connect to the heightened bridge. An example could be a roundabout that is situated directly next to the bridge deck and would need to be heightened, and thus replacement, after lifting the deck. Such a situation immediately results in non-*heightenability*. In case the surrounding infrastructure does not allow for heightening, the client should exclude the *heightenability* sub-indicator in the assessment.

| *No.* | *Symbol* | *Data required* | *Source* | *Method* |
|---|---|---|---|---|
| 1 | - | Design configuration | Designer | The designer should use the existing design to make a prove of strengthenability |

## Calculating adaptability

For calculating *adaptability*, first it is determined by the moderator or design assessor which of the four directions of *adaptability* apply to the situation. For example, it might not be necessary to make the underpass wider because of limitations further down the road. After this, it is up to the designer to identify the components and elements that need to be altered in order to facilitate this *adaptability*.

The *adaptability* of individual components is calculated as described in formula 5.1. It is the weighted average of *extensibility*, *heightenability* and *strengthenability*. In this, *extensibility* and *strengthenability* are considered double as important as *heightenability*, given the occurrence of functional demolition as a result of this aspect. As such, the *extensibility* and *strengthenability* are considered equally important, since crucial arguments for weighting one heavier than the other is lacking.

$$A_i = \frac{2*Ex+1*He+2*St}{5} \tag{5.1}$$

$$Ex = Extensibility\ of\ the\ asset$$

$$St = Strenghtenability\ of\ the\ asset$$

$$He = Heightenability\ of\ the\ asset$$