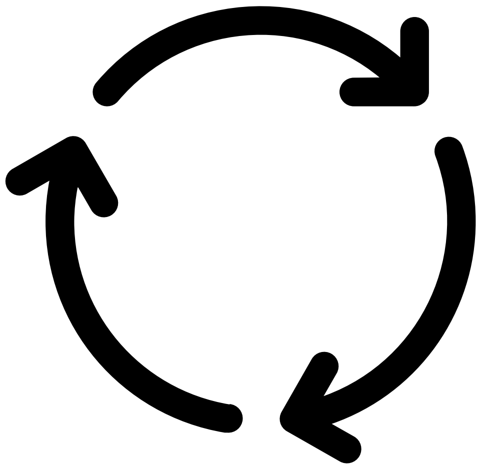
Assessing the circularity of infrastructure assets:

A methodology to inspect and assess 1 on 1 reuse of concrete components

A master thesis in fulfilment of the degree of Master of Science in Civil Engineering and Management



Sammie van Berlo

7 May 2019

UNIVERSITY OF TWENTE.

Witteveen + Bos

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Master thesis

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Preface

Before you lies the master thesis ‘Assessing the circularity of infrastructure assets: A methodology to inspect and assess 1 on 1 reuse of concrete components’. This thesis has been written in fulfilment of the degree of Master of Science in Civil Engineering and Management at the University of Twente. This research was conducted within the Asset Management division of Witteveen+Bos and focusses on developing a method and tool to help assess the ability for concrete components to be reused 1 on 1. I would like to thank several people that have helped me during my thesis.

Firstly, I would like to thank my supervisors at Witteveen+Bos, Justin Sap and Rob Dijcker, for their guidance that they have given me during my time at Witteveen+Bos and their useful and critical feedback for my thesis.

Secondly, I would like to thank my supervisors at the University Twente, Andreas Hartmann & Silu Bhochhibhoya, for the guidance and feedback that they have given me during our meetings.

Thirdly, I would like to thank all the other people at Witteveen+Bos that have helped me with input for my thesis and made sure that I really enjoyed going to the office.

Finally, I also would like to give special thanks to my girlfriend, friends and family who have given me wisdom and motivation when I was stuck with my thesis and have given me tips to successfully finish my thesis.

Sammie van Berlo

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Summary

The construction industry is one of the main focus areas of the Dutch government regarding the transition towards a circular economy. Because of the growing need for a more circular economy, Witteveen+Bos has asked for an inspection method to assess infrastructure on circularity. More specifically, this method focusses on an inspection and assessment method to assess concrete infrastructure components on their ability to be reused 1 on 1.

The circular indicators that influence the ability of a concrete component to be reused 1 on 1, are the toxicity, condition, residual lifespan, connections, retrieval, design requirements and the dimensions. In the first part of the research, for the seven circular indicators, it is studied which aspects of these indicators influence the ability of a concrete component to be reused 1 on 1. This is done by researching literature and reports and by taking interviews. Based on the findings, a set of functional requirements has been drawn up which is used for the design of the new method. Apart from the functional requirements, also a set of general requirements has been drawn up, based on existing circular assessment methods and infrastructure inspection practices. The functional requirements say more about which functional aspects need to be assessed by the method, whereas the general requirements give more general demands for the new design of the method. With the help of the general requirements, some of the functional requirements have been rejected and a set of assessment questions has been drawn up for the design of the new method. The essential information to assess 1 on 1 reuse of concrete components is:

- Information about the presence of iron fibers
- Information about the presence of composite fibers
- Information about the general condition of the component
- Information about the ability to transport a component
- Information about the ability of the component to be disassembled without completely damaging the component

In the second part of the research, the method and tool are designed through multiple design cycles. With the assessment questions and the general requirements, a first design of the method has been drawn up, together with a tool to help execute the method. After a feedback session to verify the first design of the method, a second design of the new method has been made. After a test case to validate the second design of the method, eventually a third and final design of this new method (to assess the ability for a concrete component to be reused 1 on 1) has been made, complemented with a tool to help execute the method.

For the design of the new method, the assessment questions of the seven circular indicators have been regrouped into three different categories in order to assess the ability of a concrete component to be reused 1 on 1. The three categories are Material Quality, Disassembly and Applicability.

The final method consists of a number of steps which are divided into 4 main steps; preperation, assessment questions, category scoring and recommendations. A flow chart diagram which visualises the method steps of the final method is shown in Figure 1.

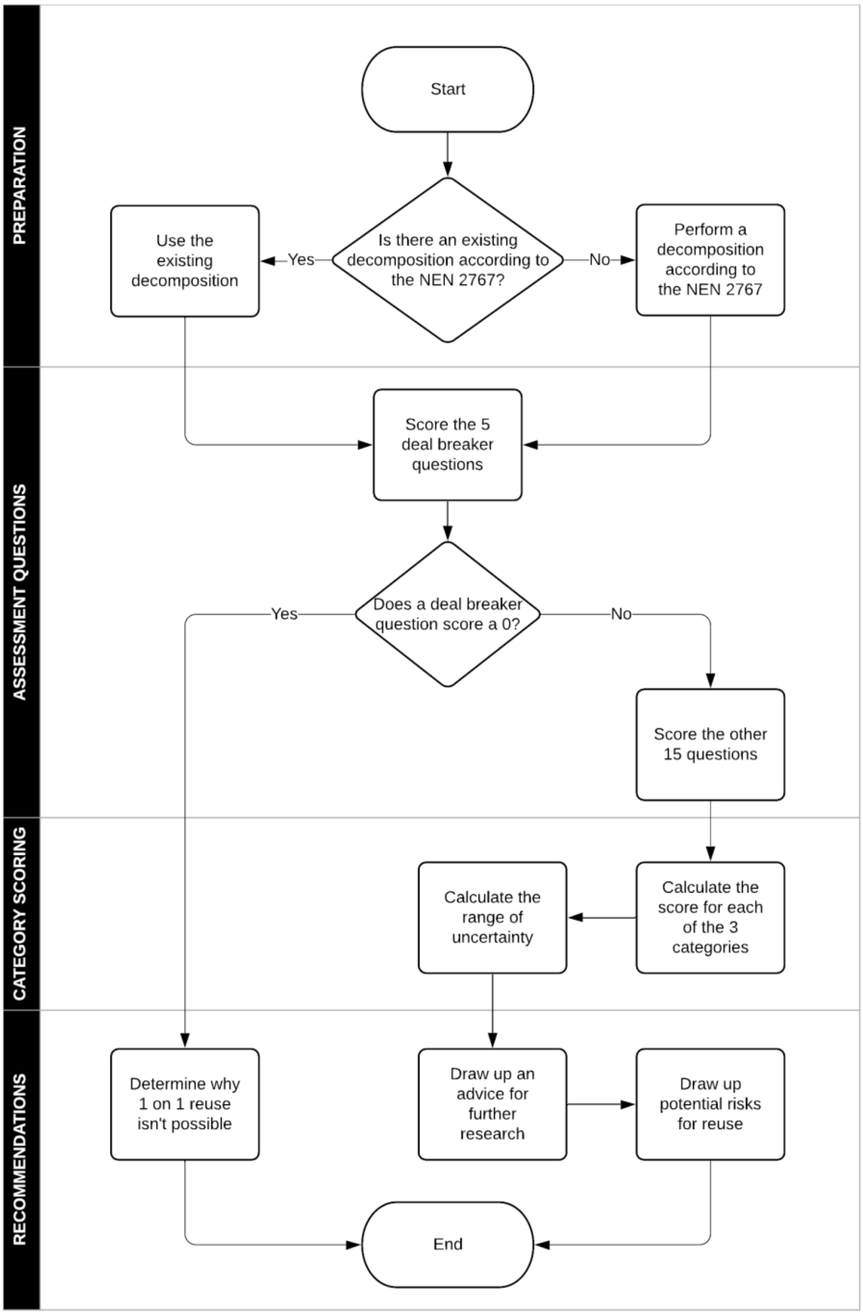

Figure 1: Flow chart diagram of the final method

- The first main step is the preparation; it must be checked if a decomposition is available and if that is not the case a new decomposition must be performed.
- The second main step is about the answering of the assessment questions for the components; First, the five deal breaker questions must be scored and it must be checked if a deal breaker question scores a 0 to assess if reuse is possible. If a deal breaker question scores a 0, reuse is not possible. If a deal breaker question does not score a 0, the other 15 remaining assessment questions must also be scored.

- The third main step is about the scoring of the categories; For the Material Quality, Disassembly and Applicability categories, a score must be calculated. Additionally, after the scores have been calculated, the level of uncertainty needs to be calculated.
- The fourth main step is about giving recommendations. If reuse is possible and if there is a certain level of uncertainty, recommendations for further research must be given, these additional researches can decrease the level of uncertainty. Additionally, potential risks for reuse of the components must be determined, that could be present if the component is going to be reused. If reuse is not possible it should be determined why the component is being rejected for reuse.

The Excel tool that is developed to execute the method, helps to perform with the main steps 2,3 and 4 of the method.

The final part of this research comprises the conclusions, discussion and recommendations. In this part of the research it is concluded that:

- The method can easily be integrated within regular NEN 2767 condition inspections.
- The method can give a quick indication if 1 on 1 reuse is possible or not.
- The method can generate unambiguous scores that can be compared with each other.
- The method can easily be adjusted if future needs for reuse assessment take place.
- The method can give difficulties in generating the same outcomes if different inspectors perform the method.
- The tool that helps to execute the method, has an interface that is easy to understand.

It is recommended that this method is being further developed by including more design cycles which would improve the validation of the method. Apart from further developing this method, it is also recommended to gain more knowledge of the circular economy on a broader level to develop a method that is able to assess other materials and for other loops of the circular economy. This method should be used as a baseline for further developments for assessing tools of circular performance of infrastructure assets. It is also recommended to integrate this new inspection and assessment method into the regular condition inspections according to the NEN 2767. The new method should be discussed with clients of Witteveen+Bos that might be interested to know if there are reusable components in their infrastructural assets.

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1 Introduction

The call for a transition towards a circular economy keeps getting more attention. Especially in the construction industry, materials and resources need to be managed more consciously. A lot of organisations in the construction industry need to move their policies towards a circular economy. Witteveen+Bos, an organization that provides consultancy and engineering services, can play an important role in the transition to a circular economy. Also in the management of infrastructure assets, there is a lot to gain in making processes more suitable for the transition towards a circular economy, which is what keeps the asset management division and the circular economy group of Witteveen+Bos busy. This research focusses on providing the asset management division and the circular economy group of Witteveen+Bos with a standardised method, which can inspect and assess infrastructure components based on the requirements of a circular economy.

1.1 Preliminary research

1.1.1 Circular economy challenge

The Dutch government has published a document called 'Nederland circulair in 2050' (The Ministry of Infrastructure and the Environment & the Ministry of Economic Affairs, 2016). This document describes the government-wide program which focusses on achieving a circular economy in 2050. The Dutch government wants to outline a perspective for a future-proof, sustainable economy and wants to keep the future generations in mind. To be able to provide future generations of necessary goods, the way that resources and materials are currently handled must fundamentally change. This means that resources must be used and extracted in an efficient and durable way and products and materials must be designed in a way that they can be reused without losing value. To achieve this, technical, social and system innovations are necessary.

The need to strive for a circular economy comes among other things from the fact that the world population has been using 34 times more materials last century. Especially the construction industry is using a lot of resources. About 50% of all raw materials are used in the construction industry and about 40% of the total amount of waste in the Netherlands is related to construction and demolition waste (Ellemmi, 2013). Additionally, about 70% of the environmental impact of an average construction material is caused by the energy that is required for the production of the material (Kay & Essex, 2009). This emphasises the need to change the way that resources and materials in the construction industry are being managed. That is why the construction industry is one of the main focus points of the Dutch government regarding the transition towards a circular economy. As a result of a circular agreement (grondstoffenakkoord), a transition agenda for the circular construction economy has been constructed. In this transition agenda, a number of goals are described; in 2023 all tenders must be circular, in 2030 a 50% reduction of CO_2 emissions must be achieved, and in 2050 an 80% reduction of CO_2emissions must be achieved (Transitieteam, 2018).

To stimulate organisations in making a transition towards more durable solutions, the government has certain focus points for interventions; It is required to have more stimulating laws and regulations, smart market incentives, stimulation of the financing market, a proper infrastructure for knowledge and innovations, and a focus on international cooperation. It is important that public and private organisations work together with a common vision and strive to come up with technical, social and system innovations regarding the transition to a circular economy. By drawing up these focus points, the government wants to stimulate more knowledge in durable solutions and burst through non-circular patterns in organisations which are being used out of habit. (The Ministry of Infrastructure and the Environment & the Ministry of Economic Affairs, 2016)

In 'Nederland circulair in 2050', the following goals have been formulated specifically for the construction industry: 1) The construction industry must mainly use reusable materials 2) The construction industry must be an innovative sector that pro-actively reacts to changes in society and changes in the market and consumer demands. This is where Witteveen+Bos can play an important role.

In 2015 the United Nations has set up 17 sustainable development goals for 2030 (United Nations, 2018), and Witteveen+Bos wants to help in achieving the 17 sustainable development goals by implementing the goals in their projects. Sustainable development goal 12 is to achieve responsible consumption, which is what a shift towards a circular economy should provide. Therefore the circular economy group of Witteveen+Bos, together with technical managers, advisers and designers, have provided 8 principles of circular design (Dijcker & Schepers, 2018), which are being applied in projects within Witteveen+Bos. These principles focus on prevention, value retention and value creation. They form a living guideline, without providing ready-made solutions (Witteveen+Bos, 2018):

1. Prevent: do not do what is not necessary
2. Extend lifespan of existing objects
3. Use current existing objects, materials and natural processes sustainably
4. Design for multiple life cycles
5. Design futureproof
6. Design for optimal maintenance
7. Design for sustainable material use
8. Design for minimal material and energy use in construction and use phase

This research is mainly focussed on the third design principle about sustainable use of existing objects, materials, resources and natural processes.

The asset management division of Witteveen+Bos has the goal to make decisions based on reliable information and well-defined goals. It aims at the full lifecycle of an asset from the preparatory work until the replacement. Because of the goals described in the 'Nederland circulair in 2050' document, there is a growing need to focus on sustainable solutions towards a circular economy and organisations in the construction industry will need to focus on this need. With a circular economy, new challenges and opportunities arise for better management and maintenance of infrastructure assets. In asset management there is a lot to gain, because currently asset management is not organised to look at the status of an asset regarding its potential to being reused. The asset management division and the circular economy group of Witteveen+Bos work together to help fulfil the goals of 'Nederland circulair in 2050' and the sustainable development goals.

There are two main reasons for an infrastructure asset to be demolished. The first reason is that its technical lifetime has ended, which means that the infrastructure asset was not designed to last any longer. The second reason is that an asset has been demolished because its functional lifetime has ended, which means that there are functional adjustments taking place to the infrastructure asset. E.g., this could happen if the regulations and requirements of an infrastructure asset change due to a change in traffic intensity. This is happening frequently, because a lot of the old infrastructure not designed for the current traffic intensity with which they have to deal with now. Research has pointed out that about 90% of all demolitions took place because of functional reasons (Dijcker & Schepers, 2018), that means that a lot of the demolished assets are technical still usable and could be used somewhere else. About 85% of the demolished components are being reused as mixed granulate and it is not being properly assessed if they can be reused 1 on 1 as a product again for other assets. 1 on 1 reuse describes the process during which discarded components are recirculated and used for the same function without destruction (Iacovidou & Purnell, 2016).

1.1.2 Definition of circularity

To be able to make a transition towards a more circular economy, it first needs to be clear what is meant with the concept of a circular economy. Figure 2 gives a simple explanation about the differences between a linear economy, an economy with feedback loops and a circular economy. It shows that in a perfect circular economy no raw materials are used and no residual waste is produced.

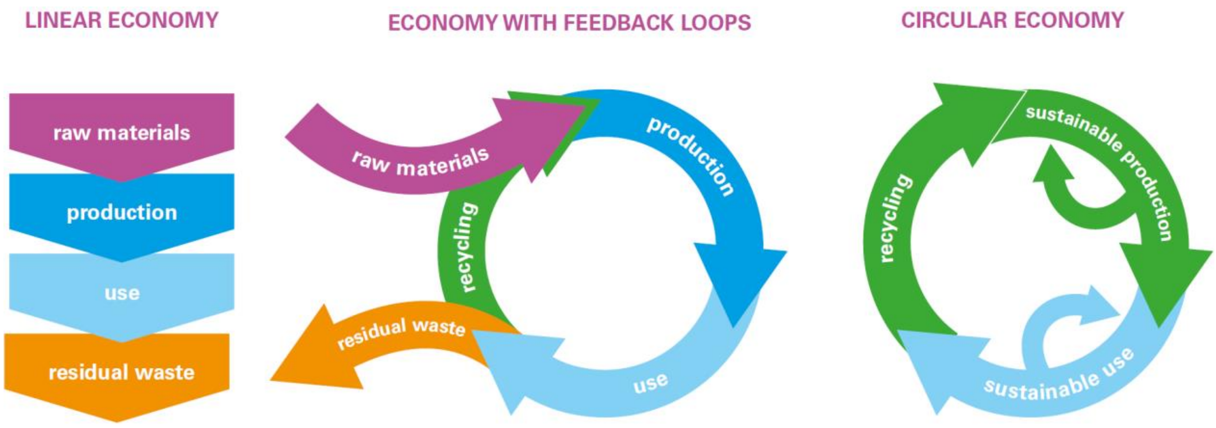


Figure 2: Differences between types of economy (RLI, 2015)

But there is still a broad spectrum of aspects which exist within the framework of a circular economy, Appendix A gives a more extensive illustration of the circular economy, which also visualises the cycle of reuse (Ellen MacArthur Foundation, 2012). Because of all these aspects, it is very hard to give a definition of what a circular economy exactly is. Because there is lack of a commonly accepted definition for a circular economy (which is confirmed by Yuan, Bi & Moriguchi (2008)), Kirchherr, Reike, & Hekkert (2017) have performed an analysis about the definition of a circular economy. They found that among 114 gathered definitions from journals, policy papers and reports, 95 different definitions of a circular economy were used. The most used definition for a circular economy is provided by the Ellen Macarthur Foundation (2012):

‘an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models’

According to Kirchherr et al. (2017), the best definition is given by van Buren, Demmers, van der Heijden & Witlox (2016), because it includes the 3R (reduce, reuse & recycle) framework, the R hierarchy, a systems perspective, environmental quality, economic prosperity and social equity:

‘The focus point in a circular economy is to not unnecessarily destroy resources. This implies far more than the reduction of waste through recycling, stresses the following focal points: reducing the consumption of raw materials, designing products in such a manner that they can easily be taken apart

and reused after use (eco-design), prolonging the lifespan of products through maintenance and repair, and the use of recyclables in products and recovering raw materials from waste flows. A circular economy aims for the creation of economic value (the economic value of materials or products increases), the creation of social value (minimization of social value destruction throughout the entire system, such as the prevention of unhealthy working conditions in the extraction of raw materials and reuse) as well as value creation in terms of the environment (resilience of natural resources).'

To avoid that circular economy implementations will only result in incremental improvements at best, instead of delivering the fundamental changes which it promises, it is necessary that good circular economy definitions will dominate. Otherwise, the concept of circular economy could eventually end up like just another buzzword in the sustainable development discussion (Kirchherr et al., 2017).

1.1.3 Schools of thought

The Ellen MacArthur Foundation, a foundation which has the goal to accelerate the transition to a circular economy by putting circular economy on the agenda of decisionmakers across business, government and academia, established 7 different schools of thought within the framework of a circular economy (Ellen MacArthur Foundation, 2018):

1. Cradle to Cradle

Cradle to Cradle focuses on design for effectiveness in terms of products with positive impact and reducing negative impacts of commerce through efficiency. It perceives the processes of nature's 'biological metabolism' as a model for developing a 'technical metabolism'. Three fundamental elements of Cradle to Cradle are; Elimination of the concept of waste, power with renewable energy and respects human and natural systems.

2. Performance Economy

Performance economy, also called functional service economy, insists on the importance of selling services rather than products.

3. Biomimicry

Biomimicry is about studying nature's best ideas and then imitate these designs and processes to solve human problems. Nature functions as a model, as a measure and as a mentor.

4. Industrial Ecology

Industrial ecology aims at creating closed-loop processes in which waste serves as an input, thus trying to eliminate undesirable by-products. Industrial ecology has an interdisciplinary nature, its principles can be applied in the service sector as well as in production processes. Apart from an emphasis on natural capital restoration it also focuses on social wellbeing.

5. Natural Capitalism

Natural capitalism is about an economy in which business and environmental interests overlap. Natural capitalism recognises the interdependencies that exist between the production and use of human-made capital and flows of natural capital. Four fundamental elements of natural capitalism are: Radically increase the productivity of natural resources, shift to biologically inspired production models and materials, move to a 'service-and-flow' business model.

6. Blue Economy

Blue economy insists on solutions being determined by their local environment and physical/ecological characteristics, putting the emphasis on gravity as the primary source of energy.

7. Regenerative Design

Regenerative design takes into account processes which are designed to ensure the restoration, renewal and revitalisation of their own sources of energy and materials.

Because of its circular nature, a circular economy has a strong link with reverse logistics (Ripanti, Tjahjono, & Fan, 2015) and the concept of reverse logistics is gaining more attention in the construction industry. Reverse logistics in the construction industry is about controlling the flow of construction components that would otherwise end up in the construction/demolition waste stream, and effectively recirculating them back to the construction stage of a new project (Hosseini, Chileshe, Rameezdeen, & Lehmann, 2014). Deconstruction, the carefully dismantling of a structure to maximise the recovery of its components for reuse (Chini & Bruening, 2003), is an intervention that can promote reverse logistics in the construction sector. It can have several advantages over the complete demolition of a structure; reuse of components, recovery of materials for recycling, reduction of waste and improvement of environmental protection. But before a component can be reused, first it has to be assessed if it is possible to reuse a component.

1.1.4 Condition score

In order to assess the possibility for components to return back in the cycle of the circular economy, data are needed. Inspections help in retrieving data from infrastructure components. Currently, the inspections of assets in the Netherlands are performed according to the NEN-2767 standard. The NEN-2767 is the standard for the condition assessment which ensures objective and uniform measurements of the physical quality of construction and installation parts of buildings and infrastructure (Normcommissie 351264 "Conditiemeting," 2017). It measures the technical condition of an asset with help of a checklist. The goal of the NEN-2767 standard is to make sure that the technical condition of an asset can be mapped in a uniform way so an easy comparison can be made between the different conditions of the assets. An asset gets a certain condition score which can range from 1 to 6 (see Table 1), this condition score is useful for setting up a long-term maintenance plan for different assets.

The NEN-2767 standard is useful to assess the technical condition of an asset. However, it is not designed to take into account the demands of a circular economy and does not assess if certain components can be reused again. But before inspections can be adjusted to the demands of the circular economy to assess reuse, first it needs to be investigated what those demands are and how to assess these demands.

Table 1: NEN-2767 condition scores (Normcommissie 351264 "Conditiemeting," 2017)

Condition score	Description	Explanation
1	Excellent condition	Incidental minor failures
2	Good condition	Incidental beginning deterioration
3	Acceptable condition	Partially visible deterioration, performance of asset not in danger of failing
4	Poor condition	Incidentally asset performance in danger of failing
5	Bad condition	Deterioration is irreversible
6	Very bad condition	Technically ready for demolition

1.1.5 Circularity assessment

As mentioned above, before the inspections can be adjusted to the demands of a circular economy, it first needs to be investigated which factors should be assessed to adjust the inspections to the demands of a circular economy. To investigate these factors, existing literature on the topic of reuse and recycling in the construction industry is analysed. Iacovidou & Purnell (2016) have performed a research about the possibilities to improve the sustainability of the construction industry by reusing and recycling construction components and waste products from other industrial processes. They have made a clear distinction between reusing and recycling; reusing indicates a process in which components are used again for the same function without demolition, recycling indicates a process in which materials are reproduced into raw materials for new products. Within the recycling process, a distinction can be made between a closed-loop recycle process if the component is recycled into the same component and an open-loop recycle process if the component is recycled into a different component (Thomark, 2000). The energy requirements which are needed for reuse are much lower than the energy requirements for recycling (Hosseini et al., 2014).

Two important factors play a role in determining a components' potential after its primary life has ended. The first factor is the reuse potential. The reuse potential is a measure of the ability of a component to keep its functionality after the end of its primary life. Appendix B shows the reuse potential rate for a range of construction components according to Iacovidou & Purnell (2016). Because these rates are also dependent on cultural, historical and organisational aspects, they are rough estimations. The second factor is the embodied carbon (EC) reuse efficiency. The EC reuse efficiency metric gives knowledge on how much carbon can be saved if the component is reused. This is difficult to determine since it can depend on size, dimensions, energy mix, material design and recycle content. Both the reuse potential and the EC reuse efficiency are important in determining if it is worthwhile to reuse a component (Iacovidou & Purnell, 2016).

At the moment literature is unclear on how EC reuse efficiency should be measured for different components. Iacovidou & Purnell (2016) emphasise that clarifications in this area are needed to develop a common understanding on the way that assets are being managed regarding its EC reuse efficiency and that the development of a framework could contribute in the assessment of the reuse value of a component. Iacovidou & Purnell suggest that confidence in reuse could be achieved by a typology system that can assist contractors and designers in the selection and performance of reused construction components. This proposed typology system would focus on the properties of a component, the nature of the recovery process and the nature of the original use:

1. Action
2. Material
3. Deployment
4. Exposure
5. Loading
6. Recovery
7. Residual
8. Connections
9. Availability
10. Generation

Appendix C gives a more extensive description of the proposed typology system.

Another set of properties to assess materials on their reuse potential is published by Geldermans (2016). This set of properties shows which properties materials should fulfil to be able to facility circularity. The properties are divided into two groups; intrinsic properties and relational properties. Intrinsic properties say something about the functional performance, the sustainability, the toxicity and the consistency with biological and technical cycles of the material or product. Relational properties say something about the dimensions, connections and performance time of the material or product. It is stated by Geldermans that neither intrinsic nor relational properties individually have decisive significance regarding circularity, but it is somewhere where these two properties cross where fulfilment regarding circularity is created. Conclusively Geldermans distinguishes seven data categories regarding assessing the circularity potential:

1. Exact composition of the material or product
2. Performance quality of the material or product
3. Intended (re)use path of the material or product
4. Performance time of the material, product component or service
5. Connections applied between materials, products or components
6. Dimensioning of materials, products or components
7. Quality of the registration system and process

As described above, Iacovidou & Purnell (2016) and Geldermans (2016) both distinguished certain properties of materials which are relevant in assessing a materials ability to be reused. Such relevant data regarding these properties could be stored in a so-called materials passport. With a materials passport, it could be easy to retrieve the necessary data. For newly build infrastructures this could relatively easily be implemented, but for a lot of existing infrastructure assets, this data is not stored properly and thus unknown. If this information is stored properly, it would make the deconstruction or disassembly of infrastructure assets easier and gives the assets more value (Duurzaam Nieuws, 2017).

According to Iacovidou & Purnell (2016), on-site assessment of construction components is currently the only way to evaluate their physical performance and ability for reuse. There is guidance on theoretical reuse potential of construction components, but achieving a successful implementation is difficult. Efforts must be made to gain a better understanding on how reuse potential properties should be clarified and to develop measures that associate reuse potential indicators with construction components during manufacturing and construction. The typology system which Iacovidou & Purnell (2016) proposed, and the properties which are defined by Geldermans (2016) could help with determining the necessary aspects which need to be investigated in inspections, which could in turn help determine if it is possible to reuse a component, regarding the demands of a circular economy.

Short-term economic issues, time constraints and a lack of appropriate skills in the industry limit the further development of reuse in the construction industry. A problem of reuse is that it is limited by building codes and standards, by the lack of confidence in the structural properties and performance of reused components and by the lack of awareness on the potential of this practice. Most of the studies about reuse are qualitative instead of quantitative and do not provide figures on the economic, environmental and social value of deconstruction.

1.2 Problem statement

It is the ambition of Witteveen+Bos to support their clients in realising their goals regarding the transition towards a circular economy. Witteveen+Bos has already been focussing on the increasing demands of a circular economy. Together with technical managers, advisers and designers, Witteveen+Bos has been working on a document which provides guidelines for circular designing (Dijcker & Schepers, 2018). This document includes a guideline for the application of circular design principles for different design strategies, the creating of space for circular designs in the MIRT (Multi-year program Infrastructure, Spatial Planning and Transport) process and the creating of boundary conditions for circular works. Additionally, a circular design tool is developed which lays down 6 necessary steps to ensure a circular design process; 1) economy design strategies, 2) circular economy principles, 3) a circular economy measuring bar, 4) a circular economy index, 5) a materials passport, and 6) a disassembly manual. Although it gives a good insight on the important principles regarding the application of a circular economy in infrastructure projects, it is still in its infancy phase. There still is not a well-developed method to inspects current infrastructure assets on their ability to be reused and to return in the loop of a circular economy. Such a method is needed to collect the necessary data in a materials passport and analyse the necessary data which will make it possible to assess if components can be reused again. Such a method could have a large impact because, as stated in the previous chapter, about 90% of demolitions of infrastructure happen because of functional reasons, which means that a lot of the demolished assets are technical still usable and could be used 1 on 1 as a product somewhere else.

Witteveen+Bos has made a start with developing a method on how to assess reuse possibilities for different concrete components. It is a decision tree, which is shown in Appendix D, That consists of different yes or no question that need to be answered to come to a certain outcome. There are four different possible outcomes as a result of the decision tree; 1) Reuse as product, 2) Recycle as raw material, 3) Recycle as granulate, and 4) Construction waste. This decision tree is based on the knowledge within Witteveen+Bos. However, it is only a rough outline and it lacks justification and quantification. Without the justification and quantification of such a method, the outcome of such an assessment may differ for different inspectors because they may have different interpretations of what they examine. This justification and quantification is needed, because the outcome of such an assessment should be the same, regardless of who is performing the inspections.

As stated before, there is also a lack of confidence in reused component. A lot of decisionmakers tend to rather choose for brand new components than for components that have already been used, although those used components are sufficient enough to fulfil their function. More justification and quantification of the assessment on the ability of a component to be reused, could convince decision makers to choose for components that have already been used, because it can give more insight in the structural properties and performance of components.

Figure 3 shows the problem analysis through a cause and effect diagram and the scope on which this research is going to focus.

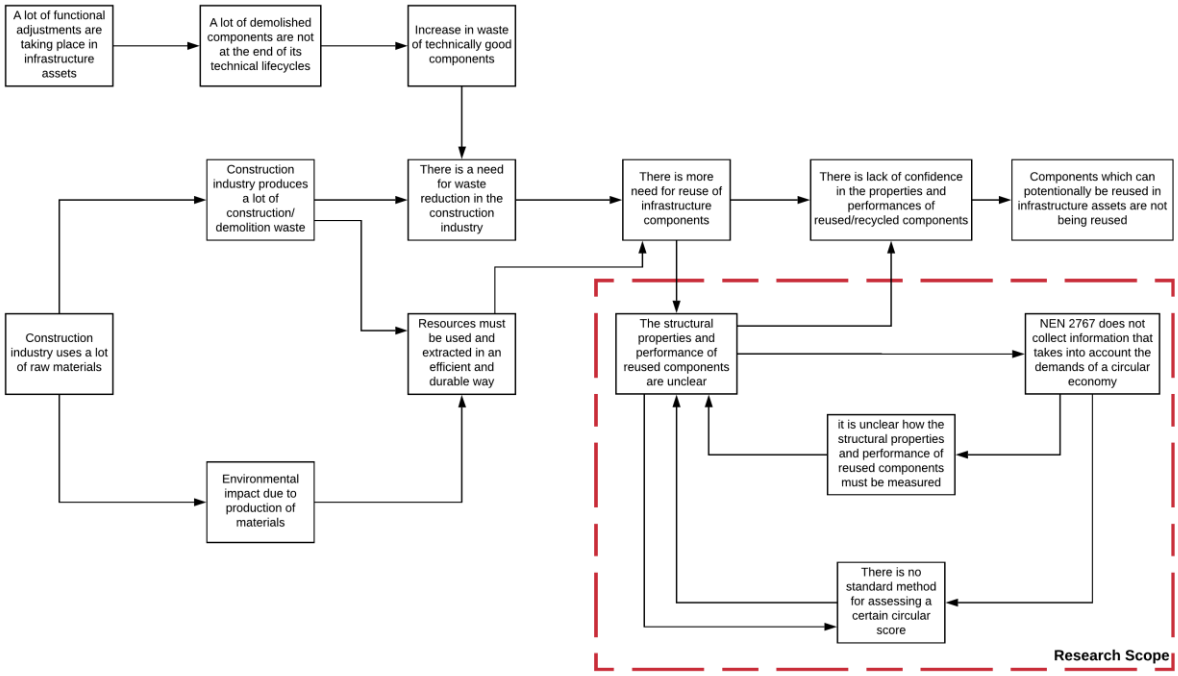


Figure 3: Cause and effect diagram

As stated before, functional adjustments are taking place. Therefore, a lot of components that are not at the end of its lifecycle are removed from infrastructure assets while they are still in good condition. At the moment these components end up as waste. This waste production together with the environmental impact of the construction industry, gives a need for waste reduction and consequently a need for more reuse of materials of infrastructure components.

However, currently it is unclear what the properties and performances of components are that already have been used. At the moment, regular inspections, such as the NEN 2767 standard, do not collect the right information to assess a components ability to be reused. there is no standard method to assess this, therefore it remains unclear how this should be measured and assessed. Because of this, there is a lack of confidence in reusing components. This lack of confidence results in the fact that component that could potentially be reused, are not being reused.

1.3 Research objective

To achieve better guidance in the shift towards a circular economy, measures must be developed that are able to value construction components on circularity during manufacturing and construction. But there is also a lot of existing infrastructure which has already been constructed and which has components that are already in use. A lot of this existing infrastructure is very old and consequently is not designed with the principles of a circular economy in mind. Also for these existing assets, it is important to manage them while taking into account the demands of a circular economy. To make sure these assets are managed properly, it is necessary that the right information is available to value the circularity of components to assess if they can be reused.

Because of the limited time span for this research, only one material is chosen to conduct the research on. The chosen material is concrete because concrete is the most used construction material and it has a very high environmental impact from in between 40% and 60% (Dijcker & Schepers, 2018). Other reasons to choose concrete is because Witteveen+Bos has already started with a very basic structure to evaluate the reusability of concrete structures, as shown in Appendix D, and because concrete has a high reuse potential, as shown in Appendix B. Therefore this research focusses on developing an inspection & assessment method for concrete structures. Also this research only focusses on dry infrastructure, since these are in a more flexible environment than wet infrastructure.

The main objective of the research is as follows:

> *Develop a method &tool to 1) inspect concrete infrastructure components on their ability to be reused 1 on 1, and to 2) calculate a certain circularity score based on those inspections.*

- The method should be able to be integrated within Witteveen+Bos, which makes use of the NEN 2767 assessment method.

This is desirable because some information which is necessary to come up with a circularity score can probably already be extracted from those assessments. The only problem is that the relevant information to calculate a circularity score is not being stored in a database because it is unknown which information is relevant to calculate a circularity score.

- This method should aim to give a kind of priority score, just like the NEN 2767.

It is difficult to give circularity an exact value, so currently a priority score is a better option. This way all components can be compared according to one standard.

- To be able to compare all components according to one standard, It is necessary that the developed method gives an unambiguous result about the circularity score of a component.

Everyone should be able to perform the method whit the same result as an outcome. If this is the case it will be possible to compare the results from everyone who performs the method, thus it becomes more likely that this method will be accepted as a standard method to score a component on its circularity.

- The method should be able to be executed relatively quick.

If a component is seriously considered to be reused, a lot of extensive research is necessary. If it can quickly be assessed if a component can potentially be reused, it becomes clear for which components it is worthwhile to perform more extensive and for which components it is not worthwhile.

- The circularity score should give more insight in a components ability to be reused 1 on 1.

This gives more confidence in the ability to reuse certain components. Therefore a higher percentage of reused components in infrastructure assets should occur.

When the method is implemented within Witteveen+Bos, the collected data could be stored in a materials passports. When that is achieved for every component, it is possible to build a database of all components in a certain area. Then it could be possible to predict when certain components need to be replaced and where those components could possibly be extracted from. In this way, a long-term construction planning based on reused materials could be created. These aspects are out of the scope for this research, but it shows the relevance of the development of such a method to value circularity.

This research aims to contribute to three main aspects. First of all, this new inspection should help Witteveen+Bos in providing their clients, which have to adjust to the new demands which are caused by the transition to a circular economy, useful information about the circular performance and current value of their assets. Also it could help in giving decision makers more confidence in using already used components. Second, this new inspection should help in gaining a more common understanding on how to assess a certain circular value in infrastructure assets. And third, this new inspection method should stimulate the shift towards a more circular economy, reduce the consumption of raw materials, stimulates the use of used products and gives other destinations to components which would otherwise have ended up in waste flows.

1.4 Research questions

Since the goal of this research is to design a method, the steps of the design and engineering cycle are used as a guideline to conduct this research (Wieringa, 2014). The steps of the design cycle are only performed until a third design once because of the limited timespan for this research. The work is divided into three different phases;

1. the collection of requirements phase, in which the necessary requirements are collected which are needed to design the new method;
2. the design cycles, in which the development of the new method is taking place through multiple design cycles with help of the requirements,
3. the finalizing phase, in which the research is concluded.

After the method has been tested and the method is evaluated, it is possible to come up with recommendations for further use of the method. Each of these phases has its own research question and sub-questions that need to be answered:

1. Collection of requirements

What are the requirements for a method to calculate a circularity score for concrete infrastructure components?

- What circularity indicators influence the circular score of existing concrete infrastructure components?
- How do current inspection regimes of concrete infrastructure assets work?
- What are the gaps/limitations of the current inspection regimes to score circularity of existing concrete infrastructure components?
- What information is necessary to calculate the circular score of existing concrete infrastructure components?
- Which of the requirements is feasible to retrieve during inspections of existing infrastructure components?

2. Design cycles

How to calculate a circularity score for existing concrete infrastructure components?

- How to retrieve the necessary information to calculate a circularity score from inspections for existing concrete infrastructure components?
- How to analyse the data retrieved from the inspections to calculate the circularity score?
- What are the results of the new method?

3. Finalizing

What are the conclusions and recommendations for the use of the method?

1.5 Research design

Figure 4 shows the summary of the research design. For each of the different phases (Collection of requirements, Design cycles and Finalizing) the research design is explained more extensively in this part.

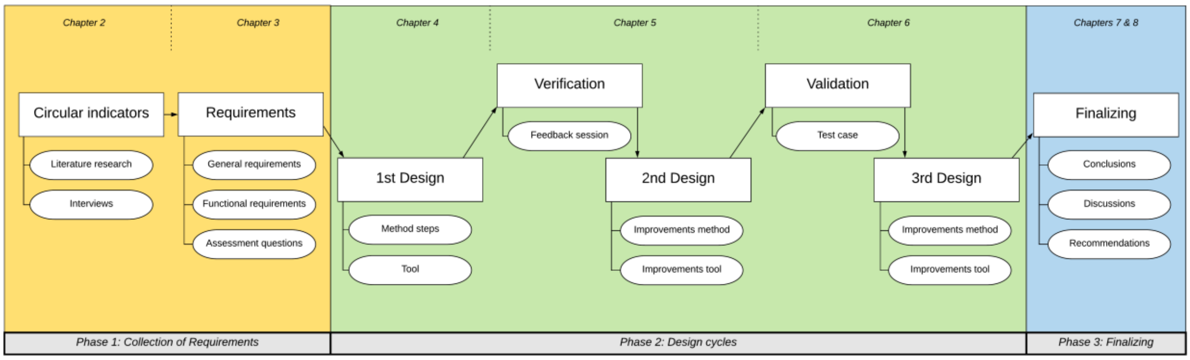


Figure 4: Research design

Phase 1 is about the drawing up of requirements for the design of the new method. Chapter 2 is at first focussing, with help of literature, what are the relevant circular indicators which are taken into account regarding the possibilities and requirements for reusing concrete materials. After the relevant circular indicators have been determined, with use of literature, reports and interviews, for each circular indicator it is investigated how it influences the ability for a concrete component to be reused 1 on 1. The interviews are held among different stakeholders regarding inspections of infrastructure assets; Inspectors, infrastructure owners and market experts. By interviewing different stakeholders, it is possible to look at the problem from multiple perspectives. Since there is not much established on how to cope with the demands of a circular economy, looking at multiple perspectives is of great importance in establishing a new inspection & assessment method.

Chapter 3 starts with drawing up a set of general requirements which are needed for the design of the new method. A research on the strengths and weaknesses of current inspection regimes and assessment methods is conducted and used for drawing up the set of general requirements for the design of the method. After a set of general requirements has been drawn up, also a set of functional requirements is drawn up, with help from the results of the research on the circular indicators from chapter 2. The functional requirements say more about which functional aspects need to be assessed by the method, whereas the general requirements give more general demands for the new design of the method. After the set of functional requirements have been drawn up, it is assessed if they are absolutely necessary to assess 1 on 1 reuse and if it is feasible to retrieve the information that is necessary to assess the functional requirement. Based on that assessment, chapter 3 concludes with a list of assessment questions which is used for the design of the new method.

Phase 2 is about the design of the new method by going through multiple design cycles. The phase starts with chapter 4, which is about the first design of the method. The functional requirements that have been drawn up in phase 1 are used as input in the design of this new method, for what aspects the method should assess. First, it is described with the help of a flowchart, how the steps of the method work. Second, the tool that is developed that helps with the execution of this method is described. The chapter concludes with an elaboration of how the general requirements were taken into account with the design of the method.

Chapter 5 is about the second design of the new method. The chapter starts with a description and results from the feedback session that has been organised to perform verification on the designed method. With help of the results from the feedback session, improvements have been made to the method and the tool, which resulted in a second design of the new method.

Phase 2 concludes with chapter 6, in which the third design of the new method is elaborated. The chapter starts with a description of and the results from the test case, on which the method is tested by four inspectors to perform validation on the designed method. With help of the results from the test case, improvements have been made on the method and the tool, which resulted in a third and final design of the method.

In phase 3 the research is finalized. In this phase, the conclusions of the research are given and the results of the research are discussed in chapter 7. The recommendations for further research and for further implications of the method are given in chapter 8.

2 Indicators on assessing the circularity

As shown in Figure 5, this research starts with a research on circular indicators with help of a literature research and interviews. This is necessary to come up with requirements for the design of the new method.

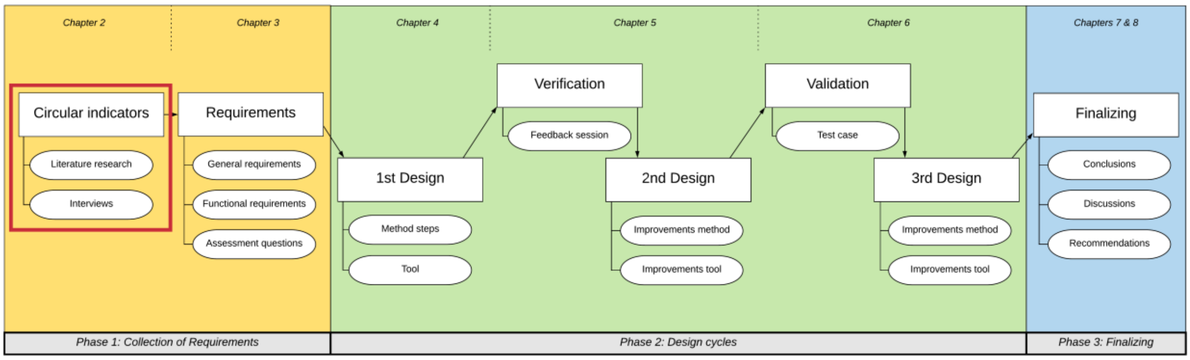


Figure 5: Research design: Chapter 2

The first step in this research is to investigate what circular indicators influence a components ability to be reused 1 on 1, and how these indicators influence a components ability to be reused 1 on 1. A selection of circular indicators has been made based on literature from Iacovudi & Purnell (2016), Geldermans (2016) and based on what Witteveen+Bos have been developing themselves, Appendix E shows how these circular indicators have been selected. Conclusively, there are 7 circular indicators which have been investigated in this chapter on how these circular indicators could influence a concrete components ability to be reused 1 on 1. The 7 circular indicator categories are;

I. Toxicity
II. Condition
III. Residual lifespan
IV. Connections
V. Retrieval
VI. Design requirements
VII. Dimensions.

For each circular indicator first a definition of the indicator is given and then it is described which aspects of this indicator could have an effect on the potential reuse of concrete components in infrastructure assets. The information in this chapter is gathered from literature, reports and interviews with inspectors, infrastructure owners and market experts. The parts that are retrieved from the interviews are referred to Appendix F. Subsequently, with the information collected in this chapter, a set of functional requirements can be drawn up which are necessary for the design of the new method. it can be determined what the necessary information is to calculate a circular score.

2.1 Toxicity

Toxic materials are defined as unwanted materials inside the concrete because they can have a negative effect on the quality of the concrete or on the health and environment. It could be the case that certain toxic materials are used in the production of the concrete. For this indicator, it needs to be checked if there are any toxic materials within the concrete components. It could be the case that certain toxic materials are used in the production of the concrete, from which it is not preferred or allowed to use them anymore. Therefore it is relevant to know from which materials the component is made of (Iacovidou & Purnell, 2016) and what the exact composition of the material is (Geldermans, 2016), to assess the reuse value of components.

Van Dijk (2018) has assessed if certain materials can be used in a circular way or if they pose a threat to the circular economy. The following materials form a risk for the circular economy:

- *Iron fibres*

Except for concrete, the presence of iron in building materials is usually not a big risk for circularity. If iron in concrete is visible to the surface and thus is being exposed to rain or water, it can corrode cause degradation to the concrete. That is why iron fibres must be completely erased from concrete additives (van Dijk, 2018). Fortunately, it is possible to visually spot iron fibres on the surface of the concrete (Interview 1&2)

- *Immobilized waste material*

The presence of immobilized waste material in building materials is a potential risk for the circularity of the other building materials if the immobilized waste material is being broken. Therefore it should not be a problem to reuse concrete components 1 on 1 with immobilized waste material already in it, but it could be a problem to recycle concrete components with immobilized waste material in it (van Dijk, 2018).

- *Steel slag*

Steel slag is a residue which is formed during the process of turning raw steel and/or scrap into steel. This residue has been recycled by adding it to the production of cement and granulate.
The presence of steel slag in building materials can be a risk for the circularity of the material, because it can have a negative effect on the pH value of the material (van Dijk, 2018).

- *Phosphorus slag*

Phosphorous slag is a stone-like residue which is formed during the process of turning phosphor ores into phosphor. This residue has been recycled by adding it into concrete. Phosphorus slag is slightly radioactive. When this problem was discovered in 1968, new regulations were set up to make sure that the radioactivity of the phosphorus slag does not exceed a critical value.
The presence of phosphorus slag in building materials can be a serious risk for the circularity of the material. This risk depends on the amount of radioactivity from the phosphorous slags. This amount of radioactivity can vary a lot, and is dependent on the used ores from certain production periods (van Dijk, 2018).

- *Blast furnace slag*

Blast furnace slag is the product of the blast furnace process in which iron ore is being heated and reduced to raw iron. Blast furnace slag is used very often in the production of blast furnace cement.
The presence of blast furnace slag in building materials can be a risk for the circularity of the other material, because it can have a strong effect on the pH value of the material, which means it can have a strong effect on the leachability (van Dijk, 2018).

- *Composite fibres*

Composite is a material that exists out of multiple different materials. In concrete usually steel, glass, macro plastic and microplastic fibres are used. These composite fibres make the concrete stronger so fewer materials are needed. However it may lower the reuse value because it can increase the risk of carbonation in the concrete, but it depends on the type of composite fibre that is used (van Dijk, 2018). Fortunately, it is possible to visually spot composite fibres on the surface of the concrete (Interview 1&2)

Apart from the materials assessed by van Dijk (2018), there are also other materials that pose a threat to the circular economy.

- *Chlorides*

Another material that has been used in the production of concrete and that forms a risk is chloride. Until 1975, 1% to 2% chlorides were allowed to be mixed in with the cement (Bouwkompaan, n.d.). This was added in prefab components because it had made the concrete harden quicker, which increased the production capacity. Unfortunately, it seemed to have negative effects regarding the corrosion of the reinforcement. Until 1975 mixing chlorides into concrete occurred frequently (Cobouw, 1995). The exact amount of chloride can be measured with drill samples in the lab, but if the concrete has been mixed with chlorides it should not be reused (interview 1&4).

- *Asbestos*

It can also happen that asbestos is being found at concrete components, this is mainly found in water drainage systems or in cable tubes which can be inside the concrete. If research needs to be performed, sometimes an asbestos-free declaration is necessary. If such a declaration is present, then it can be assumed that asbestos is not present in the asset (Interview 2). After 1983 asbestos was not used at all in concrete, so if an asset is built after 1983 it could be assumed that no asbestos is present (Arbouw, 2006).

Information about the composition of the materials inside the concrete could be stored, but if it is not properly stored, lab research is necessary to find out the exact composition of the concrete (Interview 1). The fact that there are toxic materials inside the concrete is not necessarily a bad thing, as long as it does not affect the concrete (interview 3).

2.1.1 Conclusion

- Iron fibres, composite fibres, chlorides and asbestos are a risk for the 1 on 1 reuse of concrete components because of an increased risk of corrosion and carbonation.
- Immobilized waste material, steel slag, phosphorous slag and blast furnace slag can be a risk for the circular economy if the concrete is recycled.
- Until 1975 it happened that chlorides were mixed in with prefab concrete elements. This increased the risk of corrosion.
- Information about the exact composition of the concrete could be stored somewhere, but if that is not the case, the only way to find out the exact composition of the concrete is by taking drill samples and investigate it in the lab.

2.2 Condition

The second indicator is the condition of concrete components. The condition says something about the physical quality of a component. Are there any damages visible on the component? What are the structural properties of the component? Therefore it is relevant to know the performance quality of the components (Geldermans, 2016). The exposure from forces which can be caused by traffic loading or the environment can influence the physical quality of the material (Iacovidou & Purnell, 2016). In this chapter, there is taken a look at the NEN 2767 condition assessment method, and there is taken a look at the important damage mechanisms that can hinder the reuse of concrete components.

2.2.1 NEN 2767

Currently, condition inspections of assets in the Netherlands are performed according to the NEN-2767 standard. The NEN-2767 is the standard for the condition assessment which ensures objective and uniform measurements of the physical quality of construction and installation parts of buildings and infrastructure. (NEN, 2018) It measures the technical condition of an asset with help of some kind of checklist. The goal of the NEN-2767 standard is to make sure that the technical condition of an asset can be mapped in a uniform way so an easy comparison can be made between the different conditions of the assets. Appendix G gives a more extensive elaboration on how the NEN 2767 condition assessment method works. With the NEN 2767 it is possible to assess defects. The NEN 2767 results in a general assessment of an object, but it is not specific. It is a visual inspection, so if a defect is observed, the damage mechanism may have been there for a while (interview 4).

2.2.2 Internal deterioration

Concrete can deteriorate because of internal sources and external sources. There are three possible internal sources that can cause deterioration of concrete (Betonverenging, 2009):

- *The cement is not sufficient.*

An excess of chalk, magnesium oxide or sulphate can cause the cement to be insufficient. Cement that meets the requirements of the NEN-EN 206-1 or the NEN 3550 is per definition sufficient (Betonverenging, 2009).

- *ASR (Alkali-silica reaction).*

The aggregates can react with the alkalis in the cement which can cause an expansive alkali-silica reaction (Betonverenging, 2009). ASR is a frequently occurring reaction that can cause the concrete to deteriorate (interview 1). Some aggregates for concrete can cause an expansive reaction with alkalis (sodium and potassium ions). There are three conditions which need to be met, for ASR to occur in a harmful way (Cement & Beton Centrum, n.d.):

1. The concrete must be sensitive for ASR, which means there needs to be sufficient reactive silica within the concrete.
2. There must be a sufficient amount of alkalis present within the concrete.
3. Temporarily or permanently a sufficient amount of moist must be present within the concrete.

This means that the occurrence of ASR is actually a combination of internal and external sources. Until 1990 it was assumed that ASR did not occur in the Netherlands, but this did not seem to be the case (Cobouw, 1997). The reactivity of the material depends on the crystal structure of the free silica (SiO2). In the CUR-recommendations 89, which was drawn up in 2002 to prevent ASR (Betoniek, 2002), it is described how to assess the reactivity of concrete aggregates. Portland cement is the main source of alkalis and if blast furnace cement is used (CEM III/B), it is not necessary to take any measures against ASR. It is possible to spot the difference between blast furnace cement, which is much darker, and Portland cement (Interview 1&2). In Appendix G a closer look is taken at how ASR can be detected to assess the condition of a component.

- *Internal sulphate attacks.*

internal sulphate attacks can only occur when three conditions are met (Cement & Beton Centrum, 2014):
1. Cracks that occur to the surface of the concrete.
2. The presence of water, the component must stand in a humid environment.
3. The aggregates must be sulphate containing.
If these three factors are present, there can be a risk of an expansive reaction. The chances to come across sulphate-containing aggregates in the Netherlands are very small.

2.2.3 External deterioration

There are also external sources that can cause concrete to deteriorate:

- *Frost in combination with de-icing salts*

Frost can give problems in combination with de-icing salts. The most important factor is that the water-cement factor 0,45 or lower, when this is the case there should not be any problem. If the water-cement factor is higher, then the percentage of air in the concrete should be around 3,5 till 4,5% (Betonverenging, 2009).

- *Penetration of sulphates*

Sulphates can penetrate the concrete from the outside and can cause an expansive reaction. This can happen at concrete structures along the coast which come into contact with seawater. Concrete structures can be affected by the atmosphere caused by the seawater up until 25 kilometres land inwards (Betonverenging, 2009). The NEN-EN 197-1 describes 5 types of cement that are sulphate resistant (Normcommissie 353007, 2011):

- CEM I-SR
- CEM III/B-SR
- CEM III/C-SR
- CEM IV/A-SR
- CEM IV/B-SR

When one of these cement types is used, penetration of sulphites will never become a problem.

- *Corrosion*

Chlorides and carbonation can cause the reinforcement inside the concrete to corrode (KB-Kenniscentrum, n.d.). With a potential measurement, it is possible to measure corrosion of the reinforcement. Potential measurements can be a radical investigation. However, there is also an easy way to detect corrosion, because knocking on concrete with corrosion can sound hollow (interview 2&4).

- Cracks

Constructive damage is mostly visible through cracks. Cracks can appear if the tensile strength is exceeded. Most defects can be repaired, but if there is a constructive overload it might not be worthwhile to repair the concrete, therefore it is important to know the cause of the defect (interview 2). But cracks are not necessarily a bad thing, for the optimal use of reinforcement, it is even necessary that there are cracks. If the width of the crack is not bigger than 0,4 to 0,5 millimetres, the corrosion process will stop after a short period of time because of alkalisation, constipation of the crack or a low amount of oxygen. If the crack is smaller than 0,2 millimetres, the concrete can self-heal through silting, continuous hydration and the swelling of the concrete (Betonverenging, 2009). Cracks can also be caused by chloride and carbonation (Rademaker, 2002).

Carbonation and chlorides are also frequently occurring damage mechanisms that can cause the concrete to deteriorate (interview 1). These damage mechanisms are elaborated more in the next chapter about the residual lifespan.

2.2.4 Conclusion

- With the NEN 2767 assessment, it is possible to determine a certain condition score, based on the severity, size and intensity of a defect.
- The NEN 2767 gives a general assessment of the condition, but it does not give many specifics of the defects themselves.
- Potential risks for concrete to internally deteriorate are:
    - The cement is not sufficient
    - ASR
    - Internal sulphate attacks
- Potential risks for concrete to externally deteriorate are:
    - Frost in combination with de-icing salts
    - Penetration of sulphates
    - Corrosion
    - Cracks

2.3 Residual lifespan

The third indicator is the residual lifespan of concrete components. The residual lifespan indicates how much time the component can still perform its function, also called the performance time (Geldermans, 2016). The required designed residual lifespan at the moment is 100 years and there also have been periods of 80 years. However, such a number is not a good indication of the actual residual lifespan (interview 5). There are three basic ways to calculate the residual life span: based on the condition, based on the construction and based on the material.

2.3.1 Based on the condition

In the NEN 2767, there is a way to roughly estimate the lifespan of a component based on the condition score and the theoretical lifespan. This is calculated with the following parameters and formula:

$$t = L - (L * \left(\frac{1}{2} * (C - 1)\right))$$

$t = age$
$L = theoretical\ full\ lifespan$
$C = condition$

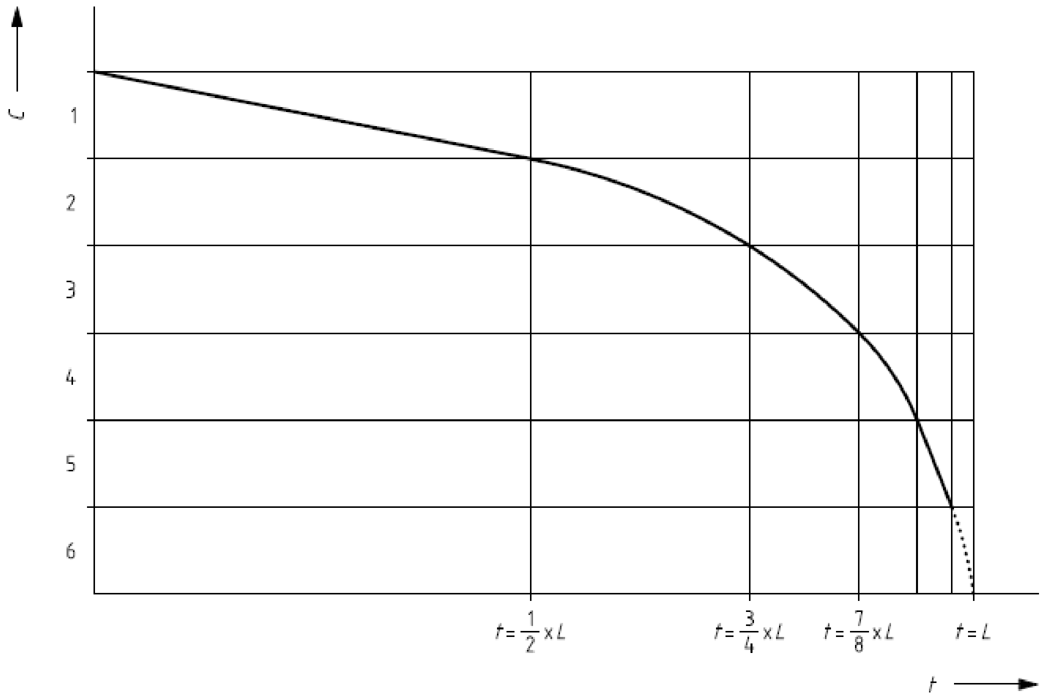


Figure 6: Theoretical lifespan based on condition (Normcommissie 351264 "Conditiemeting," 2017)

Figure 6 shows the theoretical lifespan based on the condition of an asset. This is only a rough estimation because the condition score can only be an integer between 1 and 6. Therefore there can only be 6 different outcomes for the estimation of residual lifespan.

2.3.2 Based on the construction

For the constructive part, the NEN 8700 residual life span calculation is demanded often. It bundles a lot of different investigations. It is a pretty extensive calculation which can include a lot of assumptions (TNO, 2015). A residual life span only gives a good indication and is not a hard number. There is a lot of uncertainty in calculations of a residual life span. Despite the outcome of the calculations, the advice is always to keep inspecting. A more extensive description of how the NEN8700 works is given in Appendix G.

2.3.3 Based on the material

The CUR-Recommendations 121 (2018) comes up with two types of damage mechanisms which can harm the residual life span. Based on these damage mechanisms it is possible to calculate when the reinforcement is likely to corrode. Before this is calculated, first it is necessary to perform a preliminary investigation which can consist of:

- Collecting design drawings, as-built drawings, calculations, construction specifications and notes of changes.
- Perform a (historical) research of performed inspections, the condition, maintenance reports, repairs, change in use or overload that has been taken place.
- Collect information of similar assets.

In the CUR 121 (SBRCURnet-commissie 2140, 2018) is described how to calculate the time it takes for the chloride and for the carbonation to reach the reinforcement in the concrete.

- *Chlorides*

Apart from chlorides being mixed into the concrete, it can also penetrate through the surface because of de-icing salts or seawater. This also becomes a problem when the chlorides reach the reinforcement because it can also cause the reinforcement to (KB-Kenniscentrum, n.d.).

The residual lifespan based on chloride penetration is calculated with the following formula:

$C(x,t) = C_s - (C_s - C_i) * \text{erf}(\frac{x}{\sqrt{4*D_a*t}})$

$x = depth$

$t = age$

$C_s = apparent\ chloride\ content$

$C_i = initial\ chloride\ content$

$D_a = diffusion\ coefficient$

According to the CUR 72 (SBRCURnet-commissie, 2011), the information which is needed for the input of this formula needs to be retrieved from crushed drill samples and these samples need to be investigated in the lab to measure the amount of chloride.

- *Carbonation*

Carbonation is a frequently occurring damage mechanism that can cause the concrete to deteriorate (interview 1). Carbonation is a natural process which penetrates through the concrete. Carbonation only becomes a problem when it reaches the reinforcement, because it can cause the reinforcement to corrode. With a low reinforcement coverage, there is a higher risk of corrosion because the carbonation reaches the reinforcement quicker. Right now the average coverage is 35 mm. It is possible to stop the process, but to do that a new preservation layer needs to be applied each 5 to 10 years. The penetration depth of carbonation can easily be measured with drill samples (interview 1). It is hard to estimate how deep carbonation has penetrated into the concrete. Just a visual inspection not enough and it should actually be measured.

The residual lifespan based on carbonation penetration is calculated with the following formula:

$x_c = A * \sqrt{t}$

$x_c = carbonation\ depth$

A $= empirical\ determined\ factor$

$t = age$

To retrieve this information it is necessary to measure the carbonation penetration depth. According to the CUR 72, this can be achieved by looking at drill samples, but it can also be achieved with a small massive drill, which is less accurate but also is less impactful and takes less time to perform. It is also necessary to know how deep the reinforcement lies beneath the concrete. According to the CUR 72, this can be measured with a reinforcement scanner which measures electromagnetic fields (SBRCURnet-commissie, 2011).

In the ROK (Rijkswaterstaat, 2017) it is stated that the application of blast furnace cement with a percentage of more than 50% slag, or Portland fly ash cement (CEM II/B-V) with a percentage of more than 25% coal fly ash gives, just as for ASR, the best resistance against chlorides and carbonation.

2.3.4 Conclusion

- It is possible to calculate the residual lifespan based on the NEN 2767 conditions core, that gives a very rough indication.
- Another option is to calculate the residual lifespan according to the NEN 8700, but that is a very extensive calculation and is not suitable for a quick indication.
- It is also possible to calculate the residual lifespan based on the chloride or carbonatation penetration speed. Then it can be calculated how much time it takes until the substance has reached the reinforcement.
- The residual lifespan is highly dependent on the condition of the asset. Although residual lifespan calculations are performed, the advice is always to keep inspecting, because it is not such a strict number. It is argued that it might be better to just look at the condition, because there are a lot of uncertainties in residual life span calculations.

2.4 Connections

The fourth indicator is the connection of concrete components. To know how a component is connected to other materials or components (Geldermans, 2016) is important information to be able to dismount the component. It is also important because to know if the connection of a component can be used again.

According to Chini (2005) fixtures, fittings and joints between concrete components have a major influence on whether a component can be removed from a structure, and therefore reused in their original form. Concrete components such as masonry blocks, paving slabs and building blocks are easily dismantled and reused because they have no fixtures, fittings or joints. Although, blocks are usually mortared together, which requires cleaning. If prefab beams are just stacked without a further connection it is easy to dismount the components (interview 5).

However, not every prefab concrete component can be removed easily. Prefab components in infrastructure assets almost always have a pressure layer or mortar, sometimes with reinforcement, that needs to be chopped away if the component is to be dismounted (interviews 3&6). Chini (2005) talks about prefab beams that are frequently cast in place with concrete or mortar that is stronger than the actual beams themselves. Sometimes concrete components are connected with dowels or bolts which makes it more easy to dismount a component. The problem is that at the moment there exists no standard jointing system and they are not designed with deconstruction in mind, bridges are not designed to be dismounted (Chini, 2005) (interview 3). Because of this, it is very difficult to disassemble the components without damaging them. It is not impossible to dismount the prefab components, but it is very difficult and it is questionable if it is worthwhile to dismount the component (interview 1). If the component is weakened during disassembly it could be used in a lower function (Interview 6).

It is also important to know what kind of reinforcement is used. Prestressed reinforcement can be applied to the concrete with or without attachment to the concrete (Beton Lexicon, n.d.). Pre-stress that is attached to the concrete cannot be removed from the concrete without damaging it. Pre-stress that is inside a casing and not attached directly to the concrete, could be removed and stressed later on. Making 2 beams out of 1 beam is not possible because of the course of the pre-stress. Small girders have a slightly higher potential to be adjusted and to be reused if you can remove the pre-stress, but it still takes effort. The disassembly and reuse of pre-stressed bridges, does not have a high chance to succeed (interviews 5).

Chini (2005) also states that because most concrete buildings are cast-in-situ frames, they need to be destructively demolished. Therefore it is unlikely that concrete components are reused in their original form, and at best could be crushed down and recycled. It is almost impossible to dismount large cast-in-situ works (interview 3). It is simpler to deconstruct and reuse concrete frames incorporating precast concrete beams. A modular bridge is more easy to dismount than a cast-in-situ bridge, unless it is possible to dismount the bridge as a whole. It is easier to disconnect a bridge as a whole, than all components apart from each other (interview 3).

How is it connected? How is it built? These are important questions. Information from drawings is desirable, because how something is connected can be seen in drawings. Information from drawing is desirable but that information is not always available. Sometimes it is possible to see visually how something is connected and sometimes it can also be checked on site with the help of mirrors if necessary. It is not possible to visually inspect every connection and if the information is not in drawings, destructive research is necessary (interview 5).

E. Durmisevic, Ciftcioglu, & Anumba (2001) has developed a model for assessing the disassembly potential of structures. One of the parameters in this model is the type of connection. For each type of connection, a certain score is given in which a 1 represents the best impact on disassembly and a 0 represents the worst impact on disassembly:

- Accessory external connection or connection system (1)
- Direct connection with additional fixing devices (0,8)
- Direct integral connection with inserts (0,6)
- Direct integral connection (0,5)
- Accessory internal connection (0,4)
- Filled soft chemical connection (0,2)
- Filled hard chemical connection (0,1)
- Direct chemical connection (0,1)

Later, Durmisevic & Brouwer (2002) again came up with 7 slightly different types of connections and ranged them in order from fixed to flexible:

1. Direct chemical connection
2. Direct connection between two premade components
3. Indirect connection via third chemical material
4. Direct connection with additional fixing devices
5. Indirect connection via dependent third component
6. Indirect connection via independent third component
7. Indirect with additional fixing device

Figure 7 visualizes the descriptions given by Durmisevic & Brouwer (2002)

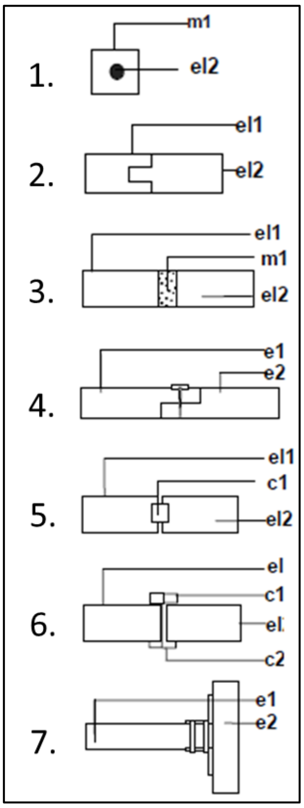


Figure 7: Type of connections (m=material, c=connector, el=element) (Elma Durmisevic & Brouwer, 2002)

According to Chini (2005), there are some concrete products that are never able to be reused in their original form because of their connections. These products are

- Foundation units and piles, because it is virtually impossible to remove them from the ground.
- Pipes and associated products, also because it is virtually impossible to remove them from the ground

2.4.1 Conclusion

- If there are no actual connections it can be easy to dismantle concrete components. This is the case with concrete building blocks and paving slabs.
- There can be a pressure layer mortar stuck to the components which makes it more difficult to dismantle prefab components, because often the mortal is stronger than the prefab concrete itself.
- It is important to know the kind of reinforcement that is used in the components.
- For cast-in-situ components, it is not very likely that they are being reused because destructive methods are needed to dismantle a cast-in-situ component.
- It is not possible to visually inspect every connection and if the information is not in drawings, destructive research is necessary.
- To assess the connections indicator, information is needed of how the asset was constructed. If that information is not available the ability to disconnect the components becomes hard to assess.

2.5 Retrieval

The fifth indicator is the retrieval of concrete components. The retrieval of the component is all about if the component can be retrieved from its structure to a new location. To reuse the component it should not be damaged during the retrieval process. Also the amount of effort in dismounting the component is an important factor. Therefore it is relevant to know which methods are needed to recover the component (Iacovidou & Purnell, 2016) and if it is possible to transport the component to a new location (Geldermans, 2016).

There are a number of aspects which need to be investigated during montage (S. J. de Boer, 2001). Before a component can be disassembled. Several of these aspects are furtherly explained in the next part:

- *Available montage hours*

The available disassembly hours are strongly dependent on the location of the component. In urban areas, noise disturbance needs to be taken into account and in some areas heavy traffic is forbidden in a certain timeslot. This means that the available hours to disassemble a component can be limited. If certain roads need to be closed in order to disassemble a component, it needs to be planned months in advance.

- *Accessibility on construction site*

Traffic on the construction site needs access to the disassembled component, there needs to be enough manoeuvring space. Sometimes it is necessary to build a construction road towards the construction site. Apart from the accessibility to the construction site, the component itself should also be accessible. Personnel should also have enough room to execute its tasks and in case of an emergency, the personnel should be able to get away quickly (Wienik, Blok, Hoekstra, & Kokkeler, 2012). Is a crane, an aerial work platform or scaffolding necessary and is it possible to place them? (interview 2&5)

- *Component weight & dimensions*

The component weight is important to know if a crane must be able to lift the component. Also for the transport itself, it is very important to know how much the component weighs, because the transport should be able to bear the weight.
For ‘normal’ transport on the road, components can have a maximum weight of 300 kN, in this case extendable trailers are being used. If a component weighs more than 300 kN, loose dolly sets are used to transport the component. In this case the rear end of the truck is being controlled manually and separate from the front end of the truck. When this is the case, police guidance is always necessary.
For ‘normal’ transport the following requirements apply in The Netherlands:

a. The maximum weight is 50.000 kg (RDW, 2012)

50.000 kg is allowed on the road (RDW, 2012), and the truck weighs about 15.000 tons. Conclusively about 35.000 kg tons is transportable by truck. For anything heavier, special transport is required. The weight of a component can be calculated with the help of the measurements and the specific weight of concrete. Usually 2400 kg/m3 is used to estimate the weight of concrete (interview 1).

b. The maximum width is 3,0 m (RDW, 2012)
c. The maximum height is 4,0 m (RDW, 2012)
d. The maximum length is 27,0 m (RDW, 2012)

Prefab components are usually transportable by road. They also arrived at the site, so it should also be possible to transport them back (interview 3&5). Abutments and other objects that are too heavy to be transported transport can only be demolished (interview 1). If special transport is required, the route needs to be checked because the transported component may for example not be able to go underneath a certain bridge (interview 1,4&5).

- *Use of a crane*

The position of the crane relative to the disassembled component is very important. Sometimes multiple cranes are necessary to move the component to the desired position. Also the soil must be strong enough to ensure that a crane can lift a heavy object safely.

Other aspects are mentioned by de Boer (2001), but they are not taken into account because it is hard to assess these aspects fall out of the scope of this research.

In the assessment model for the disassembly potential of structures (E. Durmisevic et al., 2001), also the accessibility to fixings parameter is taken into account. This describes if additional operations are necessary to access fixings and what the level of damage is to remove those fixings from a component. Again for each type of accessibility, a certain score is given in which a 1 represents the best impact on disassembly and a 0 represents the worst impact on disassembly:

- Accessible (1)
- Accessible with additional operations which causes no damage (0,8)
- Accessible with additional operations which causes repairable damage (0,6)
- Accessible with additional operations which causes damage (0,4)
- Not accessible - total damage to elements (0,1)

2.5.1 Conclusion

- To recover components the following aspects are important to consider
    - Available montage hours
    - Accessibility on construction site
    - Component weight & dimensions
    - Use of a crane
- For 'normal' transport the following requirements apply in The Netherlands:
    - The maximum weight is 50.000 kg
    - The maximum width is 3,0 m
    - The maximum height is 4,0 m
    - The maximum length is 27,0 m
- It is hard to determine how well a component can be transported if it is unknown where the component needs to be transported.

2.6 Design requirements

The sixth indicator is the design requirements of concrete components. The requirements for the design of an infrastructure asset could have been changed over the years. Therefore it is important to assess if the components of old infrastructure assets still meet the requirements of today. Are the remaining structural & functional properties still sufficient? (Iacovidou & Purnell, 2016) If that is not the case, the components might still be useful in another function. Thus it is necessary to take a look at the different design classes, the concrete properties and the reinforcement properties of concrete components.

2.6.1 Design classes

Until 2007 there was made a distinction between 3 different kinds of traffic classes (Mans, 2016):

1. Class 30, suitable for cars and lightweight freight traffic.
2. Class 45, suitable for trucks.
3. Class 60, suitable for heavy traffic.

With the current norms that are prescribed in the 'Bouwbesluit 2012', the existing assets must be tested according to the NEN 8700 and NEN 8701. There is a probability that assets which are built according to the old classes, do not meet the new requirements.

At the moment almost everything is calculated according to the highway class (interview 5). So everything that is newer than that, meets the correct requirements. The old class 60 meets those requirements, the old class 45 also could meet the requirements, and for the old class 30 it is difficult to meet those requirements.

New objects should all comply according to the lm1 (load model 1) class. That looks like the old class 60. Recently, there is also an lm1 light for small bridges in the province and inner cities. That looks like the old class 45. The old class 60 almost always complies, the old class 45 most of the time complies, for the old class 30 it is uncertain if it complies, if used in the same function. In lower functions reuse should be possible (interview 6). You could also make bicycle bridges from car bridges, that should always be possible according to the design requirements (interview 4&5).

And then there are also shear problems. Shear problems only came to light in 1975, therefore every bridge that is built before 1975 is suspicious (interview 6).

Thus it is expected that still a lot of infrastructure assets are not sufficient according to the legal framework of the NEN 8700. The following categories were expected to fulfil the requirements of the NEN 8700 (Provincie Zuid-Holland, 2011):

- An infrastructure asset that is designed according to Class 60 (VOSB 1963) or Class A (VOSB 1938).
- An infrastructure asset with a span smaller than 4 metres and older than 1960. This indicates that the infrastructure asset is designed according to Class B (VOSB 1938).
- An infrastructure asset which is built after 2005.

From the other categories, it is not necessarily expected that they fulfil the requirements of the NEN 8700. With a detailed hand calculation, it must be determined if the requirements according to the NEN 8700 are met, although from experience it is the case that most of the infrastructure assets meet the requirements.

There should be information available for most bridges according to which requirements they were designed, but if the calculations are not available it becomes difficult to determine for which class they were designed (interview 5). Another problem is that in the past lightweight concrete was used, if that is the case reuse is not possible for Rijkswaterstaat assets. Lightweight concrete weighs about 500/600 kg/m3 lighter than normal concrete, that is often used in tube bridges (Interview 2).

It is also difficult when building new structures, that other requirements apply than for existing structures, because existing structures have already proven themselves. If existing components are reused, the old components should meet the new requirements (interview 6).

2.6.2 Concrete properties

The RBK (Rijkswaterstaat, 2013) states some common rules for concrete structures.
There are 2 methods to estimate the concrete strength if there is no data of the concrete strength available and without destructive research:

1. *Based on the design value*

If the design norm and the quality of the concrete are known, an assumption of the strength can be made. If the quality is unknown, the lowest value within the old norm should be used for the assumption. Concrete is often much stronger than it is designed for. Concrete strength increases over time, in calculations the design strength is assumed. Information about the concrete properties could be present in drawings. If the information is not available in drawings, drill samples must be taken and the samples must be tested in the lab. Taking drill samples is not desirable because it implies destructive research, which is time-consuming and negative for aesthetics (Interview 1).

2. *Based on measurements of other constructions*

If there are no signs of deflection, cracks, loose stones, rust formation or efflorescence (as described by the NEN 8700 (Normcommissie 351001 "Technische Grondslagen voor Bouwconstructies," 2011)), the following assumptions of concrete strengths can be made:

- C35/45 for plates, boxes, tunnels, tubes, T-beams, mortars.
- C25/30 for horizontal plates with a thickness smaller than 250 millimetres.
- C55/67 for prefab beams

Prefab components are produced in ideal circumstances, therefore prefab is mostly of a higher quality than in cast-in-situ (interview 1&2). The strength of prefab components is often well registered and can be requested at the manufacturer (interview 1).

This only accounts for bridges which are built before 1976. For bridges which are built after that, it has not yet been confirmed which strengths may be assumed.

The actual concrete strength can deviate from the concrete strength for which the concrete was designed. To reuse concrete components it is necessary to know the strength of the concrete. The concrete strength can increase over time, but it could also be the case that the delivered concrete does not meet the requirements or that the execution of the works was not performed sufficiently. Therefore it is important to measure the concrete strength instead of assuming that the designed concrete strength is the actual concrete strength. Swinkels (2015) distinguishes three different kinds of methods to determine the concrete strength; non-destructive methods, semi-destructive methods and destructive methods; these methods are described in Appendix H.

2.6.3 Reinforcement properties

Reinforcement properties information is necessary. Maybe from drawings, otherwise research in the field is needed. It is also possible to do a verification of the drawing with scans (interview 2). Also for reinforcement properties assumptions can be made based on the norm for which they were designed and the type of steel that is used, but really detailed information is necessary. Just like for concrete, also for reinforcement there are certain methods to investigate its properties; these methods are also described in Appendix H.

2.6.4 Solutions to meet constructive requirements

If it is the case that an asset does not meet the design requirements, there are solutions to overcome this problem. There are solutions that have been drawn up by the Provincie Zuid-Holland (2011) which could help to be able to meet the requirements. The solutions are:

- Limit heavy transport (> 50 tons)
- Apply an axle load restriction
- Limit parts the lanes on the bridge deck
- Adjust the construction
    - Use slab reinforcement beneath the deck
    - Place a beam framework beneath the deck
    - Place an extra constructive coating

Which solution is the best to apply is among other things dependent on functionality, safety, availability and so on.

2.6.5 Environmental classes

With environmental classes, it is described to which circumstances the concrete must be resistant to. This is based on the risk of degradation to the concrete (Betoncentrale Twenthe BV, 2005). If a component is going to be reused, it should be able to withstand the risks of degradation that comes with the location of reuse.

As defined by the NEN-EN 206-1, there are six different environmental classes (Betoncentrale Twenthe BV, 2005):

- X0: No degradation.
- XC: Degradation caused by carbonation, concrete with reinforcement being exposed to air and moisture.
- XD: Degradation caused by chlorides such as de-icing salts.
- XS: Degradation caused by chlorides from seawater.
- XF: Degradation caused by frost and thaw changes, with or without de-icing salts.
- XA: Degradation caused by aggressive chemicals.

The level for each of these risks can be indicated with a number (i.e., XD2).

2.6.6 Conclusion

- Until 2007 there was made a distinction between 3 different kinds of traffic classes
  - Class 30
  - Class 45
  - Class 60

  There is a probability that assets which are built according to the old classes, do not meet the new requirements.
- The following categories were expected to fulfil the requirements of the NEN 8700:
  - An infrastructure asset that is designed according to Class 60 (VOSB 1963) or Class A (VOSB 1938).
  - An infrastructure asset with a span smaller than 4 metres and older than 1960. This indicates that the infrastructure asset is designed according to Class B (VOSB 1938).
  - An infrastructure asset which is built after 2005.
- There are two ways to estimate concrete strength without destructive research:
  - Based on the design value
  - Based on measurements of other constructions (only before 1976)
    - C35/45 for plates, boxes, tunnels, tubes, T-beams, mortars.
    - C25/30 for horizontal plates with a thickness smaller than 250 millimetres.
    - C55/67 for prefab beams
- Newly built infrastructure assets must meet other requirements than older assets which have already proven themselves. So if old infrastructure asset components are to be reused, they must meet the requirements of newly built assets and not the requirements of old assets.
- Solutions to meet the requirements if they are not met are:
  - A weight restriction for traffic
  - Close certain lanes of the bridge
  - Strengthen the bridge
- There are 6 types of environmental classes that apply to concrete:

2.7 Dimensions

The seventh indicator is the dimensions of concrete components. If a component uses standard dimensions (Geldermans, 2016) and has the capacity to be connected to other structural and/or functional components (Iacovidou & Purnell, 2016), the probability that the component is useful for reuse is much higher than if the component was specially designed for the specific structure. Therefore information about the dimensions of a component is relevant in order to assess if reuse is possible. How well do the components fit in other situations and are standardised components used?

According to Chini (2005), there are some concrete products that are never able to be reused in their original form because of their dimensions. These products are:

- Bridge beams and gantries, not only because of its dimensions, but also because they have high safety risks and they have jointing problems.
- Frames, beams and columns, for the same reasons as the bridge beams and gantries.
- Multi-story car parks, also for the same reasons as the bridge beams and gantries.

One major barrier for the reuse of concrete components is the dimensional barrier (Chini, 2005). Most orders for structural units such as beams and columns are for one-time build structures with unique dimensions. Therefore these components are also very unique and only fit in the structure where they are designed for. This makes It very difficult for those components to be reused, unless a structure is designed with those unique components in mind, but that is very rare. Standardised components are not used much in infrastructure (Interview 1&4).

Prefab concrete offers greater reuse potential than cast-in-place concrete. Precast often comes in standard sizes and with standard amounts of reinforcement (Webster & Costello, 2005). The greatest potential in reusing concrete components is with prefab components (Interview 5,6&7). Prefab components can be recognised relatively easy. Sometimes it is possible to spot eyebolts on prefab components. There is also a lot of repetition in prefab components, so it is useful to look for that. There is a lot of repetition in beams, box girders, full-loaders. But they are all project specifically made (interview 5).

There are construction companies that produce prefab concrete components like slabs and beams, they have more potential to be reused. Manufacturers of prefab bridge beams in the Netherlands all have a package of standard beams which are largely the same. The exact profiles differ from each other, but the principle of the solution is the same (S. J. de Boer, 2001). Prefab beams often differ in reinforcement (interview 4).

Cast-in-situ concrete components have a low potential for being reused. Cast-in-situ could be reused if it can be placed in an (almost) identical situation (interview 6), but that is often not possible because of its problems with dimensions and high costs of transport (Earle, Ergun, & Gorgolewski, 2014). Also if a cast-in-situ bridge is placed somewhere else it is likely to be over-dimensioned. Important information for dimensions are the passage width, road layout and type of bridge (Interview 5). This type of information could be found in drawings, or land measurers could be used to measure lengths (interview 1). It is possible to recognize cast-in-situ components by the spots from the formwork or to spot the centrepins which were used during the pouring process. It can also be possible to spot seams on cast-in-situ concrete (interview 5).

There could be some elements that are suitable for reuse in the same function: impact plates, curbs, wing walls, sheet pile boards. In the smaller components there is a lot of potential. Although it might look ugly because infrastructure assets will look more the same (Interview 5). Foundations are suitable for reuse if they stay on location (Interview 2).

Reuse in other functions is almost impossible. In one situation there might have been a potential for a double T beam to be used as a lift shaft. Concrete beams are almost never used in housing construction, but they could be used for office buildings to create a space in the ceiling for installations. A grid size between the 7 and 10 meters could be useful in the utility construction. Channel plate floors have standard dimensions, so maybe it would be possible to cut the concrete in the right dimensions. The infrastructure and real estate construction often have separate manufacturers. Beams and plates could have a potential for reuse (Interview 7).

In the assessment model for the disassembly potential of structures (E. Durmisevic et al., 2001), also the standardisation of product edge parameter is taken into account. For each type of standardisation, a certain score is given in which a 1 represents the best impact on disassembly and a 0 represents the worst impact on disassembly:

- Pre-made geometry (1)
- Half standardised geometry (0,5)
- Geometry made on the construction site (0,1)

2.7.1 Conclusion

- Almost all infrastructure has been tailor-made for its specific situation and have unique dimensions. Components with standardised dimensions hardly occur in infrastructure assets.
- Prefab concrete offers greater reuse potential than cast-in-situ concrete.
- Frequently used beams can be largely the same, but the exact profiles differ.
- In smaller concrete components there is a higher potential to reuse.
- In other functions it is almost impossible to reuse components.

3 Requirements

For the design of the method, general requirements and functional requirements are necessary. The functional requirements say more about which functional aspects need to be assessed by the method, whereas the general requirements give more general demands for the new design of the method. This chapter first researches existing infrastructure inspection regimes and circular assessment methods to collect information for drawing up a list of general requirements. As shown in Figure 8, in chapter 2, all the information on the circular indicators has been collected. With this information, a set of functional requirements can be drawn up. With help of the general requirements, a selection of the necessary and feasible functional requirements are made and rewritten into assessment questions which are included in the design of the method.

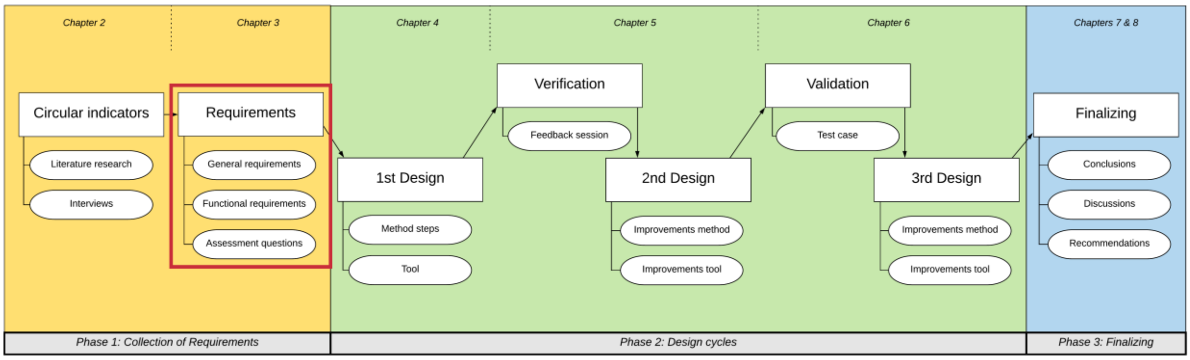


Figure 8: Research design: Chapter 3

3.1 General requirements

Based on research on circular economy assessment methods, Saidani, Yannou, Leroy, & Cluzel (2017) developed a proposed product circularity measurement framework (Appendix I). It is a proposed hierarchy of desired features to design frameworks, methods, tools, and indicators aiming at measuring product circularity performance. Based on this framework and based on current infrastructure inspection regimes in the industry (Appendix G), the following requirements for the design of the method can be drawn up:

- One of the requirements from the proposed product circularity measurement framework is that the method should be integrated. It should fit within current industrial practices and be compatible and complementary with other tools to use the strength of previous work (Saidani et al., 2017). Based on the practices that are mentioned in Appendix G, the following aspects should be included in the design of the new method:
  - The CUR 117 gives procedures, rules and demands for the inspection, advice and assessment regarding the management of infrastructure assets and technical installations. The CUR 117 could be very useful for the design of the new method, because it gives all kind of recommendations for different kind of inspections, which could be useful if follow-up research is required to furtherly assess reuse for concrete components.
  - The CUR 121 gives different ways to calculate the residual lifespan based on the chloride penetration damage mechanism and the carbonation penetration mechanism. To retrieve information for the residual lifespan based on chloride penetration, a lot of time and effort is needed. However, to retrieve information for the residual lifespan based on carbonation penetration is a lot less time consuming

and can easily be retrieved on site. That is why only the carbonation penetration part of the CUR 121 is useful to implement in the design of the new method.
    - The CRIAM quickly assesses the constructive risks of concrete infrastructure assets based on fixed parameters without the need for extensive and time-consuming calculations. CRIAM could be a useful method because of its ability to assess infrastructure assets in a relatively quick manner. Its relatively simple scoring system and fixed answer possibilities could be very useful for the design of the new method.
    - The NEN 2767 gives an indication of condition based on visual inspections, gives a standard score which makes it easy to compare, and is useful for long term maintenance planning. The NEN 2767 could be a good method for the condition indicator because it is easy to perform the assessment and thus gives a quick indication of the condition. It is very useful to implement the NEN 2767 into the new method.
    - The Handboek ASR gives a guideline to easily and visually justify the suspicion of the presence of ASR. Although, to know for sure is ASR is present, a laboratory research of drill samples needs to be performed. However, it can give a relatively quick indication if there is a suspicion of harmful ASR, and therefore it is useful to implement this into the design of the new method.
- Another requirement is that the method should be operational (Saidani et al., 2017). This means that there should be practical and meaningful guidance and data construction should be supported by developing a standardised input datasheet. Tools should be developed in software which is accessible to most users, i.e., Excel.
- Another requirement is that the method should be adaptive and flexible (Saidani et al., 2017). It should be designed with a modular non-frozen approach and make it flexible enough to be able to move and adapt with the pace of new developments
- The method should have an intuitive interface (Saidani et al., 2017). A proper graphical user interface for non-experts in the circular economy should be designed, to ease the acquisition of data and generate a comfortable visualisation of results.

There are two other requirements that are within the proposed product circularity measurement framework of Saidani et al. (2017), but to these are not included in the general requirements for the design of the method:

- One of the requirements that came from Saidani et al. (2017), is that the method should be systemic by design. A multidimensional scoring system representing different perspectives should be integrated and a distinction should be made for different loops of the circular economy. Also lifecycle thinking and different systemic levels should be included (Balanay & Halog, 2016). However, the scope of the research does not focus on different systemic levels and design of the method only focusses on one loop of the circular economy; the 1 on 1 reuse loop. Therefore it is outside the scope of the research to make a distinction for different loops of the circular economy, thus this will not be a requirement for the design of the new method.
- Another requirement is that the method should have a connection with sustainable development pillars and thus should have benefits on the economic, environmental and social level (Saidani et al., 2017). Since the newly designed should eventually lead to more reuse of materials, which leads to environmental and social benefits and also could lead to economic benefits, this requirement is not furtherly taken into account for the design of the new method.

Conclusively, when also combined with research objectives that are mentioned in chapter 1, the following final set of general requirements is drawn up for the design of the method and tool.

- **The method should be able to be easily integrated with regular inspections.**
- **The method should make use of current practices that are used in the industry.**
- **The method should be able to give a quick indication if 1 on 1 reuse is possible.**
- **The method should give an unambiguous and comparable priority score (like the NEN 2767) to assess the ability for a component to be reused 1 on 1.**
- **Every inspector should be able to execute the method in a uniform manner while getting the same results.**
- **The method should be adaptive and flexible to future developments.**
- **The method should be operational by giving a practical guideline to perform the method.**
- **The tool should have an intuitive user interface which is easy to understand.**

3.2 Functional requirements

Based on the results of the research of the indicators on assessing the circularity in chapter 2, the following functional requirements can be drawn up:

1. **The method should be able to assess concrete components on toxicity, by:**
    a. **Checking if iron fibres are present**
    b. **Checking if immobilized waste material is present**
    c. **Checking if steel slag is present**
    d. **Checking if phosphorus slag is present**
    e. **Checking if blast furnace slag is present**
    f. **Checking if composite fibres are present**
    g. **Checking if asbestos is present**
    h. **Checking if there is a risk of mixed in chlorides**

2. **The method should be able to assess concrete components on condition, by:**
    a. **Checking the general condition of the component**
    b. **Checking if the cement is sufficient**
    c. **Checking for signs of harmful ASR**
    d. **Checking if frost (in combination with de-icing salts) could be a problem**
    e. **Checking if there is a risk of internal sulphate attacks**
    f. **Checking if penetration of sulphites could be a problem**
    g. **Checking for corrosion**
    h. **Checking for cracks and determine its width**

3. **The method should be able to assess concrete components on residual lifespan, by:**
    a. **Checking the residual lifespan based on the condition**
    b. **Checking the residual lifespan based on the designed value**
    c. **Checking the residual lifespan based on the structural safety**
    d. **Checking the residual lifespan based on chloride penetration**
    e. **Checking the residual lifespan based on carbonation penetration**

4. **The method should be able to assess concrete components on connections, by:**
    a. **Checking how the component is connected**

5. **The method should be able to assess concrete components on retrieval, by:**
    a. **Checking if the component can be transported**
    b. **Checking if the component is accessible**
    c. **Checking if it is possible for a crane to reach the component**

6. **The method should be able to assess concrete components on design requirements, by:**
    a. **Checking the design class of the asset**
    b. **Checking the properties of the concrete**
    c. **Checking the properties of the reinforcement**
    d. **Checking the environmental class of the asset**

7. **The method should be able to assess concrete components on dimensions, by:**
    a. **Checking the level of standardisation of the component**

The next step is to rewrite the functional requirements into assessment questions which can be implemented in the design of the new method. The general requirements state that inspectors should be able to execute the method in a relatively quick manner. Therefore, before the functional requirements can be rewritten into assessment questions, the functional requirements have been assessed on two requirements: 1) is the functional requirement absolutely essential to assess 1 on 1 reuse? 2) Is the information for the functional requirement feasible to retrieve from regular inspections.

Based on those criteria, some of the requirements have been rejected for the design of the new method. The requirements that have been rejected are elaborated below:

- A number of requirements from the toxicity indicator are rejected. They are rejected because the information is not absolutely necessary to assess 1 on 1 reuse. Those toxic substances do no harm if they are already inside the concrete. Those materials could be a problem if the concrete is crushed and then recycled into new concrete, but not for 1 on 1 reuse. Also it is hard to assess if those materials are present inside the concrete because extensive lab research is necessary in order to determine if those materials are present. Summarised, iron and composite fibres are the only materials that pose a thread regarding 1 on 1 reuse, both increase the risk of carbonation in the concrete.
- Checking if the cement is sufficient and checking if frost in combination with de-icing salts can become a problem have been rejected. These requirements are rejected because it is hard to retrieve information about the water-cement factor inside the concrete. Also the resistance against frost has been taken into account with the different environmental classes that concrete can be designed for and this is taken into account in the design requirements indicator.
- Checking of the design class has been rejected. This is because it is very hard to assess structural safety on the component level, it is usually assessed on the asset level. For this same reason, the checking of the concrete and reinforcement constructive properties has been rejected, also because it is difficult to retrieve that information from regular inspections.

3.3 Assessment questions

With the rejections of the functional requirements taken into the account, the functional requirements have been rewritten into assessment questions which are used as an input for the design of the new method, which results in the following list of questions to assess 1 on 1 reuse:

Toxicity assessment questions:

- **Are iron fibres are visible in the surface of the concrete?**
- **Are composite fibres are visible in the surface of the concrete?**
- **Is asbestos present?**
- **Is there is a risk of mixed in chlorides?**

Condition assessment questions:

- **What is the general condition score of the component?**
- **Could ASR have been a problem?**
- **Could internal sulphate attack have been a problem?**
- **Could the penetration of sulphites be a problem?**
- **Are there any signs of corrosion?**
- **If cracks are visible, what is the maximum width of the cracks?**

Residual lifespan assessment questions:

- **What is the residual lifespan based on the condition?**
- **What is the residual lifespan based on the designed lifespan?**
- **What is the residual lifespan based on chloride penetration?**
- **What is the residual lifespan based on carbonatation penetration?**

Connections assessment question:

- **How is the component connected?**

Retrieval assessment questions:

- **Can the component be transported?**
- **How accessible is the component?**
- **If a crane is needed, is it possible for a crane to reach the component?**

Design requirements assessment question:

- **For which environmental classes is the component suitable?**

Dimensions assessment question:

- **What is the level of standardisation?**

In Appendix J an overview is shown of which functional requirements have been rewritten into which assessment questions.

4 1st Design

In the previous chapter, a set of assessment questions derived from functional requirements and a set of general requirements are drawn up. The assessment questions and general requirements are used to make the first design the new method, they describe what functional aspects the method should assess and which general requirements the new method should take into account. As shown in Figure 9, this chapter is about the first design of the new method.

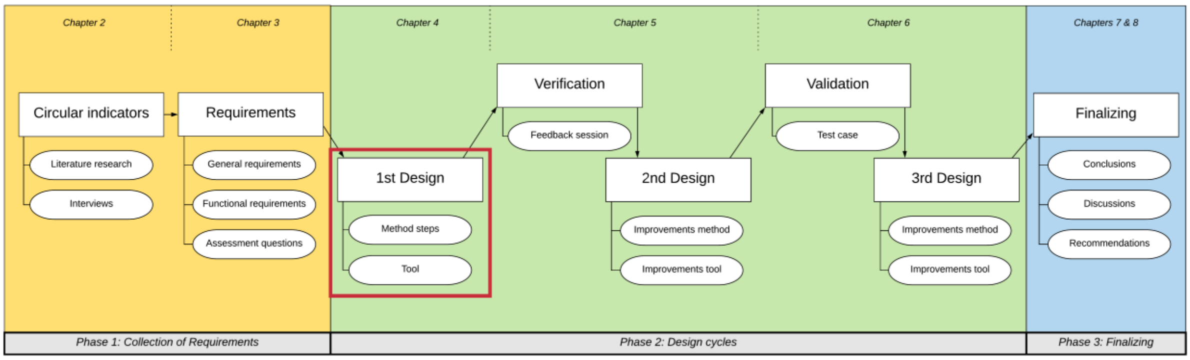


Figure 9: Research design: Chapter 4

First, the method steps are explained. Second, the tool that is developed to help execute the method is elaborated. At last, it is described how the general requirements have been taken into account in the design of the new method.

4.1 Method

In this chapter, the method steps are described. Figure 10 gives a visualisation of the method steps, these steps are elaborated one by one.

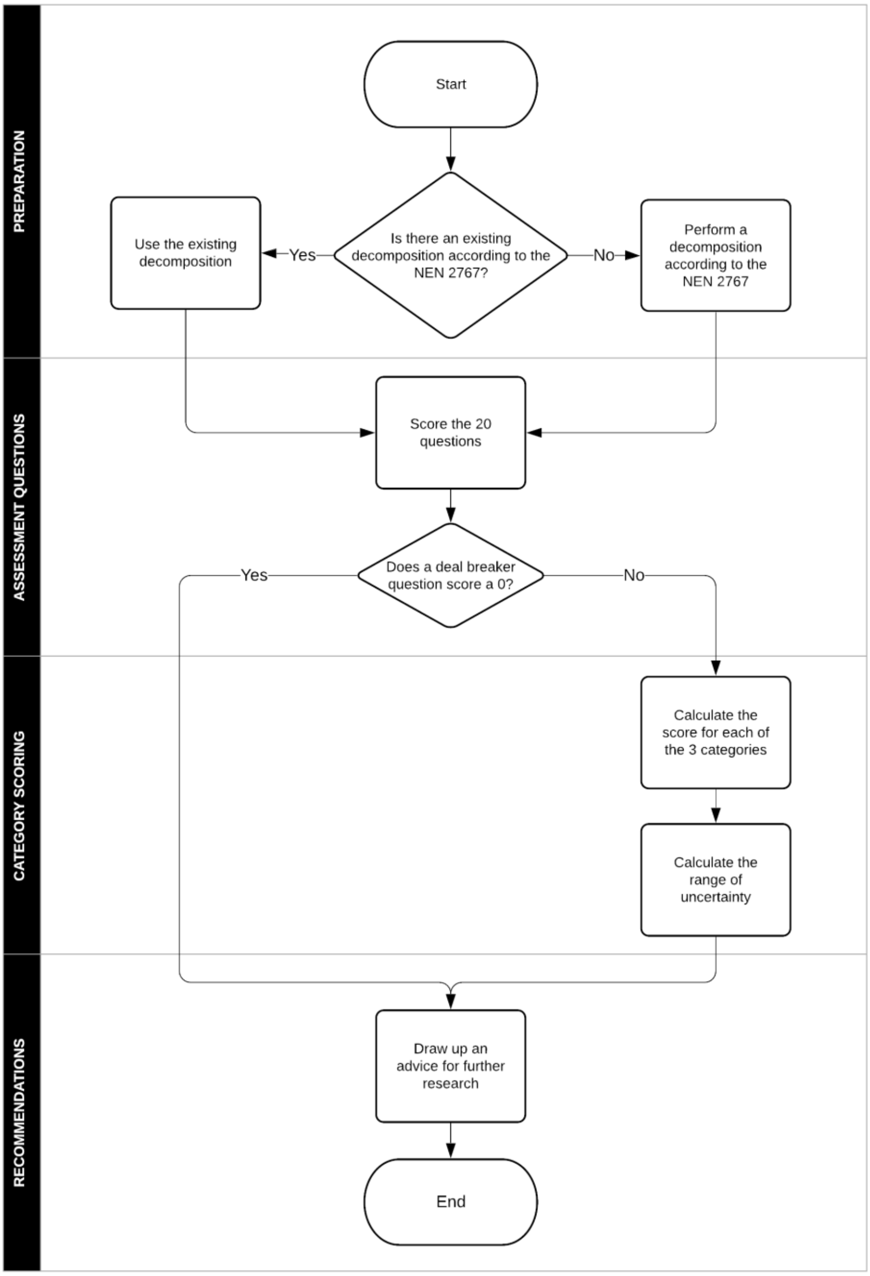


Figure 10: 1st design of the method

4.1.1 Step 1: Preparation

The first step to check if there is an existing decomposition, according to the NEN 2767, of the object that needs to be inspected and assessed. The NEN 2767 is commonly used to perform condition assessments on infrastructure assets. By using the decomposition according to the NEN 2767 as a basis, the new method fits well within the existing condition assessment according to the NEN 2767. If a decomposition has already been made because of prior condition assessments, then that decomposition can also be used for the new method. If a decomposition has not been made before, a new decomposition needs to be constructed.

4.1.2 Step 2: Assessment questions

The second step is to score all the indicators by answering the assessment questions that came out of the functional requirements. For the scoring of the assessment questions, 4 actions have been taken.

1. For each question, it is described where the information to answer that question can be retrieved. To be able for an inspector to quickly answer the questions of the new method, it needs to be clear where the information can be retrieved from.

2. Possible answers to the questions are defined. To make sure that the method can be executed in a uniform manner, all questions have predefined answers, just as the CRIAM (Which is described in Appendix G). This limits the amount of own interpretation that the inspector can put into the answering of the questions.

3. The scores for all the answer possibilities are determined. All the possible answer are getting a score with a value between 0 and 1. A 0 is the least favourable outcome for 1 on 1 reuse and 1 is the most favourable outcome for 1 on 1 reuse. By defining the score for each answer, the chance is increased that the assessment of different inspectors results in the same scores.

4. Recommended further research is described. For some answers to certain questions, it could be recommended to perform more extensive research in order to decrease the uncertainty. Therefore it is described which specific recommended research is advised to be performed.

In the next part, the four procedures for each question are described.

4.1.2.1 Step 2.1: *Score questions.*

Look up the information to answer each deal breaker question and give it a score between 0 and 1. In order to answer each question, the information required to answer the score should be looked up. It is up to the inspector in which order the information is collected for the answering of the assessment questions, because the best order to collect information can depend on the information that is available and on the planning of the inspector. When the answer is found, the score that is matching with the given answer should be given to the question.

I. Toxicity

1. <u>Are iron fibres are visible in the surface of the concrete?</u>

Although iron fibres increase the strength of the concrete, they can have a negative influence on the quality of the concrete because it increases the risk of corrosion. Therefore it is important to identify if there are iron fibres inside the concrete.

Information retrieval:
- inspection reports
- visual inspections

Scores:
- yes (0)
- no (1)

It can be visually detected on the surface if iron fibres are added inside the concrete. It should first be determined if the information can be found in photos of existing inspection reports. If that is not the case, it can easily be detected through visual inspections on site. Because this is a simple yes or no question, there are only two possible scores; 0 or 1.

2. Are composite fibres are visible in the surface of the concrete?

Although composite fibres increase the strength of the concrete, they can have a negative influence on the quality of the concrete because it increases the risk of carbonation. Therefore it is important to identify if there are composite fibres inside the concrete.

Information retrieval:
- inspection reports
- visual inspections

Scores:
- yes (0)
- no (1)

Just as is the case for iron fibres, composite fibres can be visually detected on the surface of the concrete. It should first be determined if the information can be found in photos of existing inspection reports. If that is not the case, it can easily be detected through visual inspections on site. Because this is a simple yes or no question, there are only two possible scores; 0 or 1.

3. Is asbestos present?

Asbestos is a material which is dangerous for health and it is not allowed to be used as a construction material anymore. With the help of three sub-questions, it is possible to determine if there is a risk of asbestos.

3a) Is the component build after 1983?

Information retrieval:
- Object passport

3b) If there is information about the presence of asbestos, does it say if asbestos is present?

Information retrieval:
- Design report
- Research report

3c) Does the component contain a water drainage system?

Information retrieval:
- Construction drawings

Scores:
- 3a = yes, or 3b = no, or 3c = no; Asbestos can be excluded (1)
- 3c = yes; There is a risk of asbestos being present (0,5)
- 3b = yes; Asbestos is present (0)

With the first sub-question, it can easily be excluded if asbestos could be a problem, because asbestos was not used in concrete constructions after 1983. If that is not the case, there should be taken a look at the design report of the object and at possible research reports because it could have been the case that prior research has on asbestos has been conducted in the past. If that still does not give any certainty it should be investigated if there are any water drainage systems present because that is a highly likely location in which asbestos has been in concrete infrastructure assets.

Recommended further research
When it is unknown if asbestos is present, it is advised to perform extensive asbestos research to identify the presence of asbestos.

4. <u>Is there is a risk of mixed in chlorides?</u>

Chlorides that are mixed into the concrete increases the chance of corrosion of the reinforcement. With the help of two sub-questions, it can be identified if there is a risk of mixed in chlorides.

4a) Is the component build after 1974?

Information retrieval:
- Object passport

4b) Is the component prefab?

Information retrieval:
- Construction drawings

Scores:
- 4a = no, and 4b = yes; There is a risk of mixed in chlorides (0)
- All other answers (1)

The only possible way that there is a risk of mixed in chlorides is if the component is not built after 1974 and if the component is a prefab component. If one of the two conditions do not meet, then it is not a problem.

Recommended further research
It can never be determined for sure if there are chlorides mixed into the concrete. So when there is a risk of mixed in chlorides, it is advised to perform a lab research to identify the presence of mixed-in chlorides.

II. Condition

5. <u>What is the general condition score of the component?</u>

The general condition score of the NEN 2767 gives an indication of the general condition of the component. Although this does not give information on any specific damage mechanism, it does say something about the overall quality.

Information retrieval:
- inspection reports
- visual inspections

Scores:
- 1 (1)
- 2 (0,75)
- 3 (0,5)
- 4 (0,25)
- 5 (0)
- 6 (0)

The points which are given to the certain condition scores are based on Table 2. Table 2 shows that at a condition score of 5 the deterioration is irreversible which means that reuse is not possible at a condition score of 5 and higher. At a condition score of 4, reuse should still be possible although a lower condition score is preferred. That is why the points among score 4 and lower are linearly divided.

Table 2: NEN 2767 condition scores

Condition score	Description	Explanation
1	Excellent condition	Incidental minor failures
2	Good condition	Incidental beginning deterioration
3	Acceptable condition	Partially visible deterioration, performance of asset not in danger of failing
4	Poor condition	Incidentally asset performance in danger of failing
5	Bad condition	Deterioration is irreversible
6	Very bad condition	Technically ready for demolition

6. <u>Could ASR be a problem?</u>

ASR is an expansive reaction which can damage the concrete. There are six sub-questions which help identify the risk of harmful ASR.

6a) Is the component build after 1989

Information retrieval:
- Object passport

6b) Is blast furnace cement being used

Information retrieval:
- Construction drawings

6c) Is there visible expansion and deformation of the concrete?

Information retrieval:
- inspection reports
- visual inspections

6d) Are there cracks on the surface of the concrete visible?

Information retrieval:
- inspection reports
- visual inspections

6e) Are alkali silicic geld visible?

Information retrieval:
- inspection reports
- visual inspections

6f) Are there pop-outs of concrete pieces visible?

Information retrieval:
- inspection reports
- visual inspections

Scores:
- 6a = yes, or 6b = yes (1)
- for 6c, 6d, 6e and 6f: each no adds 0,25 to the score

If at least one of the first two sub-questions can be answered with yes the risk of ASR can be excluded because after 1989 ASR was acknowledged as a problem and blast furnace cement is ASR resistant. In that case, the last four sub-questions do not need to be answered. If that is not the case then each of the last for sub-questions that can be answered with a no, add 0,25 points to the score. These four last sub-questions are derived from the Handboek ASR (Rademaker, 2002), of which a more extensive description is given in Appendix G. If all of the last sub-questions are answered with no the score becomes 1 and if all of the questions are answered with yes the score becomes 0.

Recommended further research
However, it can only be determined for sure if ASR is a problem with a lab research. So if the score is lower than 1, it is advised to perform a lab research if ASR is a real problem.

7. Could internal sulphate attack have been a problem?

Internal sulphate attacks can be problematic because it causes an expensive reaction which damages the concrete. Internal sulphate attacks are dependent on three factors which all need to be present, otherwise the reaction cannot be happening. Each of the three factors is answered with a sub-question.

7a) Does the component stand in a humid environment?

Information retrieval:
- inspection reports
- visual inspections

7b) Are cracks visible on the surface of the concrete?

Information retrieval:
- inspection reports
- visual inspections

7c) Are the aggregates sulphate containing?

Information retrieval:
- Contract documents

Scores:
- At least one of the answers is no (1)
- All answers are yes (0)

If one of the sub-questions can be answered with a no, there is no need to further answer the other sub-questions and a score of 1 should be given. For that reason, the questions are listed in order from ‘easy to answer’ to ‘difficult to answer’. The first two sub-questions can easily be answered with help of existing inspection reports or visual inspections on site. The third sub-question is somewhat more difficult because the information might not always be available inside the contract documents because that information is not standardly specified in those documents, but it could the case that it is in those documents.

Recommended further research
When the third sub-question needs to be answered and it is unknown if the aggregates are sulphate containing, it is advised to perform lab research to investigate the content of sulphates in the aggregates.

8. Could penetration of sulphites be a problem?

Apart from internal sulphite attacks, external sulphites can also be a problem. With help of two sub-questions, it can be determined if penetration sulphites could be a problem.

8a) Is there seawater within a range of 25 km?

Information retrieval:
- Maps

8b) Is CEM I-SR, CEM III/B-SR, CEM III/C-SR, CEM IV/A-SR or CEM IV/B-SR used as cement for the concrete?

Information retrieval:
- Drawings

Scores:
- 8a = yes, and 8b = no (0)
- All other answers (1)

The only possible way that penetration of sulphites could be a problem is if the component is within a 25 km range of seawater and if a cement is used which is not resistant to external sulphites. If one of the two conditions do not meet, then it is not a problem.

Recommended further research
It can happen that the information about which cement is used is not available. When that is the case, it is recommended to perform a lab research to determine the type of cement that is used.

9. Are there any signs of corrosion?

Corrosion can be a problem because it can cause the reinforcement inside the concrete to deteriorate, which can endanger the structural safety of the component.

Information retrieval:
- inspection reports
- visual inspections

Scores:
- yes (0)
- no (1)

Signs of corrosion can easily be visually detected. First there could be taken a look at inspection reports. If there are no inspection reports or if they are not sufficient, visual inspections on site should be performed. Because this is a simple yes or no question, there are only two possible scores; 0 or 1.

Recommended further research
If there is a sign of corrosion it does not necessarily mean that the functioning of the component is in any danger. Corrosion can also occur at a location that only gives aesthetic problems. That is why it is advised that if corrosion occurs it should be investigated how problematic the corrosion really is.

10. <u>If cracks are visible, what is the maximum width of the cracks?</u>

Cracks are a sign that the a component is damaged. The width of the cracks can determine how serious the damage is.

Information retrieval:
- inspection reports
- visual inspections

Scores:
- no cracks (1)
- smaller than or equal to 0,2 mm (0,67)
- between 0,2 and 0,5 mm (0,33)
- more than 0,5 mm (0)

With a crack width of up to 0,2 mm the concrete has the ability to self-heal, and up to 0,5 mm the corrosion process which can occur could automatically stop because the cracks automatically silt up.

III. Residual lifespan

11. <u>What is the residual lifespan based on the condition?</u>

Based on the condition score of the NEN2767, it is also possible to make an estimation for the residual lifespan. This is a very rough estimation, but it is an easy way to make an estimation for the residual lifespan. To be able to make an estimation of the residual lifespan based on the condition score, two sub-questions need to be answered.

11a) What is the designed lifespan?

Information retrieval:
- Design report

11b) What is the condition score?

Information retrieval:
- inspection reports
- visual inspections

Scores:
The residual lifespan based on the condition can be calculated with the following formula.

$RL = Residual\ lifespan$ (years)
$DL = Designed\ lifespan$ (years)
$C = condition$

$RL = (DL * \left(\frac{1}{2} * (C - 1)\right))$
$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

80 years is a commonly usual designed life span, that is the reason that that is the first mark at which the residual life span gets a lower score. After that, the score is linearly going down until it reaches a residual life span of 20. If a component has a residual lifespan of between the 10 and 0 years it is highly unlikely that such a component is going to fulfil the needs of a new situation, that is why after 20 years the score decreases more rapidly until it reaches a score of 0 if the residual life span is lower than 10 years.

12. <u>What is the residual lifespan based on the designed value?</u>

The residual lifespan based on the designed value is a very simple calculation. It is also a very rough estimation that does not reflect the exact residual lifespan, but it can give a quick indication.

12a) What is the designed lifespan?

Information retrieval:
- Design report

12b) What is the age of the component?

Information retrieval:
- Object passport

Scores:
The residual lifespan based on designed lifespan can be calculated with the following formula.

$RL = Residual\ lifespan$ (years)
$DL = Designed\ lifespan$ (years)
$t = age$ (years)

$RL = DL - t$
$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

The points are given the same way as for the residual lifespan based on the condition.

Recommended further research
If a component is older than the designed lifespan, it is not necessarily the case that a component can be used anymore. If that is the case, it is necessary that an extensive residual lifespan calculation is performed.

13. <u>What is the residual lifespan based on chloride penetration?</u>

If chloride reaches the reinforcement, the reinforcement may begin to corrode. It can be calculated how long it takes before the chloride reaches the reinforcement of the concrete. In order to retrieve information about the residual lifespan based on chloride penetration, a very extensive research needs to be performed. To perform this research is not included in the method, but if this information is already available because this has been investigated in the past, it is worthwhile to include these results in this method.

Information retrieval:
- research report

Scores:
$RL = Residual\ lifespan$ (years)

$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

The points are given the same way as for the residual lifespan based on the condition.

Recommended further research
If a chloride penetration research has not been performed yet, it is recommended to perform a chloride penetration research to get more detailed information about the residual lifespan.

14. <u>What is the residual lifespan based on carbonation penetration?</u>

Also if carbonation reaches the reinforcement, the reinforcement can begin to corrode. It can be calculated how long it takes before the carbonation reaches the reinforcement of the concrete. First, it needs to be checked if such a research has been performed in the past. If that is not the case, it is relatively easy to perform such a research on site.

14a) What is the residual lifespan based on carbonation penetration?

Information retrieval:
- research report

14b) What is the age of the component?

Information retrieval:
- Object passport

14c) What is the carbonation depth?

Information retrieval:
- Drilling with a small drill

14d) How deep the reinforcement is located?

Information retrieval:
- Construction drawings
- Scanners

Scores:

For the calculation of the residual lifespan based on carbonation penetration, the formula of the CUR 121 is used (SBRCURnet-commissie 2140, 2018). A more extensive explanation of the CUR 121 is shown in Appendix G.

$RL = residual\ lifespan$
$mcd = \ measured\ carbonation\ depth\ (mm)$
$t = age$ (years)

$$rd = reinforcement\ depth\ (mm)$$

$$RL = \left(\frac{dekking\ wapening}{\left(\frac{gemeten\ carbonatatie\ diepte}{\sqrt{leeftijd}}\right)}\right)^2$$

$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

If the information about the residual lifespan is already given in a research report, it is not necessary to perform the research again and the last three sub-questions can be skipped. The points are given the same way as for the residual lifespan based on the condition.

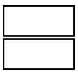
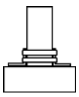
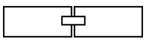
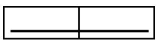
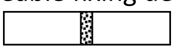
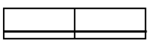
IV. Connections

15. How is the component connected?

How the component is connected says something about how easy it is to dismantle the component.

Information retrieval:
- construction drawings
- inspection reports
- visual inspections

Scores:

- No fixed connection (1) 
- Indirect with external fixing devices (0,8) 
- Indirect with an internal removeable fixing device (0,6) 
- Indirect with an internal non-removeable fixing device (0,4) 
- With a third chemical material (0,2) 
- With a direct chemical connection (0,1) 
- Prestressed reinforcement with attachment (0) 

These connections are ordered from ‘easily to remove’ to ‘hard to remove’. The scores are based on the scores from Durmisevic et al. (2001). The prestressed reinforcement with attachment has been added because it is almost impossible to remove or cut through prestressed reinforcement with attachment without damaging the concrete.

V. Retrieval

16. Can the component be transported?

To be able to reuse a component it is necessary that the component is transportable to another location. This question can be answered with three sub-questions.

16a) Does the component fit within the dimensions of 3,00x4,00x27,00 meters?

Information retrieval
- Construction drawings

16b) Weighs the component less than 35.000 kg?

Information retrieval:
- Construction drawings

16c) Is there room for the component to be transported with special transport?

Information retrieval:
- Maps
- Visual inspections

Scores:
- If 16a = yes, and 16b = yes; Component transportable with regular transport (1)
- If (16a = no, and/or 16b = no) and 16c = yes; Component only transportable with special transport (0,5)
= If 15c = no (0); Component no transportable (0)

If the first two questions can be answered with yes, then the component can be transported with regular traffic without the need for special permits. If that is the case the third sub-question does not need to be answered. The answer for the third question must be a yes or a no. Because it is difficult to determine when a component can be transported with special traffic, this question must be answered based on expert judgement.

17. How accessible is the component?

How accessible the component is says something about if it is easy to get access the component without causing damage to the component.

Information retrieval:
- construction drawings
- inspection reports
- visual inspections

Scores:
- accessible (1)
- accessible with additional operation which causes no damage (0,75)
- accessible with additional operation which causes repairable damage (0,5)
- accessible with additional operation which causes damage but component can still be used (0,25)
- not accessible without causing total damage (0)

These answers are ordered from 'most accessible' to 'less accessible'. The scores have been linearly distributed over the possible answers.

18. If a crane is needed, is it possible for a crane to reach the component?

Most components are required to be moved with a crane. If that is necessary it should be possible for a crane to reach the component.

Information retrieval:
- Maps
- Visual inspections

Scores:
- yes (1)
- no (0)

It is difficult to determine if a crane can reach the component because it depends on many different factors. That is why this question must be answered based on expert judgement.

VI. Design requirements

19. For which environmental classes is the component suitable?

This question says something about how widely the component can be deployed if it is going to be reused. To answer this question for each of the 5 types of environmental classed it needs to be determined to which class the component applies. Each sub-question applies to one of the environmental classes.

19a) For which XC class is the component suitable?

Information retrieval:
- Construction drawings

19b) For which XD class is the component suitable?

Information retrieval:
- Construction drawings

19c) For which XS class is the component suitable?

Information retrieval:
- Construction drawings

19d) For which XF class is the component suitable?

Information retrieval:
- Construction drawings

19e) For which XA class is the component suitable?

Information retrieval:
- Construction drawings

Scores:
- Each sub-question gets a score between the 0 and 1 linearly divided over all the possible classes
- the total score of this question is the average score of the sub-questions

VII. Dimensions

20. <u>What is the level of standardisation?</u>

The level of standardisation also says something about how broad a component can be deployed if it is going to be reused. The dimensions of a standardised component could easily fit in other situations because it is dimensions are more commonly used than the dimensions of a non-standardised component.

Information retrieval:
- construction drawings
- inspection reports
- visual inspections

Scores:
- fully standardised (1)
- half standardised, is a prefab component but still designed for a specific constructive situation (0,5)
- cast-in-situ (0)

Most of the prefab components are still specifically designed for an object. Often the measurements are the same, but the layout of the reinforcement differs. That is not as good as fully standardised, but still better than if the concrete is poured on location.

4.1.2.2 Step 2.2: *Check if a deal breaker question scores a 0.*

Some questions are defined as deal breaker questions. If a question is a deal breaker it means that if the answer to that question results in a score of 0 for that particular question, reuse is not possible. That is why it must be checked if one of the deal breaker questions score a 0.

- The presence of iron fibres and composite fibres are marked as a deal breaker because they give an increased risk in quality loss of the concrete (van Dijk, 2018). Because these materials are almost impossible to filter out of the concrete, these components should be kept out of the loop from a circular point of view.

- The general condition score gives some kind of threshold of what the minimal condition of a component should be. When the condition is irreversibly bad, the component should not be reused. This also has an effect on the residual lifespan based on the condition, so both the general condition score and the residual lifespan based on the condition are deal breakers.

- If a component cannot be transported, it is not possible to reuse the component in another location. Therefore it is a deal breaker.

Conclusively, below a list is shown that gives an overview of all the assessment questions that are defined as deal breakers:

1. **Are iron fibres are visible in the surface of the concrete?**
2. **Are composite fibres are visible in the surface of the concrete?**
6. **What is the general condition score of the component?**
11. **What is the residual lifespan based on the condition?**
16. **Can the component be transported?**

If any of the deal breaker questions that are mentioned above scores a 0, step 3 must be skipped.

The rest of the assessment questions are not deal breakers because there could be a way to reuse a component, no matter how the rest of the questions are answered.

4.1.3 Step 3: Category scoring

For the design of the new method, new scoring categories have been determined. To make sure that the results of the method are easy to compare, it should not give a component seven separate scores for all the indicators. That is why the seven indicators have been brought down to 3 categories on which the component is scored with the new method; Material Quality, Disassembly and Applicability.

As visualised in Figure 11, the Material Quality category contains the toxicity, condition and residual life span indicators; the Disassembly category contains the connections and retrieval indicator, and the Applicability category contains the design requirements and dimensions indicator.

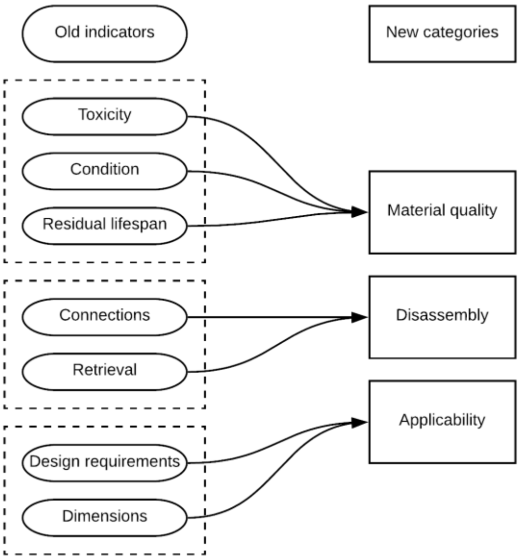


Figure 11: From the 7 indicators to the 3 new scoring categories

It is desirable to get the least amount of scores possible per component, because this makes it easier to compare and prioritize components. However, if you combine anymore of the three categories you get a score that is too general to say anything about 1 on 1 reuse. These three categories are independent which means that they do not influence each other's scores. Therefore these three categories are chosen to score separately

The toxicity, the condition and the residual lifespan indicators have been put into 1 category because they can influence each other. If a component is in a bad condition, it is very likely that the residual lifespan is lower than when the component is in a better condition. Also, if there are certain toxic materials that are inside the concrete, the concrete can be more sensitive to deterioration, which can worsen the condition and consequently the residual lifespan.

The connections and the retrieval category have also been put into 1 category because they also can somewhat influence each other. The type of connection also influences if it is possible to disassemble a component without damage or not.

The design requirements and the dimension of a component do not influence each other. But because they both say something about the applicability and it is desirable to have as few categories as possible, they have been put into one category.

4.1.3.1 Step 3.1: Calculate the score for each category.

Within each category (Material Quality, Disassembly & Applicability) the scores of all questions must be added together and divided by the maximum achievable score within that category. Then for each category, the number is multiplied by 10, which results in a score on a scale of 0 to 10.

In this part, it is described how all the answers are analysed to generate final scores. As explained before, each of the questions can be scored with a value between 0 and 1, in which 0 is the least optimal for reuse and 1 is the most optimal for reuse. Then for each category, all the scores are summed up. Based on the maximum score that can be achieved, a score on a scale between 0 and 10 is given for each of the three categories. An example of what such a score can look like is given in Figure 12. If a deal breaker question is given a score of 0, then the whole category gets a score of 0, which means that reuse is not possible.

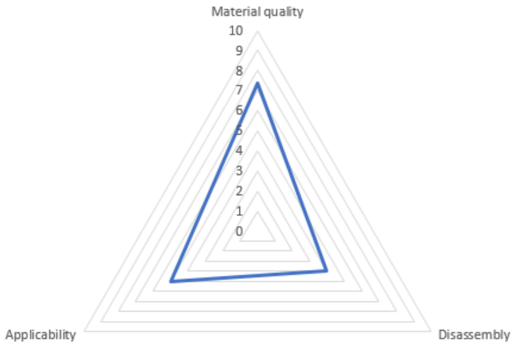


Figure 12: Visualisation of final scores

4.1.3.2 Step 3.2: Calculate the range of uncertainty.

There is also the possibility that the available data is not sufficient to be able to answer certain questions. If that is the case, then the question is not included in the calculation of the score. However, it could be the case that if sufficient data is gathered, the end score will be higher or lower. Therefore the score should be calculated an extra two times.

1. One time while assuming that all the questions that could not be answered get a score of 1 (called the '+ uncertainty score');
2. and one time while assuming that all the questions that could not be answered get a score of 0 (called the '- uncertainty score').

This way a score is calculated of the highest possible score if all questions can be answered, and of the lowest possible score if all questions can be answered. This gives an idea of the range of what the score can be if all the uncertainties are taken away. An example of what those scores can look like is given in Figure 13.

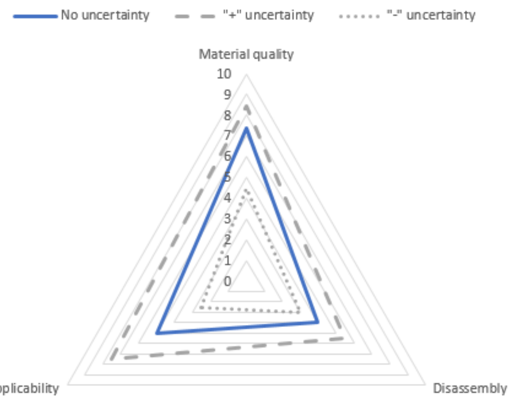


Figure 13: Visualisation of final score including uncertainties

The following example is given to clarify how the calculation of the uncertainty scores works:
The Disassembly category consists of 4 questions. For the example, it is assumed that 3 questions can be answered, but for 1 question the answer is unknown. The three questions score a total of 2 points.

For the calculation of the score, the question that could not be answered is not taken into account. This means that the score is calculated like this:

$$\frac{points\ scored}{maximum\ possible\ amount\ of\ points} * 10 = \frac{2}{3} * 10 = 6{,}67$$

For the calculation of the "+" uncertainty score, the question that could not be answered is taken into account and it is assumed that the uncertain question scores a 1. This results in the following calculation of the '+ uncertainty score':

$$\frac{points\ scored}{maximum\ possible\ amount\ of\ points} * 10 = \frac{3}{4} * 10 = 7{,}50$$

For the calculation of the "-" uncertainty score, the question that could not be answered is taken into account and it is assumed that the uncertain question scores a 0. This results in the following calculation of the '- uncertainty score':

$$\frac{points\ scored}{maximum\ possible\ amount\ of\ points} * 10 = \frac{2}{4} * 10 = 5{,}00$$

4.1.4 Step 4: Recommendations.

Based on the answers on certain questions, an advice for future research should be formulated. This recommended further research could take away some uncertainties that are in the answers of the questions and thus could give a score with fewer uncertainties. Below a list is given of what the possible recommendations for future research could be, depending on how the questions are answered:

3. *Is asbestos present?*

When it is unknown if asbestos is present, it is advised to perform an extensive asbestos research to identify the presence of asbestos.

4. *Is there is a risk of mixed in chlorides?*

It can never be determined for sure if there are chlorides mixed into the concrete. So when there is a risk of mixed in chlorides, it is advised to perform a lab research, according to the CUR 121, to identify the presence of mixed-in chlorides.

6. *Could ASR be a problem?*

However, it can only be determined for sure if ASR is a problem with a lab research. So if the score is lower than 1, it is advised to perform a lab research, according to the CUR 117, if ASR is a real problem.

7. *Could internal sulphate attack have been a problem?*

When the third sub-question needs to be answered and it is unknown if the aggregates are sulphate containing, it is advised to perform a lab research, according to the CUR 117, to investigate the content of sulphates in the aggregates.

8. Could penetration of sulphites be a problem?

It can happen that the information about which cement is used is not available. When that is the case, it is recommended to perform a lab research to determine the type of cement that is used.

9. Are there any signs of corrosion?

If there is a sign of corrosion it does not necessarily mean that the functioning of the component is in any danger. Corrosion can also occur at a location that only gives aesthetic problems. That is why it is advised that if corrosion occurs it should be investigated how problematic the corrosion really is.

13. What is the residual lifespan based on chloride penetration?

If a chloride penetration research has not been performed yet, it is recommended to perform a chloride penetration research according to the CUR 121 to get more detailed information about the residual lifespan.

4.2 Tool

A tool has been developed to help the inspector in executing the new method. The tool only helps with step 2 till step 4 of the method, which means the inspector still has to come up with a decomposition according to the NEN 2767. The tool consists of two parts; the input interface, and the output interface.

The input interface is shown in Table 3. The interface is designed to look simplistic and only gives useful information for the inspector. Three types of information are given for an inspector to fill in the answer to a question; the question, where to find the information, and what are the possible answers. By giving a fixed set of answer possibilities, less room is given for the inspectors own interpretation.

The inspector should fill in the answers in the yellow boxes. Some sub-questions do not need to be answered depending on the given answers for previous sub-questions. This is taken into consideration; if a yellow box turns into a red box it does not need to be answered anymore. The inspector only needs to check if all the yellow coloured boxes are filled with an answer.

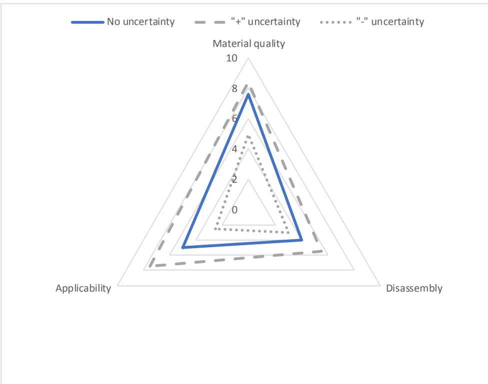
The questions are ordered in such a manner that the deal breaker questions are asked first. These are categorised as must-haves. As shown in Table 3, on the right of those questions, a result is instantly given that states if reuse is possible or not.

Also after each question, the inspector has the opportunity to write down some notes if more elaboration on the given answer is desired or if some uncertainties need to be addressed.

Table 3: The input interface

#	Required information		Where to get the information	Possible answers	Antwoord		Ruimte voor opmerkingen
	Must haves						
1	Are iron fibres are visible in the surface of the concrete?		Inspection reports Visual inspections	y = yes n = no ? = unknown	**n**	Reuse is possible	
2	Are composite fibres are visible in the surface of the concrete?		Inspection reports Visual inspections	y = yes n = no ? = unknown	**n**		
6	What is the general condition of the component?		Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard	**2**		
11	What is the residual lifespan based on the condition?	What is the designed life span?	Design report	fill in the designed life span ? = unknown	**100**		
		What is the condition of the component?	Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard	**2**		
16	Can the component be transported?	Does the component fit within the dimensions of 4,00x2,55x30,00 meters?	Drawings	y = yes n = no ? = unknown	**n**		
		Weighs the component less than 35.000 kg?	Drawings	y = yes n = no ? = unknown	**n**		
		Is there room for the component to be transported with special transport?	Maps Visual inspections	y = yes n = no ? = unknown	**y**		
	Nice to have						
3	Could internal sulphate attack have been a problem?	does the component stand in a humid environment?	Inspection reports Visual inspections	y = yes n = no ? = unknown	**n**		
		Are there cracks visible on the surface of the concrete?	Inspection reports Visual inspections	y = yes n = no ? = unknown			
		Are the aggregates sulphate containing?	Contract specifications (not standard)	y = yes n = no ? = unknown			
		Is the component build after 1983?	Pasport (DISK)	y = yes n = no ? = unknown	**n**		
		If there information about the	Design report	y = yes			

The output interface is shown in Figure 14. The scores for the three categories are shown, both in a table and visualised in a triangle. The automatically generated advice is shown based on questions that could not be answered. Finally, the residual lifespans are visualised. With a visualisation of the residual lifespan, it is possible to get a better idea for what practical timespan a component can be reused.



Advice:
-
-
Perform lab research for mixed-in chlorides
Perform lab research for ASR
-
-
-
Perform chloride penetration research

	Material quality	Disassembly	Applicability
No uncertainty	7,57	4,00	5,00
"+" uncertainty	8,41	5,50	7,50
"-" uncertainty	4,93	3,00	2,50

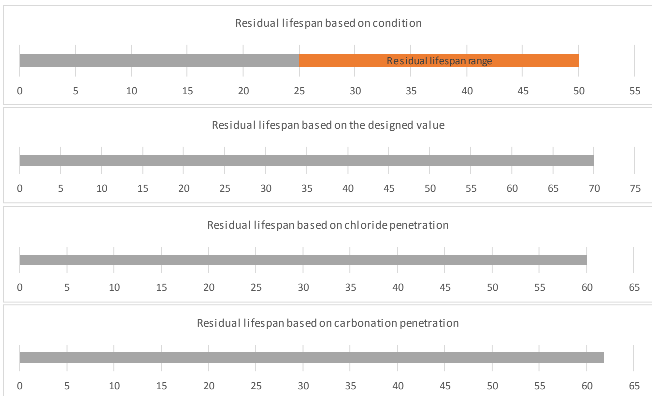


Figure 14: Output interface

4.3 Conformance with the requirements

In this part, it is being assessed how the general requirements are taken into account and are being met by the design of the new method.

- The method should be able to be easily integrated with regular inspections

The first step of the method is to make a decomposition according to the NEN 2767 standards. Since regular inspections also make use of the decomposition according to the NEN2767 standard, this new method could easily be integrated into regular inspections.

- The method should make use of current practices that are used in the industry.

The method is compatible with some current industrial practices:

  - The NEN 2767 standard is integrated within this method to assess the general condition of a component.
  - The four signs of ASR according to handboek ASR are used to assess the presence of ASR.
  - The CUR 117 is used as a recommendation for further research if that is necessary.
  - The formulas of the CUR 121 are used to calculate residual lifespans based on carbonation penetration.

- The method should be able to give a quick indication if 1 on 1 reuse is possible.

If the right information is available, all the information can be acquired relatively easy. All the answers are predefined which makes sure that the method is easy to understand. This simplicity makes it possible for the method to be executed relatively quickly.

- The method should give an unambiguous and comparable priority score (like the NEN 2767) to assess the ability for a component to be reused 1 on 1.

By scoring three different categories, the method assesses the Material Quality, Disassembly and Applicability. These scores give an indication of how the component performs for 1 on 1 reuse. The component is scored on these three categories with an unambiguous value of between 0 and 10. These scores for different components can be compared with each other.

- Every inspector should be able to execute the method in a uniform manner while getting the same results.

By giving predefined answer possibilities, there is little room for the own interpretation of the inspector. However, there are still some questions which might be interpreted differently. This is tested in the feedback session and the test case which are described in chapter 5 and chapter 6.

- The method should be adaptive and flexible to future developments.

If the requirements change in the future because of new developments in the industry, more questions could easily be added in the method. Also if it would turn out that in the future the weights of certain requirements need to change, the method could easily be adjusted.

- The method should be operational by giving a practical guideline to perform the method.

With help of the developed tool and a practical guideline, the method can be put into practice.

- The tool should have an intuitive user interface which is easy to understand.

The interface gives a minimal amount of information which is required to answer the questions. It is also made very clear where the user needs to deliver input by marking those spots. Also the results are shown in a simple graphical way which is easy to understand. If it is actually easy to understand is tested in chapter 6.

5 2nd Design

In chapter 4, the first design of the method was developed based on the functional and general requirements that have been drawn up. This chapter about the second design of the method. As shown in Figure 15, the chapter starts with the verification of the first of the method. For the verification, a feedback session was organised. Secondly, with help of the verification, improvements on the first design of the method and tool are made, which results in a second design.

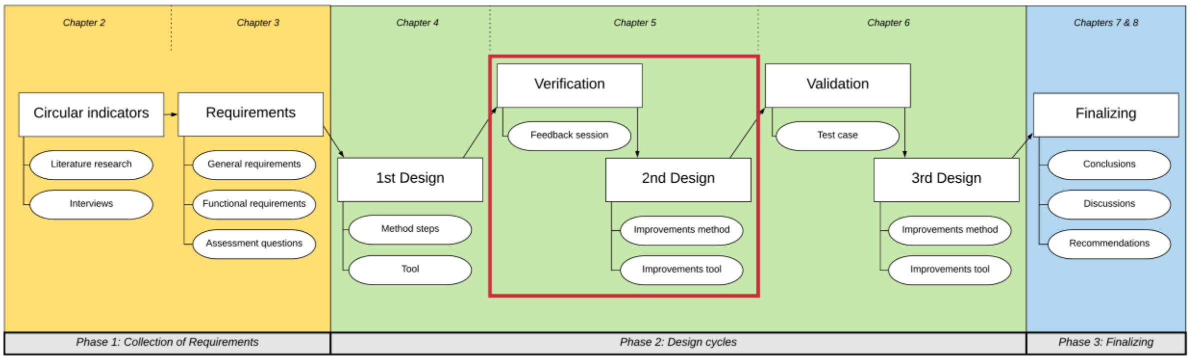


Figure 15: Research Design: Chapter 5

5.1 Verification 1st design

Verification is described as the process to assure that a model is correct and matches any agreed-upon specifications and assumptions (Carson, 2002). The verification has been performed with help of a feedback session. For the feedback session, multiple people were invited. All the people who got interviewed were invited to participate in the workshop session together with additional people from the asset management division and the circular economy group of Witteveen+Bos. The goal of the feedback session is to get feedback on the first version of the new method. First, the structure of the new method and basic the structure of the questions was briefly explained. Second, all the questions were one by one being explained by describing the answer possibilities, the scores which could be given depending on the answers, and where the information can be retrieved. For three of those question, the attendees were asked to answer the questions themselves based on an example case to test if everyone has the same perception of the questions and answers. There is elaborated on the results of the three particular questions. Third, the interface of the tool was shown. This chapter begins with a description of the results from the feedback session. After that, based on the feedback session, the improvements in the first design of the method are described, which result in the second design of the method.

Results feedback session

Every inspector should be able to get to the same results independently of each other, that is why it is important that the questions and answer possibilities are defined properly. There are some questions that can be open for the own interpretation of the inspector, despite the fact that the possible answers are predefined. Question 15, 17 and 20 in particular are very sensitive to the own interpretation of the inspector, that is why the attendees of the workshop session were asked to answer these question for an example case. This way it can be checked if the answers must be framed differently.

The example case that is used in the workshop session is that of three components from the Lexkesveerbrug in Wageningen. As shown in Figure 16, the three components are A: an edge element, B: a curbstone, and C: a beam.

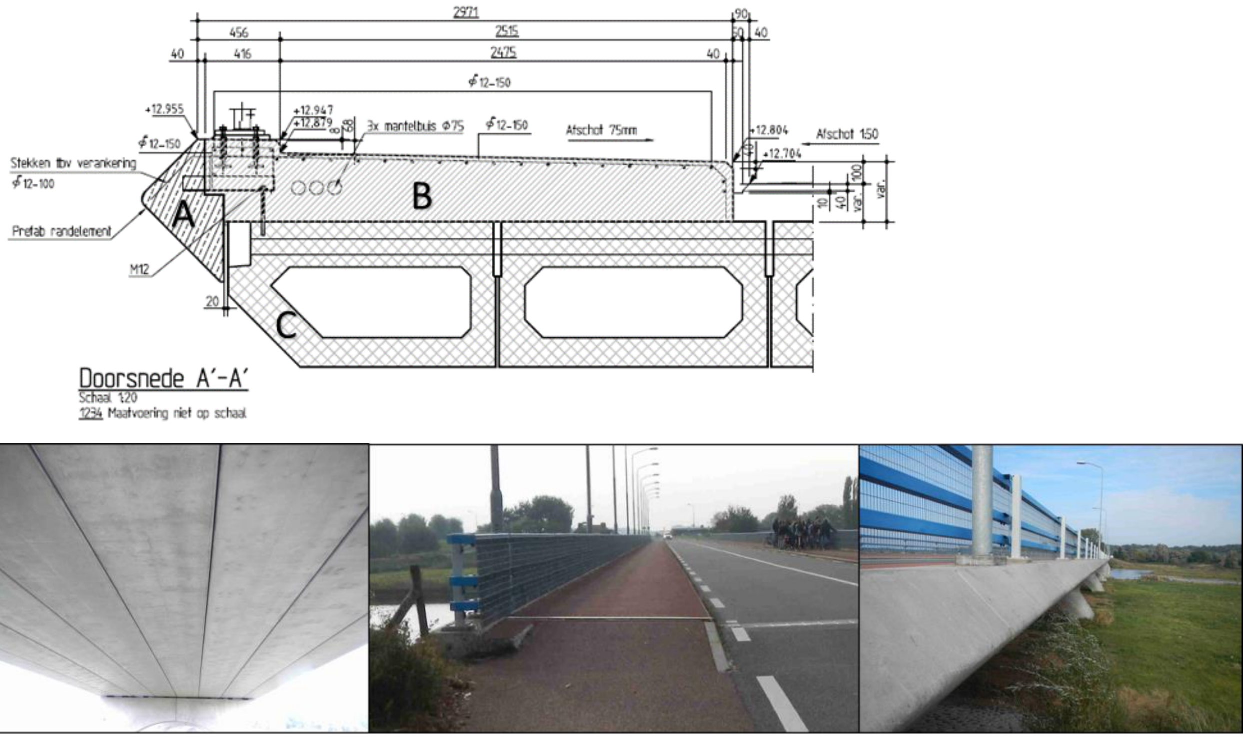
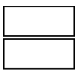


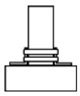
Figure 16: Information about the case used in the feedback session

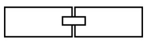
Below, the three particular questions that were asked are shown, followed by a graph that displays how many times a certain answer is given by the attendees.

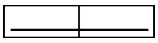
Question 15: How is the component connected?

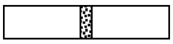
Possible answers:

a) No fixed connection 

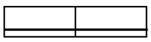
b) Indirect with external fixing devices 

c) Indirect with an internal removeable fixing device 

d) Indirect with an internal non-removeable fixing device 

e) With a third chemical material 

f) With a direct chemical connection 

g) Prestressed reinforcement with attachment 

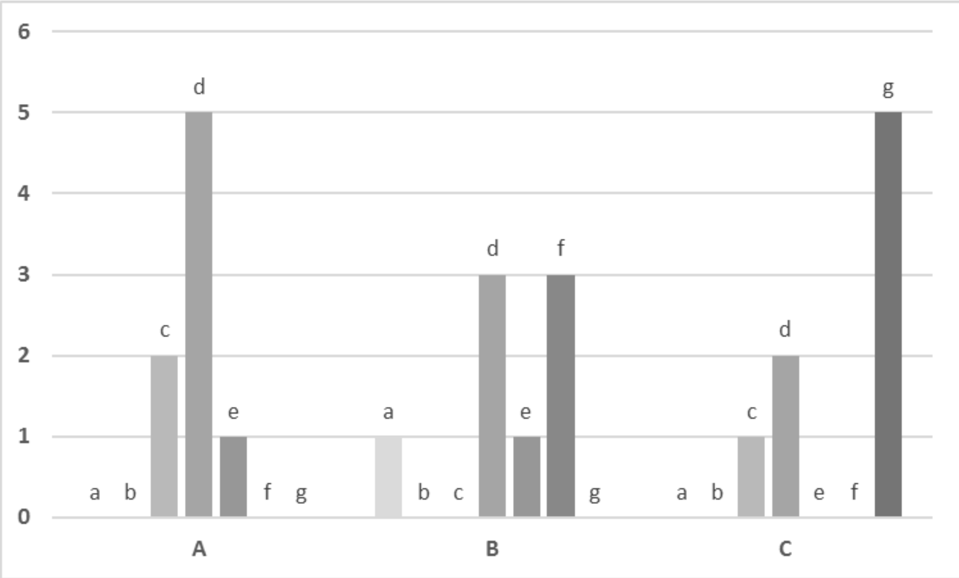


Figure 17: Results of the answers given for question 15 for the three components

As shown in Figure 17, the answers for question 15 are not unanimous. Especially for component B, there is not one answer that stands out the most. After the results were discussed, there were a few possible explanations that could explain why there was such a diversity of answers.

- Some components are connected with multiple kinds of connections. Since it is only possible to fill in one answer, it was not entirely clear the attendees which connection they had to choose. Therefore it should be made clear that the connection with the lowest score should be chosen because that connection should be the most difficult one to remove.
- It turned out that the drawing and photo’s do not give information that is detailed enough to answer the question. Therefore assumptions need to be made about how the component is connected. It should be made clear that if there is uncertainty between multiple possibilities about how the component is connected, then the connection with the lowest score from all the possible answers should be used.
- Some attendees thought that the prestressed reinforcement with attachment should not give the lowest score, because in some cases it is possible to remove the prestressed reinforcement without damaging the component. There is a follow-up question (question 17) that indicates if the component can be removed without damaging the component, however, it was not clear for the attendees that that was covered in question 17. Therefore question 15 should be described in such a way that it does not include the damage that is caused to the component during disassembly, there should be no confusion about that.

Question 17. How accessible is the component?

a) accessible
b) accessible with additional operation which causes no damage
c) accessible with additional operation which causes repairable damage
d) accessible with additional operation which causes damage but component can still be used
e) not accessible without causing total damage

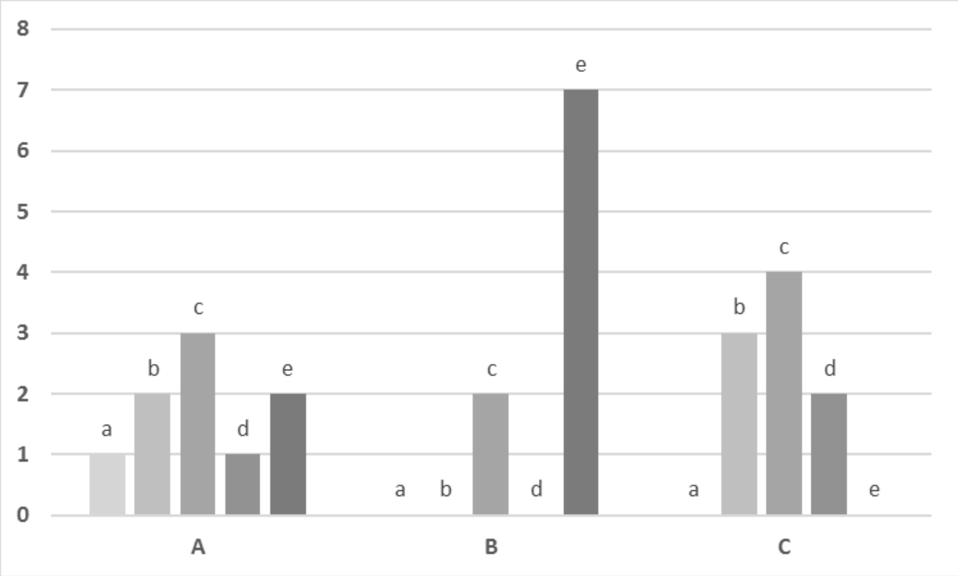


Figure 18: Results of the answers given for question 17 for the three components

As shown in Figure 18, the answers for question 17 also are not unanimous. Only for component B, there seems to be a clear answer that gets the upper hand, but for the other components, it is not entirely clear. After the results were discussed, a few possible explanations that could explain why there was such a diversity of answers came to light.

- There were some uncertainties if there was referred to damage on the component itself or to damage to other components.
- It was also not entirely clear what is meant with 'additional operation', this should be defined more clearly so there is no room for confusion

Question 20. What is the level of standardisation?

a) fully standardised
b) half standardised, is a prefab component but still designed for a specific constructive situation
c) cast-in-situ

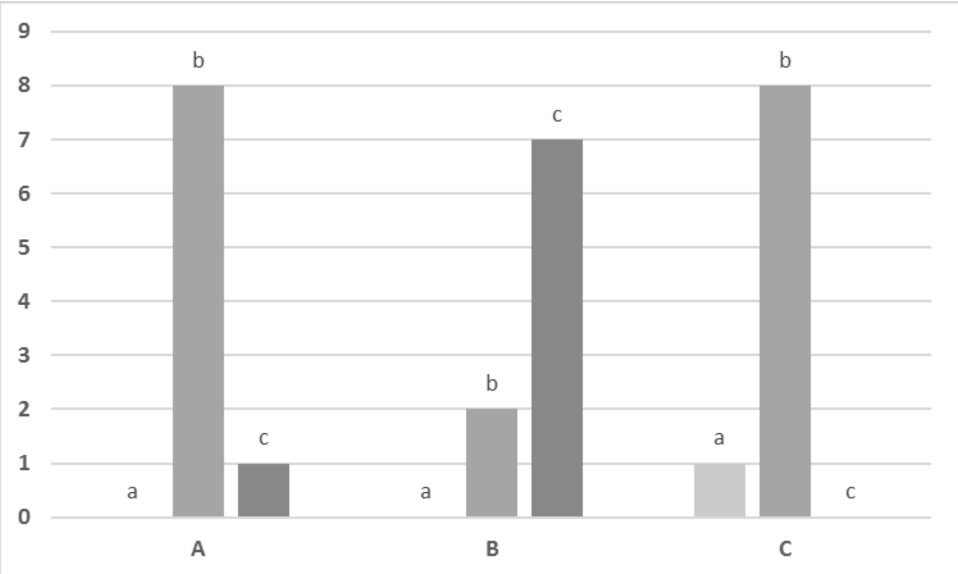


Figure 19: Results of the answers given for question 20 for the three components

As shown in Figure 19, for the answers for question 20 for every component one of the answers has the upper hand although it is still not answered completely unanimous. Also for this question, there was a suggestion for improvement after a discussion.

- A component could be pre-fab but is only designed architecturally for a specific situation, or a component could be pre-fab with standard dimensions but with a specific reinforcement layout for a specific situation. These are both half standardised but are different. A distinction needs to be made for these two types of standardisation.

Apart from these particular questions, the other questions were also being discussed in the feedback session. The other outcomes from the discussions in the feedback session are taken into account with the improvements that are described in the next chapter.

5.2 Improvements 2nd design

Based on the outcomes of the feedback session, to validate the first design, improvements on the method and on the tool have been made. These improvements are described in this part.

5.2.1 Improvements on the method

First, the improvements on the individual assessment questions are described, and second, the improvements in the structure of the method are described.

Assessment questions improvements

a number of question specific improvements have been made based on the outcome of the feedback session, these are elaborated in the next part.

3. *Is asbestos present?*

Asbestos is not only present in water drainage systems, it could also be present in other cast-in tubes for cables or other locations that cannot be generally specified. Therefore the sub-question 'Does the component contain a water drainage system?' is rewritten to 'Could there be a risk of presence of asbestos? (i.e., cast in tubes for cables or water drainage systems)'.

6. *Could ASR be a problem?*

The official recommendations to prevent ASR have only been drawn up in 2002. Although ASR became a known problem in 1990, there is no guarantee that ASR is not a problem after it became a known problem. That is why the sub-question about the construction year is changed from 'Is the component build after 1989?' to 'Is the component build after 2002?'.

Also a sub-question is added if the component stands in a humid environment because that is also a necessary condition for ASR to occur. Additionally, If the component is built before 2002 and blast furnace cement is not used, then in the output a risk is given if the component is going to be reused in a humid environment.

Another improvement regarding this question is about the description of the cracks. Cracks caused by ASR look very specific. As also mentioned in the literature review, cracks caused by ASR are never evenly distributed over the surface, they are inhomogeneously anisotropic and can be described as a 'map pattern'. Therefore the cracks the sub-question 'Are there cracks on the surface of the concrete visible?' is rewritten to 'Are there unevenly distributed cracks with a map pattern visible on the surface of the concrete?'. Also Figure 20 is added to give an example of what common cracks caused by ASR look like.

Figure 20: Example of what ASR looks like (Rijkswaterstaat, n.d.)

7. *Could internal sulphate attack be a problem?*

Because it is unknown where the component is going to be reused, the sub-question to check if the aggregates are sulphate containing, is now the first sub-question that needs to be answered. If that question is answered with a no, a score of 1 is given and the other two sub-questions do not need to be answered anymore, because then there is no risk of internal sulphates attacks.

If it is unknown if the aggregates are sulphate containing, then the related advice is given to perform a lab research on if the aggregates are sulphate containing. Additionally, if the aggregates are sulphate containing, then in the output a risk is given if the component is going to be reused in a humid environment.

8. *Could penetration of sulphites be a problem?*

Because it is unknown where the component is going to be reused, the sub-question about the type of cement is now the first sub-question that needs to be answered. If that question is answered with a yes, a score of 1 is given and the other sub-question does not need to be answered anymore, because then there is no risk of penetration of sulphites. Additionally, If CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B are not used as cement for the concrete, then in the output a risk is given if the component is going to be reused within 25 km of seawater.

9. *Are there any signs of corrosion?*

Corrosion is only a determining factor if it is the reinforcement that corrodes. Also the corrosion can be located on a small local part of a component, or throughout the whole component. Therefore two sub-questions have been added; 1. 'Are there any signs of reinforcement corrosion?', 2. 'Does the reinforcement only occur locally?'.

If the reinforcement corrosion is not the case, then it is not required to answer the second sub-question and a score of 1 is given. If it does look like reinforcement corrosion, it only scores 0,5 point if it only occurs locally. But if it is spread throughout the component, then it gets a score of 0. If a score of lower than 1 is given, the related advice is to perform a potential measurement to determine the severity of the corrosion.

10. If cracks are visible, what is the maximum width of the cracks?

There are two relevant parameters regarding the severity of cracks. The width of the cracks and the cause of the cracks. If a crack is a constructive crack it is much more dangerous than if it is just a regular crack. That is why this question is now divided into two sub-questions: 1. 'Is there a constructive crack visible?', and 2. 'What is the width of the crack?'.

The categories and points that are used for the width of the cracks for constructive and non-constructive cracks are:

Constructive cracks:
1 = cracks smaller than or equal to 0,2 mm, or no cracks (1)
2 = cracks between 0,2 and 0,5 mm (0,5)
3 = cracks more than 0,5 mm (0)

Non-constructive cracks:
1 = cracks smaller than or equal to 0,2 mm, or no cracks (1)
2 = cracks between 0,2 and 0,5 mm (0,75)
3 = cracks more than 0,5 mm (0,5)

From the workshop session, it turned out that cracks with a width 0,2 mm or smaller are very normal and do not influence the quality of the concrete. That is why that category has been merged together with the 'no cracks' category.

11. What is the residual lifespan based on the condition

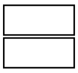
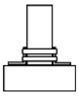
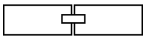
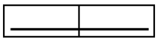
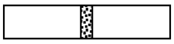
This question is not a deal breaker question anymore, because if a component has a short lifespan, it could still be reused if the new destination fits the lifespan.

16. How is the component connected?

It was unclear what connection should be selected if multiple connections are applicable to one component. Therefore it is clarified with a sentence after the question that it if multiple connections are applicable, the connection with the lowest score must be selected. Also if it cannot be detected exactly how the components are connected, the possibility with the lowest score should be selected.

Also the reinforcement with attachment option is removed from the answer possibilities. This option was added to disassemble such a component would certainly damage the component itself. However, there seemed to be situations in which that is not necessarily the case, which can make it a confusing answer. Therefore this option is removed from the answer possibilities. Also because the amount of damage to a component can is also indicated in question number 17, this answer possibility is not necessary.

Subsequently, these are the new answer possibilities with the corresponding scores:

- No fixed connection (1) 
- Indirect with external fixing devices (0,8) 
- Indirect with an internal removeable fixing device (0,6) 
- Indirect with an internal non-removeable fixing device (0,4) 
- With a third chemical material (0,2) 
- With a direct chemical connection (0) 

17. *How accessible is the component?*

Additional operations are specified as; Operations for which extra equipment to disconnect the component from the structure.

Also this question is changed in a deal breaker, because if a component cannot be removed without completely damaging the component, it will not be possible to reuse the component.

18. *If a crane is needed, is it possible for a crane to reach the component?*

Instead of asking if a crane can reach the component, it is more relevant to know if extra equipment is needed for the retrieval of a component compared to the equipment that is needed for the demolition of the component. That is why the question is rephrased to: 'Is extra equipment necessary for the retrieval of the component compared to the equipment that is needed for the demolition of the component?'

20. *What is the level of standardisation?*

There are not only half standardised components that have standard dimension but with a reinforcement layout for a specific constructive situation, there are also half standardised components with that are pre-fabricated, but which dimensions are also specifically made from a design perspective. That is why the 'half standardised, is a prefab component but still designed for a specific constructive situation' is rewritten to 'half standardised', which is a more general description and includes both types of half standardisation.

<u>Method structure improvements</u>

As shown in Figure 21, two changes in the structure of the method have been made.

The first change is that first the deal breaker questions are answered. After they have been answered their score is checked and when that is done, the rest of the questions are answered. Therefore, together with the changes in the deal breaker questions, the new sequence of questions is as follows:

Deal breaker questions:

1. *Are iron fibres are visible in the surface of the concrete?*
2. *Are composite fibres are visible in the surface of the concrete?*
3. *What is the general condition score of the component?*
4. *Can the component be transported?*
5. *How accessible is the component?*

Non-deal breaker questions:

6. *Is asbestos present?*
7. *Is there is a risk of mixed in chlorides?*
8. *Could ASR be a problem?*
9. *Could internal sulphate attack have been a problem?*
10. *Could penetration of sulphites be a problem?*
11. *Are there any signs of corrosion?*
12. *If cracks are visible, what is the maximum width of the cracks?*
13. *What is the residual lifespan based on the condition?*
14. *What is the residual lifespan based on the designed value?*
15. *What is the residual lifespan based on chloride penetration?*
16. *What is the residual lifespan based on carbonation penetration?*
17. *How is the component connected?*
18. *If a crane is needed, is it possible for a crane to reach the component?*
19. *For which environmental classes is the component suitable?*
20. *What is the level of standardisation?*

The second change is in step 4; apart from an advice for future research, also the potential risks should be stipulated if the component is going to be reused. Also when a deal breaker question scores a 0, advice for future research is not a necessary step, however it should be clear why reuse is not possible. Therefore step 4 has been divided into three sub-steps.

Step 4.1: Draw up an advice for future research

This step is equal to the original step 4 of the first design of the method

Step 4.2: Draw up potential risks for reuse

It could be the case that reuse is only at risk in a certain type of situation. Below these specific risks are described, depending on the answer of the corresponding questions:

8. Could ASR be a problem?
   If the component is built before 2002 and blast furnace cement is not used, then in the output a risk is given if the component is going to be reused in a humid environment.

9. Could internal sulphate attack have been a problem?
   If the aggregates are sulphate containing, then there is a risk of internal sulphate attacks if the component is going to be reused in a humid environment

10. Could penetration of sulphites be a problem?
    If CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B are not used as cement for the concrete, there is a risk if the component is going to be reused within 25 km of seawater.

Step 4.3: Determine why reuse is not possible

This step must only be followed if a deal breaker question scores a 0, which means that reuse is not possible. If that is the case, it should be clearly described what the reason is why reuse is not possible for the component.

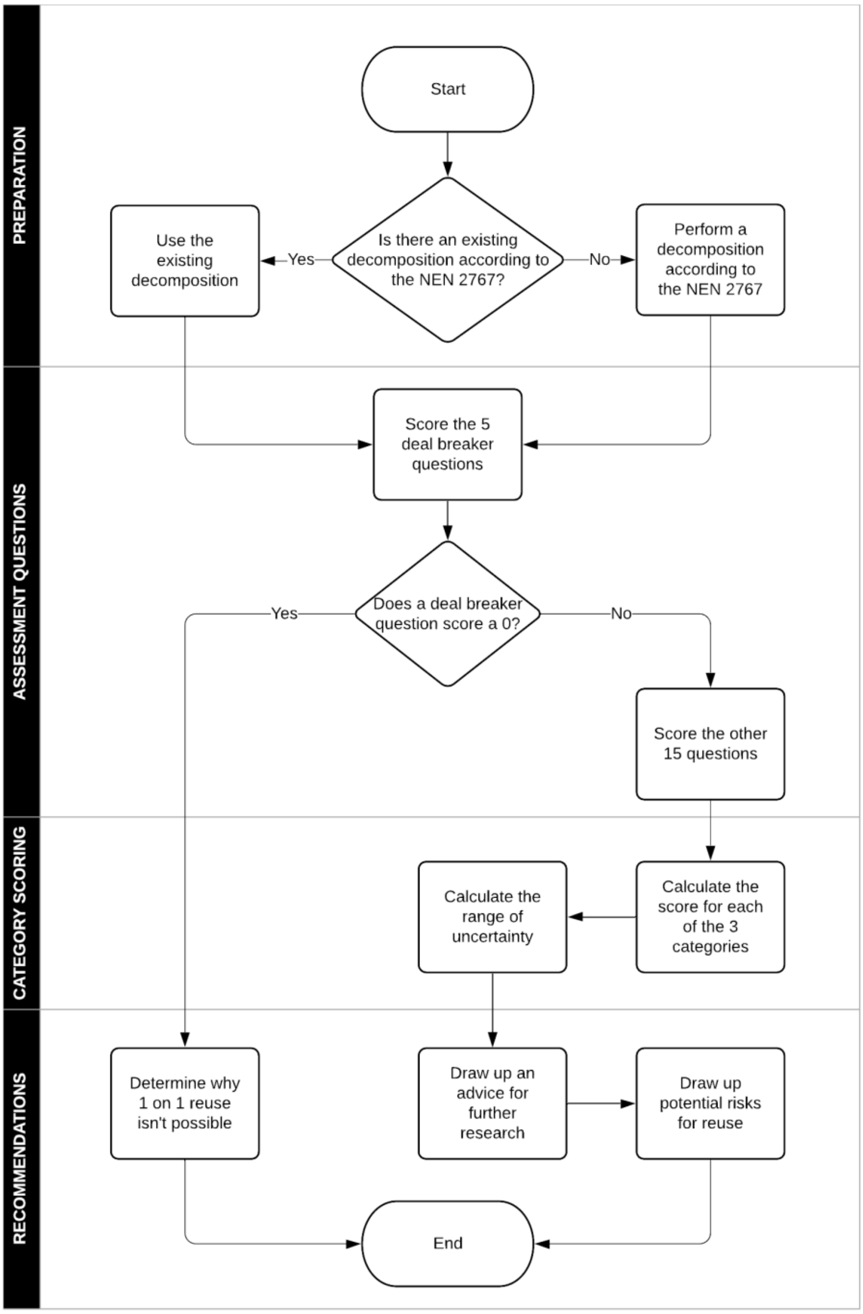


Figure 21: 2nd design of the method

Apart from the structure of the method, there are also some specific improvements that have been made to the design of the method. First of all, there were some uncertainties that came out of the session that could be clarified if a list of assumptions is drawn up before the answering of the questions. Conclusively, the following assumptions should be clear for the inspector before the questions are answered:

- The goal of the method is to quickly asses if 1 on 1 reuse is possible. If 1 on 1 reuse is really considered, much more extensive research and calculations are necessary.
- The method is for the assessment of concrete components.
- The method is for the assessment of 1 on 1 reuse on other locations, not on the same location.
- For the assessment, it needs to be taken into account that the whole structure is getting disassembled.
- The method can only assess components from the Netherlands.

5.2.2 Improvements on the tool

There are a number of improvements made to the input interface, which are shown in Table 4:

- There are two fields in which information of the component can be filled in. This way it becomes more clear which component is being assessed, and from which object the component is originating.
- It has been made more clear for which questions the information can be retrieved from a bureau study, research on-site or both. This can be seen quickly by checking the colours after the questions.
- The questions have been rearranged in such a way that the question of internal toxic materials and materials from outside that causes the concrete to deteriorate are clustered together, while they also still clustered within their own categories.

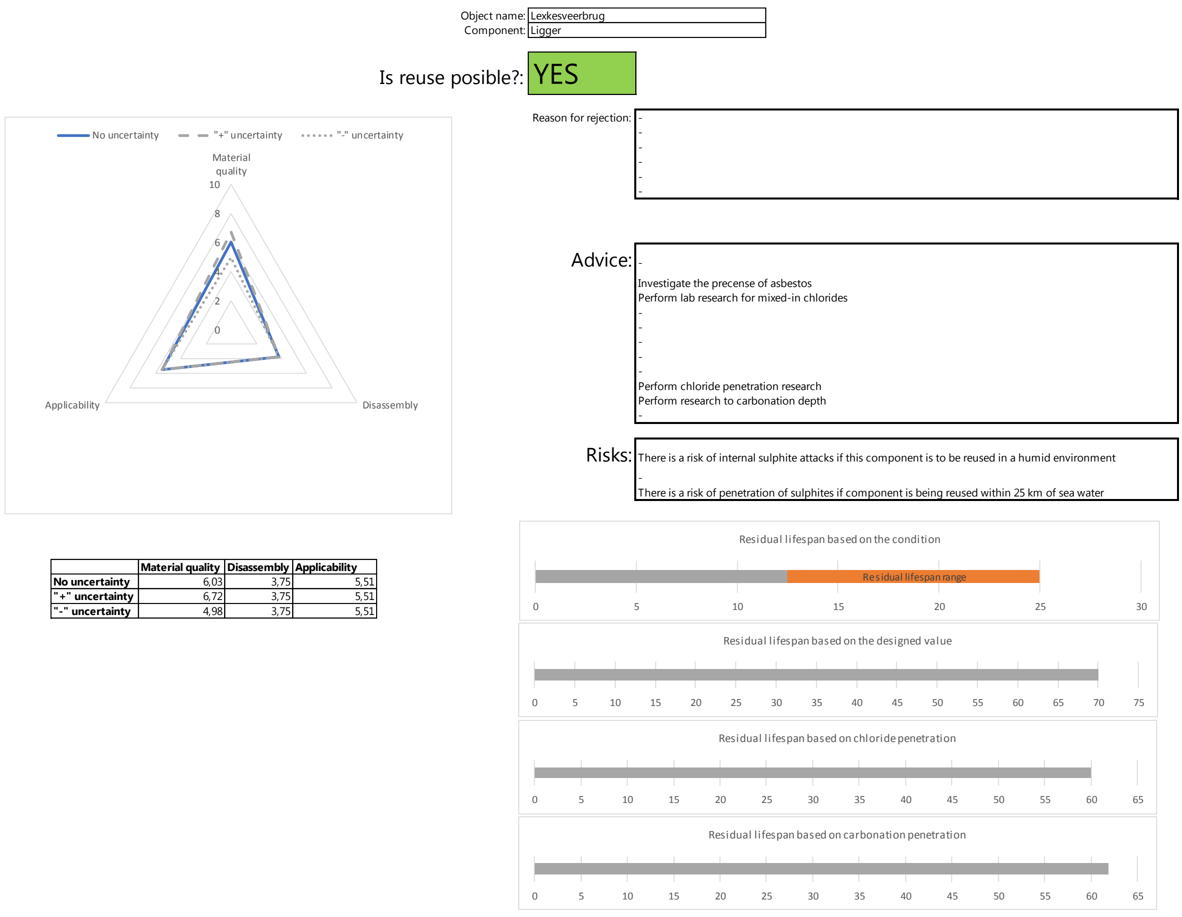
Table 4: 2nd design of user interface

		Legend		
		O	On site reserch	
Object name:	Lexkesveerbrug	B	Bureau study	
Component:	Ligger	B/O	On site research and Bureau study	

#	Required information			Where to get the information	Possible answers	Antwoord		Room for comments
	Must haves							
1	Are iron fibres are visible in the surface of the concrete?		O	Inspection reports Visual inspections	y = yes n = no ? = unknown	**n**	More information required	
2	Are composite fibres are visible in the surface of the concrete?		O	Inspection reports Visual inspections	y = yes n = no ? = unknown	**n**		
6	What is the general condition of the component?		O	Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard	**4**		
16	Can the component be transported?	Does the component fit within the dimensions of 3,00x4,00x27,00 meters?	B	Drawings	y = yes n = no ? = unknown	**n**		
		Weighs the component less than 35.000 kg?	B	Drawings	y = yes n = no ? = unknown			
		Is there room for the component to be transported with special transport?	B/O	Maps Visual inspections	y = yes n = no ? = unknown	**y**		
17	How accessible is the component?		B/O	Drawings Inspection reports Visual inspections	1 = accessible 2 = accessible with additional operation which causes no damage 3 = accessible with additional operation which causes repairable damage 4 = accessible with additional operation which causes damage, but the component can still be used 5 = not accessible without causing total damage	**?**		
	Nice to have							
4	Is asbestos present?	Is the component build after 1983?	B	Pasport (DISK)	y = yes n = no ? = unknown	**n**		
		If there information about the presence of asbestos, does it say if asbestos is present?	B	Design report Research reports	y = yes n = no ? = unknown	**?**		
		Could there be a risk of presence of asbestos? (i.e. cast in tubes for cables or water drainage systems)	B/O	Drawings Visual inspections	y = yes n = no ? = unknown	**y**		

There are a number of improvements made to the output interface, which are shown in Figure 22:

- At the top of the output, it is shown which component has been assessed and from which object the component is originating.
- Just as for the input interface, it is immediately shown if the component can be reused or not based on the deal breaker questions. If reuse is possible the box turns green and if reuse is not possible the box turns red.
- If it turns out that reuse is not possible, a box with a reference to the question on which the component is being rejected is given.
- If a component could be at risk if it is reused in a certain environment, it appears in the 'risk' box. The following risks can be given as output:
    - There is a risk of internal sulphite attacks if this component is to be reused in a humid environment
    - There is a risk of ASR if this component is to be reused in a humid environment.
    - There is a risk of penetration of sulphites if the component is being reused within 25 km of seawater.



	Material quality	Disassembly	Applicability
No uncertainty	6,03	3,75	5,51
"+" uncertainty	6,72	3,75	5,51
"-" uncertainty	4,98	3,75	5,51

Figure 22: Second design of output interface

6 3rd Design

In chapter 5, the second design of the method was developed after verification of the first design. This chapter about the third design of the method. As shown in Figure 23, this chapter starts with a validation of the second design. The validation has been executed with help of a test case which has been performed by four inspectors. First, the test case and the results from the validation session are described. After that, based on the validation session, the improvements on the second design of the method and tool are described which result in the third design.

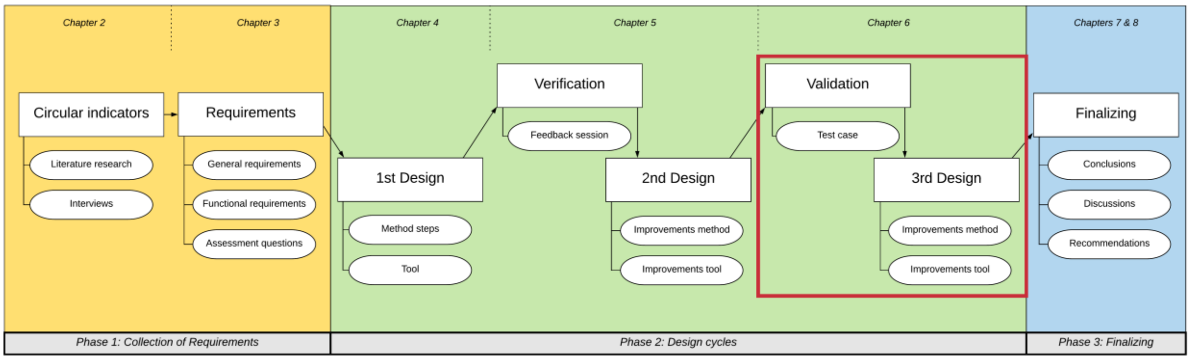


Figure 23: Research design: Chapter 6

6.1 Validation 2nd design

Validation refers to the process to assure that a model represents the real system to a sufficient level of accuracy (Carson, 2002). Part of the validation should be to look at the effects and requirements satisfaction of the method (Wieringa, 2014). A test case is used to validate the design of the new method. First, the results of the test case from the different inspectors are compared with each other, second, it is checked if the general requirements which have been set up for the design of the method are satisfied by discussing them with the inspectors that have performed the test cases.

6.1.1 Test case

The goal of this test case is to validate the design of the new method. The asset that is used as the test case the viaduct of the N370 over the Concourslaan. The method is tested by four inspectors of the asset management division of Witteveen+Bos. All four inspectors got the same test case which they needed to inspect, this way the results of all four inspectors can be compared properly. Right after the inspectors performed the method on the test case, a discussion based on the general requirements of the method was started with the inspectors to evaluate the method. Information on the test case which was presented to the inspectors is given in Appendix K.

6.1.2 Score results

After all the test cases have been performed These are the results for the end scores are shown in Table 5. For each component that is inspected and assessed a score is given for the Material Quality, Disassembly and Applicability.

Table 5: Final scores of the test case

	Beam			Pressure layer			Curb stone			Crossbar			Column			Wing wall			Wall		
	MQ	D	A	MQ	D	A	MQ	D	A	MQ	D	A	MQ	D	A	MQ	D	A	MQ	D	A
Inspector 1	9,45	4,50	10,00	9,45	0,00	0,00	9,45	0,00	0,00	8,95	4,50	10,00	9,20	5,00	10,00	9,20	7,00	0,00	9,20	7,00	0,00
Inspector 2	8,89	3,50	4,25	10,00	0,00	1,75	8,89	0,00	1,75	8,06	4,50	4,25	10,00	4,00	4,25	9,72	4,00	1,75	9,72	4,00	1,75
Inspector 3	8,86	5,00	10,00	8,61	0,00	0,00	8,86	0,00	0,00	8,05	4,50	0,00	8,86	3,50	0,00	8,86	0,00	0,00	8,86	0,00	0,00
Inspector 4	7,81	6,00	2,50	9,15	0,00	0,00	8,96	0,00	0,00	6,50	0,00	2,50	8,96	6,00	0,00	8,96	6,00	0,00	8,96	4,75	0,00
Difference	**1,64**	**2,50**	**7,50**	**1,39**	**0,00**	**1,75**	**0,59**	**0,00**	**1,75**	**2,45**	**4,50**	**10,00**	**1,14**	**2,50**	**10,00**	**0,86**	**7,00**	**1,75**	**0,86**	**7,00**	**1,75**

MQ = Material Quality, D = Dissassembly, A = Applicability

In the difference row of Table 5, the difference between the highest given score and the lowest given score for the corresponding component and category is shown. The score differences that are greater than 2 are furtherly elaborated. When looking at these differences, there are some remarkable observations:

- The score differences for the Disassembly and the Applicability category are much bigger than for the Material Quality category; for the Material Quality the biggest difference is 2,45, for the Disassembly the biggest difference is 7,00, and for the Applicability the biggest difference is 10 which is the biggest difference possible. This has to do with the fact that those two categories consist of fewer questions than the first category, therefore those scores are more sensitive to change if a question is answered differently.

- Disassembly for the wing wall and wall have a relatively large score difference of 7,00 compared to the differences for the other components in that category. This is caused by the fact that question number 17 is answered differently by one inspector, which is a deal breaker question about how much damage must be dealt to the component to get access to it. After this was discussed with the inspectors it turned out that the answers of this question were based on their own expert judgement. It has never been tried before to remove such a component, so there is no reference data to base the answer on.

- Applicability for the beam has a relatively large difference of 7,50. This is because the question about the environmental classes was interpreted differently. One of the inspectors made his own estimations about the environmental classes which are now exposed to the concrete after the inspector could not find it in the specifications, while the other two inspectors answered with a question mark after it could not be found in the specifications.

- Applicability for the crossbar and column have a relatively large difference of 10, which is the largest difference possible. This is because question number 20 is answered differently by every inspector. One inspector thought that the column was cast-in-situ on site, while the other two thought the column was prefabricated, although they did not agree on the fact if the component was fully standardised, or half standardised.

An overview of how all the individual questions were answered by the inspectors is shown in Appendix L.

6.1.3 Conformance with the requirements

To check if the new method satisfies the general requirements of the method, it was discussed with the inspectors that executed the test cases, if the general requirements of the method were met. Only the general requirements from which it was worthwhile to get the opinions from the inspectors, where discussed with the inspectors. Below a summary of the outcomes of those discussions with the inspectors is shown.

The method should be able to give a quick indication if 1 on 1 reuse is possible.

With this method, it is possible to get a quick check if 1 on 1 reuse is possible, with help of this method it could be determined for which components it is worthwhile to store them. However, this method only works if there is a sufficient amount of data available to answer these questions. If data is missing, there can be a lot of uncertainties. Also, this method does not store enough information to actually reuse a component. This is information such as dimensions and carrying capacity, which is also highly dependent on the location where the component is going to be reused.

The method should give an unambiguous and comparable priority score.

The scores of the method can be compared quite well. The results of the residual life span are somewhat difficult to interpret, because it is hard to actually give an exact value to the residual lifespan. If there is hesitation how well a component can be reused, it could be useful to be able to dig through the input to check how the score is built up. However, the most interesting part is to check if reuse is possible at all.

The method should be able to be easily integrated with regular inspections.

The method can be performed in a quick manner, every time the tool is used, it gets easier to use it the next time which means it takes less time. It probably does not cost a lot more extra time to perform this method next to regular inspections. Also for regular inspections, a bureau study is necessary, although for regular inspections it is not always necessary to go through every drawing and report It probably does not cost a whole lot of extra time, although this can also depend on the amount of data that needs to be dug through. Some of the assessment questions are also checked for regular inspections, but it could be the case that with a normal condition measurement some aspects might be overlooked that are relevant for this method, because the client requests a global inspection.

Every inspector should be able to execute the method in a uniform manner while getting the same results.

It depends on the amount of data that is available, if there are uncertainties each inspector might deal with that differently. It also depends on the knowledge and experience of the inspector, but the guideline with explanations for each question really helps with that. It also helps that the possible answers are predefined. However, for some questions there is still some room for an inspectors own interpretation. For example, each inspector might see different opportunities or barriers to remove a component.

The tool should have an intuitive user interface and should be easy to understand.

The interfaces of the tool are very easy to understand, no large problems did arise.

Apart from only discussing the general requirements, two more questions were asked:

Could this method lead to more reuse of concrete components?

Yes, it can definitely help in creating awareness that reuse could also be an option. It can show a client that reuse is given thought in the context of a circular economy. It could lead to more reuse of concrete components, but this is unsure because that is also dependent on other factors such as money, but it would definitely create more awareness. Assessing components on 1 on 1 reuse is something which has not been assessed at all before, so this method really is a step forward.

Would you use this method and recommend it to clients?

This method is relevant for assets that reach the end of their lifecycle or if renovations are taking place. Clients for which this is relevant mainly would be large asset owners on the government side, such as municipalities, provinces and Rijkswaterstaat. Also for a contractor, it could be interesting because they could also be contracted for the demolition of components, then 1 on 1 reuse could be interesting for the components that need to be removed. It is important that the client is willing to make the transition towards a circular economy and therefore consider reuse. Since the method takes a small amount of time, it can be offered as an extra service to the client, that forces them to at least think about the idea.

6.2 Improvements 3rd Design

Based on the results and discussions of the test case, improvements on the method and on the tool have been made. These improvements are described in below.

6.2.1 Improvements on the method

First, the improvements on the individual assessment questions are described, and second, the improvements in the structure of the method are described.

<u>Assessment questions improvements</u>

6. Is asbestos present?

To be less confusing, sub-question 6b is rewritten from: ‘If there is information about the presence of asbestos, does it say if asbestos is present?’ to ‘Is it certain that asbestos is present?’

7. Is there a risk of mixed in chlorides?

To help the inspector, some characteristics are given in the guideline for question 7 which could help to identify if a component is prefab or cast-in-situ:

- Prefab components can be recognised by eyebolts on the component. Prefab components can also be recognised by repetition of the same components; there is a lot of repetition in beams, box girders, full-loaders.
- Cast-in-situ components can be recognised by the spots from the formwork or by the centrepins which were used during the pouring process. It can also be recognised by the seams that can be visible at cast-in-situ concrete.

In addition, the information that can be found to identify if a component is cast-in-situ or prefab can also be found in inspection reports or during visual inspections.

8. Could ASR be a problem?

To make sure that every inspector uses has the same frame of reference when a moist environment is mentioned at question 8, a definition for a moist environment is given: An environment that could have been exposed to at least fog or dew.

To make sure that there is no confusion about what is meant with sub-question 8b, the sub-question is rewritten from ‘Is blast furnace cement being used?’ to ‘Is solely blast furnace cement being used?’

Also for sub-question 8b an addition is made to the list of where this information can be found. This information can also be found in the contract documents.

9. Could internal sulphate attack have been a problem?

For question 9 the sub-question, if there are cracks visible on the surface, is removed. These questions are removed because the reactions can also happen through microcracks. Therefore those cracks could always be a risk even if they are not visible.

To make sure that every inspector has the same frame of reference when a moist environment is mentioned at question 9, a definition for a moist environment is given: An environment that could have been exposed to at least fog or dew.

10. Could penetration of sulphites be a problem?

To make sure that there is no confusion about what is meant with sub-question 10b, the sub-question is rewritten from ‘Is CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B used as cement for the concrete?’ to ‘Is solely, or solely a combination of CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B used as cement for the concrete?’

For sub-question 10b an addition is made to the list of where this information can be found. This information can also be found in the contract documents.

12. Are cracks visible on the surface?

For question 12 it is defined more clearly what is meant with a constructive crack too make sure that every inspector has the same frame of reference of a constructive crack. A constructive crack is defined as a crack that decreases the load-bearing properties of a component.

13. What is the residual lifespan based on the condition?

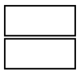
For question 13 a designed lifespan of 80 years is assumed if the designed lifespan is unknown. A designed lifespan of 80 years is chosen because of the commonly used designed lifespans, a lifespan of 80 years is the lowest. Because of this adjustment, it is more likely that uniform results will be achieved.

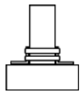
14. What is the residual lifespan based on the designed value?

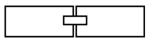
For question 14 a designed lifespan of 80 years is assumed if the designed lifespan is unknown. A designed lifespan of 80 years is chosen because of the commonly used designed lifespans, a lifespan of 80 years is the lowest. Because of this adjustment, it is more likely that uniform results will be achieved.

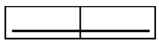
17. How is the component connected?

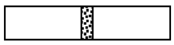
Due to the various answer possibilities, some confusion did arise during the test cases. Therefore, written examples have been provided with the answer possibilities:

- No fixed connection (1) 
(loose concrete bricks)

- Indirect with external fixing devices (0,8) 
(two components connected with bolts)

- Indirect with an internal removeable fixing device (0,6) 
(two components connected with dowels)

- Indirect with an internal non-removeable fixing device (0,4) 
(two components connected with a chemical anchor)

- With a third chemical material (0,2) 
(two components connected with a mortar)

- With a direct chemical connection (0) 
(component directly poured onto another component)

18. How accessible is the component?

For question 18 two improvements are made. The main question has been rewritten, so it becomes more clear it is about the amount of damage that must be caused to the component in order to disassemble it. Consequently, also the answer possibilities have been rewritten:

New main question: Can the component be disassembled without causing damage to the component?

Scores
- yes, without the need of additional operations (1)
- yes, but additional operations are necessary which causes no damage (0,75)
- no, but disassembly is possible with causing damage to the component that is repairable (0,5)
- no, but disassembly is possible with causing damage to the component that cannot be repaired (0,25)
- no, the component cannot be disassembled without causing total damage (0)

20. What is the level of standardisation?

For question 20 it was unclear when a component is fully standardised and when a component is half standardised. Therefore the answer possibilities have been changed to the following answer possibilities:

- non-load bearing prefab (1)
- load bearing prefab (0,5)
- cast-in-situ component (0)

The scores are divided this way because load bearing components require recalculation if they are to be reused. That is why they score lower than non-load bearing prefab components.

To help the inspector, some characteristics are given in the guideline for question 20 which could help to identify if a component is prefab or cast-in-situ:

- Prefab components can be recognised by eyebolts on the component. Prefab components can also be recognised by repetition of the same components; there is a lot of repetition in beams, box girders, full-loaders.
- Cast-in-situ components can be recognised by the spots from the formwork or by the centrepins which were used during the pouring process. It can also be recognised by the seams that can be visible at cast-in-situ concrete.

In addition, the information that can be found to identify if a component is cast-in-situ or prefab can also be found in inspection reports or during visual inspections.

Because of the changes that were made to improve the assessment questions during the different design cycles, a complete overview of all the final assessment questions is shown in Appendix M.

<u>Method structure improvements</u>

The structure of the method did not change after the validation session, therefore the method steps of the final method are still the same. A summarised version of the final method is elaborated below and shown in Figure 24. The complete and final design of the method, including an extensive description of all the steps and assessment questions, is given in Appendix N.

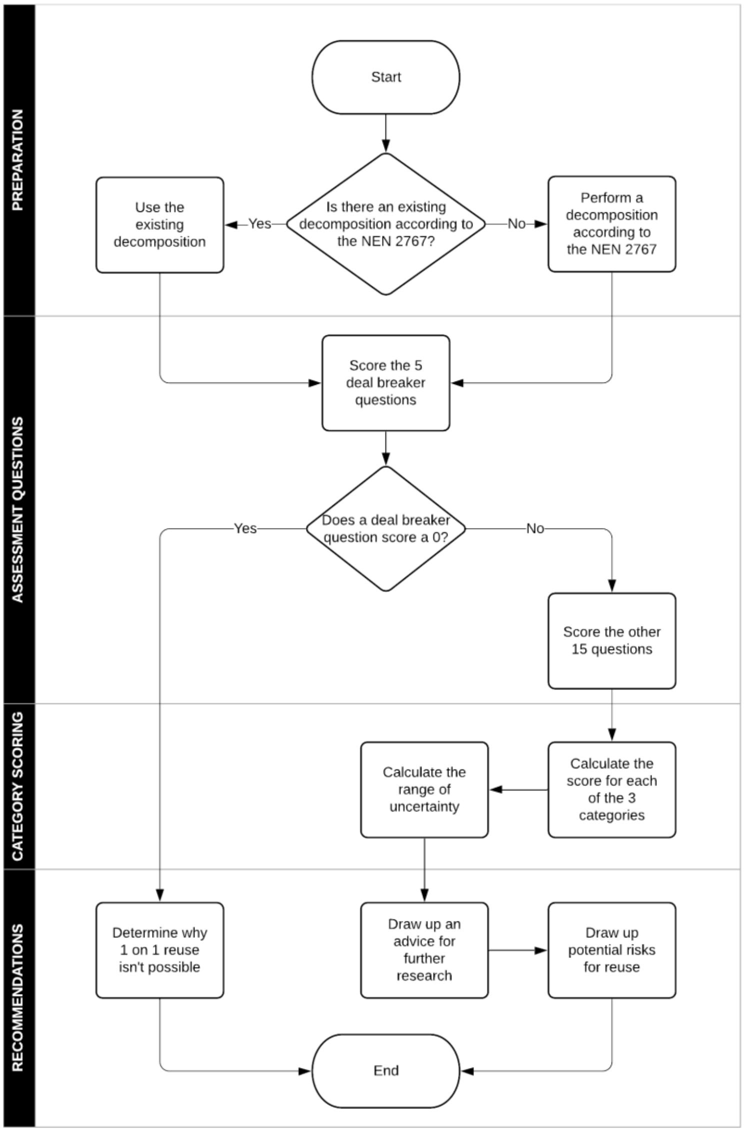


Figure 24: Final design of the new method

- The first main step is the preparation; it must be checked if a decomposition is available and if that is not the case a new decomposition must be performed.
- The second main step is about the answering of the assessment questions for the components; First, the five deal breaker questions must be scored and it must be checked if a deal breaker question scores a 0 to assess if reuse is possible. If a deal breaker question scores a 0, reuse is not possible. If a deal breaker question does not score a 0, the other 15 remaining questions must also be scored.
- The third main step is about the scoring of the categories; For the Material Quality, Disassembly and Applicability categories, a score must be calculated. Additionally, after the scores have been calculated, the level of uncertainty needs to be calculated.
- The fourth main step is about giving recommendations. If reuse is possible and if there is a certain level of uncertainty, recommendations for further research must be given, these additional researches can decrease the level of uncertainty. Additionally, potential risks for reuse of the components must be stipulated, that could be present if the component is going to be reused. If reuse is not possible it should be determined why the component is being rejected for reuse.

6.2.2 Improvements on the tool

Based on the discussion that took place with the inspectors, the following aspects are improved:

- Instead of just referring to the questions, it is now described in full sentences why a component is rejected. Consequently, these are the sentences that can appear if a component is rejected:
    - There are iron fibres present in the concrete.
    - There are composite fibres present in the concrete.
    - The general condition of the component is not sufficient for reuse.
    - The component cannot be transported.
    - The component cannot be disassembled without being destroyed.

- The risk of asbestos is added to the list of possible risks that can appear. This risk appears if it has been confirmed that asbestos is present in the component. Consequently, this is the new lists or risks that can appear:
    - There is a risk of internal sulphite attacks if this component is to be reused in a humid environment.
    - There is a risk of ASR if this component is to be reused in a humid environment.
    - There is a risk of penetration of sulphites if the component is being reused within 25 km of seawater.
    - There is a risk of reusing this component because of the presence of asbestos.

Based on the improvements that were made during the design cycles, a final and complete version of the tool is shown in Appendix O.

7 Conclusions & Discussion

As shown in Figure 25, in this chapter the finalizing phase of the research starts. First the conclusions from this research are given, and secondly, the scientific relevance, societal relevance, validity and limitations of the research are discussed. The recommendations part is described in chapter 8.

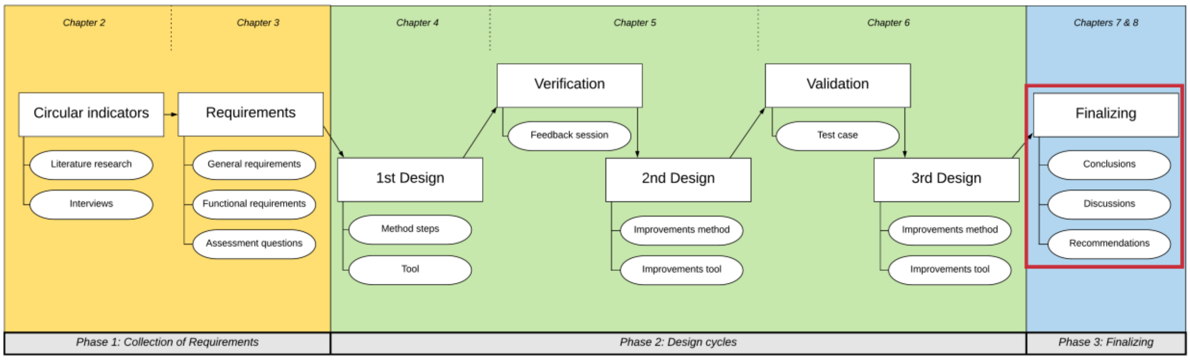


Figure 25: Research design: Chapter 7 & 8

7.1 Conclusions

The seven circular indicators that influence the ability of a concrete component to be reused 1 on 1, are the toxicity, condition, residual lifespan, connections, retrieval, design requirements and the dimensions. Each of these indicators has specific areas that influence the ability for a concrete component to be reused:

I. For the toxicity indicator, there is information about certain materials that are not desirable inside the concrete for certain materials. Some materials are only a problem if they are inside the concrete.
II. The NEN 2767 gives a general condition score, however there are some specific damage mechanisms which specifically influence the ability for a component to be reused.
III. There are multiple ways to calculate a residual lifespan, however they are all rough estimations. It is impossible to get a hard value to a residual lifespan, but these different methods can give good indications.
IV. Some types of connections are more easy to dismantle than other types. There is little information in literature and reports that can support which connections are more suitable for reuse because there is a lack of experience on the subject of reuse for infrastructure assets.
V. For the retrieval, the two main aspects that are relevant for reuse is the disassembly method and the way of transport. Just as for the connections, there is little information in literature and reports that can support which components are more retrievable than others because there is a lack of experience on the subject of reuse for infrastructure assets.
VI. An asset is designed according to a certain constructive design class, which says something about the loads which the asset must be resistant to. An asset is also designed according to a certain environmental class, which says something about which types of environments the concrete should be able to handle.
VII. Almost all infrastructure assets have been designed for a specific situation. A lot of not standard cast-in-situ components are used. Sometimes prefab components are used, but often those components are not fully standardized. There is little information in literature and reports that can support which dimensions are more suitable for reuse because there is a lack of experience on the subject of reuse for infrastructure assets.

Some currently existing infrastructure inspection regimes do take into account some parts of the mentioned circular indicators, but there is no inspection method that takes all of these indicators together into account to assess 1 on 1 reuse. However, some of the existing infrastructure inspection regimes can be integrated into the design of the new method, because they focus on 1 specific part which is also relevant for 1 on 1 reuse.

From all the functional requirements that were collected in the first phase, some were not included in the design of the method. The checking if certain materials are inside the concrete (materials that do not pose an immediate threat for 1 on 1 reuse and from which it is difficult to determine if they are inside the concrete), are not included in the design of the method, because it would cost too much time to inspect and assess that. Also, the constructive functional requirements have not been taken into account into the design of the method, because it is hard to assess those requirements on the component scale level.

The essential information which is required to be able to assess concrete components on 1 on 1 reuse is:

- Information about the presence of iron fibers
- Information about the presence of composite fibers
- Information about the general condition of the component
- Information about the ability to transport a component
- Information about the ability of the component to be disassembled without completely damaging the component

In the design of the new method, functional requirements of the seven circular indicators have been rewritten into assessment questions, and regrouped into three different categories in order to score the ability of a concrete component to be reused 1 on 1. The three categories are:

- Material Quality
- Disassembly
- Applicability

The data which is necessary for answering the assessment questions of the method, can be found in the specifications of an asset or can be retrieved during inspections on site. Each of these questions a score between 1 and 0 is given, in which a 1 is most optimal for 1 on 1 reuse, and a 0 is the least optimal for 1 on 1 reuse. Based on these individual scores, a score for the three categories can be calculated.

The method can easily be integrated within regular NEN 2767 condition inspections because it uses the decomposition according to the NEN 2767 as a basis, just like regular inspections. The method also uses the strong points of the NEN 2767 condition inspection and other existing industrial practices (the handboek ASR, the CRIAM, the CUR 117 and the CUR 121) to help assess the ability for a component to be reused 1 on 1.

The extra works, when compared with a NEN 2767 condition inspection, do not take a lot of extra time and can be executed relatively quickly. Therefore a quick indication can be given if 1 on 1 reuse is possible or not. The final scores that are given to a component are unambiguous and can be compared with each other, which makes it possible to compare multiple components with each other. However, the method works best if there is a sufficient amount of data available to answer the questions, if that is not the case there could be a lot of uncertainties in the scores.

It still seems difficult for an inspector to assess the components the same way. Although the room for the inspector's own interpretation is being limited by giving fixed answer possibilities, it seems impossible to completely exclude the own interpretation of the inspector. This happens because every inspector has a different level of knowledge and experience, therefore the results are not completely uniform. Especially when there are more uncertainties in the data, there is a higher chance that the inspectors own interpretations might differ.

To make the method operational, a guideline is written (Appendix N) and a tool is developed (Appendix O) to give practical guidance to the inspectors with the inspection and assessment of the concrete components. The tool is developed in excel, which is software that is accessible to most users. This makes it easy to use the method, which additionally increases the chance that the method will be applied. Also, from the validation sessions, it could be concluded that the standardised input and output interfaces of the tool are intuitive and easy to understand. The tool and method are flexible to change if future developments take place, the extra assessment question could easily be added to the method.

7.2 Discussion

In this part, the scientific relevance, societal relevance, validity and the limitations of the research are elaborated.

7.2.1 Scientific relevance

This research has resulted in the first scientific method that aims to assess a materials ability to be reused 1 on 1, based on literature, reports & interviews. Additionally, this research provides a tool to help perform this method. Because of the research on the circular indicators, there is now more insight on what relevant information is needed before concrete components can be assessed on 1 on 1 reuse. It also shows that there is a lack of scientific knowledge on how the connections, retrieval and dimensions indicator influence 1 on 1 reuse. Additionally, the following gaps in the literature are addressed by this research:

- Iacovidou & Purnell (2016) focuses on the identification and analysis of existing interventions that can promote the reuse of construction components. According to Iacovidou & Purnell (2016), on-site assessment of construction components is currently the only way to evaluate their physical performance and ability for reuse. There is guidance on theoretical reuse potential of construction components, but to achieve a successful implementation is difficult. More effort is needed to gain a better understanding of how reuse potential values should be clarified and to develop measures that associate reuse potential indicators with construction components during manufacturing and construction. This research also tries to fill in the gap described by Iacovidou & Purnell (2016) by developing a method that associates circular indicators with the assessment of concrete construction components to promote reuse of construction components.

- Reverse logistics in the construction industry is about aiming at controlling the flow of construction components that would otherwise end up in the construction/demolition waste stream, and effectively recirculating them back to the construction stage of a new project (Hosseini et al., 2014). According to Hosseini et al. (2014), the construction industry has not kept pace in reaping the benefits of reverse logistics compared to the manufacturing industry, because there is a lack of literature and consequently a lack of knowledge in the construction field. Hosseini et al. (2014) call for more studies focussing on regulatory aspects of the environments surrounding the reverse logistics system in the construction industry. This study is an addition to fill this gap described by Hosseini et al. (2014) by focussing on the 1 on 1 reuse on concrete components in the construction industry.

- Saidani et al. (2017) provided an overview of current ways to measure product performance in the context of a circular economy. As a result, the paper delivers a guideline for the design of frameworks that aim to measure circularity. Saidani et al. (2017) call for further works to contribute in providing new ways to measure product performance in the context of a circular economy. This research provides such a new way to measure product performance in the context of a circular economy on a specific part of the construction industry. It partly builds on the guideline which has been developed by Saidani et al. (2017).

7.2.2 Societal relevance

The Dutch government has the ambition to be fully circular in 2050 (The Ministry of Infrastructure and the Environment & the Ministry of Economic Affairs, 2016). In the context of this ambition two main goals have been formulated by the Dutch government, specifically for the construction industry to achieve that: 1) The construction industry must mainly use reusable materials, 2) The construction industry must be an innovative sector that pro-actively reacts to changes in society and changes in market and consumer demands. The new method can help organisations in achieving those goals. The new method can give organisations that manage infrastructure assets more insight into the possibilities to reuse concrete components 1 on 1. When there is more insight in a component's ability to be reused 1 on 1, it will be more likely that components are actually going to be reused 1 on 1. Additionally, if clients reuse components, this also creates more awareness for reuse in the construction industry. This could result in even more reuse in the construction industry because of a snowball effect.

More reuse of materials does not only help the Dutch government in achieving their goal to be fully circular in 2050, but it is also in line with the sustainable development goals which have been drawn up by the United Nations. It is especially in line with the fifth target of sustainable development goal 12, which is to ensure sustainable consumption and production patterns by reducing waste generations through prevention, reduction, recycling and reuse (United Nations, 2018). Companies might be interested in this method because it could help them in achieving these goals which are set up by Rijkswaterstaat and the United Nations.

7.2.3 Validity

A verification phase and a validation phase have been integrated into the design cycles to increase the validity of the research. In the first design cycle, the results from the literature research and from the interviews have been used for the design of the new method. In the second design cycle, this first design has been through verification by a feedback session. In this session, experts on the level of asset management and experts on the level of the circular economy have been invited, in which it has been verified if the specifications and assumptions that have been made in the first design of the method are agreed upon. Out of the verification of the first design of the method, a second design of the method emerged. During the third design cycle, the second design has gone through validation by a test case which has been performed by four different inspectors. From the results of these test cases, the method was validated and improved to assure that the method reaches a sufficient level of accuracy.

7.2.4 Limitations

There is made a distinction between two types of limitations; limitations due to time constraints and limitations to the method itself. The research encountered some limitations that would not have been there without time constraints. With more time more, people could have been interviewed in the requirements phase of the research. Although the same basic questions were asked to the interviewed people, they all had different levels of expertise. Therefore, if more experts where to be interviewed, possibly more information on some circular indicators would have been gathered, which could have resulted in a more complete list of functional requirements for the design of the new method.

Additionally, if there had not been any time constraints, the method could have been shown to and tested by more experts which would increase the validity of the research. The method also could have been tested on a larger number of cases. Because only one case is used for the verification and only one case is used for the validation, it is possible there are still some problems, that did not come to light with the particular case on which the method was tested. With more test cases and more design cycles, the validity would be increased.

Besides the limitations due to time constraints, there are also other limitations concerning this research. Namely, the Applicability category in the scoring of the method is sensitive to adjustments of the questions within that category. This is because of the fact that the category only consists of 2 questions. If the functional requirements for the design requirement indicator and for the dimensions indicator could be extended, the Applicability category would become less sensitive. In the recommendations chapter, ideas are given to extend the indicators.

There is no reference data to which the results of the new method can be compared to. Since there are no other methods yet that inspect and assess concrete infrastructure components, it is hard to compare the new method with other methods.

This research is only focused on concrete components in the Netherlands. In other countries, they could have different regulations regarding the use of concrete which also could mean that concrete needs to be assessed differently. The method is also only focussed on one material and only on single components. In the recommendations chapter, ideas are given to focus further research on other areas.

8 Recommendations

As shown in Figure 26, in this chapter the finalizing phase of the research is concluded.

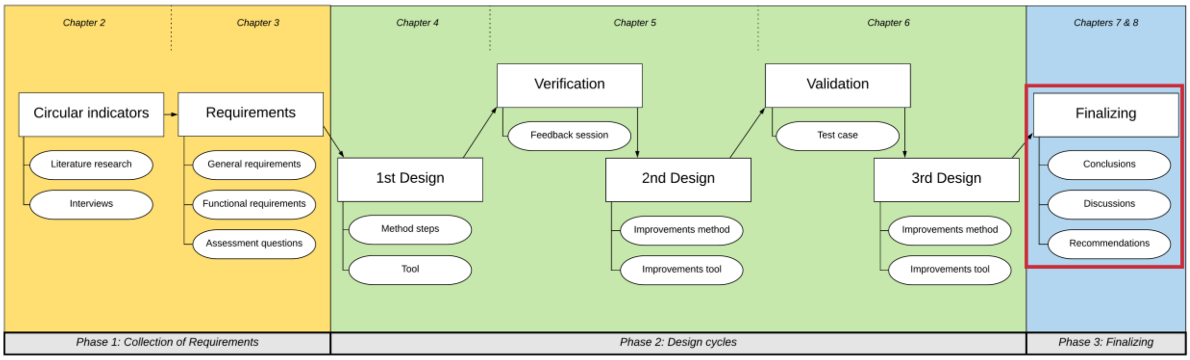


Figure 26: Research design: Chapter 7 & 8

In this chapter two types of recommendations are given. First, recommendations for further research are given, and secondly, recommendations for Witteveen+Bos are given.

8.1 Recommendations for further research

During the research on circular indicators, it became clear that for the connections, retrieval and dimensions indicators it was harder to find information on how they influence 1 on 1 reuse, than for the toxicity, condition and residual lifespan indicators. There hardly exists any theoretical research on these indicators, therefore more knowledge about these indicators should be collected by reusing more components and therefore gaining more experience.

Additionally, it is recommended to further develop this method. It could be developed further by including more design cycles and test cases which would improve the validation of the method. This method could also be furtherly developed by taking a better look at the relative weights of the functional requirements. In this research, it is assumed that all the questions are of equal importance in order to score the categories, but more research could be performed to establish weights for the specific assessment questions.

Furthermore, this method only applies to a specific material, scale and circular loop. Therefore more efforts could be invested in including a broader scope. There are multiple ways to achieve this:

- First, this research only focusses on concrete components. Such a method as is developed in this research could also be developed for other materials such as steel or wooden components, which are also commonly used in infrastructure assets. While some of the functional requirements that are also used for the design of this method could also be used for the assessment of other materials, also new functional requirements need to be investigated. Each material has specific damage mechanisms that could influence the ability for a component to be reused. I.e., ASR is a damage mechanism that only occurs for concrete components.

- Second, this method only focusses on assessing single components, while it could be the case that certain components are more suitable for 1 on 1 reuse if they are reused together as a whole. I.e., a whole bridge deck could be more suitable for 1 on 1 reuse than all the individual components separately. Probably there is not much adjustment needed to design a method that takes into account multiple components. However, there is the problem that if multiple components are assessed at the same time, it is also likely that multiple types of materials need to be assessed. Therefore research should first focus on how to assess other types of materials. What also possibly needs to be taken into account when assessing a combination of components is the constructive part. Does the combination of components still meet the design requirements regarding the distribution of forces?

- Third, the method only focusses on the 1 on 1 reuse loop of the circular economy and does not focus on other loops such as recycling or refurbishing concrete. This method could be used as a starting point to develop these methods, but probably not all the functional requirements for this method would apply to these other focus points. I.e., cracks in the concrete can negatively influence a components ability to be reused 1 on 1, but when a concrete component is being recycled through a crusher in order to make new concrete out of it, it does not matter if there are cracks in the component. The other way around, there are certain materials that do no harm if they are already inside the concrete, but they could negatively influence the concrete if the concrete is crushed to make new concrete out of it.

8.2 Recommendations for Witteveen+Bos

It is recommended for the asset management division of Witteveen+Bos to integrate this new inspection and assessment method into the regular condition inspections according to the NEN 2767, which are performed by the asset management division. The new method can help Witteveen+Bos and their clients to assess 1 on 1 reuse and consequently helps them with achieving the circular goals which are drawn up by the Dutch government.

It is easy for Witteveen+Bos to integrate the new method into the regular NEN 2767 inspections, because the new method uses the decomposition according to the NEN 2767 as a basis, and because the NEN 2767 is an important input for the new method. It would save more time to integrate this method within the NEN 2767 inspections than to perform both separately. However, if a NEN 2767 condition inspection has already been performed on an asset, this method can also be executed on its own.

Furthermore, there are some practical recommendations for the implementation of the method. The new method should be discussed with clients that could benefit from reusable components in their assets. By discussing this with the client, it forces the client to think about 1 on 1 reuse of components while they otherwise might not have considered it. If the clients are interested, they should be offered the assessment according to the new method as an extra service. By frequently applying the method next to regular inspections, a frame of reference is created.

The results of the method could be stored in a materials passport, which could be helpful to create a long-term construction planning based on reused materials. The Material Quality category is time-dependent, which means that the assessment should be updated once in a while. This can be updated with the same frequency as the NEN 2767 condition inspection is being performed. The other two categories (Disassembly and Applicability) are not time dependent. If these categories have been assessed once, the score does not change over time. Therefore, if a reassessment is taking place, only the Material Quality assessment questions need to be reassessed.

For the circular economy group of Witteveen+Bos, it is recommended to use this method as a baseline for further developments of assessment tools for circular performance in the infrastructure. The method is in line with the 3rd circular design principle of Witteveen+Bos; ‘Make sustainable use of existing objects, materials, resources and natural processes’. Therefore, it could help in the development of the circular design tool which the circular economy group of Witteveen+Bos is developing.

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Appendix A - The circular economy

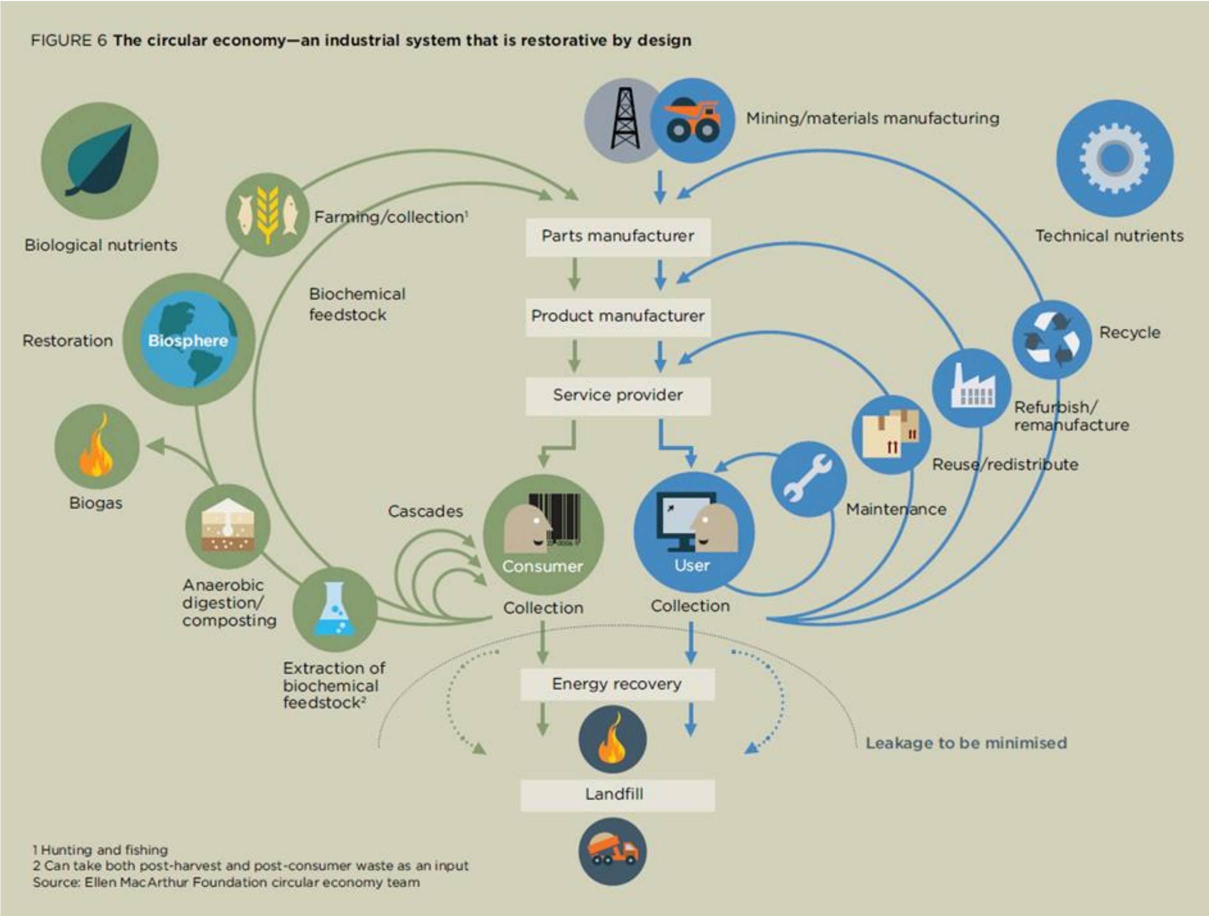


Figure 27: The circular economy (Ellen McArthur Foundation)

Appendix B - Reuse potential of materials

No Potential (0%)	Low (<50%)	Medium (~50%)	High (>50%)
Cay bricks (cement-based mortar)	Mineral wool	Steel cladding (buildings)	Clay bricks (lime-based mortar)
Steel rebar (buildings)	Gypsum wallboard	Steel cold formed sections (buildings)	Structural timber
Steel rebar (other infrastructure)	Steel rebar in pre-cast concrete (buildings)	Pre-cast concrete	Structural steel (buildings)
Steel connections	Structural steel (infrastructure)	State tiles	Concrete building blocks (with lime mortar)
Structural concrete (buildings)	Timber trusses	Timber floorboards	Concrete paving slabs and crash barriers
Asphalt (other infrastructure)	Concrete in-situ		Clay roof tiles
Asphalt roof shingles	Concrete fencing, cladding, staircases and stair units		Concrete roof tiles
Plastic pipes (water and sewage), roof sheets, floor mats, electric-cable insulation, plastic windows	Glass components		Stone paving
Concrete pipes and drainage, water treatment and storage tanks and sea and river defence units			Stone walling
Non-ferrous metal components (aluminium window frames, curtain walling, cladding, copper pipes, zinc sheets for roof cladding)			

Figure 28: Reuse potential of materials (Iacovidu & Purnel)

Appendix C - Topology system

Level 1 classifications	Description and example level 2 + classifications
1. Action	The physico-mechanical role of the component in its previous deployment, e.g. 1.1 structural (primary load bearing, such as beams or columns), 1.2 semi-structural (secondary load-bearing such as cladding, roofing), 1.3 modular (such as bricks, tiles), 1.4 functional (such as staircases, windows, lighting).
2. Material	The material from which the component is made, e.g. 2.1 concrete (plain or reinforced), 2.2 steel, 2.3 timber, and 2.4 glass. In each case, a quality would need to be specified, especially strength grade for the structural materials.
3. Deployement	The structural form or class in which the component was previously used, e.g. 3.1 domestic housing, 3.2 high-rise housing, 3.3 commercial, 3.4 industrial, 3.5 infrastructure.
4. Exposure	The environmental conditions to which the component has been subjected, e.g. 4.1 outdoor, 4.2 indoor, 4.3 marine, 4.4 chemical/corrosive, 4.5 high temperature. These conditions would be associated with quantifications (e.g. weather records, detail of chemical environments, Eurocode EN1992 exposure classes) where appropriate.
5. Loading	The loading history of the component, e.g. 5.1 static loading (live and/or dead), 5.2 fatigue loading, 5.3 impact or transient loading. Each would be associated with a quantification of the loading history where appropriate. For functional components, loadings might be expressed in other terms (e.g. electrical, traffic).
6. Recovery	The methods used to recover the component, e.g. 6.1 general demolition, 6.2 recognised demolition protocol, 6.3 component-specific recovery, 6.4. DfD/DfR/DfMA process. In each case, a likelihood of damage or contamination should be associated or specified.
7. Residual	The structural and functional properties of the component remaining, e.g. 7.1 dimensions, 7.2 structural capacity, 7.3 functional capacity. In each case, it should be specified whether the residual has been directly measured (and how) or inferred from nominal capacity adjusted for age, exposure and loading.
8. Connections	The capacity of the component to be connected to other structural and/or functional components and artefacts, e.g. 8.1 standard connections (bolt or dowel holes, recognized electrical/hydraulic/communications connector), 8.2 no connector (e.g. where component has been sawn from a monolithic connection, or otherwise removed from a non-disassemblable original connection).
9. Availability	Details of when and where a component is likely to be available, and in what quantity, e.g. 9.1 time arising, 9.2 place arising, 9.3 amount arising, 9.4 market maturity.
10. Generation	The number of times the component has already been reused, and whether the proposed new use would represent upcycling, recycling or down-cycling/cascading.

Figure 29: Proposed topology system (Iacovidu & Purnel)

Appendix D - Decision tree Witteveen+Bos

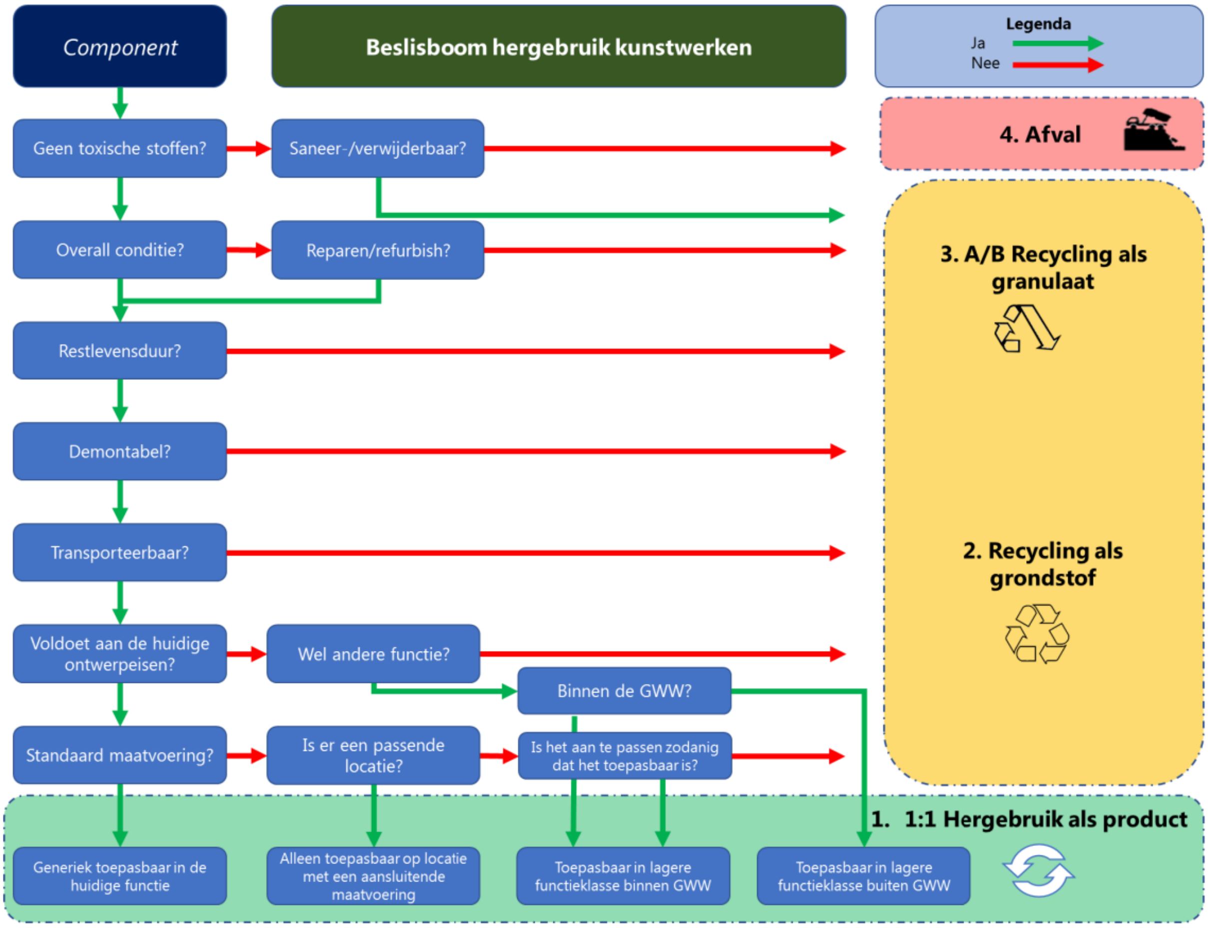


Figure 30: Decision tree for the reuse of concrete (Witteveen+Bos)

Appendix E - Selection of circular indicators

Before the inspections can be adjusted to focus on reuse of concrete components, it first needs to be determined which circular indicators need to be assessed to adjust the inspections to focus reuse and keeping in mind the demands of a circular economy.

Witteveen+Bos

Witteveen+Bos already has a little experience with inspecting and assessing infrastructure on its potential to be reused. In 2017, to prepare the planned demolition of the Boogbrug Vianen, a sustainability research for the reuse of the bridge was performed (Teeuw & Dijcker, 2017). The main focus for the project was to examine how the bridge can be demolished/disassembled in such a way that the components or materials can be used elsewhere.
For the decomposition of the bridge, the NEN 2767-1 was used as a basis. Then, all components were assessed on the following aspects:

- Condition; are there any defects?
- Fixation; how is it attached and is it dismountable?
- Standardisation; Is it a standard component with standard dimensions?
- Design directive; Does it still meet the requirements to fulfil its current function?
- Environment, health & safety; Does it still meet the current requirements for the environment, health & safety
- Opportunities; what are the opportunities to reuse the component?
- Barriers; What are the barriers to reuse the component?

After these aspects were assessed, different reuse scenarios were constructed and its outcomes were evaluated.

Also for the Prinses Marijkesluis, a similar research was conducted to examine its reuse possibilities (Hendrickx, Schutte Fischendick, Everling, & Hoogenvorst, 2018). The Prinses Marijkesluis requires large maintenance and Rijkswaterstaat already started with planning the maintenance and renovation activities. As a part of these preparations, Rijkswaterstaat wanted to investigate the possibilities in applying circular principles within the maintenance activities. 'Are there certain materials that become available and are suitable for 1 on 1 reuse?' was one of their questions. Therefore the same steps have been taken as for the Boogbrug Vianen.

The circular economy group of Witteveen+Bos has been developing a method on how to assess reuse possibilities for different concrete components. It is a decision tree, which is shown in Appendix A, in which different circular indicators are assessed with simple yes or no questions. The circular indicators that Witteveen+Bos are using are:

1. Toxic materials
   It could be the case that certain toxic materials are used in the production of the concrete, or that the concrete has been polluted because it has been exposed to external sources.
2. Overall condition
   The overall condition of the concrete says something about the physical quality of the construction. It is dependent of the loads which the concrete has had to deal with during its lifespan. Changing loads can cause deformation and cracks in the concrete, which influences the potential to reuse concrete components.
3. Residual lifespan
   It is necessary to know how long the residual lifespan for a concrete component is, to assess the

reusability of a concrete component. If the residual lifetime is too short, it might not be worthwhile to reuse a component.

4. Dismountable
   To be able to reuse a component, it should be relatively easy to dismount the component from the rest of the structure. This should be doable to dismount the component without damaging the component too much.
5. Transportable
   The concrete component should be transportable to a new location where it can be reused. If it is not possible to transport a component somewhere else, it will not be possible to reuse the component
6. Current requirements
   Before a component can be reused, it is necessary to know if the requirements of when the concrete component was designed still meet requirements of today. If it does not meet the requirements, the component might still be usable in another function with lower requirements.
7. Standardisation
   If a concrete component is standardised, the dimensions of the component are applicable in a lot of situations. This makes it is more likely that a component can be used elsewhere.

These circular indicators can be assessed to come to a certain outcome of how a concrete component can possibly be reused. There are four different outcomes possible as a result of the decision tree; 1) Reuse 1 on 1 as a product, 2) Recycle as raw material, 3) Recycle as granulate, and 4) Construction waste. This decision tree (Appendix D) is based on the knowledge within Witteveen+Bos, but it is only a rough outline and it lacks justification and quantification.

Iacovidou & Purnell

To investigate these circular indicators further, existing literature on the topic of reuse and recycling in the construction industry has been analysed. Iacovidou & Purnell (2016) have performed a research about the possibilities to improve the sustainability of the construction industry by reusing and recycling construction components and waste products from other industrial processes. A clear distinction is made between reusing and recycling; reusing indicates a process in which components are used again for the same function without demolition, recycling indicates a process in which materials are reproduced into raw materials for new products. Within the recycling process, a distinction can be made between a closed-loop recycle process if the component is recycled into the same component and an open-loop recycle process if the component is recycled into a different component (Thomark, 2000). The energy requirements which are needed for reuse are much lower than the energy requirements for recycling (Hosseini et al., 2014).

Two important factors play a role in determining a components potential after its primary life has ended (Iacovidou & Purnell, 2016). The first factor is the reuse potential. The reuse potential is a measure of the ability of a component to keep its functionality after the end of its primary life. Appendix B shows the reuse potential rate for a range of construction components. Because this rate is also dependent on cultural, historical and organisational aspects, they are rough estimations. The second factor is the embodied carbon (EC) reuse efficiency. The EC reuse efficiency metric gives knowledge of how much carbon can be saved if the component is reused. This is difficult to determine since it can depend on size, dimensions, energy mix, material design and recycle content. Both the reuse potential and the EC reuse efficiency are important in determining if it is worthwhile to reuse a component.

At the moment literature is unclear on how EC reuse efficiency should be measured for different components. Iacovidou & Purnell (2016) emphasise that clarifications in this area are needed to develop a common understanding on the way that assets are being managed regarding its EC reuse efficiency and that the development of a framework could contribute in the assessment of the reuse value of a component. Iacovidou & Purnell suggest that confidence in reuse could be achieved by a typology system that can assist contractors and designers in the selection and performance of reused construction components. This proposed typology system would focus on the properties of a component, the nature of the recovery process and the nature of the original use:

1. Action
   What is the physico-mechanical role of the component.
2. Material
   The material from which the component is made.
3. Deployment
   The structural form or class in which the component was previously used.
4. Exposure
   The environmental conditions to which the component has been subjected
5. Loading
   The loading history of the component.
6. Recovery
   The methods used to recover the component.
7. Residual
   The structural and functional properties of the component remaining.
8. Connections
   The capacity of the component to be connected to other structural and/or functional components.
9. Availability
   Details of when and where a component is likely to be available, and in what quantity
10. Generation
    The number of times the component has already been reused.

According to Iacovidou & Purnell (2016), on-site assessment of construction components is currently the only way to evaluate their physical performance and ability for reuse. There is guidance on theoretical reuse potential of construction components, but to achieve a successful implementation is difficult. Efforts must be made to gain a better understanding of how research potential values should be clarified and to develop measures that associate reuse potential indicators with construction components during manufacturing and construction.

Geldermans

To assess materials on their reuse potential, another set of properties which materials should fulfil to be able to facilitate circularity is published by Geldermans (2016). The properties are divided into two groups; intrinsic properties and relational properties. Intrinsic properties say something about the functional performance, the sustainability, the toxicity and the consistency with biological and technical cycles of the material or product. Relational properties say something about the dimensions, connections and performance time of the material or product. It is stated that neither intrinsic nor relational properties have decisive significance regarding circularity, but it is somewhere where these two properties cross where fulfilment regarding circularity is created. Conclusively Geldermans distinguishes seven data categories regarding assessing the circularity potential:

1. Exact composition of the material or product
2. Performance quality of the material or product
3. Intended re(use) path of the material or product
4. Performance time of the material, product component or service
5. Connections applied between materials, products or components
6. Dimensioning of materials, products or components
7. Quality of the registration system and process

Selected indicators

The typology system which Iacovidou & Purnell (2016) proposed, and the properties which are defined by Geldermans (2016) could help with determining the necessary aspects which need to be investigated in inspections, to help determine if it is possible to reuse a component, regarding the demands of a circular economy. In Table 6 the properties from Iacovidou & Purnell and Geldermans are connected to the circular indicators which have been proposed by Witteveen+Bos and slightly adjusted circular indicators have been set up.

Table 6: Selection of indicators

Circular Indicator	Witteveen+Bos	Geldermans	Iacovidou & Purnell
Toxicity	1	1	2, 4
Condition	2	2	1, 4, 5, 7
Residual lifespan	3	4	-
Connections	4	5	-
Retrieval	5	-	6
Requirements	6	-	7
Dimensions	7	6	8

The next part gives descriptions on what is taken into account in the created circular indicators, based on the indicators of Witteveen+Bos, Geldermans and Iacovidou & Purnell.

Toxicity
For this indicator, it needs to be checked if there are any toxic materials within the concrete components. It could be the case that certain materials are produced with toxic materials from which it is not allowed to use them anymore. Therefore it is relevant to know from which materials the component is made of and what the composition of the material consists of. It could also be the case that the component has been exposed to external toxic sources, such as chemical factories.

Condition
The condition says something about the physical quality of a component. Are there any damages visible on the component? What are the structural properties of the component? Therefore it is relevant to know the performance quality of the components. The physico-mechanical role of the component is dependent on the types of damages which are likely to occur on a certain component. The exposure

from forces which can be caused by traffic loading or the environment can influence the physical quality of the material.

Residual lifespan
The residual lifespan indicates how much time the component can still perform its function, also called the performance time.

Connections
To know how a component is connected to the complete structure is important information to be able to dismount the component.

Retrieval
The retrieval of the component is all about if the component can be recovered from its structure to a new location after its connections have been dismounted. Therefore it is relevant to know which methods are needed to recover the component and if it is possible to transport the component to a new location.

Requirements
The requirements for the construction an infrastructure asset could have been changed over the years. Therefore it is important to assess if the components of old infrastructure assets still meet the requirements of today. Are its functional properties still sufficient? If that is not the case, the components might still be useful in another function.

Dimensions
If a component is standardised, the probability that it is useful for reuse Is much higher than if the component was specially designed for the specific structure. Therefore information about the dimensions of a component is relevant in order to assess if reuse is possible.

The seventh indicator from Iacovidou & Purnell, the residual, is used two times in the created set of indicators. The residual says something about the structural and functional properties of the component remaining. In the created set of indicators, the structural properties are part of the condition indicator, and the functional properties are part of the requirements indicator. The residual indicator is used two times because it is split-up into those two indicators. Also, some indicators are probably very dependent on one another. For instance, if a component has a low condition, its residual lifespan will probably not be very high; and if a component has a high condition, its residual lifespan will probably not be very low.

Rejected indicators

Not all indicators from the literature are taken into account in the created indicators, the third, ninth and tenth indicator from Iacovidou & Purnell are not taken into account, and also the third indicator from Geldermans is not taken into account. The third indicator from Iacovidou & Purnell is the deployment, which says something about the structural form or class in which the component was previously used. Because this research only focusses on dry infrastructure assets, this indicator is fixed for this research. The ninth indicator from Iacovidou & Purnell is the availability, which says something about when and where a component is likely to be available, and in what quantity. This indicator is outside the scope of this research because this research only focusses on the assessment of how suitable a component is for reuse. If and when the actual reuse is taking place, is for the policymakers to decide. The tenth indicator from Iacovidou & Purnell is the generation, which says something about the number of times the component has already been reused. As long as the condition and the residual lifespan are being assessed, it does not seem relevant how many times the component has already been reused. The third indicator from Geldermans is the intended re(use) path. To decide where the component is going to be reused is out of the scope for this research, because this research only focusses on if certain components are suitable for reuse.

Appendix F - Interviews

Semi-structured interviews were held face-to-face among a selection experts. Each interviewee was asked how each indicator can influence a components ability to be reused 1 on 1, how the indicators could be measured or estimated, and if there are other important indicators regarding the reuse of concrete components. It was also asked how they are currently dealing with the circular economy, if they see any possibilities regarding the transition towards a circular economy in which more materials are reused, and what their own requirements are regarding such a transition towards a circular economy. The information that is collected during the interviews is summarised and structured according to the seven established circular indicators. Below the selected

- Interview #1: An inspector involved in a reuse assessment project at an engineering firm.
- Interview #2: An inspector & expert regarding residual life and constructive safety at an engineering firm.
- Interview #3: An asset advisor at a province & involved in the development of an IFD (industrial, flexible, dismountable) norm for infrastructure.
- Interview #4: An asset manager at a province.
- Interview #5: A constructor involved in a reuse assessment project at an engineering firm.
- Interview #6: A constructor involved in the development of a quick-scan to assess the structural safety at an engineering firm.
- Interview #7: An architect involved in a reuse assessment project at an engineering firm.

Interview #1

Toxicity

To find out if there are unwanted substances in the concrete, lab research is needed.
Blast furnace cement is much darker than Portland cement.
Steel fibres can be visually detected.
Composite fibres are hard to filter out of crushed concrete, so it is not desirable for clean concrete.
If the concrete is mixed with chloride it should not be reused.

Condition

With the NEN 2767, it is possible to assess defects.
ASR, chloride and carbonatation are the three main defects that are often encountered. Visually they are easy to spot.
If there is ASR in the concrete it should not be reused.
With low reinforcement coverage, there is a higher risk of corrosion. Right now the average coverage is 35 mm. It is possible to stop the corrosion process, but to do that a new preservation layer needs to be applied each 5 to 10 years.
Small defects can be repaired, but if there is a constructive overload it might not be worthwhile to repair the concrete.

Residual life span

In the past the designed residual life span was 50 years, now that is 100 years.
The residual life can be calculated through carbonation penetration.
The penetration depth of carbonation can easily be measured with drill samples. With the help of a simple formula, it is possible to calculate the residual life based on carbonation.

Connections
Beams and abutments can be connected by a pressure layer, this is difficult to disassemble. It is possible, but is it worthwhile?
If beams are connected to a plate with dowels, it is possible to disassemble them.
How components are connected can be seen in drawings. It can also be checked on site with help of mirrors if necessary.

Retrieval
About 30 tons is transportable by truck. 50 tons is allowed on the road, and the truck weighs about 15 tons. For anything heavier, special transport is required. Also for anything with a width of more than 2,5 meters and a height of more than 4,1 metres, special transport is required.
The route needs to be checked.
Usually, 2400 kg/m3 is used to estimate the weight of concrete.
Measurements can be taken with a land-measurer.
Abutments and other objects that are too heavy to transport can only be demolished. It is hard to separate them in small pieces and then connect them together.
Prefab components are usually transportable by road.
Stability of the component is also important.

Requirements
Prefab components are produced in ideal circumstances
The traffic class for which it is calculated is important.
Reinforcement properties information is necessary. Maybe from drawings, otherwise research in the field is needed.
Concrete is often much stronger than it is designed for.
For the exact calculation of strengths, destructive research is necessary.
Rebound hammer tests are unreliable.
When drill samples need to be performed, the aesthetic aspect is also important.
The concrete strength of prefab components is often well documented. This can be requested at the manufacturer.
There is different concrete for different environmental classes, this information may be stored, but to be sure a lab research is needed

Dimensions
Standardised components are not used much in infrastructure.
You can shorten beams, but you cannot divide them in 2.
Prefab components can be recognised when you look at the joints of the concrete. Sometimes it can also be possible to recognise eyebolts in prefab components. Cast-in-situ component scan be recognised by centrepins.

General
Costs to reuse can be of high importance.
In the past manhours were cheaper, but now materials are more cheap, so it is cheaper to just built something new.
Except for the actual safety, the perception of safety is also important. Therefore aesthetics also can be important.
Smart crushing is a new way of recycling.

Interview #2

Toxicity

Asbestos can be present in water drainage systems or in cable tubes which can be inside the concrete.
If research needs to be performed, sometimes an asbestos-free declaration is necessary.
Fibres can be visually detected.
Slags are used often in the cement. Every class of concrete has another cement. It is easy to spot the difference between Portland cement and blast furnace cement.
For the chemical composition, lab research is needed.
ASR sensitive concrete has also been used in the past.

Condition

With the NEN 2767, you can get a general assessment of an object, but it is not specific. More specific inspections are defined in the CUR 117.
With a potential measurement, you can measure corrosion of the reinforcement. Potential measurements can be a radical investigation. If there is corrosion, concrete can sound hollow.
Chloride and carbonation are very important because they can cause corrosion of reinforcement. If you know the penetration depth and if you know the depth of the reinforcement, you can calculate a residual lifespan based on that.
The penetration depth can be measured with drill samples.
Low concrete quality is often more porous and thus more sensitive to penetration.
If prestressed beams show cracks, I would really worry, then it is not necessary to look at reuse.
Most defects can be repaired but you want to know the cause of the defect.

Residual life span

The NEN 8700 constructive residual life calculation is demanded often if a residual life span calculation needs to be performed. It bundles a lot of different investigations. The outcome is not a strict number, but it gives a good indication.
Residual life based on the constructive element plays a part, but also based on the material.
It works on asset level and on component level.

Connections

If Beams are just stacked without a connection they can be reused. If they are connected with mortars and reinforcement it is more difficult, but not impossible.
Information from drawings is desirable. Sometimes it is possible to see visually.
How is it built is an important question.

Retrieval

Is a crane needed? Or aerial work platforms? Or scaffolding? Is it possible to place the equipment? Those are important questions.

Requirements

Information in the drawings regarding concrete and reinforcement properties can be assumed to be correct. You can do a verification of the reinforcement properties with scans.
Concrete strength increases over time, in calculations we assume design strength. In the lab concrete strength can be measured. Tensile strength is about 10% of tensile strength.
There are methods to meet the requirements if they are not met. i.e., decrease traffic intensity.

Lightweight concrete weighs about 500/600 kg/m3 lighter. Often used in tube bridges.
Based on the ridges on the reinforcement, it is possible to determine the manufacturer.
Prefab concrete most of the time is of a higher quality than cast-in-situ.
Rebound hammers are unreliable.
Ultrasonic pulse rate can be used to measure lengths.
Assets from the 60s and 70s have a lot of problems with shear problems

Dimensions
You can relatively easy spot if something is prefab or not. It is easy to spot eyebolts. It is easy to see sports from the formwork.
A beam loses its constructive function if you saw it in half.
Foundations are suitable for reuse on the same location.

General
Sometimes an old structure meets the requirements, but it is still cheaper to build something new.
There is also experimentation with different residual products inside the concrete.
Repaired concrete is not necessary of lesser quality than new concrete.

<u>Interview #3</u>

Toxicity
It is not a bad thing if there are toxic materials inside the concrete if it stays in the concrete, as long as it does not affect the properties of the concrete negatively.

Condition
There are still shear problems with some old bridges.
You are not inspecting your asset every day but only when a defect is observed.
There is a lot of data about the physical state of an object. Every 1, 3 or 5 years there is an inspection and that information is publicly available in inspection reports.

Residual life span
This is also part of the NEN 2767.

Connections
Bridges are not built to be dismounted, which make reuse difficult.
With concrete, there is almost always a pressure layer or mortar which needs to be chopped away. Also, the reinforcement is often connected. Maybe there are a few situations without a pressure layer.
Cyclist tunnels are often built with separate elements that can be dismounted. Curbstones and paving stones are also easy to dismount.
Large cast-in-situ works are almost impossible to dismount and are very expensive.
It is more easy to disconnect a bridge as a whole, than all components apart from each other. A bicycle bridge is often 1 beam and could be reused as a whole.
We work on a norm for IFD building. These are guidelines of how the interfaces should be. It is possible to assess if current infrastructure assets meets the new requirements.

Retrieval
Prefab beams are also transported to the site, so it should also be possible to transport them back. That is not the case with cast-in-situ. It is expensive to cut out a block out of cast-in-situ concrete in order to transport it.

Requirements
Concrete gets more strong when it gets older.
You want to know how strong it is. What is inside the concrete? What kind of reinforcement?
There are three classes for traffic intensity, these classes have been formed in the 80s. the first class is the really small rural bridges, the second class is about 90% of all bridges. The third class is for the really big assets with a high risk.
There should be information available for most bridges according to which requirements they were designed.

Dimensions
Mostly a bridge does not fit somewhere else because its tailor made. There should be a shift in culture to use components that do not precisely fit. Reuse in other functions is almost not possible.
There could be some elements that are suitable for reuse: impact plates, curbs, wing walls, sheet pile boards. The smaller manufacturers stuff. Bicycle tunnel elements can also be reused, although they often have different dimensions.

General
It is much more expensive to cut out concrete than to make new concrete.
Some owners are conservative to changes.
Middle management and engineering firms are afraid of modular building because they are afraid to lose work.

Interview #4

Toxicity
Concrete should not be used as a waste bin. You could investigate the composition of the concrete in the lab. You could also check if the information is stored, but not everything is stored properly.
If a bridge is well maintained, but it is full of chlorides, it is not suitable for reuse.
Chrome 6 is inside the cement, but when it is in the concrete it is not a problem.

Condition
The NEN 2767 is a visual inspection. If a defect is observed, the damage mechanism may have been there for a while. Chloride and carbonatation should actually be measured. Maybe you should know more than just the look.
When the asphalt layer sounds hollow when you knock on it, it can be a sign of reinforcement corrosion. With drill samples, it is possible to know for sure.

Residual life span
In the past, we had some calculation rules to calculate the propagation of the concrete and make an estimation of the residual life based on that calculation. That seemed to be very inaccurate. They are in the CUR 172.

Connections

It depends on the construction method.
Is normal reinforcement used or are prestressed cables used? If the cables are prestressed, then it is hard to chop into pieces.
It might be possible to saw a plate including pressure layer, that is a lot of effort.

Retrieval
The transport route is important. The needed permits are important
Beams that have been transported to the site can also be transported away from the site.
A component should stay stable during lifting, there are ways to strengthen the component during lifting if that is necessary.
Every bridge is unique, also in ways to dismount and transport. Everything can be moved, but has its price.

Requirements
We have some slim designed bridges which are class 30. Reuse is difficult for those. It is difficult and expensive to demonstrate a sufficient level of structural safety for reuse. To know for sure, destructive investigation is needed.
The CRIAM is an assessment for structural safety.
You could make bicycle bridges from car bridges.
Concrete gets stronger over time.
There is a CUR for lower governments to get quicker calculations than according to the NEN 8700.
In the 60s 70s 80s a lot of really slim bridges were designed.

Dimensions
Information could be in drawings. If that is not the case dimensions are easy to measure.
Standard components are not really used in infrastructure. There are certain beams which are used a lot, but they still differ in the reinforcement layout. Most industries keep the data of their prefab elements.

General
I see a lot of potential in building new bridges correctly.
Most bridges are replaced when a new function is desired. If that is the case, you could reuse a bridge in a good state
Maybe a concrete depot should be considered to make it available to everyone that needs it.
There needs to arise an incentive to handle your assets circular.
Maybe you should assess assets according to some kind of decision tree.
If you cannot calculate a bridge according to the requirements, but you do not see any defects, most of the times the inspection frequency just goes up.
I would like to know some recommendations for passport information.

<u>Interview #5</u>

Toxicity
In the ’70s there was a period of poor prefab concrete. There are periods that asbestos is used. There are periods that quick hardener is used, this increases the chances of carbonation. There is a period of degradation because of ASR. These thing does not necessarily mean that is not sufficient, but there is a higher risk.

Condition
NEN 2767 gives a general indication of defects.
If there are major cracks visible then something is wrong.
If there are shear problems a construction can be strengthened.

Residual life span
Unwanted materials and condition determine the residual life.
The CUR 172 tried to give residual lifespan an exact value, but that was inaccurate. There is a lot of uncertainty in the calculation of residual life spans. Despite the calculations, the advice is always to keep inspecting.
The designed residual lifespan now is 100 years. There also has been a period of 80 years. But such a number is not a good indication for the actual residual lifespan.
The degradation of the concrete will be the main factor for the residual lifespan. How porous is the concrete? How much chloride penetration? .
It is better to look at the condition than to estimate the residual life.

Connections
If a component is modular it is easier to dismount
To dismount in small pieces, a bridge deck with beams is easier than cast-in-situ. Unless it is possible to dismount the bridge as a whole.
It is not possible to visually inspect every connection, sometimes there is equipment to help you with this, but drawings are also relevant. Drawings are needed, if these are not available, destructive research is needed.
It should be possible to remove the pressure layer in pieces and connect them elsewhere with another connection layer, but this demands some creativity. This has (almost) never been done before.
Pre-stress that is attached inside the concrete cannot be dismounted. Pre-stress that is inside a casing could be removed and stressed later on, but that is far-fetched.
The disassembly and reuse of pre-stressed components do not have a high chance to succeed.
Important questions are: is the component prefab or cast-in-situ? What is the type of pre-stress that is used?

Retrieval
The weight of the component is important, to determine the type of crane. Also, the reach of the crane is important, to determine the type of crane. Also, the surface on which the crane stands is important.
The transport route is important. Over the road or over water? If you know how components got there, you know how they can get back.
For the weight of reinforced concrete, we usually calculate 2500 kg/m3. If there is a lot of uncertainty about the weight, it is possible to weigh the bridge by pushing it up with oil pressure.
The stability of the component can be assessed when looking at the building method.
Demolition is easier than reuse because components can be transported in smaller parts.

Requirements
Fatigue is a really difficult matter because the outcome is probably that the bridge cannot be used anymore, while it probably still can be used. To calculate fatigue you need to know the history. These estimations are very conservative and thus gives a high likelihood that a healthy component is being rejected.
In the past, there were traffic classes 30, 45 and 60. From the 40s till around 2000. At the moment almost everything is calculated according to the highway class. So everything that is 10 years old meets

the correct requirements. The old 60 meets those requirements, 45 also could meet the requirements, 30 is difficult.
You can easily make a bicycle bridge out of a car bridge.
Without the calculation that is performed, it is difficult to determine the class. Sometimes it is on the drawings but not always.
In the RBK, there is a guidance for strength and reinforcements.
The ROK give demands for new build structures.

Dimensions
You should look at passage width, road layout, type of bridge.
You can see if something is prefab or cast-in-situ by looking for seams.
There is also a lot of repetition in prefab components. There is a lot of repetition in beams, box girders, full-loaders. But they are all project specifically made. For reuse look for repetition. In prefab there is the most potential for reuse.
Also in the smaller components there is a lot of potential. Although it might look ugly because everything will look the same.
Make 2 beams out of 1 beam is not possible because of the course of the pre-stressed reinforcement.

General
It is also possible to design an asset based on what materials are coming available.
You should have a client that is prepared to invest extra money for reuse.
A quick-scan in an early stage could be very useful. Then you can create an overview and you make it measurable. This increases the chance of reuse.
Clients should be prepared to take a risk.

<u>Interview #6</u>

Toxicity
-

Condition
It is possible to test the effects of chlorides and carbonatation with help of drill samples or potential measurements.

Residual life span
To calculate the residual lifespan, a drill sample is taken, and the chloride and carbonation penetration is measured. This result is exploited to an expected residual lifespan.

Connections
Prefab beams are often monolith connected. It is necessary to remove the layer on top.
It could also weaken a component if it is dismounted, it can be hard to not damage the component.
If it is weakened it could be used in a lower function.

Retrieval
Beams are easier to transport than monolith decks.
A bicycle bridge deck of about 4 metres is about the maximum that can be transported by the road.

Requirements
CRIAMS have risk models based on experiences from the past.
Before 1975 shear problems were not an issue, so every infrastructure asset before 1975 is suspicious.
If you apply a bridge in a lower class, shear problems are not the case.
New objects should all comply according to the lm1 (load model 1) class, which looks like old class 60. Since a short time, there is also an lm1 light for small bridges in the province and inner cities, which looks like old class 45. 60 almost always complies, 45 most of the time complies, for 30 it is uncertain if it complies if used in the same function. Use something in a lower class than it is designed for should not be a problem at all.
There are calculation rules to estimate how many tension changes an asset can handle. Smaller bridges have a smaller chance of fatigue problems. If estimations are necessary they are very conservative. This is described in the RBK, which describes what constructively needs to be assessed. In the end, extensive constructive calculations are needed to show structural safety, that can be difficult.
In the past lightweight concrete was used, if that is the case reuse is not possible. It is hard to determine hard figures on in what year certain concrete, for instance lightweight concrete, is used. In the same periods, a lot of different concrete is used.
For building new structures, other requirements apply than for existing structure, because existing structures have already proven themselves. If you reuse existing components, it should meet the new requirements.

Dimensions
The biggest potential is in prefab elements.
For cast-in-situ, a nearly identical situation is required.

General
There should be a constructive header among the indicators. In which you can test strength and fatigue. Although there is some overlap with the condition.
It creates a better perspective for the future if we make materials dismountable from the beginning.
If you zoom out this problem seems simple, but when you go deeper it gets more difficult. Your subject is difficult, relevant but difficult.

<u>**Interview #7**</u>

Toxicity
This is good to take into consideration because it is also about health.

Condition
-

Residual life span
Are condition and residual life span not the same?

Connections
This is very important. Detailed drawings should be examined to check how something is connected. It can be verified with inspections.
Concrete with concrete is often connected with mortars. If concrete is connected with steel it could be connected with bolts.

Retrieval
Transport and it is emissions are also important regarding circularity.

Requirements
Everything is designed for a certain strength, so you cannot just reuse it in another situation.

Dimensions
It is hard to reuse components in other functions, because it is likely that you get an over-dimensioned bridge. In construction rules of thumb are used to calculate the required dimensions for a certain span. You can also use those rules the other way around.
Concrete beams are almost never used in housing construction, but they can be used for office buildings to create a space in the ceiling for installations. The infrastructure and real estate construction often have separate manufacturers. A grid size between the 7 and 10 meters could be useful in the utility construction.
In a previous project, I estimated that a double T beam could be used as a lift shaft.
Beams and plates could have a potential for reuse.

General
I do not know if it is better for circularity to 1 on 1 reuse or to recycle components.
You should take a look at where a component could possibly be reused.
I never got the direct assignment to design with reuse in mind. If you design with reuse in mind you often go over budget. Also as a designer, you want to create a local identity.

Appendix G - Infrastructure inspection methods

First existing infrastructure assessment methods are investigated. There is taken a look at the CUR 117, CUR 172, CRIAM and an investigation which has documented in the report called Kunstwerken in Control (Provincie Zuid-Holland, 2011). The NEN 2767 and the NEN 8700 are also two relevant assessment methods, but they are already elaborated on in the previous chapter.

This appendix gives a more extensive description of the infrastructure inspection regimes that have been analysed. At the moment the current infrastructure inspection regimes do not take into account reuse of components at all. However, there are some points from the existing methods which can be taken into account into the design of the new method.

NEN 2767

Currently, condition inspections of assets in the Netherlands are performed according to the NEN-2767 standard. The NEN-2767 is the standard for the condition assessment which ensures objective and uniform measurements of the physical quality of construction and installation parts of buildings and infrastructure. (NEN, 2018) It measures the technical condition of an asset with help of some kind of checklist. The goal of the NEN-2767 standard is to make sure that the technical condition of an asset can be mapped in a uniform way so an easy comparison can be made between the different conditions of the assets. Each asset gets a certain condition score which can range from 1 to 6 (Table 7).

Table 7: NEN 2767 Condition scores (Normcommissie 351264 “Conditiemeting,” 2017)

Condition score	Description	Explanation
1	Excellent condition	Incidental minor failures
2	Good condition	Incidental beginning deterioration
3	Acceptable condition	Partially visible deterioration, performance of asset not in danger of failing
4	Poor condition	Incidentally asset performance in danger of failing
5	Bad condition	Deterioration is irreversible
6	Very bad condition	Technically ready for demolition

This condition score is useful for setting up a long-term maintenance plan for the different assets. The NEN-2767 standard is useful to assess the technical condition of an asset. However, it is not designed to assess if certain components can be reused again.
The NEN 2767 assumes that there are 3 levels of decomposition. The three levels are 1) object 2) element and 3) component. For each component, a condition score can be calculated.
The NEN 2767 condition score is calculated with 3 different parameters;

1. Severity
   Severity determines the extent to which the defect influences the component. The severity is depended of the kind of defect. There is a large defect list in which all possible defects are described, and in this list the severity of the defect is stated. The inspector must recognise the specific defect on site. There are three levels of severity: small, serious and severe.

2. Size
   Size determines how much of the component is covered with the defect. The inspector must estimate the size on site. There are five levels of size: <2%, 2%-10%, 10%-30%, 30%-70%, ≥70%.
3. Intensity
   Intensity determines the stage of degeneration of the defect. The inspector must estimate the intensity on site. There are three levels of intensity: early stage, advanced stage, final stage.

For each of severity score, a different matrix is constructed in which the size and intensity are the parameters. From those matrices it is possible to read the corresponding condition score, the possible scores are shown in Table 8.

Table 8: NEN 2767 Condition scores based on severity, size and intensity

Geringe gebreken					
Omvang Intensiteit	1) Incidenteel (< 2 %)	2) Plaatselijk (2 % tot 10 %)	3) Regelmatig (10 % tot 30 %)	4) Aanzienlijk (30 % tot 70 %)	5) Algemeen (≥ 70 %)
1) Beginstadium	1	1	1	1	2
2) Gevorderd stadium	1	1	1	2	3
3) Eindstadium	1	1	2	3	4

Serieuze gebreken					
Omvang Intensiteit	1) Incidenteel (< 2 %)	2) Plaatselijk (2 % tot 10 %)	3) Regelmatig (10 % tot 30 %)	4) Aanzienlijk (30 % tot 70 %)	5) Algemeen (≥ 70 %)
1) Beginstadium	1	1	1	2	3
2) Gevorderd stadium	1	1	2	3	4
3) Eindstadium	1	2	3	4	5

Ernstige gebreken					
Omvang Intensiteit	1) Incidenteel (< 2 %)	2) Plaatselijk (2 % tot 10 %)	3) Regelmatig (10 % tot 30 %)	4) Aanzienlijk (30 % tot 70 %)	5) Algemeen (≥ 70 %)
1) Beginstadium	1	1	2	3	4
2) Gevorderd stadium	1	2	3	4	5
3) Eindstadium	2	3	4	5	6

With the NEN 2767, it is possible to assess defects. The NEN 2767 results in a general assessment of an object, but it is not specific. It is a visual inspection, so if a defect is observed, the damage mechanism may have been there for a while (interviews).

Handboek ASR

The Handboek voor orienterende inspectie ASR (Rademaker, 2002) gives a guideline to easily and visually justify the suspicion of the presence of ASR. The outcome of this guideline only says something about a suspicion. To know for sure is ASR is present, a laboratorial research of drill samples needs to be performed. With the instructions in the guideline, any inspector should be able to assess if the observed defect has been caused by ASR without a need for a destructive investigation and without hindering the traffic.

First, it is useful to determine if the concrete is based on blast furnace cement or on Portland cement. The chance of ASR development in concrete based on blast furnace cement is much lower than in

concrete based on Portland cement. It is not always known which cement has been used, sometimes a green/blue like colour on the surface can point towards blast furnace cement, but it does not always give an answer. The kind of cement can also be assessed with the help of a field test. By adding a drop of 10% hydrochloric acid on the concrete, the cement reacts with the substance. If there is slag inside the cement, the hydrochloric acid reacts with the slag. Then the gas H2S releases from the reaction which smells like rotten eggs. If that is the case, then there is probably dealt with blast furnace cement. Apart from the cement that is used, the age of the asset is also important in the assessment of ASR in the concrete. ASR often only shows itself after 5 to 10 years, however there are also forms of ARS which develops after 70 to 80 years.
Only when enough information is collected, the visual inspection starts. There are 4 sings which can indicate the presence of ASR during visual inspections:

1. Expansion and deformation of the concrete

Although it is difficult to observe expansion of the concrete, there are some observations which can indicate expansion as a result of ASR, assuming that there are no design and construction flaws.

- Expansion joints that are clogged up
- Joint profile that is pushed out of the expansion joint
- Unusual misalignment of the supports
- The side of the deck is no longer aligned with the side of the land abutment
- Unusual bends in other structural parts

The above observations can be a result of ASR, but it is possible that there are other causes.

2. Cracks on the surface of the concrete

- Often the sign of cracks in the surface is the first sign of the possible presence of ASR. Cracks that are caused by ASR. Cracks that are caused by ASR are never evenly distributed over the surface, they are inhomogeneously anisotropic and sometimes described as a ‘map pattern’.
- If cracks have been repaired in the past by injecting it with some kind of injection resin, it is possible that an ASR reaction causes the cracks to expand more widely.
- Dark edges around the aggregate material can be a sign that the aggregate material has been a part of the ASR reaction within the concrete. This can be observed with microscopic research in the lab and with field research. By using a potassium iodide solution the dark edges around the aggregate material can be made more clear. Also, the edges around the cracks can get a brown or purple like colour because of ASR, although these observations can sometimes be misleading, because cracks in the conservation can also discolour by contamination that looks like ASR.
- When the alkali-silica reaction is still active it is also possible to observe a movement perpendicular to the surface by rubbing with the fingertips against the small cracks.

3. Presence of alkali silicic gels

- The gel is located in the cracks
- The gel has a white, sometimes yellow, glassy colour.
- The gel is soft and can be pressed with a sharp object.
- When the gel dries out, cracks can become visible at the surface of the gel.
- The gel can expand through the pores of the concrete which can cause drops.

4. Pop-outs of concrete pieces

Because of extreme swellings of the gel within the concrete pop-outs can be observed in the concrete. The size of these pop-outs can vary from a few millimetres to around 15 millimetres.

NEN 8700

Based on the NEN 8700, the residual lifespan of an asset must be at least 15 years. Most infrastructure assets are designed with a life span of 100 years, so after 85 years only 15 out of the 100 years are left. This requirement is commonly used with infrastructure owners, although the NEN 8700 advises taking a minimum lifespan of 30 years into account.

The NEN 8700 is a standard for the assessment for the safety and usability of existing structures. This assessment is typically applied if
1) repairs are required,
2) adjustments, expansions or renovations are required,
3) change in use, loads or the surroundings are applied,
4) the end of the designed lifespan has been reached, and
5) there are signs of insufficient construction strength.

The NEN 8700 can assess
1) if the construction of an existing structure part or complete structure has a sufficient level of sustainable safety and usability,
2) if an existing structure has a certain performance level regarding the sustainable safety and usability, and
3) if an existing structure part or complete structure needs to be disapproved regarding the structural safety.
(TNO, 2015) The first step in assessing the current situation, is to collect a lot of information about the use of the structure. The second step is to perform a technical investigation if there is not enough information to perform the calculation of the structure. This investigation can include the uncovering of foundations to determine the properties of the reinforcement, or the measuring of the amount of chloride. The third step is the calculation. Based on the requirement and load combination specified in the NEN 8700 and on the desired residual lifespan, the calculation is performed. If the outcome of the calculation is not sufficient there are three options;
1) another safety level needs to be pursued,
2) more technical investigations are needed to reduce uncertainties in the calculations, or
3) measures need to be taken to improve the structural safety.
The information which is necessary for the calculation is information about the geometry, material properties, loads and current condition (cracks, deflections, discolouration). Sources for that information are; contract specifications, drawings, codes and results of additional measurements and inspections. However, information from contract specifications and drawing must be handled carefully because there can be a lot of possible deviations from the actual situation. To use that information without verification is only allowed for non-critical parameters on which there is no suspicion of possible deviations.

For the constructive part, the NEN 8700 residual life span calculation is demanded often. It bundles a lot of different investigations. It is a pretty extensive calculation which can include a lot of assumptions (Interview). A residual life span only gives a good indication and is not a hard number. There is a lot of uncertainty in calculations of a residual life span. Despite the outcome of the calculations, the advice is always to keep inspecting.

CUR 117

There is a need for uniformity and unambiguity in 1) procedures, 2) rules and requirements regarding work activities and 3) the goal and minimal level of reporting. The CUR-recommendation 117 gives procedures, rules and demands for the inspection, advice and assessment regarding the management of infrastructure assets and technical installations. The CUR-recommendation 117 wants to realise the following goals (SBRCURnet-commissie 1715, 2015):

1. Create awareness in maintenance and management
2. Make sure the roles and responsibilities for the client and contractor are clear
3. Handle resources efficiently
4. Secure the quality and safety of assets and meet the laws and regulations
5. Secure the quality and depth of inspections, assessments and reports.
6. Ensure a safe way to inspect and advise.

Different inspection- and advice categories have been set up for which these goals can be achieved through the procedures of the CUR 117, these are summarised in Table 9.

Table 9: Summary of CUR 117

User safety	Current state	Future state	Special information requirements
A1 - Look	B1 - Inventory	C1 - Risk analysis	D1 - Investigation material properties
	B2 - Condition inspection	C2 - Long-term maintenance planning and budget estimation	D2 - Sophisticated financial validation
	B3 - Contractual pre-assessment	C3 - Constructive reflection	D3 - Verification calculation
	B4 - Contractual end-assessment	C4 - Analysis residual lifespan	D4 - Monitoring
	B5 - Recovery advice		

Each category has its own requirements which need to be followed.

CUR 172

According to CUR 172 to manage concrete constructions there are 4 steps that need to be taken into account.

- Make an inventory
  - Select the necessary and useful data.
  - Systematically register fixed data.
- Inspect
  - Prepare which, when and how to inspect the components.
  - Execute the inspection by making sure the site is accessible, observe and measure the right data.
  - Document the results properly
- Analyse and advice
  - Diagnose what has caused the current situation
  - Make a prognosis about the situation if nothing changes
  - Generate options and their consequences for further steps
  - Choose the best option
- Maintain (if necessary)
  - Prepare a budget while taking into account other priorities

- Establish further activities and costs
- Execute a tender procedure
- Make sure the execution of the works lead to the desired result
- Deliver the end product with sufficient quality
- Register the new situation

The first step to make an inventory is a step that needs to be performed one time. Step two to step 4 need to be performed in a cyclic manner.

CRIAM

The CRIAM stands for Constructive Risk Index Assessment Model. To determine constructive risks in concrete structures through calculations can be very expensive and time-consuming, therefore the CRIAM is developed (A. de Boer & Booij, 2012).

In the CRIAM there are three main parameters: the completeness of the archive, the change of use and the current state of the object. These main parameters all get a score between 1 and 3, in which 1 is no risk, 2 is a moderate risk and 3 is a high risk. The summation of these parameters is indicated with the letter A.

Then there are the secondary parameters, these are a large number of sub-aspects of the main parameters. The scores of the properties of the concrete and the reinforcement are pretty much the same. The aspects regarding the traffic loads are important, as well as the aspects regarding the lanes. The most important defects are the forming of cracks and chloride penetration as a result of de-icing salts. The summation of these parameters is indicated with the letter B.
The total score of the object is a multiplication of A x B. If this score is lower than 54 the risk is low, and if the score is higher than 80 the risk is high.

Table 10, Table 11, Table 12, Table 13 and Table 14 show some interesting risk scores for certain parameters which are used in the CRIAM.

Table 10: CRIAM score for changes in lane use

Changes in lane use	Score
No lane change	0
Small lane change	1
Mediocre lane change	2
Large lane change	3

Table 11: CRIAM score for distance to edge

Distance to edge	Score
< 0,8 m	3
0,8 m < d < 1,4 m	2
> 1,4 m	1

Table 12: CRIAM score for changes in traffic

Changes in traffic	Score
No changes	0
Small changes	1
Mediocre changes	2
Large changes	3

Table 13: CRIAM score for construction year

Construction year	Score
< 1974	3
1974 - 1995	2
> 1995	1

Table 14: CRIAM score for crack width

Crack width	Score
No crack	0
< 0,2 mm	1
< 0,5 mm	2
> 0,5 mm	3

In the period before 1974, as confirmed by interviews, shear problems were not taken into account in the norm for concrete constructions, and in 1995 there were some adjustments in this norm. That is why separation is made between those construction periods in terms of risks, as is shown in Table 13.

Still, it is likely that important information is missing, this is also taken into account in the CRIAM, which is why according to the CRIAM lot of assets do not score a low risk. However, the CRIAM results in a less time-consuming assessment method of constructive risks in comparison with extensive calculations. Also, the CRIAM scores have been validated based on recalculations, which makes it is a proven and accepted method to assess constructive risks in a uniform way.

Kunstwerken in control

In Kunstwerken in control, the Provincie Zuid-Holland (2011) has performed a research on the structural safety of her infrastructure assets. In the research, it is assessed if the infrastructure assets meet the minimal requirements. Based on inspections it is determined if the infrastructure assets have enough strength for the daily traffic loads which the infrastructure assets have to deal with. To assess if there is a risk regarding the structural safety of an infrastructure asset, five questions asked. These 5 questions have been answered with help of inspection rapports, inspection photos, construction drawings and calculations from the operational archive.

1. Is the asset older than 85 years old?

Based on the NEN 8700, the residual lifespan of an asset must be at least 15 years. Most infrastructure assets are designed with a life span of 100 years, so after 85 years only 15 out of the 100 years are left. This requirement is commonly used with infrastructure owners.

2. Are there signs of shear problems?

Infrastructure assets before 1975 are not designed according to the current design standards. These infrastructure assets can possibly be constructed without being tested on possibly required shear reinforcement. Aspects which have a possible influence on this are; year of construction, type of bridge deck, slimness, loading and prestressing. To determine if these factors can cause any possible danger, three questions have been set up:

a. Gives the slimness calculation a reason to assess the infrastructure asset further?

The slimness is the length of the bridge deck divided by the thickness of the bridge deck. If this value is larger than 19, then a hand calculation needs to be performed.

b. Indicate the results from the hand calculation a possible thread?

The allowable shear stress is based on concrete class B45. With a so-called unity check, it is checked if the calculated shear stress is larger than the allowable stress, the calculation must be performed more detailed.

c. Indicate the results from the detailed calculation a possible constructive thread?

The true concrete strength must be determined with help of drill samples. With data from the samples, a more detailed unity check can be performed.

3. Did the infrastructure asset receive another function?

If the function of an infrastructure assets has changed, it is also possible that the loading which the infrastructure asset has to bear has changed. Therefore it needs to be determined if the function has changed, if the infrastructure asset has been adjusted because of the change in function, and if the change in function also changed the load on the infrastructure asset.

4. Are damages visible with potential constructive consequences?

Based on the opinion of an expert, it has been determined if the damage is located in a place where there is a thread to the constructive safety of the infrastructure asset. In particular, there is taken a look if there are any damages which decrease the protection of the reinforcement. Unprotected reinforcement can cause corrosion.

After the damages have been determined, the damages are taken into account into the calculations of the unity check. Again, first a hand calculation is performed and if the infrastructure asset is rejected based on the hand calculation, a more detailed calculation is performed.

5. Are there signs of an alkali-silica reaction (ASR)?

An alkali-silica reaction can be recognised by the appearance of horizontal crackle formation in the concrete. It needs to be determined if the ASR is located in a place where there is a thread to the constructive safety of the infrastructure asset. Most of the times it is located at the sham sides of infrastructure assets, which does not threaten the constructive safety. If it is located on a place where there is a thread to the constructive safety, drill samples from the concrete need to be taken which need to be microscopically investigated in a lab.

Appendix H - Concrete & Reinforcement research methods

Concrete

Swinkels (2015) comes up with two non-destructive methods to determine the strength of concrete;

- Rebound hammer

A rebound hammer shoots a steel pin with a spring at a high speed on the concrete surface. The kickback of the pin gives a value for the modulus of elasticity, which is related to the concrete pressure strength. Before the measurement is performed, first the concrete area must be sanded. The measure must be performed according to the NEN-EN 12504-2[4], which states that on one location 9 different measurements must take place with a distance of at least 25 mm between each other. The median will be considered as the result of the method. The result can give an indicative concrete strength, but it is not sufficient to give the exact strength. The interviews argue that the use of schmidthamers is highly unreliable.

- Ultrasonic pulse rate

By measuring the speed of an ultrasonic pulse through the concrete, the modulus of elasticity can be determined, which is related to the concrete pressure strength. The speed can be measured by placing a sender and a receiver on both sides of a concrete element. The results of this measure are strongly dependent on the way the method is executed and on the moisture content of the concrete. Therefore it is also not sufficient enough to give the exact strength.

In the semi-destructive category, Swinkels (2015) comes up with one method;

- Pull-out strength

It is a method in which a little anchor is placed within the concrete when the concrete is poured, or the anchor is placed later with special milling tools. By applying force on the little anchor, it is possible to retrieve information about the concrete strength. This gives only information about the surface of the concrete and is dependent on reinforcement and local defects in the concrete. Therefore it is also not sufficient enough to give the exact strength.

Swinkels (2015) comes up with one destructive method to determine the concrete strength;

- Determine strength with help of drill samples

This is the most accurate way to determine the concrete strength of existing concrete components. Drill samples need to be taken with a diameter of at least 100 mm. The cylinders must be straight and the ends must be flat and square. Because it is impossible to drill 100% straight, the drill samples will be adjusted. Therefore it is necessary to take larger drill samples than is minimally required.

According to SGS Intron (2016), there are two other ways to perform destructive research; to determine the density, porosity and permeability of concrete, small drilling samples can be taken from the concrete. With help of gas permeometry, only drilling samples with a diameter of 1 cm and a length of 2 cm are needed to determine these aspects. It is also possible to determine the compressive and tensile strength from those small concrete drilling samples.

Another method is DRMS. With DRMS it can be measured how mechanical properties of concrete change when you go deeper into the concrete. This is a micro-drilling system which measures the resistance of the concrete and relates it accurately to the location within the concrete.

Reinforcement

According to SGS Intron (2016), there are two suitable non-destructive inspection methods to retrieve information about the reinforcement of the concrete;

- Radar

The radio waves from the radar will reflect because of the reinforcement bars which are present within the concrete, this creates certain radar profiles. With help of these radar profiles, it is possible to determine the locations of the reinforcement bars.
There are some limitations regarding the radar method. The exact depth of the reinforcement can only be established after a limited destructive research. The radar can only look 0,5 meter deep in the concrete. The penetration depth of radio waves is also dependent on the amount of reinforcement. If the reinforcement density is too high (usually at a c.t.c. distance < 100 mm), it is only possible to look at the nearest layer of reinforcement. If the reinforcement density is even higher (usually at a c.t.c. distance < 40 mm), the reinforcement bars cannot even be separated from each other. Also, the diameter of the reinforcement bars cannot be measured with help of a radar.

- Ferro-scan

A ferro-scan can detect disturbances in the magnetic field, which can determine the location and diameter of the reinforcement bars.
There are also some limitations regarding the ferro-scan method. Although the ferro-scan method is able to measure the diameter of reinforcement bars, a ferro-scan can only look 0,1 meter deep in the concrete. Also, when there is a lot of surrounding reinforcement, there is a lot of uncertainty in the results of the diameter. With sensor systems, it is possible to measure the amount of chloride within the concrete. The chloride concentration can say something about the chance that reinforcement corrosion can occur.

Appendix I - Proposed product circularity measurement framework

Saidani et al. (2017) take a look at methods to assess circularity. The Material Circularity Indicator (MCI), Circular Economy Toolkit (CET) and the Circular Economy Indicator Prototype (CEIP) have been assessed by Saidani, Yannou, Leroy, & Cluzel (2017). Based on their assessment Saidani et al. (2017) have developed a proposed product circularity measurement framework, on which some of the general requirements in this research are based.

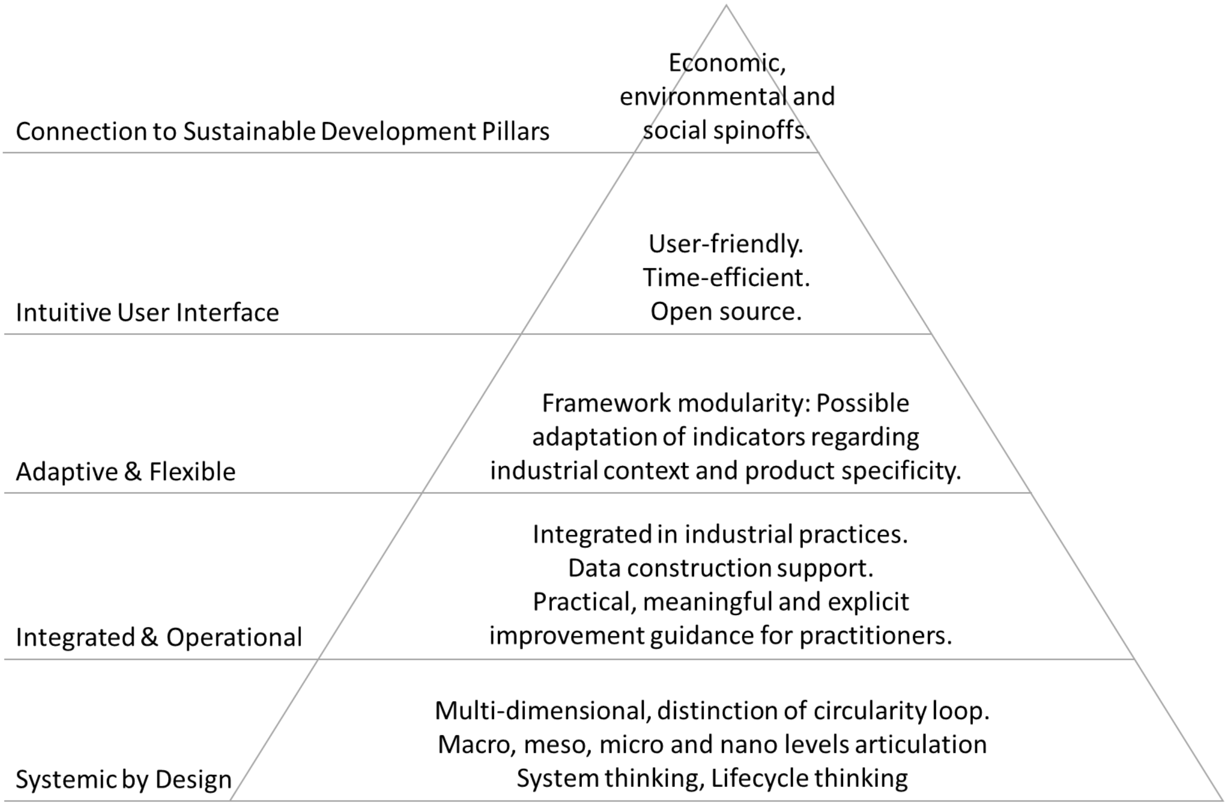


Figure 31: Proposed hierarchy of desired features to design frameworks, methods, tools, and indicators aiming at measuring product circularity performance (Saidani et al., 2017)

Appendix J - From functional requirements to assessment questions

In this appendix, it is shown in Table 15, which functional requirements are rejected and how the functional requirements that have not been rejected, have been rewritten into assessment questions.

Table 15: From functional requirements to assessment questions

Circular indicator	Functional requirements	Assessment questions
Toxicity	Checking if iron fibres are present	Are iron fibres are visible in the surface of the concrete?
	Checking if immobilized waste material is present	
	Checking if steel slag is present	
	Checking if phosphorus slag is present	
	Checking if blast furnace slag is present	
	Checking if composite fibres are present	Are composite fibres are visible in the surface of the concrete?
	Checking if asbestos is present	Is asbestos present?
	Checking if there is a risk of mixed in chlorides	Is there is a risk of mixed in chlorides?
Condition	Checking the general condition of the component	What is the general condition score of the component?
	Checking if the cement is sufficient	
	Checking for signs of harmful ASR	Could ASR have been a problem?
	Checking if frost (in combination with de-icing salts) could be a problem	
	Check if there is a risk of internal sulphate attacks	Could internal sulphate attack have been a problem?
	Checking if penetration of sulphites could be a problem	Could the penetration of sulphites be a problem?
	Checking for corrosion	Are there any signs of corrosion?
	Checking for cracks and determine its width	If cracks are visible, what is the maximum width of the cracks?
Residual lifespan	Checking the residual lifespan based on the condition	What is the residual lifespan based on the condition?
	Checking the residual lifespan based on the designed value	What is the residual lifespan based on the designed lifespan?
	Checking the residual lifespan based on the structural safety	
	Checking the residual lifespan based on chloride penetration	What is the residual lifespan based on chloride penetration?
	Checking the residual lifespan based on carbonation penetration	What is the residual lifespan based on carbonatation penetration?
Connections	Checking how the component is connected	How is the component connected?
Retrieval	Checking if the component can be transported	Can the component be transported?
	Checking if the component is accessible	How accessible is the component?
	Checking if it is possible for a crane to reach the component	If a crane is needed, is it possible for a crane to reach the component?
Design requirements	Checking the design class of the asset	
	Checking the properties of the concrete	
	Checking the properties of the reinforcement	
	Checking the environmental class of the asset	For which environmental classes is the component suitable?
Dimensions	Checking if the level of standardisation of the component	What is the level of standardisation?

Appendix K - Test case information

This appendix describes the case that is used for the validation of the method. Because of time constraints, an object is chosen that already has been inspected. Therefore the inspectors that test the new method do not need to perform an inspection on site to be able to test the method. The inspection of this object was part of a series of objects which needed to be inspected for the project ‘Aanpak Ring Zuid Groningen’. This object was chosen because it has a variety of different types of concrete components. To make sure that every inspector assesses the same components, it has been stated in advance which components the inspectors need to assess. This is important because the answers need to be compared in order to validate the method.

First, some general information of the object that is assessed for this test case is given. Second, the components that the inspectors needed to assess are listed. Third the available information that is given to the inspectors to assess the component is described. Fourth the guideline that has been provided to the inspectors to help them in executing the method is given.

Object information

Figure 32: Overview photo of test case

Name: Viaduct N370 over the Concourslaan
Description: Western and eastern viaduct over the Concourslaan.
Object type: Viaduct
Road: Provincial road N370
Hectometre: 3,7
Construction year: 1976
Coordinates: N 53.204635° E 6.551008°
Object length: 30 meters
Object width: 10 meters

To be inspected components

- Beam
- Pressure layer
- Curbstone
- Crossbar
- Column

- Wing wall
- Wall

Available data

- Inspection and research report (KW06.01 Inspectie- en onderzoeksrapport)
- Construction drawings
    - Drawings of column reinforcement
    - Drawings of individual prefab beams
    - Drawings of layout prefab beams
    - Drawings according to construction specifications
    - Drawings of prestressed concrete
- Calculations
- Contract specifications
- Inspection photos

Guideline

Data

- The object on which the method is tested is the Viaduct N370 over the Concourslaan
- According to the NEN 2767 decomposition, All concrete components need to be assessed. This means that each of the following components needs to be assessed with the method:
    - Beam
    - Pressure layer
    - Curbstone
    - Crossbar
    - Column
    - Wing wall
    - Wall
- In this case, there will be no inspection on location. Therefore try to get the necessary information as much as possible from the photos, drawings and the inspection rapport that have been included
- On google maps, the object can also be seen. https://goo.gl/maps/jhXy5ePV9nF2

Assumptions

- The goal of the method is to quickly asses if 1 on 1 reuse is possible. If 1 on 1 reuse is really considered, much more extensive research and calculations are necessary. With this method, it is possible to quickly exclude component for 1 on 1 reuse, which makes it no longer necessary to conduct extensive research into those components.
- The method only focusses on concrete components.
- For some questions, the NEN 2767 condition score is necessary as an input. Since the NEN 2767 condition measurement is not conducted, a condition score of 2 can be assumed if it cannot be assessed properly.
- I will be present at the office, so you can ask me anything if something is not clear.
- Please do not consult with each other. It is also the intention of this research to investigate if everyone can get to the same results.

Fill in Excel tool

- Before you are going to assess a component, take the empty excel file and save it separately with the name 'Beoordelingsmethode hergebruik_Viaduct N370 Concourslaan_Component'.
- In the input tab, all yellow boxes need to be filled in, if a box turns red, it is not necessary anymore to fill in that box.
- Behind each question, there is room to make some remarks if your answer needs any clarifications.
- It could be the case that after all 'must have' questions have been answered, that reuse is not possible. Normally this means that the 'nice to have' questions do not have to be answered anymore. But for the sake of the research, the 'nice to have' questions still needs answering.
- If all yellow boxes in the 'input' tab have been filled in, de results are shown in the 'output' tab.
- In this guideline every question is elaborated, please keep it with you when you are answering the questions in excel.

Appendix L - Results test case

In this appendix, the answers that the inspectors have been given during the test case are shown.

Beam

Table 16: Answers given during test case for the beam

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	2	1	2	2	0
4	y	y	y	y	1
	y	y	y	y	1
					1
5	4	4	3	4	0
6	n	n	n	n	1
	?	y	n	y	0
	y		n		0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				y	0
				n	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	y	y	y	y	1
	n	n		n	0
	n	n		n	0
	n	n		n	0
	n	n		n	0
11	n	n	n	n	1
					1
12	1	1	1	1	1
	n	n	n	n	1
13	100	?	80	80	0
	2	1	2	2	0
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	37	0
16	?	?	?	80	0
	43	43	44	43	0
	?	?	?	2	0
	35	25	?	35	0
17	4	6	4	6	0
18	y	y	y	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	1	2	1	2	0

Pressure layer

Table 17: Answers given during test case for the pressure layer

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	2	1	2	2	0
4	n	n	n	n	1
					1
	n	n	n	n	1
5	5	5	5	5	1
6	n	n	n	n	1
	?	n	n	?	0
	y	n	n	n	0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				n	0
				n	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	n	y	y	?	0
	n	n		n	0
	n	n		n	0
	n	n		n	0
	n	n		n	0
11	n	n	?	?	0
			?		0
12	1	1	?	1	0
	n	n	?	n	0
13	100	?	80	80	0
	2	1	2	?	0
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	?	1
16	?	?	?	80	0
	43	43	?	43	0
	?	?	?	2	0
	?	25	?	35	0
17	4	6	6	6	0
18	n	y	y	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	3	3	3	3	1

Curbstone

Table 18: Answers given during test case for the curbstone

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	2	2	2	2	1
4	y	n	n	n	0
	y			n	0
		n	n	n	0
5	5	5	5	5	1
6	n	n	n	n	1
	?	n	n	?	0
	y	n	n	n	0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				n	0
				n	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	n	y	y	n	0
	n	n		n	0
	n	y		n	0
	n	n		n	0
	n	n		n	0
11	n	n	n	n	1
					1
12	1	2	1	1	0
	n	y	n	n	0
13	100	?	80	80	0
	2	3	2	2	0
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	?	1
16	?	?	?	80	0
	43	43	44	43	0
	?	?	?	10	0
	?	25	?	35	0
17	4	6	6	6	0
18	n	y	n	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	3	3	3	3	1

Crossbar

Table 19: Answers given during test case for the crossbar

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	3	2	4	3	0
4	y	y	y	y	1
	y	y	y	y	1
					1
5	4	2	4	5	0
6	n	n	n	n	1
	?	y	n	y	0
	y		n		0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				y	0
				y	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	y	n	y	y	0
	n	n		n	0
	y	y		y	0
	n	n		n	0
	n	n		n	0
11	n	n	n	n	1
					1
12	1	2	1	1	0
	n	y	n	n	0
13	100	?	80	80	0
	2	2	4	3	0
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	37	0
16	?	?	?	80	0
	43	43	44	43	0
	?	?	?	10	0
	?	25	?	35	0
17	4	6	4	4	0
18	y	y	y	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	1	2	3	2	0

Column

Table 20: Answers given during test case for the column

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	2	1	2	2	0
4	y	y	y	y	1
	y	y	y	y	1
				n	0
5	4	3	4	4	0
6	n	n	n	n	1
	?	n	n	?	0
	y	n	n	n	0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				n	0
				n	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	y	y	y	n	0
	n	n		n	0
	y	n		n	0
	n	n		n	0
	n	n		n	0
11	n	n	n	n	1
					1
12	1	1	1	1	1
	n	n	n	n	1
13	100	?	80	80	0
	2	1	2	2	0
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	?	1
16	?	?	?	80	0
	43	43	44	43	0
	?	?	?	10	0
	40	25	?	35	0
17	3	6	6	6	0
18	y	y	y	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	1	2	3	3	0

Wing wall

Table 21: Answers given during test case for the wing wall

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	2	2	2	2	1
4	y	y	y	y	1
	y	y	y	y	1
				n	0
5	4	3	5	4	0
6	n	n	n	n	1
	?	n	n	?	0
	y	n	n	n	0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				n	0
				n	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	y	y	y	n	0
	n	n		n	0
	y	n		n	0
	n	n		n	0
	n	n		n	0
11	n	n	n	n	1
					1
12	1	1	1	1	1
	n	n	n	n	1
13	100	?	80	80	0
	2	2	2	2	1
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	?	1
16	?	?	?	80	0
	43	43	44	43	0
	?	?	?	10	0
	?	25	?	35	0
17	4	6	6	6	0
18	n	y	y	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	3	3	3	3	1

Wall

Table 22: Answers given during test case for the wall

Question	Insp. 1	Insp. 2	Insp. 3	Insp. 4	Equal?
1	n	n	n	n	1
2	n	n	n	n	1
3	2	2	2	2	1
4	y	y	n	y	0
	y	y		n	0
			y	y	0
5	4	3	5	4	0
6	n	n	n	n	1
	?	n	n	?	0
	y	n	n	n	0
7	y	y	y	y	1
					1
8	?	?	?	?	1
				n	0
				n	0
9	?	y	y	?	0
	n			n	0
10	n	n	n	n	1
	?	?	y	?	0
	y	y	y	n	0
	n	n		n	0
	y	n		n	0
	n	n		n	0
	n	n		n	0
11	n	n	n	n	1
					1
12	1	1	1	1	1
	n	n	n	n	1
13	100	?	80	80	0
	2	2	2	2	1
14	100	?	80	80	0
	43	43	44	43	0
15	?	?	?	?	1
16	?	?	?	80	0
	43	43	44	43	0
	?	?	?	10	0
	?	25	?	35	0
17	4	6	6	6	0
18	n	y	n	n	0
19	?	3	?	0	0
	?	3	?	0	0
	?	0	?	0	0
	?	0	?	0	0
	?	0	?	0	0
20	3	3	3	3	1

Appendix M - Complete final list of assessment questions

Table 23: Complete list of assessment questions

Circular indicator	Score category	Question	Sub question	Data location	Possible answers
Toxicity	Material quality	Are iron fibres are visible in the surface of the concrete?		Inspection reports Visual inspections	yes no
		Are composite fibres are visible in the surface of the concrete?		Inspection reports Visual inspections	yes no
		Is asbestos present?	Is the component build after 1983?	Pasport	yes no
			Is het certain that asbestos is present?	Design report Research reports	yes no
			Could there be a risk of presence of asbestos? (i.e. cast in tubes for cables or water drainage systems)	Drawings Visual inspections	yes no
		Is there is a risk of mixed in chlorides?	Is the component build after 1974?	Pasport	yes no
			Is the component prefab?	Drawings Visual inspections	yes no
Condition		What is the general condition of the component?		Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard
		Could ASR be a problem?	Is the component build after 2002?	Pasport	yes no
			Is solely blast furnace cement being used?	Drawings Contract documents	yes no
			does the component stand in a humid environment? (An environment that could have been exposed to at least fog or dew)	Inspection reports Visual inspections	yes no
			Is there visible expansion and deformation of the concrete?	Inspection reports Visual inspections	yes no
			Are there visible cracks on the surface?	Inspection reports Visual inspections	yes no
			Are there visible alkali silicic gels present?	Inspection reports Visual inspections	yes no
			Are there visible pop-outs of concrete pieces?	Inspection reports Visual inspections	yes no
		Could internal sulphate attack have been a problem?	Are the aggregates sulphate containing?	Contract specifications	yes no
			does the component stand in a humid environment? (An environment that could have been exposed to at least fog or dew)	Inspection reports Visual inspections	yes no
		Could penetration of sulphites be a problem?	Is solely, or solely a combination of CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B used as cement for the concrete?	Drawings Contract documents	yes no
			Is there seawater within a range of 25 km?	Maps	yes no
		Are there any signs of corrosion?	Are there signs of reinforcement corrosion?	Inspection reports Visual inspections	yes no
			Does the reinforcement only occur locally?	Inspection reports Visual inspections	yes no
		Are there cracks visible on the surface?	What is the width of the crack	Inspection reports Visual inspections	cracks smaller than or equal to 0,2 mm, or no cracks cracks between 0,2 and 0,5 mm cracks more than 0,5 mm
			Is it a constructive crack? (a crack that decreases the load bearing properties of a component)	Inspection reports Visual inspections	yes no
Residual lifespan		What is the residual lifespan based on the condition?	What is the designed life span?	Design report	the designed life span
			What is the condition of the component?	Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard
		What is the residual lifespan based on the designed value?	What is the designed life span?	Design report	the designed life span (years)
			What is the age of the component?	Pasport	the age (years)
		What is the residual lifespan based on chloride penetration?		Research reports	the residual life span based on chloride penetration
		What is the residual lifespan based on carbonation penetration?	If this has been investigated, what are the results?	Research reports	the residual life span based on carbonation penetration
			What is the age of the component?	Pasport	the age (years)
			What is the carbonation depth?	Measure with small drill	the carbonation depth (mm)
			How deep the reinforcement is located?	Drawings Scanners	how deep the reinforcement lies beneath the surface (mm)
Connections	Disassembly	How is the component connected? (If multiple answers are applicable, the answer with the highest number should be filled in)		Drawings Inspection reports Visual inspections	No fixed connection Indirect with external fixing devices Indirect indirect with internal removeable fixing device Indirect with internal non-removeable fixing device Via third chemical material Direct chemical
Retrieval		Can the component be transported?	Does the component fit within the dimensions of 3,00x4,00x27,00 meters?	Drawings	yes no
			Weighs the component less than 35.000 kg?	Drawings	yes no
			Is there room for the component to be transported with special transport?	Maps Visual inspections	yes no
		Can the component be disassembled without causing damage to the component?		Drawings Inspection reports Visual inspections	yes, without the need of additional operations yes, but additional operations are necessary which causes no damage no, but the damage that is caused to the component is repairable no, but the component can still be used, although the damage can't be repaired no, the component can't be disassembled without causing total damage
		Is extra equipment necessary for the retrieval of the component compared to the equipment that is needed for the demolition of the component?		Inspection reports Visual inspections	yes no
Design requirements	Applicability	For which environmental classes is the component suitable?	For which XC class is the component suitable?	Drawings	no XC class XC1 XC2 XC3 XC4
			For which XD class is the component suitable?	Drawings	no XD class XD1 XD2 XD3
			For which XS class is the component suitable?	Drawings	no XS class XS1 XS2 XS3
			For which XF class is the component suitable?	Drawings	no XF class XF1 XF2 XF3 XF4
			For which XA class is the component suitable?	Drawings	no XA class XA1 XA2 XA3
Dimensions		What is the level of standardisation?		Drawings Inspection reports Visual inspections	non-load bearing prefab (1) load bearing prefab (0,5) cast-in-situ component (0)

Appendix N - Final design of the method

In this Appendix, the steps are described to execute the final design of the method and can be used as a guideline to perform the method.

Before the start of the method, the following assumptions need to be taken into account:

- The goal of the method is to quickly asses if 1 on 1 reuse is possible. If 1 on 1 reuse is really considered, much more extensive research and calculations are necessary.
- The method is for the assessment of concrete components.
- The method is for the assessment of 1 on 1 reuse on other locations, not on the same location.
- For the assessment, it needs to be taken into account that the whole structure is getting disassembled.
- The method can only assess components from the Netherlands.

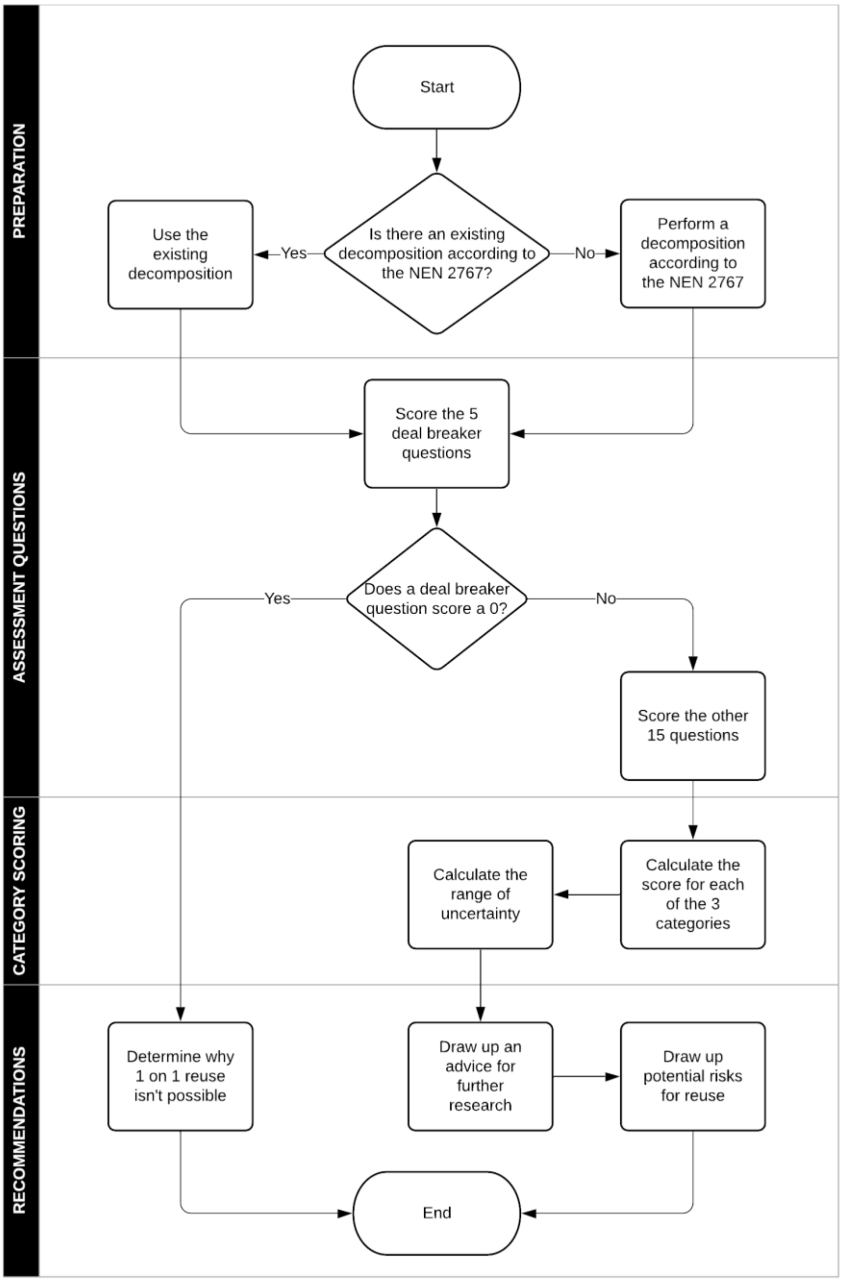


Figure 33: Final design of the new method

Step 1: Preparation

The first step to check if there is an existing decomposition, according to the NEN 2767, of the object that needs to be inspected and assessed. The NEN 2767 is commonly used to perform condition assessments on infrastructure assets. By using the decomposition according to the NEN 2767 as a basis, the new method fits well within the existing condition assessment according to the NEN 2767. If a decomposition has already been made because of prior condition assessments, then that decomposition can also be used for the new method. If a decomposition has not been made before, a new decomposition needs to be constructed.

Step 2: Assessment questions

The second step is to score all the indicators by answering the assessment questions that came out of the functional requirements in chapter 3.

Step 2.1: Score the deal breaker questions.

Look up the information to answer each deal breaker question and give it a score between 0 and 1. In order to answer each question, the information required to answer the score should be looked up. When the answer is found, the score that is matching with the given answer should be given to the question.

Some questions are deal breakers and some questions are not. If a question is a deal breaker it means that if the answer to that question results in a score of 0 for that particular question, reuse is not possible. Below a list is shown that gives an overview of all the questions that are deal breakers.

1. Are iron fibres visible in the surface of the concrete?
2. Are composite fibres visible in the surface of the concrete?
3. What is the general condition score of the component?
4. Can the component be transported?
5. Can the component be disassembled without causing damage to the component?

The presence of iron fibres and composite fibres are marked as a deal breaker because they give an increased risk in quality loss of the concrete. Because these materials are almost impossible to filter out of the concrete, these components should be kept out of the loop from a circular point of view.

The general condition score gives some kind of threshold of what the minimal condition of a component should be. When the condition is irreversibly bad, the component should not be reused. This also has an effect on the residual lifespan based on the condition, so both the general condition score and the residual lifespan based on the condition are deal breakers.

If a component cannot be transported, it is not possible to reuse the component in another location. Therefore it is a deal breaker.

For the assessment questions, 4 steps have been taken.

1. For each question it is described where the information to answer that question can be retrieved. To be able for an inspector to quickly answer the questions of the new method, it needs to be clear where the information can be retrieved from.

2. Possible answers to the questions are defined. To make sure that the method can be executed in a uniform manner, all questions should have predefined answers. This limits the amount of own interpretation that the inspector can put into the answering of the questions.

3. The scores for all the answer possibilities are determined. All the possible answer are getting a certain score with a value between 0 and 1. A 0 is the leas favourable outcome for 1 on 1 reuse and 1 one is the most favourable outcome for 1 on 1 reuse. By defining the score for each answer the chance is increased that every inspector's assessment results in the same scores.

4. Recommended further research is described. For some answers to some questions, it could be recommended to perform a more extensive research in order to decrease the uncertainty. Therefore it is described which specific recommended research is advised to be performed.

1. <u>Are iron fibres are visible in the surface of the concrete?</u>

Although iron fibres increase the strength of the concrete, they can have a negative influence on the quality of the concrete because it increases the risk of corrosion. Therefore it is important to identify if there are iron fibres inside the concrete.

Information retrieval
- inspection reports
- visual inspections

Scores
- yes (0)
- no (1)

It can be visually detected on the surface if iron fibres are added inside the concrete. It should first be determined if the information can be found in photos of existing inspection reports. If that is not the case, it can easily be detected through visual inspections on site. Because this is a simple yes or no question, there are only two possible scores; 0 or 1.

2. <u>Are composite fibres are visible in the surface of the concrete?</u>

Although composite fibres increase the strength of the concrete, they can have a negative influence on the quality of the concrete because it increases the risk of carbonation. Therefore it is important to identify if there are composite fibres inside the concrete.

Information retrieval
- inspection reports
- visual inspections

Scores
- yes (0)
- no (1)

Just as is the case for iron fibres, composite fibres can be visually detected on the surface of the concrete. It should first be determined if the information can be found in photos of existing inspection reports. If that is not the case, it can easily be detected through visual inspections on site. Because this is a simple yes or no question, there are only two possible scores; 0 or 1.

3. What is the general condition score of the component?

The general condition score of the NEN 2767 gives an indication of the general condition of the component. Although this does not give information on any specific damage mechanism, it does say something about the overall quality.

Information retrieval
- inspection reports
- visual inspections

Scores
- 1 (1)
- 2 (0,75)
- 3 (0,5)
- 4 (0,25)
- 5 (0)
- 6 (0)

The points which are given to the certain condition scores are based on Table 2. Table 2 shows that at a condition score of 5 the deterioration is irreversible which means that reuse is not possible at a condition score of 5 and higher. At a condition score of 4, reuse should still be possible although a lower condition score is preferred. That is why the points among score 4 and lower are linearly divided.

Table 24: NEN 2767 condition scores

Condition score	Description	Explanation
1	Excellent condition	Incidental minor failures
2	Good condition	Incidental beginning deterioration
3	Acceptable condition	Partially visible deterioration, performance of asset not in danger of failing
4	Poor condition	Incidentally asset performance in danger of failing
5	Bad condition	Deterioration is irreversible
6	Very bad condition	Technically ready for demolition

4. Can the component be transported?

To be able to reuse a component it is necessary that the component is transportable to another location. This question can be answered with three sub-questions.

4a) Does the component fit within the dimensions of 3,00x4,00x27,00 meters?

Information retrieval
- Construction drawings

4b) Weighs the component less than 35.000 kg?

Information retrieval
- Construction drawings

4c) Is there room for the component to be transported with special transport?

Information retrieval
- Maps
- Visual inspections

Scores
- If 4a = yes, and 4b = yes; Component transportable with regular transport (1)
- If (4a = no, and/or 4b = no) and 4c = yes; Component only transportable with special transport (0,5)
= If 4c = no (0); Component no transportable (0)

If the first two questions can be answered with yes, then the component can be transported with regular traffic without the need for special permits. If that is the case the third sub-question does not need to be answered. The answer for the third question must be a yes or a no. Because it is difficult to determine when a component can be transported with special traffic, this question must be answered based on expert judgement.

5. Can the component be disassembled without causing damage to the component?

How accessible the component is says something about if it is easy to get access the component without causing damage to the component.

Information retrieval
- construction drawings
- inspection reports
- visual inspections

Scores
- yes, without the need for additional operations (1)
- yes, but additional operations are necessary which causes no damage (0,75)
- no, but disassembly is possible with causing damage to the component that is repairable (0,5)
- no, but disassembly is possible with causing damage to the component that cannot be repaired (0,25)

- no, the component cannot be disassembled without causing total damage (0)

These answers are ordered from 'most accessible' to 'less accessible'. The scores have been linearly distributed over the possible answers. Additional operations are specified as; Operations for which extra equipment to disconnect the component from the structure.

Step 2.2: Check if a deal breaker question scores a 0.

If a deal breaker question is scored with a 0, it means that 1 on 1 reuse is not possible for the component. That is why it must be checked if the deal breaker questions score a 0. If a deal breaker questions scores a 0, the rest of the steps until step 4.3 must be skipped.

Step 2.3: Score the rest of the questions.

Look up the information to answer each question and give it a score between 0 and 1. In order to answer each question, the information required to answer the score should be looked up. It is up to the inspector in which order the information is collected for the answering of the assessment questions, because the best order to collect information can depend on the information that is available and on the planning of the inspector. When the answer is found, the score that is matching with the given answer should be given to the question.

6. <u>Is asbestos present?</u>

Asbestos is a material which is dangerous for health and it is not allowed to be used as a construction material anymore. With help of three sub-questions, it is possible to determine if there is a risk of asbestos.

6a) Is the component build after 1983?

Information retrieval
- Object passport

6b) Is it certain that asbestos is present?

Information retrieval
- Design report
- Research report

6c) Could there be a risk of presence of asbestos? (i.e., cast in tubes for cables or water drainage systems)

Information retrieval
- Construction drawings

Scores
- 6a = yes, or 6b = no, or 6c = no; Asbestos can be excluded (1)
- 6c = yes; There is a risk of asbestos being present (0,5)
- 6b = yes; Asbestos is present (0)

With the first sub-question, it can easily be excluded if asbestos could be a problem, because asbestos was not used in concrete constructions after 1983. If that is not the case, there should be taken a look at the design report of the object and at possible research reports because it could have been the case that prior research has on asbestos has been conducted in the past. If that still does not give any certainty it should be investigated if there are any water drainage systems present because that is a highly likely location in which asbestos has been in concrete infrastructure assets.

Recommended further research
When it is unknown if asbestos is present, it is advised to perform an extensive asbestos research to identify the presence of asbestos.

7. <u>Is there is a risk of mixed in chlorides?</u>

Chlorides that are mixed into the concrete increases the chance of corrosion of the reinforcement. With the help of two sub-questions, it can be identified if there is a risk of mixed in chlorides.

7a) Is the component build after 1974?

Information retrieval
- Object passport

7b) Is the component prefab?

Information retrieval
- Construction drawings
- inspection reports
- Visual inspections

Prefab components can be recognised by eyebolts on the component. Prefab components can also be recognised by repetition of the same components; there is a lot of repetition in beams, box girders, full-loaders.

Cast-in-situ components can be recognised by the spots from the formwork or by the centrepins which were used during the pouring process. It can also be recognised by the seams that can be visible at cast-in-situ concrete.

Scores
- 7a = no, and 7b = yes; There is a risk of mixed in chlorides (0)
- All other answers (1)

The only possible way that there is a risk of mixed in chlorides is if the component is not built after 1974 and if the component is a prefab component. If one of the two conditions do not meet, then it is not a problem.

Recommended further research
It can never be determined for sure if there are chlorides mixed into the concrete. So when there is a risk of mixed in chlorides, it is advised to perform a lab research to identify the presence of mixed-in chlorides.

8. Could ASR be a problem?

ASR is an expansive reaction which can damage the concrete. There are six sub-questions which help identify the risk of harmful ASR.

8a) Is the component build after 2002?

Information retrieval
- Object passport

8b) Is solely blast furnace cement being used?

Information retrieval
- Construction drawings
- Contract documents

8c) Does the component stand in a humid environment? (An environment that could have been exposed to at least fog or dew)

Information retrieval
- inspection reports
- visual inspections

8d) Is there visible expansion and deformation of the concrete?

Information retrieval
- inspection reports
- visual inspections

8e) Are there cracks on the surface of the concrete visible?

Figure 34: Example of what ASR looks like (Rijkswaterstaat, n.d.)

Information retrieval
- inspection reports
- visual inspections

8f) Are alkali silicic geld visible?

Information retrieval
- inspection reports
- visual inspections

8g) Are there pop-outs of concrete pieces visible?

Information retrieval
- inspection reports
- visual inspections

Scores
- 8a = yes, or 8b = yes, or 8c = no (1)
- for 8d, 8e, 8f and 8g: each no adds 0,25 to the score

If at least one of the first two sub-questions can be answered with yes the risk of ASR can be excluded because after 1989 ASR was acknowledged as a problem and blast furnace cement is ASR resistant. In that case, the last four sub-questions do not need to be answered. If that is not the case then each of the last for sub-questions that can be answered with a no, add 0,25 points to the score. These four last sub-questions are derived from the Handboek ASR (Rademaker, 2002). If all of the last sub-questions are answered with no the score becomes 1 and if all of the questions are answered with yes the score becomes 0.

Recommended further research
It can only be determined for sure if ASR is a problem with a lab research. So if the score is lower than 1, it is advised to perform a lab research if ASR is a real problem.

Risk
If the component is built before 2002 and blast furnace cement is not used, then in the output, a risk is given if the component is going to be reused in a humid environment.

9. Could internal sulphate attack have been a problem?

Internal sulphate attacks can be problematic because it causes an expensive reaction which damages the concrete. Internal sulphate attacks are dependent on three factors which all need to be present, otherwise, the reaction cannot be happening. Each of the three factors is answered with a sub-question.

9a) Are the aggregates sulphate containing?

Information retrieval
- Contract documents

9b) Does the component stand in a humid environment? (An environment that could have been exposed to at least fog or dew)

Information retrieval
- inspection reports
- visual inspections

Scores
- At least one of the answers is no (1)
- All answers are yes (0)

If the first sub-question is answered with a no, there is no need to furtherly answer the other sub-questions and a score of 1 should be given.

Recommended further research
If it is unknown if the aggregates are sulphate containing, it is advised to perform a lab research to investigate the content of sulphates in the aggregates.

Risks
If the aggregates are sulphate containing, then there is a risk of internal sulphate attacks if the component is going to be reused in a humid environment

10. Could penetration of sulphites be a problem?

Apart from internal sulphite attacks, external sulphites can also be a problem. With help of two sub-questions, it can be determined if penetration sulphites could be a problem.

10a) Is there seawater within a range of 25 km?

Information retrieval
- Maps

10b) Is solely, or solely or a combination of CEM I-SR, CEM III/B-SR, CEM III/C-SR, CEM IV/A-SR or CEM IV/B-SR used as cement for the concrete?

Information retrieval
- Drawings
- Contract documents

Scores
- 10a = yes, and 10b = no (0)
- All other answers (1)

The only possible way that penetration of sulphites could be a problem is if the component is within a 25 km range of seawater and if a cement is used which is not resistant to external sulphites. If one of the two conditions do not meet, then it is not a problem.

Recommended further research
It can happen that the information about which cement is used is not available. When that is the case, it is recommended to perform a lab research to determine the type of cement that is used.

Risk
If CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B are not used as cement for the concrete, there is a risk if the component is going to be reused within 25 km of seawater.

11. Are there any signs of corrosion?

Corrosion can be a problem because it can cause the reinforcement inside the concrete to deteriorate, which can endanger the structural safety of the component.

11a) Are there any signs of reinforcement corrosion?

Information retrieval
- inspection reports
- visual inspections

11b) Does the reinforcement only occur locally?

Information retrieval
- inspection reports
- visual inspections

Scores
- 11a = yes, and 11b = no (0)
- 11a = yes, and 11b = yes (0,5)
- 11a = no (1)

Signs of corrosion can easily be visually detected. First, there could be taken a look at inspection reports. If there are no inspection reports or if they are not sufficient, visual inspections on site should be performed. Because this is a simple yes or no question, there are only two possible scores; 0 or 1.

Recommended further research
If there is a sign of corrosion it does not necessarily mean that the functioning of the component is in any danger. Corrosion can also occur at a location that only gives aesthetic problems. That is why it is advised that if corrosion occurs it should be investigated how problematic the corrosion really is.

12. If cracks are visible, what is the maximum width of the cracks?

Cracks are a sign that the component is damaged. The question if the crack has a negative influence on the constructive properties of a component and the width of the cracks can determine how serious the damage is.

12a) Is there a constructive crack visible? (a crack that decreases the load-bearing properties of a component)

Information retrieval
- inspection reports
- visual inspections

12b) What is the width of the crack?

Information retrieval
- inspection reports
- visual inspections

Scores
Constructive cracks
1 = cracks smaller than or equal to 0,2 mm, or no cracks (1)
2 = cracks between 0,2 and 0,5 mm (0,5)
3 = cracks more than 0,5 mm (0)

Non-constructive cracks
1 = cracks smaller than or equal to 0,2 mm, or no cracks (1)
2 = cracks between 0,2 and 0,5 mm (0,75)
3 = cracks more than 0,5 mm (0,5)

With a crack width of up to 0,2 mm the concrete has the ability to self-heal, and up to 0,5 mm the corrosion process which can occur could automatically stop because the cracks automatically silt up.

Recommended further research
If cracks are visible it does not necessarily mean that the functioning of the component is in any danger. cracks can also occur at locations that only gives aesthetic problems. That is why it is advised that if cracks are visible it should be investigated how problematic the cracks really are.

Residual lifespan

13. What is the residual lifespan based on the condition?

Based on the condition score of the NEN2767, it is also possible to make an estimation for the residual lifespan. This is a very rough estimation, but it is an easy way to make an estimation for the residual lifespan. To be able to make an estimation of the residual lifespan based on the condition score, two sub-questions need to be answered.

13a) What is the designed lifespan?

Information retrieval
- Design report

13b) What is the condition score?

Information retrieval
- inspection reports
- visual inspections

Score
The residual lifespan based on the condition can be calculated with the following formula.

$RL = Residual\ lifespan$ (years)
$DL = Designed\ lifespan$ (years)
$C = condition$

$$RL = \left(DL * \left(\frac{1}{2} * (C - 1)\right)\right)$$

$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

80 years is a commonly usual designed life span, that is the reason that that is the first mark at which the residual life span gets a lower score. After that, the score is linearly going down until it reaches a residual life span of 20. If a component has a residual lifespan of between the 10 and 0 years it is highly unlikely that such a component is going to fulfil the needs of a new situation, that is why after 20 years the score lowers more rapidly until it reaches a score of 0 if the residual life span is lower than 10 years. If the designed lifespan is unknown, a designed lifespan of 80 years can be assumed.

14. What is the residual lifespan based on the designed value?

The residual lifespan based on the designed value is a very simple calculation. It is also a very rough estimation that does not reflect the exact residual lifespan, but it can give a quick indication.

14a) What is the designed lifespan?

Information retrieval
- Design report

14b) What is the age of the component?

Information retrieval
- Object passport

Score
The residual lifespan based on designed lifespan can be calculated with the following formula.

$RL = Residual\ lifespan$ (years)
$DL = Designed\ lifespan$ (years)
$t = age$ (years)

$RL = DL - t$
$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

The points are given the same way as for the residual lifespan based on the condition. If the designed lifespan is unknown, a designed lifespan of 80 years can be assumed.

Recommended further research
If a component is older than the designed lifespan, it is not necessarily the case that a component can be used anymore. If that is the case, it is necessary that an extensive residual lifespan calculation is performed.

15. What is the residual lifespan based on chloride penetration?

If chloride reaches the reinforcement, the reinforcement can begin to corrode. It can be calculated how long it takes before the chloride reaches the reinforcement of the concrete. In order to retrieve information about the residual lifespan based on chloride penetration, a very extensive research needs to be performed. To perform this research is not included in the method, but if this information is already available because this has been investigated in the past, it is worthwhile to include these results in this method.

Information retrieval
- research report

Score
$RL = Residual\ lifespan$ (years)

$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

The points are given the same way as for the residual lifespan based on the condition.

Recommended further research
If a chloride penetration research has not been performed yet, it is recommended to perform a chloride penetration research to get more detailed information about the residual lifespan.

16. What is the residual lifespan based on carbonation penetration?

Also if carbonation reaches the reinforcement, the reinforcement can begin to corrode. It can be calculated how long it takes before the carbonation reaches the reinforcement of the concrete. First, it needs to be checked if such a research has been performed in the past, if that is not the case it is relatively easy to perform such a research on site.

16a) What is the residual lifespan based on carbonation penetration?

Information retrieval
- research report

16b) What is the age of the component?

Information retrieval
- Object passport

16c) What is the carbonation depth?

Information retrieval
- Drilling with a small drill

16d) How deep the reinforcement is located?

Information retrieval
- Construction drawings
- Scanners

Scores
For the calculation of the residual lifespan based on carbonation penetration, the formula of the CUR 121 is used (SBRCURnet-commissie 2140, 2018).

$RL = residual\ lifespan$
$mcd = \ measured\ carbonation\ depth\ (mm)$
$t = age$ (years)
$rd = reinforcement\ depth\ (mm)$

$RL = (\frac{dekking\ wapening}{(\frac{gemeten\ carbonatatie\ diepte}{\sqrt{leeftijd}})})^2$
$RL >= 80$ (1)
$RL >= 60$ (0,8)
$RL >= 40$ (0,6)
$RL >= 20$ (0,4)
$RL >= 10$ (0,2)
$RL < 10$ (0)

If the information about the residual lifespan is already given in a research report, it is not necessary to perform the research again and the last three sub-questions can be skipped. The points are given the same way as for the residual lifespan based on the condition.

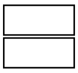
Connections

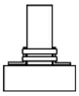
17. How is the component connected?

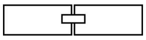
How the component is connected says something about how easy it is to dismantle the component.

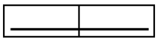
Information retrieval
- construction drawings
- inspection reports
- visual inspections

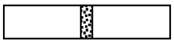
Scores

- No fixed connection (1) 
(loose concrete bricks)

- Indirect with external fixing devices (0,8) 
(two components connected with bolts)

- Indirect with an internal removeable fixing device (0,6) 
(two components connected with dowels)

- Indirect with an internal non-removeable fixing device (0,4) 
(two components connected with a chemical anchor)

- With a third chemical material (0,2) 
(two components connected with a mortar)

- With a direct chemical connection (0) 
(component directly poured onto another component)

These connections are ordered from ‘easily to remove’ to ‘hard to remove’. If multiple connections are applicable, the connection with the lowest score must be selected. Also, if it cannot be detected exactly how the components are connected, the possibility with the lowest score should be selected.

Retrieval

18. Is extra equipment necessary for the retrieval of the component compared to the equipment that is needed for the demolition of the component?

Most components require equipment to be disassembled as well as to be demolished. However, it is more relevant to know if extra equipment is needed for the retrieval of a component compared to the equipment that is needed for the demolition of the component.

Information retrieval
- Maps
- Visual inspections

Score
- yes (1)
- no (0)

The answer to this question depends on many different factors and is hard to quantify. That is why this question must be answered based on expert judgement.

Design requirements

19. For which environmental classes is the component suitable?

This question says something about how widely the component can be deployed if it is going to be reused. To answer this question for each of the 5 types of environmental classed it needs to be determined to which class the component applies. Each sub-question applies to one of the environmental classes.

19a) For which XC class is the component suitable?

Information retrieval
- Construction drawings

19b) For which XD class is the component suitable?

Information retrieval
- Construction drawings

19c) For which XS class is the component suitable?

Information retrieval
- Construction drawings

19d) For which XF class is the component suitable?

Information retrieval
- Construction drawings

19e) For which XA class is the component suitable?

Information retrieval
- Construction drawings

Scores
- Each sub-question gets a score between the 0 and 1 linearly divided over all the possible classes
- The total score of this question is the average score of the sub-questions

20. What is the level of standardisation?

The level of standardisation also says something about how wide a component can be deployed if it is going to be reused.

Information retrieval
- construction drawings
- inspection reports
- visual inspections

Scores
- non-load bearing prefab (1)
- load bearing prefab (0,5)
- cast-in-situ component (0)

Most of the prefab components are still specifically designed for an object. Especially for load bearing prefab components, often the measurements are the same, but the layout of the reinforcement differs. If they are to be reused, recalculations are necessary, that is why non-load bearing components score better than load-bearing components.

Step 3: Category scoring

As visualised in Figure 30, the Material Quality category contains the toxicity, condition and residual life span indicators; the Disassembly category contains the connections and retrieval indicator, and the Applicability category contains the design requirements and dimensions indicator.

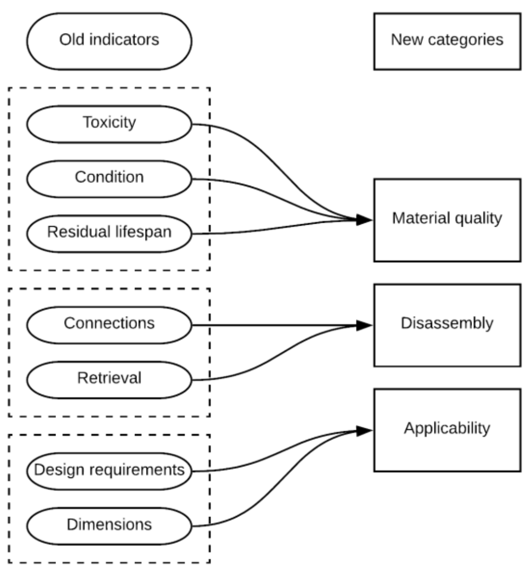


Figure 35: From the 7 indicators to the 3 new scoring categories

These three categories are chosen to score separately because it is desirable to get the least amount of scores possible per component, because this makes it easier to compare and prioritize components. However, if you combine anymore of the three categories you get a score that is too general to say anything about 1 on 1 reuse. These three categories are independent which means that they do not influence each other's scores.

The toxicity, the condition and the residual lifespan indicators have been put into 1 category because they can influence each other. If a component is in a bad condition, it is very likely that the residual lifespan is lower than when the component is in a better condition. Also, if there are certain toxic materials that are inside the concrete, the concrete can be more sensitive to deterioration, which can worsen the condition and consequently the residual lifespan.

The connections and the retrieval category have also been put into 1 category because they also can somewhat influence each other. The type of connection also influences if it is possible to disassemble a component without damage or not.

The design requirements and the dimension of a component do not influence each other. But because they both say something about the applicability and it is desirable to have as few categories as possible, they have been put into one category.

Step 3.1: Calculate the score for each category.

Within each category (Material Quality, Disassembly & Applicability) the scores of all questions must be added together and must be divided by the maximum achievable score within that category. Then for each category that number must be multiplied by 10, which results in a certain score on a scale of 10.

In this part, it is described how all the answers are analysed to generate final scores. As explained before, each of the questions can be scored with a value between 0 and 1, in which 0 is the least optimal for reuse and 1 is the most optimal for reuse. Then for each category, all the scores are added up. Based on the maximum score that can be achieved, a score on a scale between 0 and 10 is given for each of the three categories. An example of what such a score can look like is given in Figure 36. If a deal breaker question is given a score of 0, then the whole category gets a score of 0, which means that reuse is not possible.

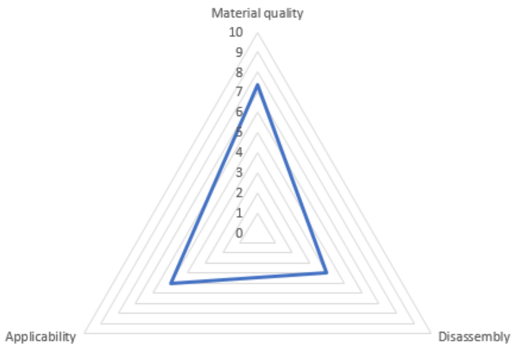


Figure 36: Visualisation of final scores

Step 3.2: Calculate the range of uncertainty.

For each question that could not be answered, the score should be calculated twice. One time while assuming that all the uncertain questions get a score of 1; and one time while assuming that all the uncertain questions get a score of 0. This way a score is calculated of the highest possible score if all questions can be answered, and of the lowest possible score if all questions can be answered. This gives an idea of the range of what the score can be if all the uncertainties are taken away.

There is also the possibility that the available data is not sufficient to be able to answer certain questions. If that is the case then the question is not included in the calculation of the score. However, it could be the case that if sufficient data is gathered, the end score is higher or lower. Therefore two extra scores are calculated; first it is calculated what the score would be if all the unanswered questions would get a score of 1, called the "+" uncertainty score; second it is calculated what the score would be if all the unanswered questions would get a score of 0, called the "-" uncertainty score. An example of what those scores can look like is given in Figure 37.

Figure 37: Visualisation of final score including uncertainties

The following example is given to clarify how the calculation of the uncertainty scores works:
The Disassembly category consists of 4 questions, for the example it is assumed that 3 questions can be answered, but for 1 question the answer is unknown. The three questions score a total of 2 points.

For the calculation of the score, the uncertain question is not taken into account. This means that the score is calculated like this:

$$\frac{points\ scored}{maximum\ possible\ amount\ of\ points} * 10 = \frac{2}{3} * 10 = 6{,}67$$

For the calculation of the "+" uncertainty score, the uncertain question is taken into account and it is assumed that the uncertain question scores a 1. This results in the following calculation of the '+ uncertainty score':

$$\frac{points\ scored}{maximum\ possible\ amount\ of\ points} * 10 = \frac{3}{4} * 10 = 7{,}50$$

For the calculation of the "-" uncertainty score, the uncertain question is taken into account and it is assumed that the uncertain question scores a 0. This results in the following calculation of the '- uncertainty score':

$$\frac{points\ scored}{maximum\ possible\ amount\ of\ points} * 10 = \frac{2}{4} * 10 = 5{,}00$$

Step 4: Recommendations

Step 4.1: Draw up an advice for future research

Based on the answers of certain questions, an advice for future research should be formulated. This recommended further research could take away some uncertainties that are in the answers of the questions and thus could give a score with fewer uncertainties. Below a list is given of what the possible advice for future research could be, depending on how the questions are answered:

6. Is asbestos present?

When it is unknown if asbestos is present, it is advised to perform an extensive asbestos research to identify the presence of asbestos.

7. Is there is a risk of mixed in chlorides?

It can never be determined for sure if there are chlorides mixed into the concrete. So when there is a risk of mixed in chlorides, it is advised to perform a lab research, according to the CUR 121, to identify the presence of mixed-in chlorides.

8. Could ASR be a problem?

It can only be determined for sure if ASR is a problem with a lab research. So if the score is lower than 1, it is advised to perform a lab research, according to the CUR 117, if ASR is a real problem.

9. Could internal sulphate attack have been a problem?

When the third sub-question needs to be answered and it is unknown if the aggregates are sulphate containing, it is advised to perform a lab research, according to the CUR 117, to investigate the content of sulphates in the aggregates.

10. Could penetration of sulphites be a problem?

It can happen that the information about which cement is used is not available. When that is the case, it is recommended to perform a lab research to determine the type of cement that is used.

11. Are there any signs of corrosion?

If there is a sign of corrosion it does not necessarily mean that the functioning of the component is in any danger. Corrosion can also occur at a location that only gives aesthetic problems. That is why it is advised that if corrosion occurs it should be investigated how problematic the corrosion really is.

15. What is the residual lifespan based on chloride penetration?

If a chloride penetration research has not been performed yet, it is recommended to perform a chloride penetration research according to the CUR 121 to get more detailed information about the residual lifespan.

Step 4.2: Draw up potential risks for reuse

It could be the case that reuse is only at risk in a certain type of situation. Below these specific risks are described, depending on the answer of the corresponding questions:

6. Is asbestos present?
   If asbestos is present, there is a risk of reusing this component.

8. Could ASR be a problem?
   If the component is built before 2002 and blast furnace cement is not used, then there is a risk if the component is going to be reused in a humid environment.

9. Could internal sulphate attack have been a problem?
   If the aggregates are sulphate containing, then there is a risk of internal sulphate attacks if the component is going to be reused in a humid environment

10. Could penetration of sulphites be a problem?
    If CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B are not used as cement for the concrete, there is a risk if the component is going to be reused within 25 km of seawater.

Step 4.3: Determine why reuse is not possible

This step must only be followed if a deal breaker question scores a 0, which means that reuse is not possible. If that is the case, it should be clearly described what the reason is why reuse is not possible for the component.

Appendix O - Final tool

The tool is made in excel and consists of an input interface and an output interface. In the input interface, all the method questions need to be answered and filled in. When all the questions have been answered, the output interface shows the results.

The tool is developed to help the inspector in executing the new method. The tool only helps with step 2 till step 4 of the method, which means the inspector still has to come up with a decomposition according to the NEN 2767. The tool consists of two parts; the input interface, and the output interface. The interfaces are designed to look simplistic and to only give useful information for the inspector.

Input interface

The input interface is shown in Table 25 & Table 26.

There are two fields in which information of the component can be filled in; the object name and the component. This way it becomes more clear which component is being assessed, and from which object the component is originating.

Three types of information are given for an inspector to fill in the answer to a question;

1. The assessment question.
2. Where to find the information to answer the assessment question. it has been made more clear for which questions the information can be retrieved from a bureau study, research on-site or both. This can be seen quickly by checking the colours after the questions.
3. The answer possibilities for the assessment question. By giving a fixed set of answer possibilities, there is less room given for the inspectors own interpretation.

The inspector should fill in the answers in the yellow boxes. Some sub-questions do not need to be answered depending on the given answers for previous sub-questions. This is taken into consideration by if a yellow box turns into a red box it does not need to be answered anymore. The inspector only needs to check if all the yellow coloured boxes are filled in with an answer.

The questions are ordered in such a manner that the deal breaker questions are asked first. These are categorised as must-haves. As shown in Table 3: The input interface, on the right of those questions there is instantly given a result that states if reuse is possible or not. If reuse is possible the box turns green, if reuse is not possible the box turns red, and if more information is required the box turns orange. If reuse is not possible, the inspector knows that it is not worthwhile to continue with the method. After that, the other questions are standing in the same order as they have been elaborated on in the previous part.

Also after each question, the inspector has the opportunity to write down some notes if more elaboration on the given answer is desired or if some uncertainties need to be addressed.

Table 25: Final input interface 1/2

Object name:	Lexkesveerbrug
Component:	Ligger

Legend	
O	On site reserch
B	Bureau study
B/O	On site research and Bureau study

#	Required information			Where to get the information	Possible answers	Fill in answer		Room for comments
	Must haves							
1	Are iron fibres are visible in the surface of the concrete?		O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n	Reuse is possible	
2	Are composite fibres are visible in the surface of the concrete?		O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n		
3	What is the general condition of the component?		O	Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard	4		
4	Can the component be transported?	Does the component fit within the dimensions of 3,00x4,00x27,00 meters?	B	Drawings	y = yes n = no ? = unknown	n		
		Weighs the component less than 35.000 kg?	B	Drawings	y = yes n = no ? = unknown			
		Is there room for the component to be transported with special transport?	B/O	Maps Visual inspections	y = yes n = no ? = unknown	y		
5	Can the component be disassembled without causing damage to the component?		B/O	Drawings Inspection reports Visual inspections	1 = yes, without the need of additional operations 2 = yes, but additional operations are necessary which causes no damage 3 = no, but the damage that is caused to the component is repairable 4 = no, but the component can still be used, although the damage can't be repaired 5 = no, the component can't be disassembled without causing total damage	4		
	Nice to have							
6	Is asbestos present?	Is the component build after 1983?	B	Pasport	y = yes n = no ? = unknown	n		
		Is het certain that asbestos is present?	B	Design report Research reports	y = yes n = no ? = unknown	?		
		Could there be a risk of presence of asbestos? (i.e. cast in tubes for cables or water drainage systems)	B/O	Drawings Visual inspections	y = yes n = no ? = unknown	y		
7	Is there is a risk of mixed in chlorides?	Is the component build after 1974?	B	Pasport	y = yes n = no ? = unknown	n		
		Is the component prefab?	B/O	Drawings Visual inspections	y = yes n = no ? = unknown	y		
8	Could internal sulphate attack have been a problem?	Are the aggregates sulphate containing?	B	Contract specifications (not standard)	y = yes n = no ? = unknown	?		
		does the component stand in a humid environment? (an environment that could have been exposed to at least fog or dew)	B/O	Inspection reports Visual inspections	y = yes n = no ? = unknown			
9	Could penetration of sulphites be a problem?	Is solely, or solely a combination of CEM I, CEM III/B, CEM III/C, CEM IV/A or CEM IV/B used as cement for the concrete?	B	Drawings Contract documents	y = yes n = no ? = unknown	n		
		Is there seawater within a range of 25 km?	B	Maps	y = yes n = no ? = unknown	n		

Table 26: Final input interface 2/2

10	Could ASR be a problem?	Is the component build after 2002?	B	Pasport	y = yes n = no ? = unknown	n	
		Is solely blast furnace cement being used?	B	Drawings Contract documents	y = yes n = no ? = unknown	?	
		does the component stand in a humid environment? (an environment that could have been exposed to at least fog or dew)	B/O	Inspection reports Visual inspections	y = yes n = no ? = unknown	y	
		Is there visible expansion and deformation of the concrete?	O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n	
		Are there visible cracks on the surface?	O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n	
		Are there visible alkali silicic gels present?	O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n	
		Are there visible pop-outs of concrete pieces?	O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n	
11	Are there any signs of corrosion?	Are there signs of reinforcement corrosion?	O	Inspection reports Visual inspections	y = yes n = no ? = unknown	n	
		Does the reinforcement only occur locally?	O	Inspection reports Visual inspections	y = yes n = no ? = unknown		
12	Are there cracks visible on the surface?	What is the width of the crack	O	Inspection reports Visual inspections	1 = cracks smaller than or equal to 0,2 mm, or no cracks 2 = cracks between 0,2 and 0,5 mm 3 = cracks more than 0,5 mm	3	
		Is it a constructive crack? (as a crack that decreases the load bearing properties of a component)	O	Inspection reports Visual inspections	y = yes n = no ? = unknown	y	
13	What is the residual lifespan based on the condition?	What is the designed life span?	B	Design report	fill in the designed life span ? = unknown	100	
		What is the condition of the component?	O	Inspection reports Visual inspections	1, 2, 3, 4, 5 or 6 according to the NEN 6727 standard	3	
14	What is the residual lifespan based on the designed value?	What is the designed life span?	B	Design report	fill in the designed life span (years) ? = unknown	100	
		What is the age of the component?	B	Pasport (DISK)	fill in the age (years) ? = unknown	30	
15	What is the residual lifespan based on chloride penetration?		B	Research reports	fill in the residual life span based on chloride penetration ? =unknown	60	
16	What is the residual lifespan based on carbonation penetration?	If this has been investigated, what are the results?	B	Research reports	fill in the residual life span based on carbonation penetration ? =unknown	?	
		What is the age of the component?	B	Pasport	fill in the age (years) ? = unknown	30	
		What is the carbonation depth?	O	Measure with small drill	fill in the carbonation depth (mm) ? = unknown	20	
		How deep the reinforcement is located?	B/O	Drawings Scanners	fill in how deep the reinforcement lies beneath the surface (mm) ? = unknown	35	
17	How is the component connected? (If multiple answers are applicable, the answer with the highest number should be filled in)		B/O	Drawings Inspection reports Visual inspections	1 = No fixed connection 2 = Indirect with external fixing devices 3 = Indirect indirect with internal removeable fixing device 4 = Indirect with internal non-removeable fixing device 5 = Via third chemical material 6 = Direct chemical	4	
18	Is extra equipment necessary for the retrieval of the component compared to the equipment that is needed for the demolition of the component?		B/O	Inspection reports Visual inspections	y = yes n = no ? = unknown	?	
19	For which environmental classes is the component suitable?	For which XC class is the component suitable?	B	Drawings	0 = no XC class 1 = XC1 2 = XC2 3 = XC3 4 = XC4 ? = unknown	2	
		For which XD class is the component suitable?	B	Drawings	0 = no XD class 1 = XD1 2 = XD2 3 = XD3 ? = unknown	2	
		For which XS class is the component suitable?	B	Drawings	0 = no XS class 1 = XS1 2 = XS2 3 = XS3 ? = unknown	2	
		For which XF class is the component suitable?	B	Drawings	0 = no XF class 1 = XF1 2 = XF2 3 = XF3 4 = XF4 ? = unknown	2	
		For which XA class is the component suitable?	B	Drawings	0 = no XA class 1 = XA1 2 = XA2 3 = XA3 ? = unknown	2	
20	What is the level of standardisation?		B/O	Drawings Inspection reports Visual inspections	1 = non load bearing prefab component 2 = load bearing prefab component 3 = cast in situ component ? = unknown	2	

Output interface

The output interface is shown in Figure 38.

At the top of the output, it is shown which component has been assessed and from which object the component is originating.
Just as for the input interface, it is immediately shown if the component can be reused or not based on the deal breaker questions. If reuse is possible the box turns green and if reuse is not possible the box turns red. If it turns out that reuse is not possible, a box with a description of why a component is rejected is given. Consequently, these are the sentences that can appear if a component is rejected:

- There are iron fibres present in the concrete.
- There are composite fibres present in the concrete.
- The general condition of the component is not sufficient for reuse.
- The component cannot be transported.
- The component cannot be disassembled without being destroyed.

The scores for the three categories are shown, both in a table and visualised in a triangle.

The automatically generated advice is shown based on the uncertainties that are still present in the answers. The following advice can be given as output, depending on the answers:

- If component is going to be reused in a humid environment, perform lab research for suplhate containing aggregates
- Investigate the presence of asbestos
- Perform lab research for mixed-in chlorides
- Perform lab research for ASR
- Lab research to determine the type of cement that is used
- Perform a potential measurement and determine the severity of the corrosion
- Perform chloride penetration research
- Perform research to carbonation depth
- Perform lab research to determine the environmental classes

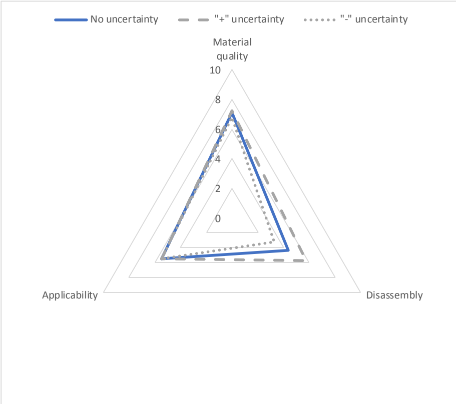
If a component could be at risk if it is reused in a certain environment, it appears in the 'risk' box. The following risks can be given as output:

- There is a risk of internal sulphite attacks if this component is to be reused in a humid environment.
- There is a risk of ASR if this component is to be reused in a humid environment.
- There is a risk of penetration of sulphites if the component is being reused within 25 km of seawater.
- There is a risk of reusing this component because of the presence of asbestos.

Also, the residual lifespans are visualised. With a visualisation of the residual lifespans, it is possible to get a better idea for what practical timespan a component can be reused.

Object name: Lexkesveerbrug
Component: Ligger

Is reuse posible?: **YES**



	Material quality	Disassembly	Applicability
No uncertainty	7,11	4,33	5,51
"+" uncertainty	7,24	5,75	5,51
"-" uncertainty	6,80	3,25	5,51

Reason for rejection:
-
-
-
-
-
-

Advice:
If component is going to be reused in a humid environment, perform lab research for suplhate containing aggre
Investigate the precense of asbestos
Perform lab research for mixed-in chlorides
-
-
-
-
-
-
-

Risks:
-
-
-
There is a risk of penetration of sulphites if component is being reused within 25 km of sea water

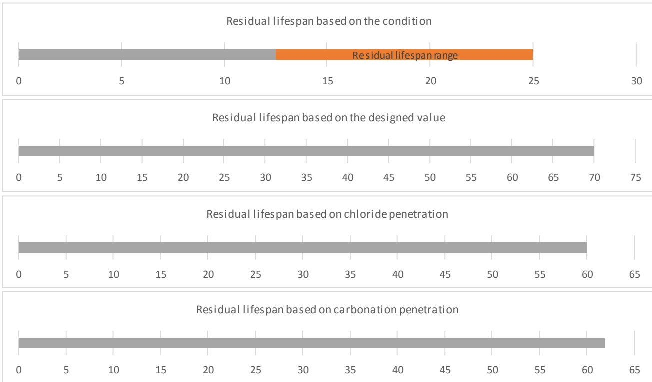


Figure 38: Final output interface