Master Thesis

Towards sustainable and circular maintenance strategies for (existing) civil construction objects

Developing a tool to stimulate the integration of sustainability and circularity via collaboration throughout the maintenance stage in the Dutch context

Written by

Menouschka R. Baldew

Final Version

Master Thesis

"We hold the future in our hands, together, we must ensure that our grandchildren will not have to ask why we failed to do the right thing and let them suffer the consequences"
(UN Secretary-General Ban Ki-moon, 2007)

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Written by
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Master of Science in Construction Management and Engineering at Delft University of Technology, Faculty of Civil Engineering and Geosciences, The Netherlands

[30/01/2023]

TU Delft Delft University of Technology

Colophon

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ARCADIS

Preface

As a young woman in engineering, I have always been fascinated by the concept of sustainability in a very broad sense. After moving to the Netherlands, I was very impressed by how much awareness there already is regarding sustainability within the built environment and the civil engineering sector. However, I also noticed very quickly that there are still opportunities within this field of research. Throughout my study period at the Masters' Construction Management and Engineering (CME) at TU Delft, I became more curious about the concepts of circular economy and sustainability integrated into my field of study. For that reason, I choose the 'Design&Integration' (D&I) specialization within CME. After doing a research internship in the summer of 2021 at the municipality of Amsterdam, I was even more intrigued to research opportunities for sustainability integration within the civil engineering sector. When it was time to start searching for a thesis topic, I quickly knew that the maintenance of existing civil objects combined with sustainability was something I wanted to explore more.

I would like to thank the members of my thesis committee at TU Delft for the knowledge-sharing and support. I want to start by showing my gratitude towards my first supervisor, Dr. Dominika Teigiserová, for her input, bi-monthly meetings, and for always showing her enthusiasm throughout the research period. Also, a word of appreciation to my second supervisor, Dr. Yuang Yang, for sharing his insights regarding the civil construction sector with me throughout the whole process. Furthermore, I want to show my gratitude to the chair of my thesis committee, Dr. Daan Schraven. Throughout the process, he always shared his vision and experiences with research which helped me throughout the process. And last but not least, I want to say thank you to Henk-Jan Schat, my daily supervisor at Arcadis, for his support and knowledge-sharing throughout the period. Always triggering me to think outside the box. The same goes for the head of the Contracting department at Arcadis, Ronald van Schie.
And finally, for the ones close to my heart: I want to thank all of you for the kind words, immense support, and love I received throughout my whole study period in Delft. Especially my parents on the other side of the ocean, this one is for you.

As a young child growing up, I always wanted to create an impact, and change the world. And this is just the start of my journey to do so.

Have a good read!
Menouschka R. Baldew

Delft, Netherlands
30/01/2023

Executive Summary

The Dutch government is aiming to have a fully circular economy by 2050. To achieve this goal, they want to: (i) reduce carbon dioxide (CO_2) emissions by more than 49% in 2030 and in 2050 by 95% compared to the numbers in 1990 (Rijksoverheid, 2019) and (ii) reduce the use of primary materials by half. These goals need to be reached within all sectors, thus also within the construction industry. The lifecycle of projects within the civil construction sector consists of various stages, ranging from initiating the idea to procuring and tendering, designing the object, constructing, operating, and maintaining the object to eventually demolishing it at the end-of-life stage (Renuka et al., 2014). Currently, the maintenance strategies applied for example for bridges are rather cost-oriented than sustainability-oriented (G. Xu & Guo, 2022). Based on the research context and the identified research problem, the following main research question is formulated:

In what way can the dimensions covering sustainability and circular economy be integrated during the pre-procurement stage and throughout the execution of maintenance works for existing civil engineering objects?

Methodology

To answer the main research question, a qualitative design-thinking research methodology was applied, namely the "Double Diamond Method", which is considered to be an iterative process within four stages of discovering, defining, developing, and eventually delivering. The first part of the "Double Diamond Method", discovering and defining, focuses on executing literature review based on concepts related to the sub-research questions such as barriers and enablers, collaboration, and indicators. During the first part, also semi-structured interviews were conducted with 13 experts from both public and market parties operating in the Dutch civil engineering sector. Then, the results of both the literature review and semi-structured interviews led to the design brief. The second part of the Double Diamond, developing and delivering, focuses on developing and delivering a tool that could enhance the sustainability and circular economy via collaboration between involved parties in the maintenance stage of existing civil objects.

Results

The results of applying the research methodology are twofold. The first part covers the results of the literature review and semi-structured interviews, whereas the second part resulted in the development of the tool in MS Excel.

Barriers & enablers

the various barriers are clustered into five (5) levels, namely (1) organizational/ social level, (2) construction industry level, (3) regulatory level, (4) environmental level, and (5) economic level. The levels furthermore consist of various barriers such as lack of knowledge, lack of

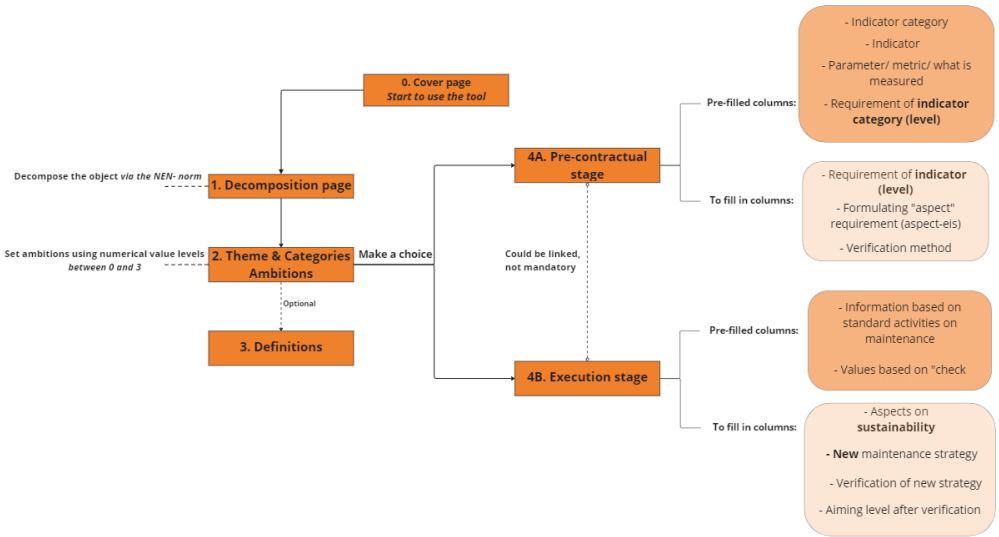
awareness, and lack of collaboration among actors in the sector. An important enabler that could overcome to a certain extent some of the identified barriers is collaboration. Throughout the semi-structured interviews, barriers also related to lack of collaboration, lack of knowledge, and the maintenance part of the sector being relatively conservative/traditional were identified by interviewees. There is thus consensus found comparing the literature and interview results on the concept of barriers and enablers to stimulate sustainability and circular economy within the maintenance stage.

Indicators

Review of literature, together with a process of analyzing indicators based on processes and requirements found in literature, led to a list of indicators relevant to stimulate sustainability and circularity within the maintenance stage. The indicators were divided into 4 main themes based on the dimension of sustainability and circular economy, namely environmental impact, social impact, economical impact and Circularity impact

The tool – Maintaining sustainably and circularly in a collaborative way

The developed tool can be used to stimulate sustainability and circular economy within two phases, namely the **pre-contractual stage,** and the **execution stage**. Below, a simplified overview of the content of the tool and the processes applicable to the tool is shown.



From a variety of perspectives, the interview results show that people involved in the maintenance sector are focused on maintaining the object as it is always done. Sustainability might introduce risks and uncertainties. With the development of this tool, a first step is made to help the actors involved in this stage of the lifecycle. Instead of prescribing what must be done, the tool gives freedom to the user to what extent they want to consider sustainability in the maintenance by assigning values to these aspects. The tool allows exploring what are ambitions, but also what is possible in relation to sustainability and circular economy. With a positive outcome on the validation, the tool is ready to be applied within the practice and test more!

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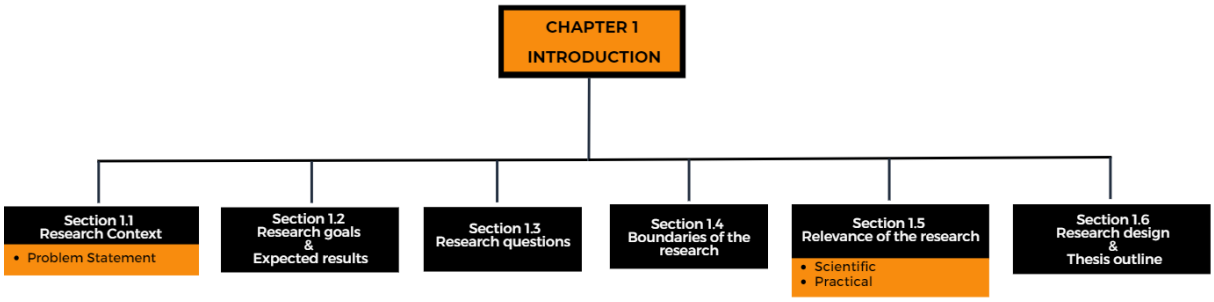
List of Abbreviations/ Acronyms

AHP	Analytical Hierarchical Processes
CE	Circular Economy
CO_2	Carbon Dioxide
DDM	Double Diamond Method
EU	European Union
FSSD	The Framework for Strategic Sustainable Development
FMECA	Failure Mode, Effects & Criticality Analysis
GAO	Gebruikersafhankelijk onderhoud *(In English: Use-dependent maintenance)*
GHG	Greenhouse Gasses
HVWN	Hoofdvaarwegennet *(In English: Main Waterway Network)*
HWN	Hoofdwegennet (*Main Road Network*)
HWS	Hoofdwatersysteem *(In English: Main Water System)*
IenM	Ministry of Infrastructure and Water Management
KPI	Key Performance Indicators
LCA	Lifecycle assessment
LCC	Lifecycle costs
LCM	Life-cycle management
NO_2	Nitrogen dioxide
O&M	Operation and Maintenance
P-IHP	Prestatie-gestuurd Instandhoudingsplan
PBC	Performance- Based Contract
PSS	Product-service system
RDM	Research Design Method
RWS	Rijkswaterstaat
SAO	Storingsfankelijk onderhoud *(In English: Failure-dependent maintenance)*
SD	Sustainable Development
SVO	Standaard Verzorgend Onderhoud *(in English: Standard Maintenance Activities)*
TAO	Toestandsafhankelijk onderhoud *(In English: State-dependent maintenance)*
TBL	Triple Bottom Line
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
UN	United Nations
V&V	Verification & Validation
VenR	Vervanging en Renovatie opgave *(In English: replacement and renovation task)*

List of Definitions

Asset management	"Coordinated activity of an organization to realize value from assets" (Okoh, 2019)
Circular Economy	"An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017)
Collaboration	"Tools that provide all stakeholders (dependent on their user privileges) access to the most up-to-date information. Tools also provide a detailed overview of the project status allowing management to track progress, etc." (Ahern et al., 2015; Shelbourn et al., 2007)
Construction industry	"The industrial branch of manufacturing and trade related to building, repairing, renovating, and maintaining different infrastructure objects" (Hussain et al., 2022)
Design thinking	"Design thinking is generally defined as an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign" (Razzouk & Shute, 2012)
Indicator	"A measurable value that demonstrates how effectively a company is achieving key business objectives" (Griffiths et al., 2003)
Sustainable development	"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987)
Stakeholders	"Those who can influence processes and final results, whose environments are affected by the project, and who are to receive both (in) direct wins and losses"
Sustainable (development) strategy	"a coordinated, participatory, and iterative process of thoughts and actions to achieve economic, environmental, and social objects in a balanced and integrative manner" (Lyytimäki, 2012)
Sustainability	"The adoption of principles of sustainable development in infrastructure development projects execution, by striking a balance between environmental protection wellbeing and economic prosperity for the benefits of both the present and future generations" (Munyasya & Chileshe, 2018)
sustainability criterion	"The yardstick against which a sustainability indicator is measured" (Sahely et al., 2005)
Sustainability indicator	"A sustainability indicator represents an aspect of sustainability in each proposed alternative" (Koo et al., 2009)
Stakeholder	"Those who can influence processes and final results, whose environments are affected by the project, and who are to receive both (in) direct wins and losses" (T. H. Y. Li et al., 2016)
Theme	"A pattern that captures something significant or interesting about the data and/or research question" (Stranges et al., 2014)
Tool	" A piece of equipment that you use to help you do a job"

1. Introduction



1.1 Research context

The Dutch government has certain goals for the upcoming years. One of these goals is aiming to have a fully circular economy by 2050. To achieve this goal, the Dutch government wants to: (i) reduce carbon dioxide (CO_2) emissions by more than 49% in 2030 and by 95% in 2050 compared to the numbers in 1990 (Rijksoverheid, 2019) and (ii) reduce the use of primary materials by half. These goals need to be reached within all sectors, thus also within the construction industry.

The construction industry is an overarching term and is defined as follows: "the industrial branch of manufacturing and trade related to building, repairing, renovating and maintaining different infrastructure objects"(Hussain et al., 2022). To avoid confusion about the term "construction industry", it is worth mentioning that the construction industry focuses on more than only the construction stage of infrastructure objects (Hussain et al., 2022). The total lifecycle of projects within the civil construction sector consists of various stages, ranging from initiating the idea to procuring and tendering, designing the object, constructing, operating, and maintaining the object to eventually demolishing it at the end-of-life stage (Renuka et al., 2014). Each stage within the lifecycle of projects in the civil construction sector is based on certain requirements and objectives that need to be achieved. **Appendix A** elaborates on the various stages within the total lifecycle and how these stages are linked to one another. Research by 'Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (*TNO*)' shows that within the construction industry, the largest sources of CO_2 are construction equipment fuel, electricity use, asphalt, and cement (TNO, 2021). Due to the goals set by the Dutch government as mentioned above, it comes as no surprise that the construction sector might need to reconsider its way of executing activities.

Within the civil construction sector, there is a focus on a range of civil infrastructure assets or civil engineering assets (Mahmoodian et al., 2022) such as roads, bridges, tunnels, and sluices. Large quantities of these objects are constructed for a lifespan between 60 and 120 years and therefore have a relatively long service life (TNO, 2021). Well-functioning objects are the result of timely maintenance activities carried out by the asset owners, or in some cases with help and input provided by third parties such as contractors. In the Netherlands, most civil engineering structures are either owned by the Ministry of Infrastructure and Water

Management (*IenM*), a province[1], a municipality[2], or a water board[3] (*in Dutch: Waterschap)*. The authority 'Rijkswaterstaat (*RWS*)' manages the objects on behalf of the abovementioned ministry. In total RWS manages three (3) national networks. Each one of these networks consists of a range of civil engineering objects (*in Dutch: kunstwerken*), all categorized based on their functionality (Ministerie van Infrastructuur en Waterstaat, 2022). Below a description is given of the three (3) national networks (Ministerie van Economische Zaken, 2013):

I. Hoofdvaarwegennet (*HVWN - in English: Main Waterway Network*)- covers approximately 3437 km of canals and rivers, as well as sluices and bridges;
II. Hoofdwatersysteem (*HWS – in English: Main Water System*)- covers 90192 km² of surface water, as well as dunes, dikes, weirs, and storm surge barriers;
III. Hoofdwegennet (*HWN - in English: Main Road Network*)- covers roads, viaducts, tunnels, and aqueducts.

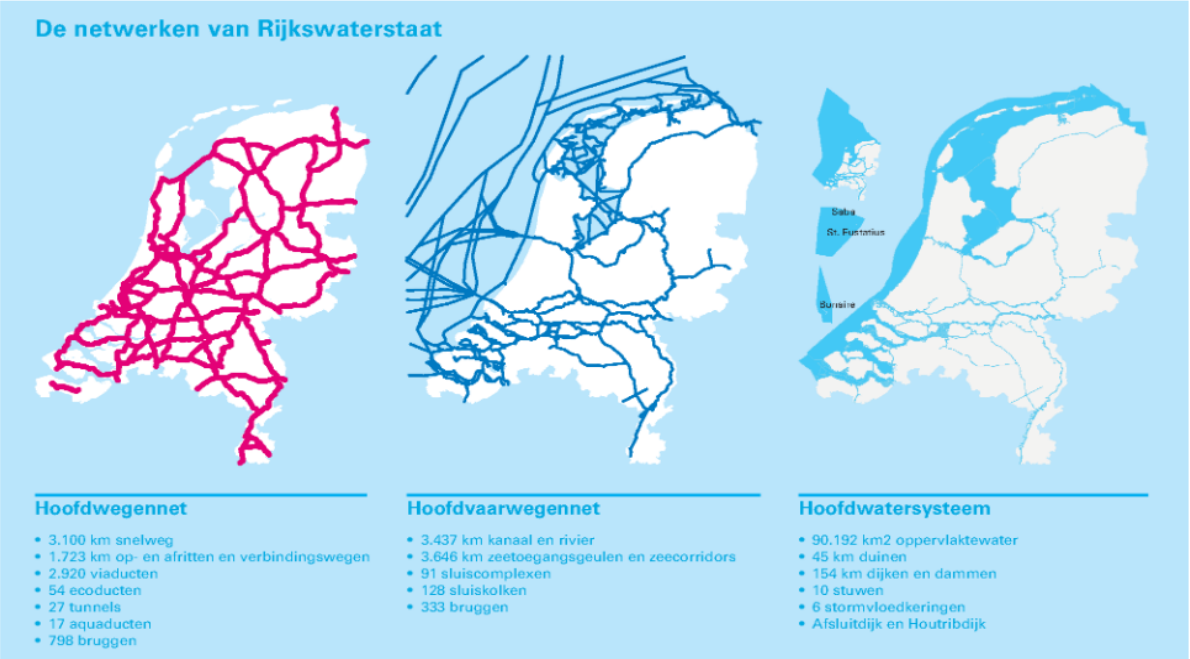


Figure 1 Overview of the networks managed by RWS (Ministerie van Economische Zaken, 2013)

Figure 1 shows an overview of all the networks managed by RWS, furthermore showing that the networks are stretched all over the country. Research institution TNO published a report indicating that the number of civil engineering structures in the Netherlands varies from eighty-five thousand (85000) bridges and viaducts (*in Dutch: bruggen en viaducten*) to seventy-eight hundred (7800) pumping stations (*in Dutch: pompgemalen*) (TNO, 2021). Depending on factors such as their functionality and mechanisms, these objects are subdivided into practice. An example found within practice shows that there are bascule bridges (*in Dutch: beweegbare bruggen*) and fixed bridges (*in Dutch: vaste bruggen*).

[1] In the Netherlands, there are in total 12 provinces
[2] In the Netherlands, there are in total 344 municipalities
[3] In the Netherlands, there are 21 waterboards

It is estimated that the existing civil engineering structures in the Netherlands are currently worth around 300 billion euros (TNO, 2021).

There is a shift witnessed from building new to prolonging the life of existing assets by maintaining, renovating, and/or replacing these objects (Nicolai & Klatter, 2015). Maintaining, renovating, and replacing is part of the "operation and maintenance *(O&M)*" phase; this is considered to be one stage within the total lifecycle (Renuka et al., 2014) as described in **Appendix A**.

Focusing solely on the maintenance component of O&M, attention is driven toward the main objective which includes maintaining the functionality of the object, or asset. This will eventually lead to prolonging the life of such an asset. Part of the work within maintenance is related to asset maintenance management which includes various activities ranging from inspections to condition ratings and eventually deciding on maintenance strategies, minor changes, or major replacement works (Mahmoodian et al., 2022). Especially the latter is getting more attention these days in the Dutch practice via the "vervanging en renovatie opgave" (*In the Dutch context, this is often referred to b as the 'VenR opgave' by RWS; in English: replacement and renovation task).* This initiative emphasizes the replacement and renovation works of existing civil engineering structures. Published studies show that a large number of civil engineering structures in the Netherlands were built around the post-World War II era (Klerk & Den Heijer, 2017; TNO, 2021). As a result, these structures will reach the end of their technical lifespan in the upcoming years and therefore replacement, repair, and/or large upgrade works need to be taken into account (TNO, 2021; van Breugel, 2017). Nevertheless, the daily maintenance activities in order to keep the functionality of the objects are still necessary to be executed.

Currently, however, the maintenance strategies applied for bridges are rather cost-oriented than sustainability-oriented (G. Xu & Guo, 2022). Research on sustainable bridge design and maintenance as an example shows that there are nine (9) drivers for maintenance strategies considered by experts, namely (1) finance, (2) speed of completion, (3) funding choices, (4) functionality, (5) buildability, (6) maintainability, (7) minimal disruption to traffic, (8) construction technique, and (9) constructability (Balogun et al., 2020). The same research also concluded that environmental considerations related to CO_2, nitrogen dioxide (NO_2), and other Greenhouse Gases (*GHG*) associated with the actual maintenance activities are not considered. The component of sustainability within the maintenance stage is often seen as a 'tick-box exercise' (Balogun et al., 2020).

The following can be summarized based on the above research context:

(i) Civil construction assets require maintenance works to keep their functionality. This is also the case for civil engineering objects in the Dutch context (Klerk & Den Heijer, 2017; Mahmoodian et al., 2022; Nicolai & Klatter, 2015; TNO, 2021);
(ii) Within the maintenance stage of these civil construction objects such as roads, bridges, and sluices various activities are carried out ranging from inspections to condition ratings eventually leading to decisions on maintenance strategies, minor changes, or major replacement works (Mahmoodian et al., 2022);
(iii) Within maintenance activities and consideration of those, the concept of sustainability is still a "tick-the-box" exercise rather than considering sustainability in a broad perspective and detail (Balogun et al., 2020; G. Xu & Guo, 2022);
(iv) The Dutch government aims to have a fully circular economy by 2050. Next to this, they want to (1) reduce carbon dioxide (CO_2) emissions by more than 49% in 2030 and 2050 by 95% compared to the numbers in 1990 (Rijksoverheid, 2019) and (2) reduce the use of primary materials by half. Achieving these objectives might also lead to including (more) sustainable maintenance activities within the civil construction sector;
(v) From a more practice-oriented perspective, a large amount of the civil engineering objects in the Netherlands were built around the 60s of the last century. These objects are mainly managed by RWS. This is the case for all three national networks managed by RWS, namely (a) 'HVWN', (b) 'HWS', and (c) 'HWN' which are described earlier in the chapter.

1.1.1 Problem statement

The conclusion from points (i) until (v) shows that there is a need to re-consider current maintenance strategies applied for civil engineering objects to achieve goals set by the national government such as having a fully circular economy by 2050. Research shows that the traditional way of applying maintenance strategies to civil engineering structures may no longer be feasible considering the several challenges the sector is facing. Innovative solutions and reasoning are needed to be explored. This can be done together with partners, market players, and the consideration of existing processes. Aspects such as sustainability and circularity are less visible and barely included in current maintenance activities. Based on the above, the following problem statement is formulated:

"With the goals set by the national government to have a fully circular economy in 2050, it is necessary to re-evaluate the current maintenance strategies for existing civil works within the Netherlands, due to little to no sustainable as well as circular aspects applied"

1.2 Research goal & Expected results

With this research, an attempt is made to incorporate concepts of sustainability and circularity in the process of (1) the pre-contractual stage of maintenance contracts and (2) the execution stage of the maintenance activities for assets within the 'HVWN' network managed by RWS. Furthermore, there is the aim to fill the gap and identified problems described in previous sections by understanding the reason behind the missing elements of sustainability currently incorporated in the maintenance stage. A suggestion to do so is by developing a tool, that could not only stimulate the integration of sustainability but next to that also enhance collaboration, decision-making, and monitoring processes between the client (*in Dutch: opdrachtgever)* and the contractor (*in Dutch: opdrachtnemer)*.

1.3 Research questions

Based on the problem statement above, the following main research question is formulated:

In what way can the dimensions covering sustainability and circular economy be integrated during the pre-contractual stage and throughout the execution of maintenance works for existing civil engineering objects?

Due to the complexity of the main research question as stated above, six (6) sub-research questions are formulated. These questions are based on the chronological order of information necessary to answer the main research question:

SQ1: What are applicable definitions for sustainability and circularity in the context of maintenance? Due to the importance of concepts such as sustainability and circularity within this research, it is necessary to define these concepts. Exploring various definitions found in the scientific field will lead to stating definitions for both sustainability and circularity that are fit for the context of this research.

SQ2: What methodology can be applied to design and develop a tool to stimulate sustainability and circular economy in the maintenance stage? This sub-question is focused on exploring the suitable methodological approach to the identified problem. Answering this sub-question will result in an overview of the various research methodologies that will be used to gather data, design, and develop a tool applicable to integrate sustainability and circularity within the maintenance works.

SQ3: What are the barriers and enablers for stimulating sustainability and circular economy within the maintenance stage? Reviewing existing data will result in an overview of barriers that are currently withholding sustainable maintenance strategies. Next to that, the review of enablers useful to the identified barriers will also be taken into account.

SQ4: What is the effect of collaboration on stimulating sustainability and circular economy within the maintenance stage? This sub-question will explore the effect(s) of collaboration on stimulating sustainability and circularity within the maintenance of existing civil construction objects.

SQ5: What are the requirements for developing a tool that could be used to stimulate sustainable maintenance strategies? Based on the information gathered throughout the research, the requirements for designing and developing the tool will be set. These requirements will be used as a basis for the design and development process.

SQ6: What procedures can help practitioners effectively implement and integrate sustainability and circularity in the maintenance stage? With the practical side of the industry also involved in the research to a certain extent, this sub-question will answer how the developed tool can be used within the practice, including the added value to the practice.

1.4 Boundaries of the research

There are certain boundaries set to make the research manageable within the allocated time and available resources:

- **The research company**

  The research is carried out in collaboration with the Engineering Consultancy bureau 'Arcadis Nederland B.V' within the Contract Management department. For this research, it is considered to have close contact with other departments within the company, such as asset management. Due to its large client base and expertise in different projects, the company advises and assists both the public sector and market parties. This gives the research extra weight since the perspective of both sides can be included. The research will only focus on applications in the Dutch civil engineering sector, due to regulations and processes that might differ in comparison to other countries.

- **Type of civil engineering structures**

  In the Netherlands, RWS maintains the three (3) networks as described in **section 1.1**. For this research, it is chosen to solely focus on the objects within the 'HVWN network' (*In Dutch: Hoofdvaarwegennet*; *in English: Main Waterway Network*). As shown in **Figure 1**, objects within this network are lock complexes (*in Dutch: sluiscomplexen)*, lock chambers (*in Dutch: sluiskolken)*, and bridges (*in Dutch: bruggen)*. These objects overall consist of the following four (4) main components namely: (1) civil part, (2) steel part, (3) mechanical part, and (4) installations. Especially (3) and (4) are components that are not part of objects within the 'HWN network' and therefore could be of added value to include in the research. Some objects within 'HWS network' also contain components (1) until (4), however, due to the time limitations of the research, it is decided to only focus on objects within the 'HVWN network'.

- **Responsibility allocation**
  In the Dutch context, there is no fixed organizational setup for allocating the responsibilities of the maintenance of civil engineering structures. In most cases, RWS is the main owner of the assets. Depending on the contract type, the responsibilities regarding management and maintenance can be allocated to third parties such as a contractor. Current analysis shows that the contractor has a lot of freedom in carrying out the work (Alsharqawi, 2018). But, to stimulate sustainability closer collaboration might be required.
- **Contract types and plans**
  For the maintenance activities of existing civil engineering objects by RWS, mainly Performance-Based Contracts (*PBCs; In Dutch: prestatiecontracten;)* are awarded. For that reason, the focus of the research will only include this type of contract. Next to contracts, there are also plans delivered containing the strategies. These will also be considered for the research.

1.5 Relevance of the research

The research and the results must also add value to the scientific community. Nevertheless, with the research being carried out in collaboration with Arcadis Nederland, the practical side is also taken into account.

1.5.1 Scientific relevance

Considering the identified problem on a global level, organizations such as the United Nations (*UN*) have been researching principles to adopt in sustainable infrastructure planning and development. In a report published by this organization, it is further explained that evidence-based decision-making is considered an important aspect of sustainable infrastructure (UNEP, 2021). Furthermore, monitoring of the object together with the involvement of stakeholders should also be considered. From the report by the UN (UNEP, 2021), it is concluded that the focus for adopting sustainability within the infrastructure sector is currently mainly on new to-be-built assets and less focused on existing objects. This is something to consider more in-depth as the majority of existing civil engineering objects in the western part of the world, including the Netherlands, were built after the world-war II era. Additionally, aspects related to knowledge, material behavior, and structural performance were then substantially less developed compared to today (Scope et al., 2021). The same can be concluded about sustainability and circular economy due to the growing interest and importance of these, especially to include throughout the lifecycle of civil construction objects (TNO, 2021).

Within the scientific community, there have been various studies done (Balogun et al., 2020; Coenen et al., 2021; Du et al., 2014; Lingegård et al., 2021; Navarro et al., 2021) that emphasize on the integration of sustainability and circularity within the early stages of the lifecycle such as procurement, design, and construction of civil objects. As an example of one of the studies (Coenen et al., 2021), a framework was developed that can be of added value to the

procurement phase. However, more specific research focusing on the integration of sustainability and circular economy in the stages after construction, such as the maintenance stage, is under-exposed within the scientific field. Retaining the value of an asset can be best captured by maintaining this. It is furthermore confirmed that maintenance is important to achieve a circular economy (Ellen MacArthur Foundation, 2013; Ferreira, 2018), due to its service-prolonging character (Scope et al., 2021). Extending the service life of structures could be considered an attractive sustainable solution (Scope et al., 2021), however, they do not further explore these solutions within the scientific field. With this research, attention is given to this aspect.

Evaluating maintenance strategies with the use of indicators (Arya et al., 2015; van Breugel, 2017) can help achieve and consider sustainability and circular economy throughout the maintenance stage. It found that elaborate research has been done on sustainable indicators and assessment methods (for e.g (Chen et al., 2020; Faber & Sorensen, 2002; Vilutiene & Ignatavičius, 2018)). However, there is no complete process in which current maintenance strategies for existing civil objects are evaluated and re-considered with the help of sustainability and circularity indicators. Even with the impact of the maintenance on the environment, society, and the economy widely causing concerns among academics (Chen et al., 2020), it is yet not fully researched. With the focus then on indicators, it is found that the environmental pillar and economic pillar of sustainability are receiving more attention compared to the social aspect of it (Chen et al., 2020; Scope et al., 2021). Integration and equal consideration of all three pillars are essential to achieve sustainability.

1.5.2 Practical relevance

As mentioned in the introduction of this chapter, the current worth of civil engineering assets in the Netherlands is around € 300 billion (TNO, 2021). Changing views by the national government (Rijksoverheid, 2019) show that there is an urge from the practice to explore the possibilities of maintaining existing civil engineering structures by considering more in-depth concepts such as sustainability and circular economy. Good to acknowledge is that the asset owners often do not execute the works themselves, but award the works via procurement to market parties (Rijkswaterstaat, 2022). Clients and contractors often use the expertise of (engineering) consultancies during this stage. With the research being executed in collaboration with Engineering consultancy 'Arcadis Nederland B.V.', more insights will be gained from the practice side. Market parties like engineering consultancies and contractors can stimulate the process and decision-making by collaborating with the client. This can lead to integrating more sustainable and circular performance agreements in contracts, and throughout the execution. Conversations in the earlier stages of the research process with experts show that parties involved in the maintenance stage stated that to achieve goals related to circularity, there should be a shift in the current manner of working. This research will be of added value to practice since there is currently no strategic and systematic manner in which the client and contractor can consider sustainability and circularity in the maintenance stage of existing civil engineering objects.

1.6 Research design & Thesis outline

The content of the thesis is based on answering the various sub-research questions mentioned in **section 1.3**. **Figure 2** gives an overview of the outline of the thesis together with various key takeaways for each chapter. The reader just read the **first chapter** which covered an introduction to the research problem and research questions. **Chapter two (2)** will present the scope of the research in the form of a theoretical scope. To further research the problem at hand, a research methodology is chosen to help gather, analyze and investigate necessary data. This is described in **chapter three (3)**. Considering the problem at hand, and the aim of the research, it is most suitable to apply design thinking principles due to the aim of developing a tool. **Chapter four (4)** will cover the analysis and results based on the application of the methodology described in the previous chapter. Furthermore, **chapter five (5)** will critically evaluate and discuss the outcomes of the study. This chapter will furthermore discuss the limitations of the research. **Chapter six (6)** will elaborate on the conclusion of the research and **chapter seven (7)** will conclude with a set of recommendations for further research.

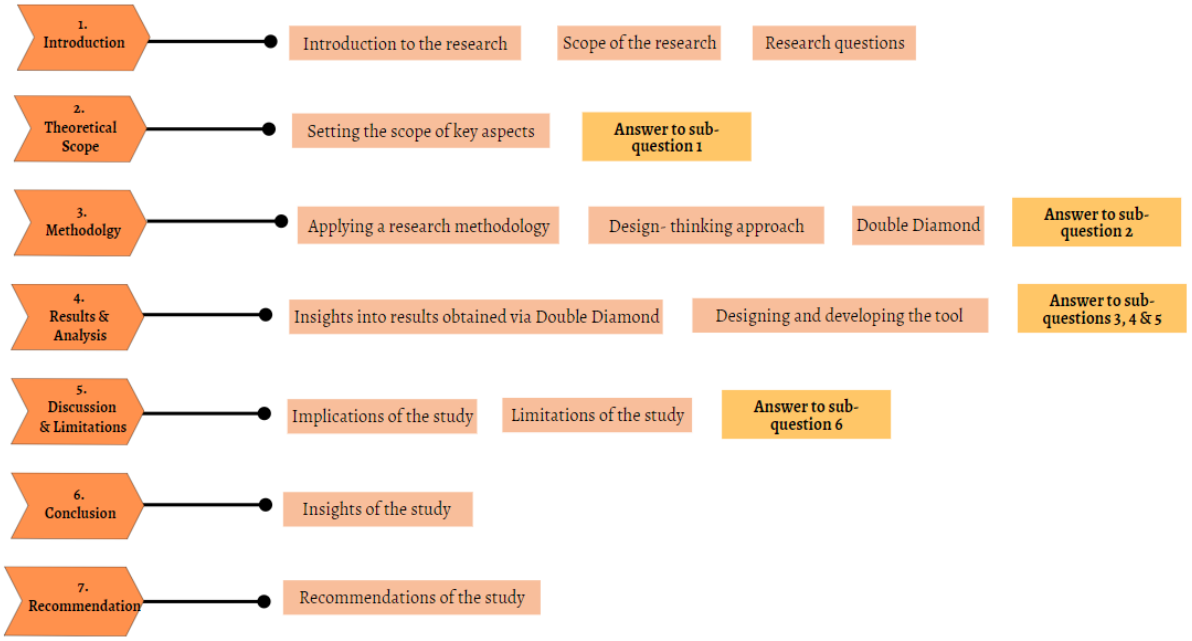
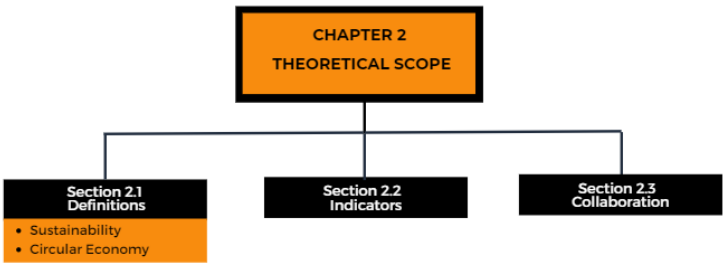


Figure 2 Research Design – Thesis outline including key takeaways from each chapter

2. Theoretical Scope



The second chapter of the thesis is dedicated to defining key concepts relevant to the research. This chapter will provide an answer to the first sub-research question (**SQ1**) as mentioned in the introductory chapter and sounds as follows: *'What are applicable definitions for sustainability and circularity in the context of maintenance?'*

2.1 Definitions- Sustainability & Circular Economy

As sustainability and circular economy are key aspects, it is important to define these terms in the research context. The terms are often used interchangeably and defined by authors in various ways. Due to the various definitions found in the literature on these key aspects, an elaborate review of the process for finding suitable definitions can be found in **Appendix B**.

Sustainable Development

From reviewing numerous articles on the terms 'sustainability' and 'sustainable development (*SD*)', it is concluded that these two terms are often used interchangeably; this is also confirmed by others in the scientific field (Glavič & Lukman, 2007; Olawumi & Chan, 2018; Sartori et al., 2014). Sustainable Development as defined in the Brundtland Report (Brundtland, 1987) is considered to be most fitted for this research. This definition sounds as follows:

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987)

Sustainability

Within the scientific field, there are various definitions found on sustainability by different authors (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Munyasya & Chileshe, 2018; Sahely et al., 2005). Reviewing these definitions, resulted in finding the fitted definition applicable to this research namely:

"The adoption of principles of sustainable development in infrastructure development projects execution, by striking a balance between environmental protection wellbeing and economic prosperity for the benefits of both the present and future generations" (Munyasya & Chileshe, 2018)

Considering the above definition, it could be said that the research at hand focuses not specifically on infrastructure development, however, the focus is on developing sustainable strategies to be implemented into the maintenance stage of the lifecycle. In that manner, the term "infrastructure development" could be linked with the research. Next to that, the definition also implies the connection to sustainable development and directly includes 2 out of 3 dimensions of sustainability namely environmental protection and economic prosperity. The social aspects are indirectly included in the definition due to referencing the present and future generations. Sustainable development is achieved via the three (3) dimensions of sustainability namely (1) the environmental, (2) the economic, and (3) the social dimension.

Within the field of science, there is a debate going on regarding the relationship between the three dimensions of sustainability (Tennakoon & Janadari, 2022). This is elaborated on in **Appendix B**. Considering the research at hand, the "circles of sustainability" often referred to as the "triple bottom line (*TBL*)" or "weak sustainability" is most fitted for this research due to (i) the focus on all three dimensions, (ii) the consideration from the economic perspective and (iii) its link to the circular economy.

Circular Economy

Analyzing the different definitions of CE shows that the majority of these include the link between economic systems and environmental aspects, 2 out of 3 dimensions of sustainability. One definition found on CE (Kirchherr et al., 2017) includes all 3 dimensions of sustainability including the way these can be incorporated on various levels. Another definition (Geissdoerfer, Savaget, Bocken, & Jan, 2017) includes aspects such as resource input and waste, emission, and energy leakage as components to be minimized via various ways such as maintenance. In **Appendix B** more definitions of CE can be found. Within this research, maintenance is considered to be an important key component. It is concluded that the broadness of the following definition of CE is most fitted here:

> **"An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations"** (Kirchherr et al., 2017)

CE is based on the concept of closed-loop systems compared to the traditional, linear economy, or make-use-dispose line of thinking (Ellen MacArthur Foundation, 2013). Research (Geissdoerfer, Savaget, Bocken, & Hultink, 2017) on closed-loop systems shows that it promotes more appropriate and environmentally suitable use of resources. Applying the concept behind CE will lead to attaining circularity. The definitions found for CE and

circularity show strong links to sustainability and sustainable development (*SD*) which will be explored next.

Sustainability & Circular Economy

There have been attempts made in the scientific world to fill in the gap and understand the relationship better between SD and CE (Geissdoerfer, Savaget, Bocken, & Jan, 2017; Mart & Aguayo-gonz, 2019).

To start with, there is a contrast in goals between these two. On the one hand, CE focuses on closed-loop systems, eliminating resource inputs, waste, and emissions. The main priority here is the economic system with primary benefits to the environment and less/ indirectly to the social aspects. The CE has placed the environmental dimension of sustainability in the foreground to recognize the need for a favorable economic context, but has, on many occasions, left the social objective out of the scope (Mart & Aguayo-gonz, 2019). On the other hand, the goal of sustainability is more open-ended due to the dimensions and the broader definition set by different authors. With sustainability, an attempt is made to create equality and a balance among the three dimensions.

Then, considering the relationship, it is implied that the concepts of CE and sustainability are somewhat diffused (Geissdoerfer, Savaget, Bocken, & Jan, 2017). There is this rising attention to the concept of CE addressing issues within the sustainability concept focusing on environmental, social, and economic challenges. CE could be viewed as a condition to reach sustainability (Geissdoerfer, Savaget, Bocken, & Jan, 2017). CE strategies can be of effective use within the 3 areas of sustainable value namely environmental value, economic value, and social value (Mart & Aguayo-gonz, 2019).

The added value of sustainability in the context of CE

While circularity has a positive influence on certain aspects of sustainability, it does not elaborately considers the social dimension. For that reason, it could be relevant to include sustainability explicitly in the research since missing dimensions are identified within the concept of CE. The expectation is that the adoption of the CE will fundamentally transform economic activities, thereby limiting dependence on non-renewable and intensive carbon flows, and leaning towards more sustainable production and consumption. There is a prioritization of economic systems with primary benefits to the environment with CE (Geissdoerfer, Savaget, Bocken, & Jan, 2017). To achieve the goals related to sustainable development, it is required to integrate tools, techniques, and frameworks such as circularity (Mart & Aguayo-gonz, 2019). In summary, **Figure 3** shows an overview of the applicable definitions suitable for the context of the research. Defining the terms also provides an answer to sub-research question one (**SQ1**): ***'What are applicable definitions for sustainability and circularity in the context of maintenance?'***

Figure 3 Chosen definitions for various relevant terms in the context of this research

2.2 Indicators

Measuring the success of anything can be done according to key performance indicators (*KPIs*) (Hristov, 2019). To measure progress toward resource productivity, indicators of success are required (Griffiths et al., 2003). Indicators are useful for monitoring and measuring the state by considering a manageable number of variables or characteristics. An indicator can be defined as follows:

"a measurable value that demonstrates how effectively key (business) objectives are achieved" (Griffiths et al., 2003)

Indicators are a result of applied strategies. The indicators can be obtained through the data generated from activities, data that is gathered daily, or during maintenance works. There is a need to address the dimensions of sustainability via indicators to reconsider maintenance strategies since this is currently limited (Rohman et al. 2017, Sutrisna & Goulding 2019).

An identified way to assess progress toward sustainability is by using indicators (Lyytimäki, 2012). As sustainability and circular economy are central concepts to this research, it is worthy to select indicators that reflect these concepts.

Sustainability indicators

Dimensions of sustainability are often evaluated through sustainability indicators. These indicators can be categorized into environmental, economic, and social categories (Balkema et al. 2002). A sustainability indicator is defined as follows:

"A sustainability indicator represents an aspect of sustainability in each proposed alternative" (Koo et al., 2009)

Furthermore, to achieve sustainability, there should be a balance between all three dimensions of sustainability and none should be neglected (Kordi et al., 2021). However, it is concluded that not all dimensions receive the same attention and/or are included due to reasons such as lack of awareness and complications in definitions.

Circularity indicators

CE is a growing topic, especially in the European Union (*EU*), that promotes the responsible and cyclical use of resources possibly contributing to sustainable development. CE is turned into defined action plans supported by specific indicators. To understand what kind of indicators are used in CE, The 9R- framework as shown in **Figure 4** shows the strategies that can be used to consider CE practices and therefore achieve circularity. Others adapted this 9-R framework to strategies that then can be used to take indicators into account, see **Figure 5**.

Some authors refer to the concept of CE as one where boundaries are not always rigged. In that context, there is a need for specific methods to measure the CE progress. In this context, indicators can be useful in various implementation scales and as a tool to assess CE (EASAC, 2016; Geng et al., 2012).

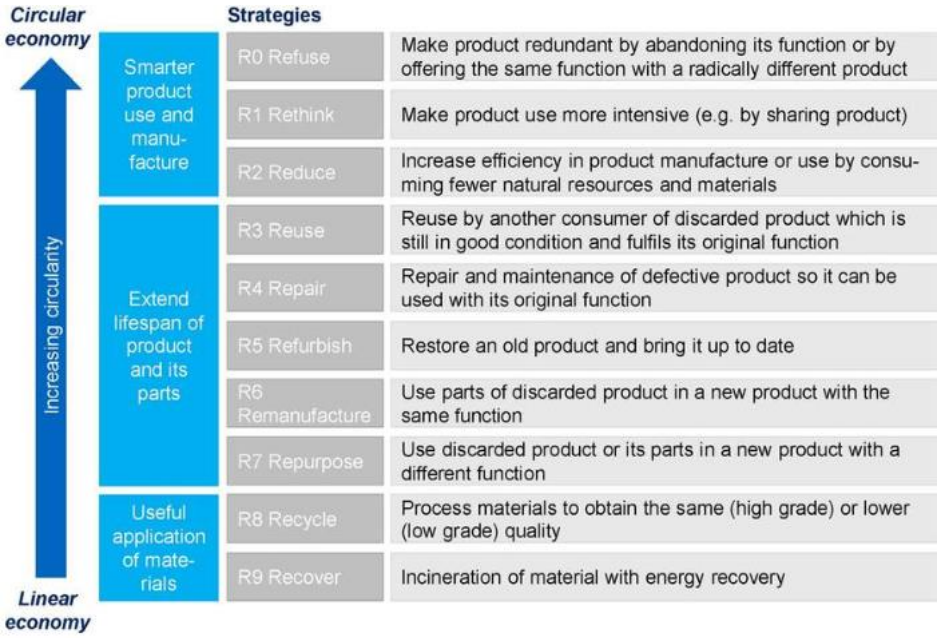


Figure 4 9R framework (Kirchherr et al., 2017)

Strategy 1	Preserve the **function** of products or services provided by circular business models such as sharing platforms, PPS (use- and result-oriented), and schemes promoting product redundancy and multifunctionality.
Strategy 2	Preserve the **product** itself through lifetime increase with strategies such as durability, reuse, restore, refurbish, and remanufacture.
Strategy 3	Preserve the product's **components** through the reuse, recovery and repurposing of parts.
Strategy 4	Preserve the **materials** through recycling and downcycling.
Strategy 5	Preserve the **embodied energy** through energy recovery at incineration facilities and landfills.
Strategy 6	Measure the linear economy as the **reference scenario** or the absence of a preservation strategy to show the status, progress, or regress towards CE. For example, the indicator for waste generation per person in a year (EC, 2018a) might show whether the promotion of CE is generating less waste.

Figure 5 Strategies adapted based on the 9R framework (Moraga et al., 2019)

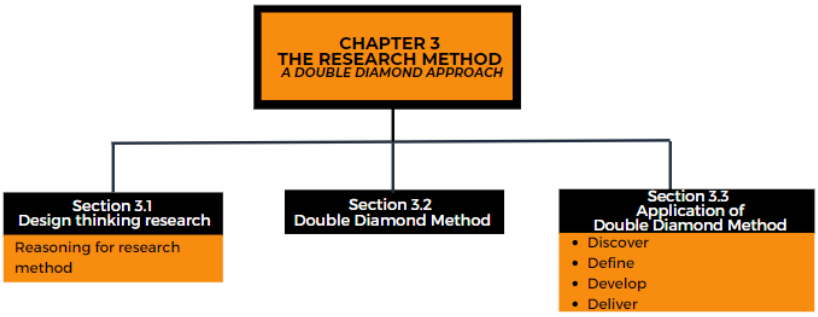
2.3 Collaboration

Sustainability is playing an increasingly important role in the civil construction sector and throughout the various life stages of the lifecycle, even a shift has been witnessed in regards to increase attention to concepts such as sustainability and circular economy (Arayici & Aouad, 2015; Bal et al., 2013). In this case, collaboration and effective communication among parties involved in the civil construction sector play an important role to give attention to the concepts and embrace the shift (Arayici & Aouad, 2015). Sustainability goes together with innovation. Achieving and implementing innovation go together with the ability to collaborate. Others (Lu et al., 2019; Mihelcic et al., 2003) also show that sustainability is both inter and trans-disciplinary whereby collaboration is needed. However, systematic approaches to strategies assist stakeholders in carrying out sustainable and effective maintenance practices (Hauashdh et al., 2022). One applicable definition found on collaboration is:

"Tools that provide all stakeholders (dependent on their user privileges) access to the most up-to-date information. Tools also provide a detailed overview of the project status allowing management to track progress, etc." (Ahern et al., 2015; Shelbourn et al., 2007)

Describing and defining collaborative working is context-dependent, however above definition thus indicates the goal of collaboration among parties.

3 Methodology: The Double Diamond Approach



The third chapter of the thesis will elaborate on the research methodology. The chapter will provide an answer to the second sub-research question (SQ2) as mentioned in the introductory chapter and sounds as follows: '*What methodology can be applied to design and develop a tool to stimulate sustainability and circular economy in the maintenance stage?'*

3.1 Design thinking research

Design-thinking research is a methodological approach that aligns with research methods from the fields of engineering, where products are designed for specific purposes. Design thinking can be defined as follows:

> **"an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback and redesign"** (Razzouk & Shute, 2012)

Within design thinking there is a relationship between two interdependent spaces namely the space of knowledge (K) and the space of concepts (C); Space "K" contains all established knowledge available, while Space "C" includes concepts that are neither true nor false in the space of knowledge (K) about an object (Hatchuel & Weil, 2003). Within the concept of design-thinking, the creativity of humans is at the center together with the collaboration between involved stakeholders. The process of design thinking is characterized as iterative, exploratory, and interactive (Braha & Reich, 2003). The main idea behind the design thinking methodology is two-tiered. First, the problem is identified and addressed. Secondly, a solution to the problem is designed in the form of a tool for example (Reiser et al., 2001). The latter stage furthermore focuses on testing and validating the proposed solution.

The objective of the research is important to be considered when choosing the applicable research methodology. The goal of this research is to explore and consider in which way sustainability and circularity can be incorporated into the maintenance stage of existing civil objects by developing a tool. For this, the knowledge derived from theory and practice can be of relevance. In literature, various types of design-thinking approaches have been distinguished such as "Research Design Method (*RDM*)", and "Double Diamond Method (*DDM*)".

3.2 The Double Diamond Method – A design thinking approach

After reviewing types of design-thinking methodologies, it was decided to use the "Double Diamond Method". This method is developed around 2005 by the British Design Council. It is characterized as a step-by-step iterative process that can be applied to carry out the research in a structured manner. Furthermore, it's in the line of thinking covering design research which is to explore scientific knowledge, as well as helping actors solve real problems (Feng & Hannafin, 2011).

The methodology emphasizes both diverging and converging processes and consists of various stages as seen in **Figure 6**. During each stage, different research methods can be chosen to collect and analyze the data. All the stages have certain objectives, however in general: (i) **Discover** – gathering insights into the problem; (ii) **Define**- create a design brief that clearly defines the challenges based on the insights gathered in (i); (iii) **Develop** – developing potential solutions and; (iv) **Deliver** – selecting and validating the solution that works for the actors involved.

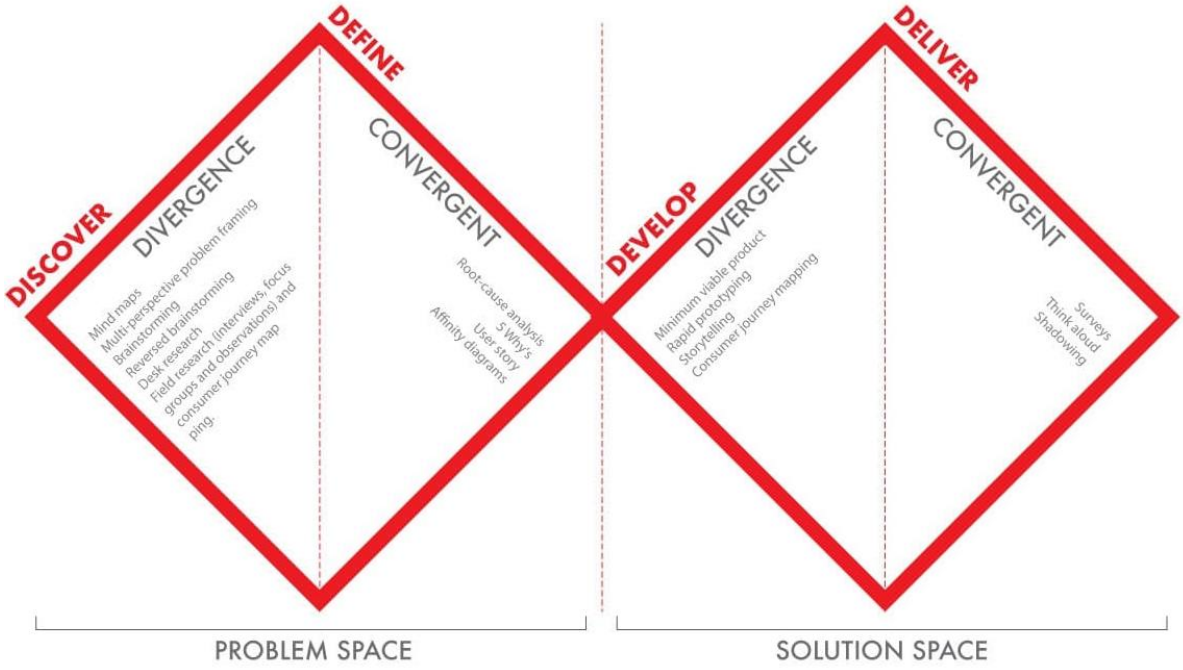


Figure 6 The Double Diamond Methodology

3.3 Application of the Double Diamond Method

This section will provide an answer to the sub-research question two (**SQ-2**): *'What methodology can be applied to design and develop a tool to stimulate sustainability and circular economy in the maintenance stage?'*

Figure 7 shows the adapted version of the "Double Diamond Method", and how this methodology is applied to the research including the various research activities carried out throughout the process.

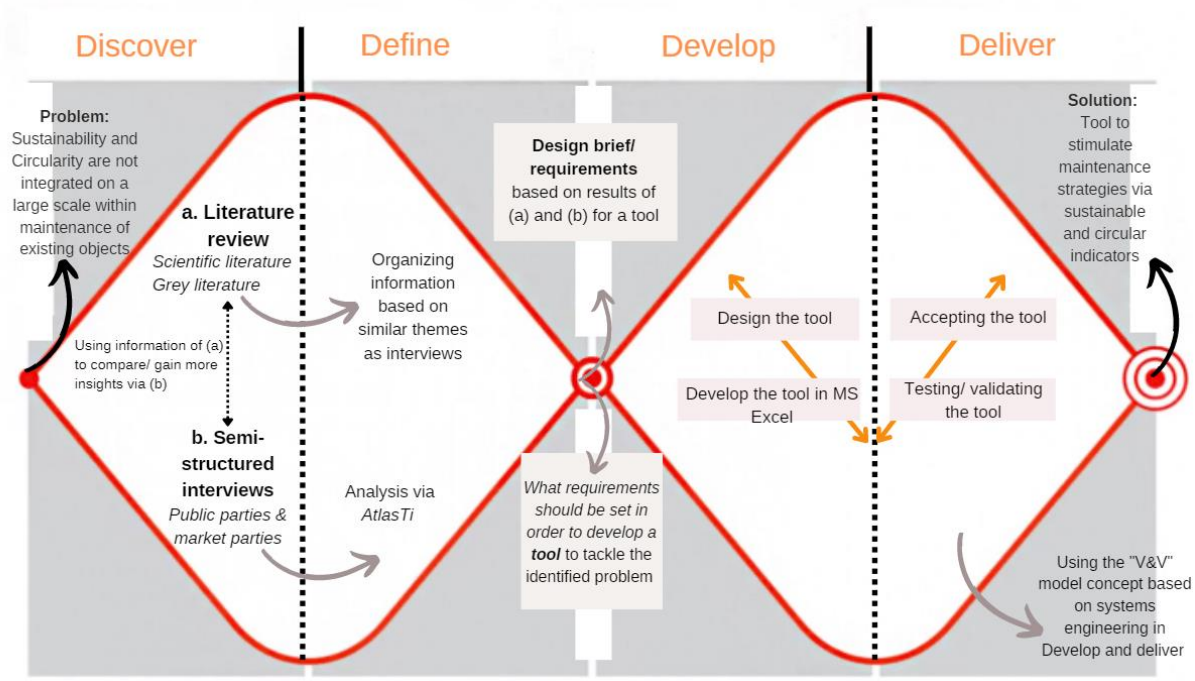


Figure 7 The adapted Double Diamond applicable for the research

Figure 7 consists of the following main stages:

- **Discover**: An elaborate literature review together with semi-structured interviews will be conducted;
- **Define**: The obtained data will be analyzed and the findings will lead to a set of requirements that is necessary to integrate and stimulate sustainability and circularity throughout the maintenance of civil engineering objects via the development of a tool. This is considered to be the "design brief";
- **Develop**: The solution to the problem will be designed and developed in the form of a tool;
- **Deliver**: The tool will be validated via sessions with experts and accepted.

Within the 'develop' and 'deliver' stages as seen in **Figure 7**, the theory behind the "Verification & Validation (*V&V*) model" is integrated and adapted to the research. It is decided to include this theory since the V&V model is used as an approach to assess credibility and creates opportunities for improving the design/ model (Carson, 2002). Furthermore, the V&V is part of the development process of complex systems and consists of various stages as seen in **Figure 8.** The left-hand side of the model consists of the verification phases, whereas the right-hand side covers the validation phases. Both verification and validation consist of different stages, or activities, that need to be carried out to conclude on the verification and/or validation status. In the literature (Olsina et al., 2020), it was found that in some cases confusion may arise regarding the objectives of the verification and validation. In a general sense, the distinction between verification and validation is checking whether you have developed it right (*verification*) and whether you have developed the right thing (*validation*) (Olsina et al., 2020).

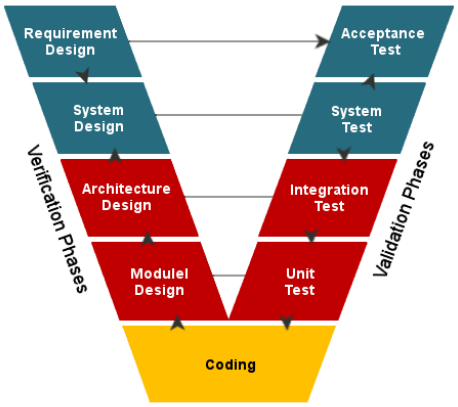


Figure 8 The V&V-model for the systems engineering process

It is found that the V&V model can be made project- or context-dependent. Within the literature, there are examples found that show the application of the V&V- model/ theory within various fields (e.g. (Oberkampf & Trucano, 2008)). An example close to the field of civil engineering in the Dutch context shows that the V&V model is integrated within the guidelines regarding the management and maintenance of civil engineering objects set up by Rijkswaterstaat (Bakker et al., 2010). The guideline focuses on the five (5) stages of the total lifecycle of an object ranging from (1) concept, (2) development, (3) realization, and (4) usage, to (5) demolition. These five stages are then integrated into a "V-model" as seen in **Figure 9**. From this, it can be concluded that the theory behind the V&V model is to a certain extent already incorporated within the civil engineering sector which is also the sector of interest for this research.

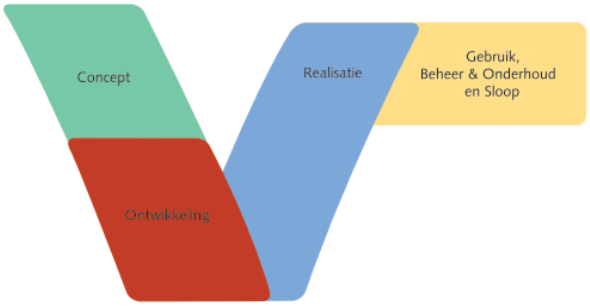


Figure 9 The five (5) life stages of an object integrated within the V-model by Rijkswaterstaat as part of the "Systems Engineering Leidraad" (Bakker et al., 2010)

Due to the understanding of the verification and validation process, it is decided to include relevant steps derived from **Figure 8** to check the verification and validation of the tool. In the developing stage as seen in **Figure 7**, two (2) steps are carried out namely (1) designing the tool, and (2) developing the tool in a computer software. These two steps are related to activities covering the verification aspect of the V&V model. Furthermore, within the deliver stage as seen in **Figure 7**, the main activity is to test/ validate the tool.

Each stage of the applied double diamond method will be further explained below.

Part I- Diamond 1: Discover and Define stage

3.3.1 The Discover Stage

Designing appropriate solutions require elaborate knowledge of the identified problem(s). The identified problem within this research is that currently concepts such as sustainability and circular economy are not elaborately integrated into the maintenance stage of existing civil construction objects such as bridges and sluices. It is of great importance to explore the identified problem more in-depth and gain insights by collecting data via two (2) manners namely **(1) literature review** and **(2) semi-structured interviews**. Next to that, information gathered via meetings, and talks/ informal interviews with people working within the sector and academia will also be considered to be relevant sources of information.

3.3.1.1 Literature Review

Existing knowledge is considered to be an important building block for research (Snyder, 2019). One way to obtain existing knowledge is by conducting a literature review which is described as a way of collecting and synthesizing existing research (Snyder, 2019; Tranfield et al., 2003).

The purpose of reviewing the literature is to gain a better understanding of the current status, and what changes will need to occur in order to focus more on sustainability and circularity within the maintenance stage of existing civil construction objects. For this research, it is also important to take the Dutch context into account.

There are various manners identified to conduct the literature review such as (i) systematic, (ii) semi-systematic, and (iii) integrative reviews (Snyder, 2019). Considering the applicability of (i), (ii), and (iii) (Snyder, 2019) and the purpose of the literature review for this research, it was decided to use a semi-systematic approach for conducting the literature review. One of the reasons for choosing this is because of the thematic analysis (Braun & Clarke, 2006) or content analysis techniques used for identifying and analyzing information within literature (Snyder, 2019). The approach also puts more focus on qualitative information. It is designed for topics that have been conceptualized differently and studied by various groups of researchers within diverse disciplines (Wong et al., 2013). It is also an applicable method to discover the progress of a topic within the field of research. For the literature review, the focus is on several research areas, such as (a) barriers and enablers to sustainable maintenance and (b) collaboration, and is thus simply not possible to review all articles related to these topics. It is therefore decided to apply a **semi-systematic literature review together with a content analysis approach**.

Semi-systematic literature review strategy

After deciding on the approach for conducting the literature review, it is also important to set the strategy. The literature review strategy is adapted based on existing processes for conducting literature reviews (e.g. (Snyder, 2019; Wong et al., 2013)). The literature review for this research is divided into reviewing two (2) types of literature, namely: (1) scientific

literature and (2) grey literature. It is important to acknowledge that the strategy for reviewing (1) and (2) differ to a certain extent.

Scientific literature

Figure 10 shows a schematic overview of the process of conducting the scientific literature review. For this review, it is chosen to solely focus on scientific articles found within the database of *Scopus Elsevier*. Various keyword searches are applied based on the four (4) key topics (K.T.) relevant to the research and to answering **SQ-3** and **SQ-4** as introduced in the first chapter. These four key topics are (1) barriers in sustainability/ circular economy, (2) enablers in sustainability/ circular economy, (3) collaboration, and (4) indicators. The first results of the articles found based on the keyword searches are filtered via inclusion criteria to refine the results. The following inclusion criteria are applied (a) publication stage "final"; (b) language "English" and (c) Open Access articles. The articles are then analyzed by reading the abstract of each article. Each abstract is analyzed on elements that could be linked and considered to be relevant to the key topics mentioned earlier. This results in a batch of articles relevant to the research. The relevant articles are then further read and the content of the articles is then analyzed. The keyword searches for each key topic are shown in **Figure 10**.

- **Key topic 1 Barriers:** It is found that adopting sustainability within the infrastructure sector is currently mainly on new to-be-built assets and less focused on existing objects (UNEP, 2021). For this research, it is therefore of interest to first explore what the barriers are for withholding sustainability and circular economy within the maintenance stage of existing civil objects. Since the focus of the research at hand is mainly on civil construction objects such as bridges, and sluices, excluding buildings, it was first decided to focus on barriers specifically for these civil construction objects. However, due to a lack of results, it was decided to consider these barriers in a larger and broader context within the civil engineering sector, rather than only including the maintenance stage.
- **Key topic 2 Enablers:** Where there are identified barriers, there is also the need to overcome these barriers, namely via enablers or opportunities. It was decided to review enablers that could be of relevance to breaking barriers that are withholding sustainability and circular economy incorporation within the maintenance stage of existing civil objects. Also in the case of reviewing enablers, it was decided to expand the search areas by considering the enablers in a larger and broader context within the civil engineering sector, rather than only including the maintenance stage.
- **Key topic 3 Collaboration:** From the scientific point of view, it is concluded that collaboration (Lu et al., 2019; Mihelcic et al., 2003) plays an important role in re-evaluating current maintenance strategies and exploring options to incorporate and stimulate sustainability and circular economy. With this key topic, it is considered to discover the literature from the academic point of view concerning various collaboration types and the effects of collaboration on sustainability.

- **Key topic 4 Indicators:** Applying indicators (Lyytimäki, 2012) can have an impact on re-evaluating current maintenance strategies and exploring options to incorporate and stimulate sustainability and circular economy. It is therefore of relevance to research more on the indicators that can have an effect on sustainability and circular economy and could be useful for stimulating that in the maintenance stage.

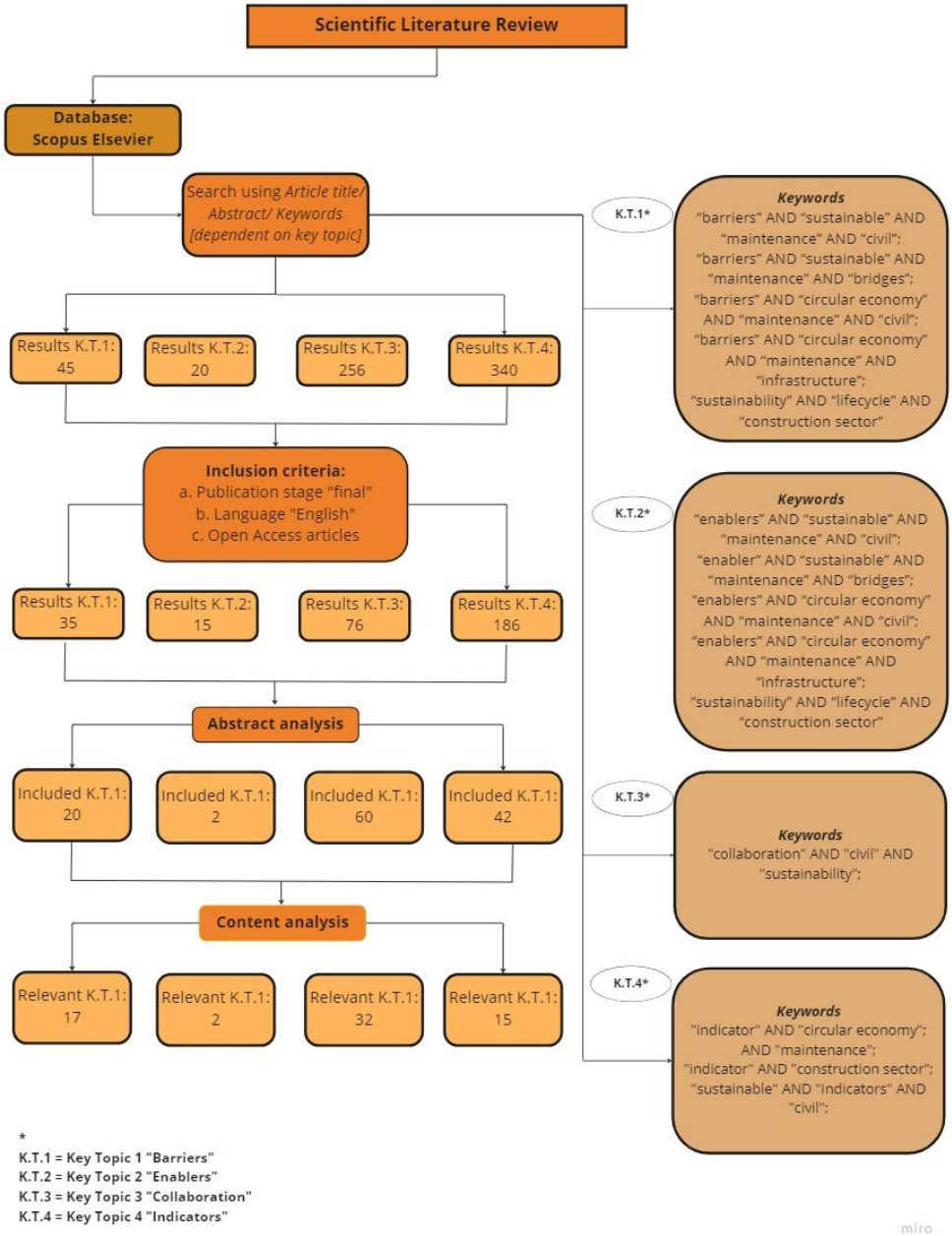


Figure 10 Overview of conducting scientific literature review

Grey literature

Next to reviewing scientific literature, grey literature was also consulted as part of gaining more insights, especially into the practice side of the research. Grey literature consists of information and documents that are produced on various levels within the practice such as

the government, industry, and institutions. These documents are often not screened by scientific publishers, however, they do give insights into the broader context.

With the Dutch civil engineering sector being important to the research, documents from authorities such as Rijksoverheid and Rijkswaterstaat are consulted. Most of the documents are open source and are accessible via the world wide web. Also, reports considered to be relevant to the research are reviewed when found in databases such as Google Scholar. With the research being conducted in collaboration with Arcadis Nederland B.V., reports and other written information were also provided in case it could be useful to the research.

As in the case with the scientific literature review, there are also key research areas identified to make the search for grey literature manageable. These key search areas are described below. **Figure 11** shows an overview of the process of conducting the grey literature review. Important to acknowledge here, is that the process for conducting the grey literature review is not as elaborately shown as the scientific literature review.

- **Key search area 1 Contractual agreement**: For the maintenance of existing civil engineering objects, maintenance contracts are awarded. With the research being conducted in the Dutch context, it is important to gain insights into the contractual agreements relevant to maintenance activities, and the processes included for obtaining the contracts via tendering and procurement.
- **Key search area 2 Maintenance management activities and strategies:** Every civil engineering object has a maintenance plan which consists of the maintenance activities carried out. With maintenance being one of the key areas within this research, it is important to gain insights into what kind of maintenance activities are carried out. As mentioned in the scope of the research in the first chapter, the focus will only be on civil engineering objects within the 'HVWN network' managed by RWS. This means that solely maintenance strategies for sluices and bridges are reviewed.
- **Key search area 3 Indicators:** Indicators are not a new concept within the practice nor for the civil construction sector. Even though there is no specific guideline or information found on indicators specifically for stimulating sustainability and circular economy within the maintenance stage, it was decided to search for indicators within the grey literature. Within the practice, but also in the Dutch context there have already been studies done on indicators that could for example stimulate a circular economy. One example of such as initiative in the Netherlands is "platform CB'23".

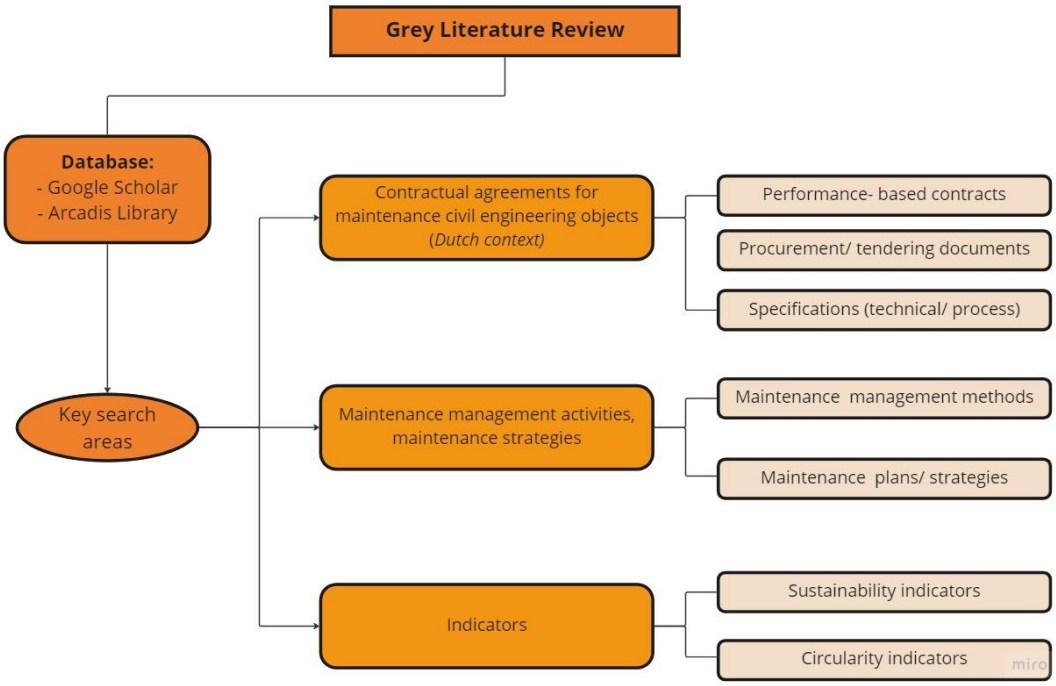


Figure 11 Overview of conducting the grey literature review

3.3.1.2 Semi-Structured Interviews

Stakeholder involvement is considered to be an important aspect of the research. The reason for including this is based on the fact that collaboration and effective communication among parties involved play an important role to give attention to sustainability and circular economy and embrace the shift (Arayici & Aouad, 2015). Since the research at hand also has a practical side to it, it was decided to gain more insights from the practice by conducting interviews.

As interviews are categorized as a more subjective way of obtaining data, the aspect of validity is often seen as a threat to qualitative research since such methods frequently do not offer numbers or quantification of responses. Applying semi-structured interviews provides however high validity due to the gathering of firsthand detailed accounts of perceptions, actions, and roles among practitioners (Ahlin, 2019). Next to that, consistency is an important aspect of the credibility of the data. Therefore, an interview strategy is set up, including starter questions. This will ensure that all participants will have the same questions asked no matter the deviation that comes with conducting the semi-structured interviews.

Choice of interview type (semi-structured)

Semi-structured interviews can be defined as a qualitative approach to collecting data (Ahlin, 2019). Furthermore, it allows participation and discussion of primary people working in that particular environment (Ahlin, 2019). This is also a way to include busy high-ranking officials, who are then allowed to freely give their opinion (Rubin & Rubin, 2012).

The basis for the semi-structured interview is a dialogue between a researcher and an interviewee, guided by a flexible interview protocol and supplemented by follow-up questions, discussions, and comments. The starter questions are in most cases based on information resulting from the literature review.

Semi-structured interviews set-up

The interviews are conducted to get practical insights into the identified problem based on an elaborate literature review. Practitioners from various organizations and backgrounds are interviewed. The interview strategy is shown in **Appendix C**.

Below a description is given about some of the key concepts that form the basis for the interview strategy shown in **Appendix C**:

- **Defining Sustainability and Circular Economy**: These concepts are defined in various ways in the literature. It is concluded that the definition of both terms is sector-dependent. Before applying and considering these in the maintenance stage, it is necessary to know how these are defined by practitioners. For that reason, it was asked during the semi-structured interviews how the interviewee would define (a) sustainability within the maintenance stage of civil engineering objects, (b) circularity/ circular economy within the maintenance stage of civil engineering objects, and then (c) the link between these two concepts.
- **Barriers and enablers**: From the literature review, it is concluded that at the moment sustainability and circular economy are not thoroughly integrated and considered yet within the maintenance stage for existing civil objects. For that reason, the interviewees are asked if they see barriers and enablers for integrating the concepts of sustainability and circularity within the maintenance stage.
- **Collaboration**: From reviewing the literature, it is considered that collaboration between actors involved could be considered a stimulus to bridge certain barriers for integrating sustainability and circularity in the maintenance stage. Based on that, this aspect was further explored with the interviewees.
- **Indicators**: The literature review shows that indicators can be considered a helpful aspect that could stimulate actors to take sustainability more into consideration. The interviewees were asked about their familiarity with indicators to stimulate sustainability and their insights on that.

The logical reasoning behind these questions and key discussion points should give the researcher more insights.

Selection of interviewees/ participants

One of the key advantages of conducting semi-structured interviews compared to methods such as questionnaires, for example, is that with semi-structured interviews, the interviewees are not selected on a random basis. This gives the researcher the chance to select participants based on certain criteria and to include multiple perspectives.

The selection of participants is an important part of any research project to ensure that data is collected from the most knowledgeable people or agencies (Ahlin, 2019). The criteria for selecting participants applicable to this research are:

1) The participants hold certain practical knowledge about the research at hand. The expertise of the participants on topics such as sustainability incorporated within maintenance, contract management, or asset management. This refers to 'judgment sampling'.
2) The inclusion of the participants in this project was a natural fit either because of their status/ experience in the field or due to a professional relationship between the researcher and the participant.
3) Availability and willingness to participate.
4) All interviewees should be working in the Dutch civil engineering sector.
5) In the transition towards more sustainability and circularity in the maintenance stage, it is important to consider the situation from the perspective of the public and market sectors and how this should be steered to achieve the set of goals.
    - Involvement of the public sector: It is decided to include representatives from RWS, the municipality of Amsterdam, and the Province of North Holland. Initial research concluded that the two latter parties have a strong vision of sustainability integrated within their organization and also within the maintenance of civil engineering objects. For that reason, it was chosen to include them, to gather a broader perspective from the public sector.
    - Involvement of market parties: It is decided to only include the perspective of the main contractors that have the lead within maintenance projects. Other sub-parties in the supply chain were excluded from the research due to time constraints. Participants of two contractors operating in the Dutch civil construction market were willing to participate in the interviews.

Within the maintenance stage of a civil engineering object in the Dutch context, different actors are involved. It is chosen to not randomly choose representatives but choose them based on the above-stated criteria. **Table 1** shows all interviewed participants, including their expertise and interview date.

Conducting the semi-structured interviews

The interviews are conducted based on the before-handed set-up strategy as seen in **Appendix C.** In summary, the semi-structured interview setup consisted of three main parts:

- Part 1: Introduction to the research
- Part 2: Introduction of each main item, starter question(s) to each main item, and follow-up questions. In the interview protocol, there were some follow-up questions for each item, but throughout the interview, it could happen that the followed-up question was determined at that moment
- Part 3: Ending, future perspective, questions from respondents' side

The interviews were conducted in Dutch since the civil engineering sector is mostly Dutch-speaking oriented, and all interviewees were most comfortable with the interview being in Dutch rather than English. The aim was to have semi-structured interviews for around 45 minutes because as a researcher you want to get the necessary information from the participants, but also don't want the interviews to last too long and create fatigue for both the participant and interviewee.

Is it important to guarantee the confidentiality of the identity and information in the case of conducting the interviews. The confidentiality of this research is preserved in the following:

1) The procedure of Human Research Ethics (HREC) committee of the TU Delft;
2) At the start of the interview, the researcher explained to the interviewee how the information will be stored and in which way it will be used.

Table 1 All interviewees participated in the research in the period between September 2022- October 2022

Public sector	Expertise	Interview Date
Province of North Holland_A	Sustainability and innovation	27th of September 2022
Province of North Holland_B	Operation & Maintenance; sustainability in O & M	6th of October 2022
Province of North Holland_C	Asset Management	13th of October 2022
Municipality of Amsterdam	Working on sustainable policies for infrastructure assets	3rd of October 2022
Rijkswaterstaat_A	Sustainable Procurement; sustainable O & M	30th of September 2022
Rijkswaterstaat_B	Operation & Maintenance; Asset management	30th of September 2022
CROW	Sustainability; Tendering and Program management	26th of September 2022
Market parties	**Expertise**	**Interview Date**
Consultant	Sustainability; Circular Economy; Juridical background	25th of September
Arcadis Nederland B.V._A	Contract management	29th of September 2022
Arcadis Nederland B.V._B	Contract management; Technical manager contract(or)	6th of October 2022
Contractor A_1	Project management (tendering)	17th of October 2022
Contractor A_2	Asset management	17th of October 2022
Contractor B	Sustainability calculations	18th of October 2022

3.3.2 The Define Stage

The defining stage of the "Double Diamond Method" will focus on processing and filtering the gathered data. It will eventually lead to the design brief and set the context and requirements for developing the tool. This section is two-folded. The first part will focus on the process of analyzing the interviews. The second part will elaborate on how the results from the literature review will be compared and combined with the results of the interviews.

3.3.2.1 Interview Analysis

In general, the process after conducting the interviews involves analyzing and interpreting data, applying codes, categorizing the codes, and looking for patterns (Creswell, 2013).

One of the methods for analyzing the interviews is according to Braun & Clarke's 6-step framework due to the clear and usable framework for doing thematic analysis (Stranges et al., 2014). Braun & Clarke's 6-step framework is shown in **Figure 12**. The framework consists of various phases, each with a certain objective and carried out in a certain order.

Phase	Description of the process
1. Familiarizing yourself with your data:	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas.
2. Generating initial codes:	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3. Searching for themes:	Collating codes into potential themes, gathering all data relevant to each potential theme.
4. Reviewing themes:	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic 'map' of the analysis.
5. Defining and naming themes:	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme.
6. Producing the report:	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis.

Figure 12 The six phases of a thematic analysis according to Braun and Clarke (Braun & Clarke, 2006)

For the research, the 6-step framework is adapted as seen in **Figure 13**. The various phases applied to the research are described below.

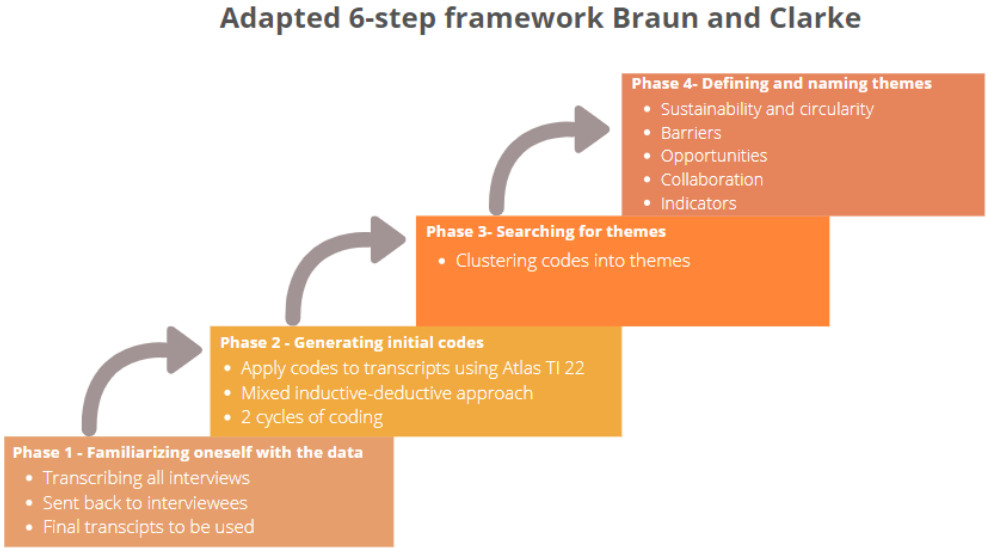


Figure 13 Adapted framework for processing interviews

Phase 1 – Familiarizing oneself with the data

Transcribing the interviews

With the consent of the participant, the interview was recorded. The (video) recording was then fully transcribed. Fully transcribed means, that a complete written record is made of spoken words during the interview. In the transcripts, words such as "uhm" and the time it took to answer a question were not taken into account in the transcript, because it was not the goal of the interviews to analyze the time it took respondents to answer the question. During this stage, it is also important to make notes (Skjott Linneberg & Korsgaard, 2019). However, results and findings are not simply concluded from the transcripts. Processing the raw data can be done by applying "coding".

Coding can be seen as giving a segment of a text a certain label, which can consist of a short word for example. Coding can lead to the reduction of empirical material and make data more accessible for analysis. Codes are the fundamental building blocks of what will later become themes and any item of data that might be useful in addressing the research question(s) should be coded (Byrne, 2022).

Phase 2- Generating initial codes

Coding

After the transcripts were approved, it was time to further process and analyze the interviews. The software **Atlas Ti 22** is used as a tool for analyzing the interview data. In Atlas Ti, codes are used to label certain texts within the transcripts, so an overview is made with all data that has a certain code to it. For the coding part, the transcripts were read thoroughly, screened, and coded.

Approach to coding

There have been three (3) ways identified as an approach to coding namely (1) inductive–open coding, (2) deductive-predefined list of coding, and (3) a mix of inductive and deductive approaches. For this research, it was chosen to have a combination of both inductive and deductive elements due to then cycling back and forth between data and theory. Having such an approach suggests that the researcher remains open to surprises in the data while at the same time keeping structure via the theories. For this research, two cycles of coding are applied, as shown in **Table 2:**

- First cycle coding: All transcripts are reviewed, sentence by sentence. It was then decided to give a "code" to quotes/ expressions that could be of relevance. This led to an overview of common words, expressions, and quotes expressed by all interviewees. In the case an expression or word might have relevant information but could not be assigned a code, a new code was made.

- Second cycle coding: The common words, expressions, and quotes that were coded in the first cycle, were now reviewed again and again until existing codes could be accommodated under 1 specific code. The codes were then defined.
- Clustering: After finishing the second cycle of coding, these were now clustered into themes. The themes are somehow linked to key concepts linked to the literature review.

Phase 3 – Searching for themes

After the second cycle of coding, it is time to examine and cluster codes that belong to one theme. The trick is to look for an overarching structure or process that can be understood at a theoretical level. A 'theme' is defined as follows:

"a pattern that captures something significant or interesting about the data and/or research question" (Stranges et al., 2014)

Phase 4 - Defining and naming the themes

The outcome of the first-cycle coding, second-cycle coding, and clustering is shown in **Table 2**. Therefore, when codes are clustered together according to similarity and regularity, patterns are born, and you can begin to analyze the connections between them.

3.3.2.2 Literature review results versus interview results

Comparing the literature review to the interview results will eventually lead to the design brief, or more to say, the requirements. The result here is to define the changes necessary to apply sustainability and circularity in the maintenance stage.

Table 2 Coding interviews via Atlas Ti

First cycle coding [Common words/ expressions]	Second cycle coding [Final coding]	Clustering [Themes]
Habitat, planet	C#1: Environmental dimension	Defining sustainability & Circular Economy
Vague, comprehensive, umbrella term, concreteness lacking	C#2: Clarity definition	
Future generations	C#3: Social dimension	
Material re-usage, loop economy	C#4: Circular Economy	
Culture, unfamiliarity, conservative, knowledge	C#5: People related	Barriers
Introduction of risks, uncertainty, innovations, no experiments	C#6: Transitional stage	
Budget restrictions, revenue models, no money available	C#7: Financial (re)sources	
Hard to specify sustainability, not standardized	C#8: Contracting barrier	
Missing standardization, status quo, and functionality important	C#9: Others	
Monitoring, End-Of-Life, Cooperation public/market	C#10: Execution	Opportunities
Procurement requirements, tendering, sustainability in procurement	C#11: Sustainable procurement	
Policy, frameworks, processes, strategies	C#12: Regulatory	
Research, concrete proposals, ideas, collaborating, transparency	C#13: [public/market] cooperation	
Portfolio, two-phase, bouwteams, performance-based	C#14: Approach	Collaboration
MKI, CO2 emissions, Air quality, Biodiversity, Energy usage,	C#15: Environmental categories	Measuring
Circularity Index, Lifecycle costs, KPI, reusable	C#16: Other categories	

Part II- Diamond 2: Develop and Deliver stage

For this research, only some key elements of the V&V model are taken into account, namely, (1) the design, (2) coding, (3) testing, and (4) acceptance/delivery. Important to note however is that due to the incorporation of the V&V model into the Double Diamond, the iterative character of the Double Diamond leads to an iteration of the V&V throughout the develop and deliver stage.

3.3.3 The Develop stage

A tool is developed that will stimulate sustainability and circularity by steering on indicators and enhancing collaboration between parties. The development stage is part of the left side of the "V&V model" which contains various stages according to the verification phase. Throughout the development stage, the following steps will be taken for this research:

1. The tool will be designed first by making some sketches based on the requirements which resulted from the first part of the diamond.
2. In MS Excel, the coding of the tool will be done in various sheets based on the design in step 1.

At the end of the development stage, **verification** can be done by checking if the requirements are included.

3.3.4 The Deliver stage

The deliver stage within the "Double Diamond method", consists mainly of the validation phases according to the "V&V model" as shown in **Figure 8**. After the tool was developed, it was decided to use existing case-material to test the tool. There will be two sessions held in which experts from various backgrounds will go through the tool and give their feedback.

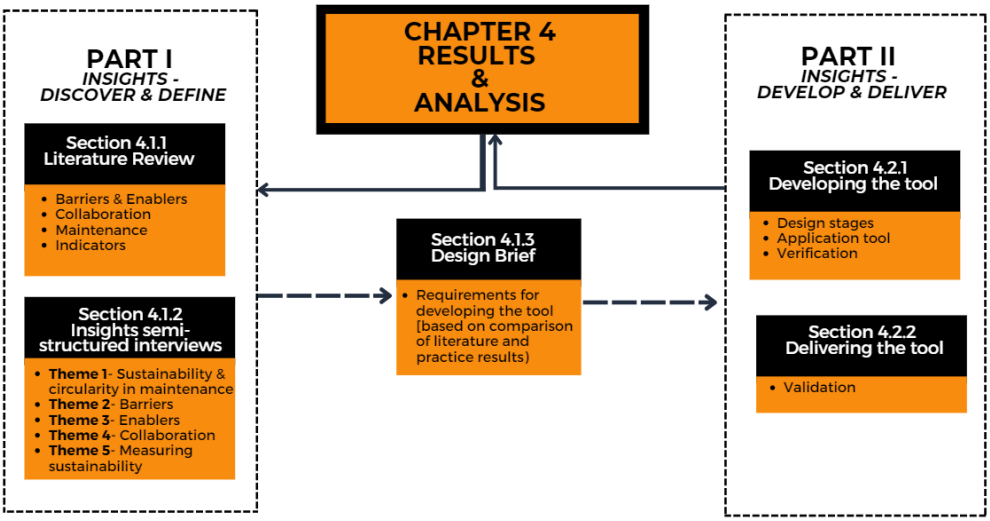
Case Study

To test the tool, it was decided to fill in case-relevant information. It was chosen to consider the case "Performance-based contract for maintenance of HoutribComplex". Maintenance for the Houtribcomplex was part of the SHERPA project, whereby Arcadis Nederland together with other parties was involved in the maintenance of this complex. This project is already finalized, but the case material is still relevant and useful to test the tool.

Validation session

There are two sessions planned before the final delivery of the tool. These sessions are part of the test/ validation part. During these sessions, the tool will be demonstrated by applying the information from the above-stated case. With information from the case, the tool will be reviewed and reflected on via a session with experts, where their input is taken into consideration. The output of these sessions will be taken into account to some length and within the possible boundaries.

4. Results & Analysis



The fourth chapter of the thesis will elaborate on the analysis and results found by applying the Double Diamond Method research method. The chapter will provide an answer to sub-research question three (SQ3): *'What are the barriers and enablers for stimulating sustainability and circular economy within the maintenance stage?'* Furthermore, the chapter will provide an answer to sub-research question four (SQ4): *'What is the effect of collaboration on stimulating sustainability and circular economy within the maintenance stage?'* At last, the chapter also included the answer to sub-research question five (SQ5): *'What are the requirements for developing a tool that could be used to stimulate sustainable maintenance strategies?'*

4.1 Part I: Insights - Discover & Define results

This section of the chapter is two-fold. The first part focuses on the results of the literature review and the semi-structured interviews. The second part is focused on combining the results of the literature review and semi-structured interviews which leads to the requirements for the design and development of the tool.

4.1.1 Literature review results

The literature review part will dive more into specific aspects considered to be relevant to the research as a result of reviewing scientific and grey literature. Furthermore, the review is mainly based on key elements arising from sub-question 3 (SQ3) and sub-question 4 (SQ4). With this research focusing mainly on the maintenance stage, it is necessary to also explore this part within the literature. As briefly mentioned in the theoretical scope of the research, an identified way to assess progress toward sustainability is by using indicators (Lyytimäki, 2012). As sustainability and circular economy are central concepts to this research, literature will also be consulted to explore more regarding applicable indicators to these concepts.

4.1.1.1 Barriers & Enablers

From initial analysis, it was concluded that current maintenance strategies for existing civil engineering objects do not consider the concepts of sustainability and circular economy in a

broad context. This section will therefore elaborate on the barriers and enablers found within the literature related to the aforementioned concepts. A barrier can be seen as an obstacle or hindrance. The opposite of a barrier is an enabler; a way to overcome the identified barrier (Giesekam et al., 2018). It is further acknowledged that to develop strategies that put focus on sustainability concepts it is required to identify potential barriers and enablers (Placet et al., 2015).

"Sustainability barriers" are specific barriers preventing or blocking to some extent reaching sustainable objectives within the sector (Laurett & do Paço, 2019). By identifying and considering these barriers, a first step is made toward more sustainable solutions. Additionally, it was considered to identify barriers that are withholding the incorporation of the circular economy within the maintenance stage.

With limited research done specifically on barriers and enablers for sustainability and circular economy integration in the maintenance stage of civil objects such as bridges, excluding buildings, it was decided to consider the barriers from a broader perspective. There have been similarities identified between barriers and enablers for achieving circular economy and sustainability. An overview of various barriers and enablers found within the literature (Arayici & Aouad, 2015; Bal et al., 2013; Giesekam et al., 2018; C. Z. Li et al., 2022; Placet et al., 2015) and applicable to the scope of this research is shown in **Figure 14**.

As seen in **Figure 14** the various barriers are clustered into five (5) levels, namely (1) organizational/ social level, (2) construction industry level, (3) regulatory level, (4) environmental level, and (5) economic level. The levels furthermore consist of various barriers. These barriers will not be discussed and elaborated on, one by one since this is not the aim of the research. It is important to acknowledge that these barriers are found by conducting a literature review, but it could be that there are more barriers than the ones identified and shown in **Figure 14**. Furthermore, in some cases, the barriers within one cluster can be a result of another barrier within another cluster. As an example, a lack of horizontal and vertical collaboration (*see cluster: organization/ social level*) can be the result of insufficient collaboration tools available (*see cluster: construction industry level*). Or, the insufficient availability of collaboration tools could be a result of a lack of knowledge (*see cluster: organization/ social level*). In other cases, barriers within one cluster can also be a result of a barrier within the same cluster.

Next to the barriers, there are enablers identified. The enablers are not clustered, nor linked to one of the five clusters. The reason for this is that an identified enabler could be linked to various barriers. In order to keep a clear overview, it was decided to list identified enablers in **Figure 14**. As for the identified enablers, it was concluded from the literature (Arayici & Aouad, 2015; Placet et al., 2015) that "collaboration" is a key enabler to identified barriers related to sustainability and circular economy. It was decided to further explore this enabler in more detail for the research. Another enabler linked to collaboration and thus also of interest to further consider is "stakeholder engagement". This is also identified as an enabler

to achieve sustainability (Bal et al., 2013; Hofmann, 2019; Kordi et al., 2021; Romero et al., 2009). **Figure 14** furthermore shows that other enablers could also be of relevance to the research such as "procurement" and "designing tools".

The answer to sub-research question three (**SQ3**): '*What are the barriers and enablers for stimulating sustainability and circular economy within the maintenance stage?*' could be found in **Figure 14** as this gives a complete overview of the barriers and enablers identified for sustainability and circular economy within the maintenance stage. On the one hand, the barriers are clustered within five (5) levels. For the research at hand, all barriers and clusters are relevant however for this research it is not manageable to overcome all barriers. On the other hand, the enablers are not clustered since one enabler could be linked to various barriers. The enablers are therefore identified on a more general level. Eventually, the main enablers that will be focused on for this research are "collaboration", "stakeholder engagement" and "designing tools". It could be that throughout the research, certain enablers could be indirectly relevant.

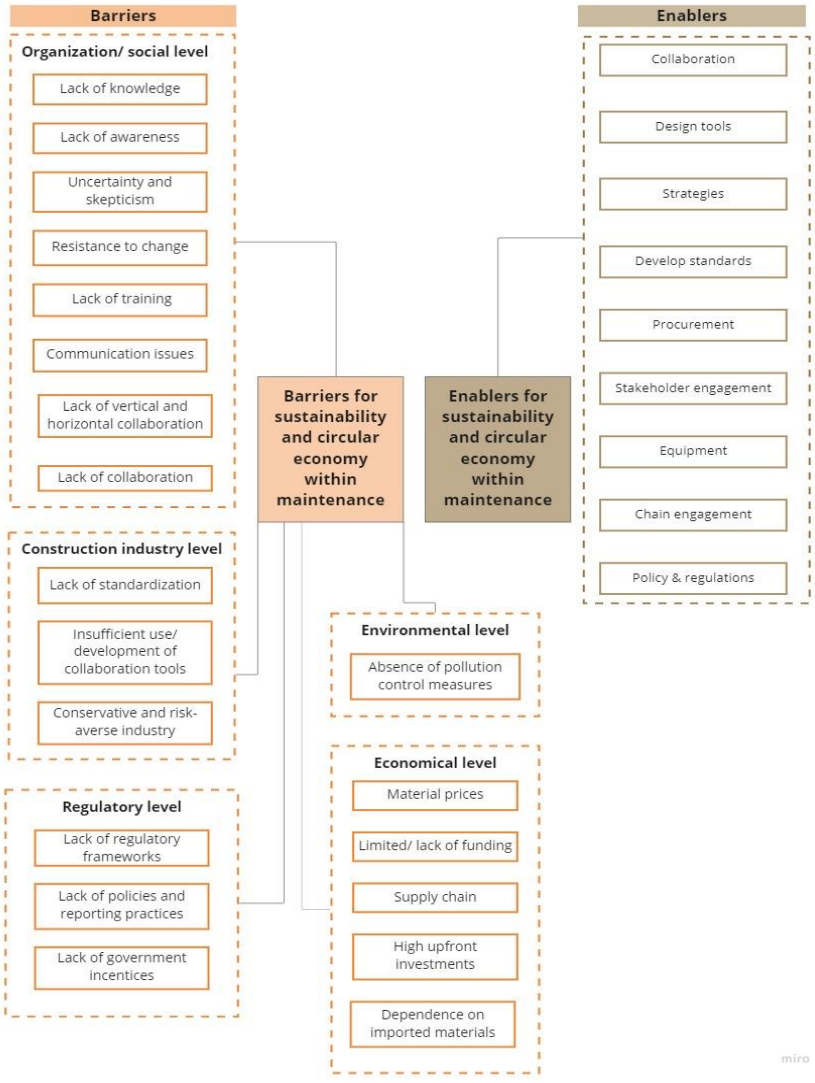


Figure 14 An overview of barriers and enablers that are found to be relevant from the literature and applicable to the scope of the research

4.1.1.2 Collaboration & Stakeholder engagement

As "collaboration" and "stakeholder engagement" are identified as certain enablers to overcoming barriers for integrating sustainability and circular economy within the maintenance stage of civil construction objects, it is relevant to further explore these.

4.1.1.2.1 Collaboration as an enabler

Literature review shows that there has been research conducted regarding the integration of collaboration within the lifecycle of civil construction projects (Faris et al., 2022; Ganeshan et al., 2001; Larsson, 2020). As an example, a lack of communication and effective collaboration to support information sharing between parties was found to be a gap (Guo et al., 2010) in construction projects. Eventually, a virtual model based on both static and dynamic information was produced that can be useful for the parties involved (Guo et al., 2010). This is one example showing how collaboration between parties can be stimulated through the deployment of tools. This can be seen as an inspiration in the context of the current research.

With collaborative approaches leading to improving the status of the civil construction sector, there has been a framework developed focusing on the implementation of collaboration (Faris et al., 2022). The study, however, only covers the phase until the construction stage of the lifecycle. The maintenance stage is not considered. As previously mentioned in the theoretical scope, one definition found on collaboration applicable to this research is:

"Tools that provide all stakeholders (dependent on their user privileges) access to the most up-to-date information. Tools also provide a detailed overview of the project status allowing management to track progress, etc." (Ahern et al., 2015; Shelbourn et al., 2007)

Describing and defining collaborative working is context-dependent, however above definition thus indicates the goal.

With a shift witnessed towards the increase of attention to concepts such as sustainability and circular economy within the various lifecycle stage of the civil construction sector (Arayici & Aouad, 2015; Bal et al., 2013), collaboration and effective communication among parties involved in the civil construction sector play an important role (Arayici & Aouad, 2015). Others (Lu et al., 2019; Mihelcic et al., 2003) show that sustainability is both inter and trans-disciplinary whereby collaboration is needed.

For this research, it is important to discover how collaboration can be stimulated throughout the maintenance stage to achieve sustainability and circularity. However, due to the specific focus of the research, it was found that there is limited research done on collaboration types specifically for the maintenance stage of civil objects. It was therefore decided to take a broader context into account by researching collaboration types applied to (one or more stages of) the lifecycle of civil construction sector projects. There have been five (5) project collaboration types identified (Shelbourn et al., 2007):

1. Communication and insight,
2. Internal and cross-collaboration,
3. Know-how and power-sharing,
4. Clustering and
5. Teamwork efficiency.

One type of collaboration that has shown the potential to improve business in various contexts is collaborative 'partnering' arrangements (Larsson, 2020). Some key characteristics and benefits of collaborative partnering are shown in **Table 3**

Table 3 characteristics and benefits of collaborative partnering

	Characteristics	Benefits
Collaborative Partnering	- Long-term commitment between multiple stakeholders - Effective coordination - Relations based on trust - Commitment to common goals - Mutual understanding of aspects.	- Increases in efficiency - Cost-effectiveness - Opportunities for innovation - Improvements in project deliveries

With collaborative 'partnering' arrangements, stakeholder involvement is included to support sustainability. Furthermore, collaboration should be integrated into management practices to promote sustainability. In addition to that, sustainable practices also require effectiveness and innovation which are facilitated by collaboration (Larsson, 2020). To meet the needs and demands of sustainable maintenance practices, strategic approaches should be considered together with the actors involved (Hauashdh et al., 2022). However, the focus is currently too much on shifting risks to parties rather than seeking collaboration among parties to achieve common goals and objectives (Engebø et al., 2020). Within maintenance projects, contract agreements apply for longer periods between a public client and contractor/supplier. In these cases, collaboration is then built on trust, open communication, and common goals (Larsson, 2020).

Achieving collaboration

Deciding on a collaborative approach is one thing. Another thing is to have that effective collaboration. There should be three (3) strategic areas considered to achieve effective collaboration namely technology strategy, business strategy, and people strategy (Shelbourn et al., 2007). An overview of these three strategic areas is seen in **Figure 15**.

Only emphasizing on collaboration is not the only ingredient to positive impact and success. Trust and maintaining this is also of immense importance. Collaborative relationships also can be further explored via the use of tools (Shelbourn et al., 2007).

Effective collaboration is only achievable through the innovative design and development of a more balanced "collaboration strategy" that does not solely rely on sophisticated

information and communication technologies, but also includes the "softer" aspects such as business and people. Next to these three (3) key strategies, six (6) factors need to be considered to execute and develop these key strategies namely: (1) vision, (2) trust, (3) communication, (4) processes, (5) technologies, and (6) stakeholder engagement (Shelbourn et al., 2007).

Figure 15 The three key areas to achieve effective collaboration (Shelbourn et al., 2007)

Another enabler closely linked to collaboration is stakeholder engagement. It is also one of the six factors that need to be considered to achieve effective collaboration (Shelbourn et al., 2007).

4.1.1.2.2 Stakeholder engagement as an enabler

It is currently witnessed in both practice and the scientific field that the responsibilities among stakeholders are not always clearly defined (Engebø et al., 2020). However, systematic approaches to strategies assist stakeholders in carrying out sustainable and effective maintenance practices (Hauashdh et al., 2022).

In cases where sustainability and/ or circular economy play an important role, stakeholder engagement is becoming more important (Bal et al., 2013; Hofmann, 2019). Stakeholder involvement together with stakeholder behavior can create incentives to achieve sustainability and circular economy throughout the lifecycle of construction projects and thus throughout the maintenance stage (Bal et al., 2013; Hofmann, 2019; Kordi et al., 2021; Romero et al., 2009).

Stakeholders or actors can be defined as follows:

"those who can influence processes and final results, whose environments are affected by the project, and who are to receive both (in) direct wins and losses" (T. H. Y. Li et al., 2016).

Ways to involve stakeholders

Figure 16 gives an overview of a 6-step stakeholder engagement process to stimulate the integration of sustainability via stakeholder engagement (Bal et al., 2013). These steps are based on the total project lifecycle and are iterated. Since the maintenance stage is part of the lifecycle, it could be assumed that these steps are also applicable. The goal of each step in the process is elaborated on in **Table 4**.

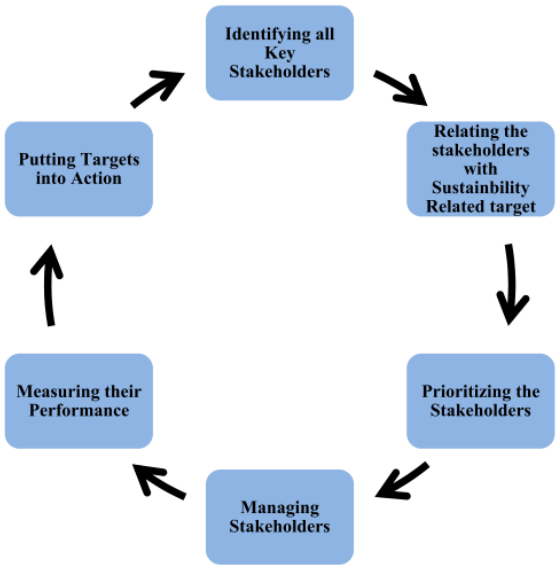


Figure 16 Project Stakeholder Engagement Process for Sustainability [Adapted from **(Bal et al., 2013)**]

Considering the fourth sub-research question (SQ4): '*What is the effect of collaboration on stimulating sustainability and circular economy within the maintenance stage?'* – it could be stated that collaboration is seen as an important enabler to sustainability and circular economy in the maintenance stage. Sustainable practices also require effectiveness and innovation which are facilitated by collaboration (Larsson, 2020). Previous research on collaboration (Engebø et al., 2020; Larsson, 2020; Shelbourn et al., 2007) shows that there are various types and ways to enhance collaboration. Collaborative 'partnering' arrangement is one type of collaboration that has shown the potential to improve business in various contexts (Larsson, 2020), thus also within the civil construction sector. With collaboration, aspects such as communication, trust, processes, and technology are important to consider (Shelbourn et al., 2007). Achieving collaboration is furthermore strongly dependent on the engagement between the stakeholders involved. Stakeholders can influence projects through decision-making (Kordi et al., 2021). It is important to also recognize that the collaboration between involved actors is also dependent on the contract type. However, the focus is currently too much on shifting risks to parties rather than seeking collaboration among parties to achieve common goals and objectives (Engebø et al., 2020). Within maintenance projects, contract agreements apply for longer periods between a public client and contractor/supplier. If sustainability and circular economy need to be achieved within the maintenance stage, it is important to enhance and work towards more collaborative partnering arrangements and actor involvement.

Table 4 Elaborate 6-step stakeholder engagement process [adapted from (Bal et al., 2013)]

Step #	Objective
1. Identifying all stakeholders	If the overall planning process and the purpose of the project are clear then it will be easier to find out who these stakeholders are.
2. Relating the stakeholders with sustainability targets	It must be ensured that key stakeholders of the project understand the commitment to sustainable development and the objectives of the project. When the sustainability criteria are set, then sustainability strategies can be developed by stakeholders.
3. Prioritizing the stakeholders	based on the stakeholder's potential impact on project success—in terms of achieving sustainability-related targets.
4. Managing the stakeholders	also involves managing the stakeholder relationship. Managing relationships with stakeholders helps raise the consciousness of the project and make it better prepared to deal with changing stakeholder needs; it also makes it more able to respond efficiently and effectively to the difficulties that may arise or issues that need to be resolved.
5. Measuring performances	The main purpose of performance measurement is to measure and improve the efficiency and quality of the performance and identify opportunities for progressive improvements in performance. For each measure, performance needs to be defined to identify the data to measure and to understand the important aspects that will effectively make up the action plan to ensure the right thing is measured in an appropriate way.
6. Putting targets into actions	Participants confirmed that after measuring performance, which will quantify the stakeholder's contribution in an individual area related to sustainability, plans can be developed and in some cases modified to ensure that sustainability-related targets continue to be met.

4.1.1.3 Maintenance

Important to acknowledge is that maintenance is only one (1) stage within the total lifecycle of an asset. In **Appendix A**, elaborate information can be found on the total lifecycle and the relation of the different stages.

Maintaining and monitoring objects is an important aspect to consider (S. Xu et al., 2019). Maintenance includes all actions that are related to the technical, administrative, and managerial aspects carried out to maintain the functionality or restore it in such a way that the desired functionalities of an asset can be met (Okoh, 2019). The manner in which civil engineering objects are maintained depends on the maintenance plan and maintenance strategies. The structural safety and serviceability throughout the service life of an asset are also crucial aspects that should be ensured (Sun et al., 2015). Poorly executing and not considering proper maintenance management can be of negative impact on the asset as well as on the organizational level due to the severity of losses and damages (Okoh, 2019).

4.1.1.3.1 Maintenance strategies

Figure 17 shows an overview of various maintenance strategies (Abbassi et al., 2022) for civil engineering assets, including (dis)advantages compared to other strategies.

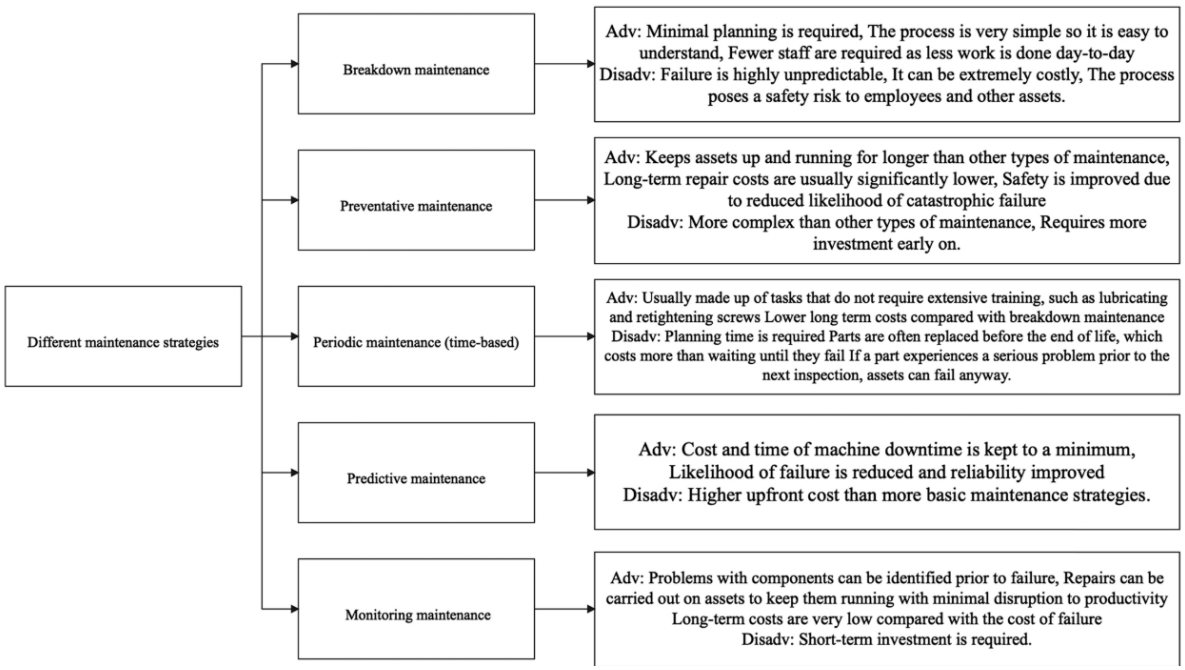


Figure 17 Common maintenance strategies in infrastructure engineering **(Abbassi et al., 2022)**

A common distinction made in literature (Scope et al., 2021) refers to corrective and preventive maintenance actions. The first one, corrective maintenance, includes actions or measures that are only applied to restore the original functionality after a failure has been detected. The latter refers to more systematic maintenance approaches based on criteria or predetermined actions independent of the failure of an asset (Scope et al., 2021).

4.1.1.3.2 Maintenance management approaches

In a broader context, optimal asset management approaches are related to efficient and effective maintenance management methods that put focus on optimizing activities related to the total lifecycle (Okoh, 2019; Parra, 2020). The line of thinking behind lifecycle management strategies should be considered to keep assets at a certain level of performance and functionality, whereby availability and reliability are key.

In 2014, the international asset management standard was released, ISO55000. Asset management is defined as:

"coordinated activity of an organization to realize value from assets" (Okoh, 2019)

The asset management approach is linked to the stages and activities within the lifecycle of assets as seen in **Figure 18**. Asset management is focused on coordinating and optimizing activities such as planning, asset development, asset care (or maintenance), asset life extension, asset decommissioning, and asset disposal. It regards decision-making through the total life cycle of the physical asset from its creation or acquisition, use, maintenance, and renewal or disposal.

Due to its cyclic character, is concluded that the activity of maintenance can influence or affect the various stages of the lifecycle (Okoh, 2019). Examples of how this can be considered are:

during the procurement/ development phase, maintenance personnel can ensure quality by verifying and confirming the specifications of the assets and spare parts supplied and could promote the aspect of maintainability. Another example is applying maintenance in the maintenance phase itself would mean that maintenance personnel possesses the technical know-how to retain items or restore them to a state in which they can perform their required functions.

Every asset owner has an asset management strategy that they follow and comply with. Current asset-management approaches are mainly based on economic principles that are primarily driven by traditional consumption-based interpretations of economic growth.

Figure 18 Asset management over the lifecycle of a civil construction object

Maintenance within Asset management principle

As maintenance is part of the asset management principle, there have been researches emerging that incorporate maintenance management processes with the ISO-55000 asset management standard (Okoh, 2019; Parra, 2020).

One approach (Parra, 2020) covers the integration of the traditional management process or Maintenance Management Model (*MMM*) in the ISO-55000 standards. This integration is shown in **Figure 19**. The research thus explains that there are possibilities to expand traditional maintenance models. It could also be considered to further expand the traditional MMM with concepts such as sustainability and circular economy.

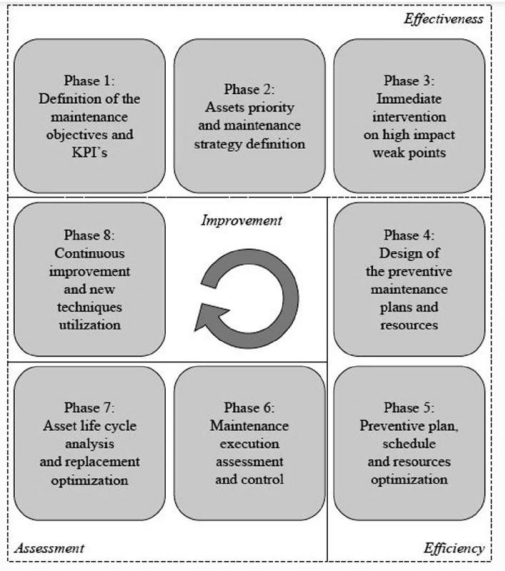


Figure 19 Maintenance Management Model integrated into an ISO55000 process standard (Parra, 2020)

Another study explores the possibilities of incorporating tools for both ISO55000 asset management systems together with tools for maintenance management processes (Okoh, 2019). The asset management system in the ISO 55000 standards consists of the following seven elements: (1) context of the organization, (2) leadership, (3) planning, (4) support, (5) operation, (6) performance evaluation, and (7) improvement. Integrating the ISO55000 standards into the maintenance management system, led to the asset maintenance management process (AMMP), as seen in **Figure 20**.

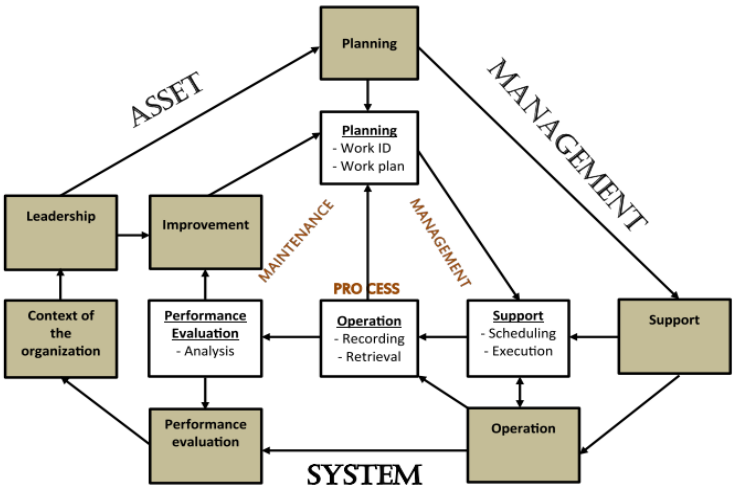


Figure 20 Asset management system integrated into AMMP

**the unshaded boxes represent the maintenance management phases, whereas the shaded boxes represent the asset management system elements*

In conclusion, reviewing the application of ISO55000-standard for asset management incorporated into maintenance management shows that there is a gap within the research

found. This gap shows the missing element of considering sustainability within maintenance management systems for civil engineering objects according to ISO555000 *(due to zero results in SCOPUS via "sustainability AND "maintenance management plan" AND "ISO55000")*

4.1.1.3.3 Maintaining in the Dutch context

With this research being executed in the context of the Dutch civil construction sector, it is relevant to gain insights into the approach of the public authority responsible for the management of civil engineering objects, namely RWS. They are the largest asset management agency for public infrastructure in the Netherlands.

Maintenance strategies

It is found that the following maintenance strategies are in general applied by RWS within the civil engineering sector (Steenwinkel, 2006):

a) Failure-dependent maintenance *(in Dutch: Storingsafhankelijk onderhoud- SAO):* It is considered to replace and/or repair the system or element (s) at the point where it becomes apparent that the system is failing.
b) Use-dependent maintenance (*in Dutch: Gebruiksafhankelijk onderhoud- GAO*): The component is replaced or overhauled after a given calendar time, after a given period of use, or after a given number of claims. Thus, the replacement is determined based on the usage.
c) State-dependent maintenance (*in Dutch: Toestandsafhankelijk onderhoud- TAO*): maintenance is only done after the need is established via a condition assessment.

Figure 21 shows how the strategies applied by RWS as mentioned above are linked to more general strategies found in literature, namely the preventive and corrective maintenance strategies.

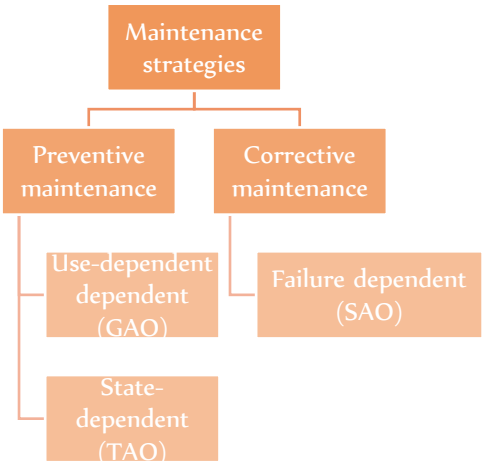


Figure 21 Preventive and corrective maintenance strategies linked to the maintenance strategies used by RWS

Contracting for maintenance works

Depending on the contract type awarded during earlier stages such as the design and construction stage of the asset, the client can decide to award the maintenance stage via another contract type. In a range of countries such as Canada and the UK, performance-based contracts are awarded (Alsharqawi, 2018) for existing civil construction objects.

In the Netherlands, most large civil objects were built around the '60s of the last century. After completion of the structures, the asset owner, in most cases, RWS, got the responsibility to manage these by operating and maintaining these. However, throughout the years there was a shift. RWS gave more responsibilities to the market parties to maintain these objects. Currently, RWS awards performance-based contracts to maintain existing civil engineering objects within their networks. This type of contract also influences the management of the objects.

Deciding on a procurement strategy depends on the situation at hand. The Dutch procurement law states the Dutch Public Procurement Act is applicable and that all public works should be publicly tendered. In the Netherlands, announcements for tenders including relevant documentation are published on the official website used by governmental bodies to publish their works that are open to being procured, 'TenderNed'. During the tendering, a procurement guide (*in Dutch: Aanbestedingsleidraad)* is published by the client. This document gives an overview of the requirements for tendering. Since the focus of this research will be on maintaining existing civil engineering objects awarded with performance-based contracts, other types of contracts are excluded from the research. **Figure 22** shows the process flow of contracting for existing civil engineering objects.

The performance-based contracts (*PBCs*) give to some extent freedom to the contractor in carrying out the work. In the Dutch context, this contract type consists of various documents which are set up by the client. Furthermore, they cover the requirements that the contractor has to fulfill. The documents that are part of the performance-based contracts are:

- Basic Agreement (*in Dutch: Basisovereenkomst)*
- Demand specifications (*in Dutch: Vraagspecificties)*. This is further divided into:
    - Demand specifications General (*in Dutch: Vraagspecificties Algemeen)*
    - Demand specifications Requirements (*in Dutch: Vraagspecificties Eisen)*
    - Demand specification Processes (*in Dutch: Vraagspecificties Proces)*
- Appendices (*in Dutch: Bijlagen)*
- Annexes (*in Dutch: Annex)*

Maintaining the civil objects

RWS published several documents that confirm their vision of the lifecycle management of these objects. RWS uses the Plan-Do-Check-Act cycle, which is one of the most often used asset management models (Marlow & Burn, 2008). They also used the approach "RAMSSHEEP" (an *acronym for Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economics, Politics)* to fulfill requirements related to the object. These requirements are referred to as "aspect-requirements" (*in Dutch: aspect-eisen).* Review of documentation shows that the primary focus from RWS is on *Reliability (**R** in **R**AMSSHEEP)* and *Availability (**A** in R**A**MSSHEEP).* It can be considered, to put more focus on the *Environmental* aspects (***E** in RAMSH**E**EP)* by including these in the maintenance strategies of civil engineering objects, which are currently little to no integrated.

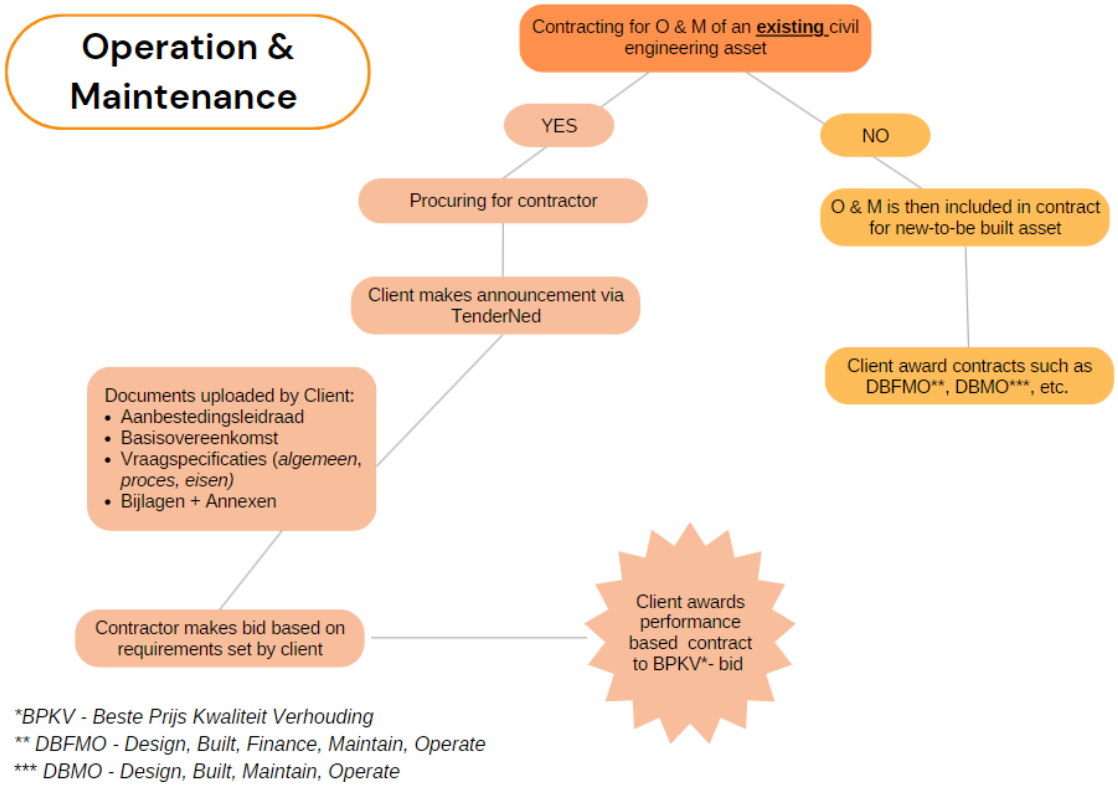


Figure 22 Overview of flowchart obtaining operation and maintenance works for civil engineering objects

Since this research focuses on the maintenance of existing civil construction objects within the 'HVWN' network managed by RWS in the Dutch context, it was decided to further explore. Throughout a maintenance contract, various activities are carried out. Two (2) phases are considered to be of importance to this research:

1. The phase before putting the procurement online, the pre-contractual stage
2. The phase after obtaining the maintenance contract, the execution stage

Both (1) and (2) are crucial in the case of considering options to integrate sustainability in the maintenance of existing civil engineering objects. Analyzing these documents and stages thoroughly, led to the following conclusion regarding the two (2) stages:

(1) The phase before putting the procurement online, the pre-contractual stage

For the research, the documents published by the client are analyzed and reviewed on the concepts of sustainability and circular economy. A thorough process of reviewing these resulted in the following: the "demand specifications requirements" (*in Dutch: Vraagspecificties Eisen)* consist of the requirements for the object. These requirements can be distinguished into 3 main groups, namely:

1. "Top-eis"(*in English: top requirement)*: This applies to all works; the existing area should function and perform in such a manner that its functions are fulfilled and its safe use and management remain possible;
2. "Functie-eis" (*in English: functional requirements)*: These requirements make the functionality (function) of the object explicit;
3. "Aspect-eis" (*in English: aspect requirement)*: These requirements make the performance explicit with respect to the concept of RAMSSHEEP.

The "aspect-eis" (*in English: aspect requirement)* shows the most opportunities for integrating sustainability and circular economy, and even exploring these more than currently done. "Duurzaamheid, milieu en omgeving" (*In English: Sustainability, environment, and surroundings*) are currently part of the "RAMSSHEEP", however, they include minimal concepts of sustainability.

In the process of procurement and tendering, the client sets out these requirements. These requirements also have a verification method linked to them but are currently very generically described. Currently, both requirement and verification methods are described in a too generic way and do not include specific requirements and verification methods on sustainability and circular economy.

(2) The phase after obtaining the maintenance contract, the execution stage

The PBCs are built up in such a way that the contractor has the responsibility throughout the contract period concerning the maintenance of the civil objects. The contractor needs to fulfill the requirements set by the client in the different requirement documents such as (i) Demand specifications General (*in Dutch: Vraagspecificties Algemeen)*, (ii) Demand specifications Requirements (*in Dutch: Vraagspecificties Eisen),* and (iii) Demand specification Processes (*in Dutch: Vraagspecificties Proces).*

One of the main responsibilities of the contractor is to deliver a maintenance plan according to the requirements set by the client. The maintenance plan consists of various information relevant to carrying out the maintenance such as:

1) Decomposition of the object on element level according to the applicable NEN standard, NEN 2767;
2) Maintenance activities on element level according to the FMECA, or risk-driven approach;
3) Maintenance activities on element level according to corrective maintenance strategies;
4) Maintenance activities on element level according to preventive maintenance strategies;
5) Maintenance activities related to the "daily maintenance activities", or referred to as standard maintenance (*in Dutch: standard verzorgend onderhoud (SVO));*
6) Data on carrying out inspections;
7) Risk profiles.

The freedom of the contractor to carry out the works often leads to him fulfilling the requirements but does not explore nor include sustainability and circularity in a broad context. Based on reviewing the content of maintenance plans as described above, it is concluded that (ii), (iii), (iv), and (v) show opportunities to integrate more sustainability and circularity. However, for this research, it is decided to start by focusing only (v). The reason for this is that with this research a first step is made to consider sustainability and circular economy within the maintenance stage. Also, since the activities in (5) are mainly focused on daily maintenance activities, it could be concluded that here the most impact on sustainability and circularity could be achieved. Nevertheless, the effect on sustainability for (ii), (iii), and (iv) can be researched in the future.

Risk-driven maintenance approach

Currently, the risk-driven approach for maintenance is considered in the Netherlands. The risk-driven approach is based on the concept of FMECA *(Failure Mode, Effects & Criticality Analysis)* which is considered to be a quantitative failure analysis. This approach leads to the so-called "prestatiegestuurde Instandhoudingsplannend" (P-IHP – *In English: performance-driven Conservation Planning)*. The FMECA is not considered to be a large part of this research, however, it is important to mention that with FMECA, the risk profile of objects on the element level is decided based on theoretical knowledge. The results of this analysis for elements of a certain object are then used to have a risk-drive maintenance approach. The risk-driven approach can be applied to both corrective and preventive maintenance strategies.

Maintenance data

There are currently various methods identified for monitoring and obtaining data on civil engineering objects throughout the maintenance stage. This is project and context-dependent, however, some of the methods are: (1) on-site inspections carried out by personnel (2) computer visions that involve the development of reality capture technologies, (3) image processing techniques to generate human-like understanding from digital images and video

materials, (4) data acquisition via laser scanning and photogrammetry (Sun et al., 2015; S. Xu et al., 2019).

NEN 2767

An object has a certain hierarchical division. When considering maintenance strategies for an object, it is often decomposed according to a certain standard. In the Netherlands, the decomposition is done according to the NEN 2767. **Figure 23** shows an example of such a decomposition. Next to the decomposition, of an object, there is also the norm for measuring the condition of an element of an object as seen in **Table 5**.

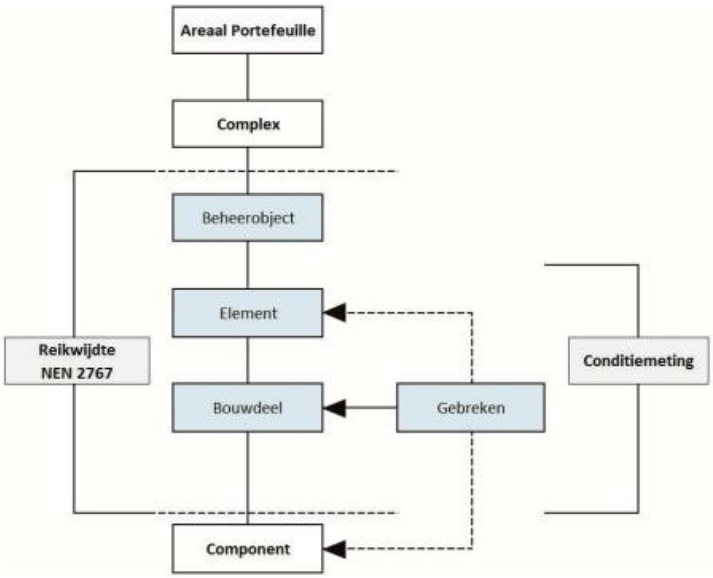


Figure 23 Example decomposition of an object according to the NEN2767

Table 5 Norm with the condition score based on the NEN2767 [adapted, translated to English]

Condition score	Description	Explanation
1	Excellent condition	Occasional minor defects
2	Great condition	Occasional onset of aging
3	Fair condition	Locally visible aging functional performance of building and plant parts not at risk
4	Moderate condition	Functional performance of a building and plant parts at risk
5	Poor condition	aging is irreversible
6	Very poor condition	Ready for demolition

4.1.1.3.4 Sustainability and circular economy in the maintenance stage

As sustainability and circular economy are the main concepts to be explored and integrated within the maintenance stage for this research, it was discovered that various researchers have been exploring possibilities of integration of sustainability within one or more stages of the lifecycle. Some focus on sustainable incorporation in 'early' stages such as the pre-construction stage (Kylili et al., 2022), while others focus more on the design stage (Ek et al.,

2020). There is also a movement among researchers to consider sustainability integration within the complete lifecycle (Brooks et al., 2021; Lenferink et al., 2013).

The focus on circular economy integrated into the lifecycle was to some extent limited compared to sustainability. This was concluded by searching for articles on the keyword topics in the SCOPUS database. There are articles published on the integration of the circular economy concept within the lifecycle stage of civil construction projects (Ahmed et al., 2020; Alizadeh, 2016; Case & Jarosław, 2022; Coenen et al., 2020, 2021; Hossain et al., 2020). However, there is limited research done on integrating these concepts within solely the maintenance stage. One of the conclusions from reviewing literature shows that to apply sustainability and circularity in the maintenance stage of the lifecycle, strategies should be reconsidered and re-assessed (Munyasya & Chileshe, 2018). Next to that, considering sustainability and circular economy should also include the integration of tools and indicators (Mart & Aguayo-gonz, 2019).

4.1.1.4 Indicators

An identified way to assess, communicate and monitor the progress toward sustainability is via indicators (Balasubramanian, 2020; Lyytimäki, 2012). This is also the case for assessing the progress toward a circular economy. The indicators can then be used to (re) consider, (re) formulate, and (re) develop maintenance strategies. In general, there are two (2) main categories of indicators (Canadian International Development Agency (CIDA), 1997; Lyytimäki, 2012; Strauss et al., 2022) namely:

1. **Quantitative indicators**: These can be defined as indicators that eventually give a numerical or a percentage value. Measuring is the base for change and impact.
2. **Qualitative indicators**: Often these types of indicators do not give a numerical value. They are more or less based on descriptive actions, people's judgments, and perceptions.

There is a discussion going on, about combining qualitative and quantitative indicators (Canadian International Development Agency (CIDA), 1997; Lyytimäki, 2012), also in the context of assessing and stimulating sustainability (Scerri, 2009). It is concluded that in some cases, to stimulate and create an effective practice of sustainability, both quantitative indicators and qualitative indicators need to be considered and taken into account (Scerri, 2009). The combination of the quantitative-qualitative indicator approach can be referred to as a **mixed indicator**. Thus, indicators can be categorized into the following three categories: (1) quantitative indicators; (2) qualitative indicators, and (3) mixed indicators.

4.1.1.4.1 Selection of indicators

There are in literature numerous indicators found that can be relevant to the research. To avoid an overload of indicators, it is necessary to collect and analyze the indicators. There is no generic methodology found for collecting and monitoring indicators (Sahely et al., 2005). However, there has been an identification process found within the literature based on seven

(7) steps (Fernández-sánchez & Rodríguez-lópez, 2010). For the research, it is decided to have an adapted identification process setup for identifying sustainability and circularity indicators for the maintenance stage, as shown in **Table 6**. The indicators are analyzed based on certain guiding principles (Foxon et al., 2002) such as applicability, traceability, the effect of applying an indicator and the monitoring aspect.

Table 6 Steps for selecting indicators for the research

Step no.	Description
1. Identifying indicators	**Reviewing existing scientific literature** on indicators to stimulate sustainability and circular economy (in the maintenance stage); **Reviewing existing grey literature** on indicators to stimulate sustainability and circular economy (in the maintenance stage).
2. Interviews	**Semi-structured interviews** to gain insights from practitioners about the current knowledge and implementation of indicators.
3. Comparison with other areas	Sustainability within the maintenance stage of other sectors has been more elaborately researched. Data were also extracted from other areas such as the **building environments, project management area.**
4. Analysis indicators via checklists	All the indicators were mapped in an excel sheet and analyzed based on certain guiding principles by (Foxon et al., 2002) such as: Applicability: Can it be useful for the maintenance stage? Traceability: What is the source? Affect: Provide credible and reliable information on changing conditions Monitoring: Able to identify trends/ changes/ track progress and anticipate future development Strategies influence: Pressures and responses concerning strategies
5. Diagramming techniques	Distribute a comprehensive list of indicators suitable for the research can be found in **Appendix D.**

4.1.1.4.2 Stimulating sustainability and circular economy via indicators

The environmental, economic, and social dimensions of sustainability are often evaluated through sustainability indicators. Below a description can be found of each dimension in the form of an indicator (Sahely et al., 2005):

- Environmental: These indicators are largely concerned with optimal resource utilization for example the use of water, nutrients, energy, and land. They also focus on aspects that minimize waste production.
- Economic: Large costs are involved throughout the whole lifecycle management of assets. Today, economic indicators such as capital costs and operation and maintenance costs continue to play an important role in decision-making as part of a larger set of indicators. Indicators in the economic dimension also cover investments related to research and development.

- Social: The dimension of social sustainability is not yet too elaborately researched as an indicator (Kordi et al., 2021). These are more difficult to quantify and received relatively less attention in the engineering literature compared to the other two sustainability dimensions. However, lately, there is a rise in attention witnessed of social indicators, for example by Kate Raworth via the concept of Doughnut Economics (Raworth, 2017). Certain social indicators are participation, acceptance, housing, and gender equality. Here improving the quality of life is essential.

For the research, the focus is, therefore, more on 2 sorts of indicators, namely (1) group of indicators to stimulate sustainability and therefore then sustainable development, and (2) group of indicators to stimulate circularity. Furthermore, to achieve sustainability, there should be a balance between all three dimensions of sustainability as mentioned above and none should be neglected (Kordi et al., 2021). There are various reasons currently identified why not all three dimensions are achieving the same kind of attention within the sector. Factors that relate to this are the lack of awareness, complications in definitions and implementation.

Set of indicators

After conducting the first step by identifying indicators via literature review as described in **Table 6**, it was decided for this research to map the indicators found into four main themes based on the focus of stimulating sustainability and circular economy:

1. Main theme #1: Environmental impact
2. Main theme #2: Social impact
3. Main theme #3: Economical impact
4. Main Theme #4: Circularity impact

The first three themes, namely themes #1, #2, and #3 are related to the dimensions of sustainability, whereas the fourth theme is focused on circular economy. Furthermore, each theme has certain "indicator categories". Each "indicator category" consists of a range of indicators. An example of the relation between a "theme", "indicator category", and "indicator" is shown in **Figure 24**.

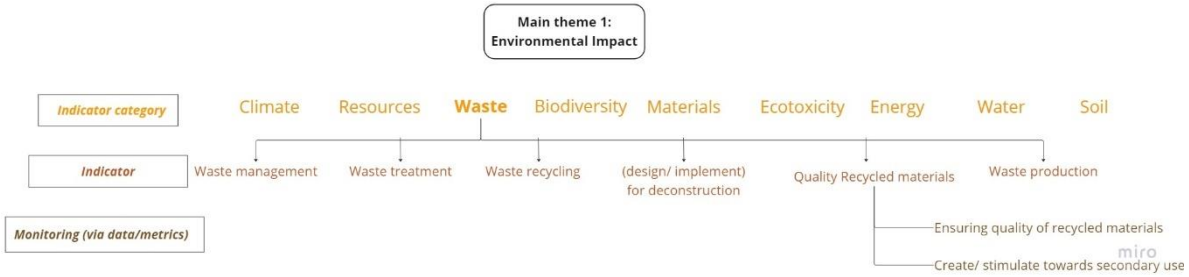


Figure 24 An overview of an example of the relationship between a main theme (Environmental impact), its indicator categories, related indicators, and the applicable monitoring options. In this figure, the indicators for the indicator category "waste" are shown.

Table 7,

Table 8,

Table 9, and **Table 10** shows an overview of each main theme, indicator category, and related indicators (Abadi et al., 2021; Arya et al., 2015; Chen et al., 2020; Corona et al., 2020; Diaz-sarachaga et al., 2016; Faber & Sorensen, 2002; Platform CB '23, 2022; Rackwitz et al., 2005; Selim & Saeed, 2021; Vilutiene & Ignatavičius, 2018) after conducting the identification process steps no.1, no. 3, and no 4 as described in **Table 6**. In **Appendix D** a more extensive list is shown including the objective and monitoring process per indicator.

Table 7 Overview of main theme 1: environmental protection, including the set of "indicator category" and related indicators

Main theme 1: Environmental protection	
Indicator category	***Indicator***
Climate	Estimation of carbon dioxide associated with activity
Resources	Resources measured and minimized – Energy
	Resources measured and minimized - Materials
	Resources measured and minimized - Land
	Resources measured and minimized - Water
Waste	Waste Recycling
	(design/ implement) for deconstruction
	Quality Recycled materials
	Waste treatment
	Waste production
	Waste management
Biodiversity	Protection flora and fauna
	Natural heritage
Materials	Equipment and materials with ecological labels
	Use of regional materials
	Use of durable materials
	Reused/ recycled materials
	Product footprint via MKI
Ecotoxicity	Air quality
	Dust
	GHG emissions
Energy	Renewable energy
	Energy consumption
	Energy efficient drivers
	Energy recovery
	Light pollution
Water	Water Saving
	Water consumption
	Protection of water resources

	Water leakage
Soil	Erosion and sedimentation control plan

Table 8 Overview of main theme 2: social impact, including the set of "indicator category" and related indicators

Main theme 2: Social impact	
Indicator category	***Indicator***
Actors	Participation
	Multidisciplinary
	Communication
Users	Noise
	Accidents
	Communication
	public safety
	Vibrations
	Dust
Integration	Local workers during maintenance
	Raising levels of training and information
	Safety and health of workers

Table 9 Overview of main theme 3: economic impact, including the set of "indicator category" and related indicators

Main theme 3: Economic impact	
Indicator category	***Indicator***
Costs	CBA
	LCC
	Local economy
	Investment costs
	Material costs
	Inspection time
	Labour time
Technical	Durability
	Research & Design (R&D)
	Constructability
Service-tariff	

Table 10 Overview of main theme 4: circularity impact, including the set of "indicator category" and related indicators

Main theme 4: Circularity impact	
Indicator category	***Indicator***
Strategies	Technologies for circularity
	Closed loop systems
	Circularity awareness and skills among employees

	Maximize economic impact
	Secondary market mechanisms
Redesign	Prolongation of use phase
	Circular-end-of life
	Circular logistics
	Innovation
Reduce	Reduce quantity
	Reduce dependency
	Reduce complexity
	Reduce impact
Re-use	Reparability and maintainability
Refurbish	Refurbishment and upgradability of products
	Accessibility and reusability of components
Recycle	Material composition and separability
	Properties for recycling
	Use of recycled material
Recover	Waste to energy

4.1.1.4.3 Strategies influenced by indicators

There is a need to address the dimensions of sustainability via indicators to reconsider maintenance strategies since this is currently limited (Rohman et al. 2017, Sutrisna and Goulding 2019). Eventually, the idea of this research is to explore how strategies and indicators can together be considered and used to stimulate more sustainability and circularity in the maintenance stage of existing civil objects.

Resulting of the theory behind strategies (Mintzbergen,1986), it can be concluded that first, **formulate** what should be done to maintain the object, then **develop strategies** to aim for the goal, namely incorporating sustainability and circularity in the maintenance strategies.

A "sustainable (development) strategy" can be defined as follows:

> **"a coordinated, participatory, and iterative process of thoughts and actions to achieve economic, environmental, and social objects in a balanced and integrative manner"**
> (Lyytimäki, 2012)

This definition is considered to be very generic, however, it could be an interesting definition to implement and consider sustainable maintenance strategies and what to consider when talking about that. "Participatory" and "iterative process" are two words within this definition that can be linked to collaboration (between actors).

How strategies can be influenced by indicators

The Framework for Strategic Sustainable Development (*FSSD*) often also referred to as the "The Natural Step Framework" is developed to explore and explain the progress of various concepts, indicators, and tools related to sustainability (Robert et al., 2013; Korhonen, 2004; Marshall and Toffel, 2005; Ny, 2009). The objective of the FSSD proposes that concepts,

approaches, and tools, can be of use in a strategic way towards implementation of sustainability. This framework is adapted and made applicable to the research as shown in **Figure 25**. The Framework has a certain flow and is based on an iterative character. It shows the order of activities and the relation between maintenance strategies, actions, and indicators. The latter can be incorporated into the tool. This framework can be used as a basepoint for designing the tool.

In conclusion, various aspects have been reviewed as part of the literature review. All these aspects are linked to one another to get a complete picture of the research at hand. Next to reviewing the literature, it was decided to gain more in-depth insights from practice experts, their opinion was taken into consideration by carrying out these semi-structured interviews. The results of these interviews will be elaborated on in the next section.

Figure 25 FSSD framework adapted to the research at hand

4.1.2 Semi-structured interview results

To gain insights from the practice side into the research problem, semi-structured interviews are conducted. In total 13 participants, all active in the Dutch civil engineering sector were interviewed throughout the period between September 2022 and October 2022 as seen in **Table 11**. The duration of each interview was between 45-60 minutes. Due to the protection of the identities of the respondents, the transcripts are not part of the thesis document.

The analysis of the interviews resulted in five (5) main themes and several sub-themes:

- **Theme 1: Sustainability in maintenance**
  - Sub-theme 1.1 Defining sustainability
  - Sub-theme 1.2 Sustainable maintenance
  - Sub-theme 1.3 Circular Economy
- **Theme 2: Barriers to sustainable & circular strategies**

- **Theme 3: Enablers for sustainable & circular strategies**
- **Theme 4: Collaboration**
  - Sub-theme 4.1 Contractual Agreements
  - Sub-theme 4.2 Collaboration between parties
- **Theme 5: Measuring sustainability**
  - Sub-theme 5.1 Indicators

The analysis of the interviews is conducted according to Braun & Clarke's 6-step framework due to the clear and usable framework for doing thematic analysis (Stranges et al., 2014) as shown in **Figure 12,** and with the use of the Atlas Ti 22 software. This section will merely focus on the key takeaways for each theme. **Appendix E** covers the elaborate results of the interview analysis.

In general, two main perspectives are considered throughout the maintenance phase namely the perspective of the client, whereby throughout this research the client is considered to be (a representative of) the public sector. The other is the perspective of the market party. For this research, the market parties only consist of (representatives) from main contractors and consultancy bureaus. Other market parties with more specific expertise also relevant in the maintenance stage were excluded from this research since in practice these parties are working as sub-contractors for the main contractors. In this way, these parties are indirectly linked to the main contractors interviewed.

Throughout the analysis of the interviews, it is important to trace back the perspective/ representation of the interviewee's response to create that validity. The following abbreviation references are used for the interviewees.

Table 11 All interviewees participated with abbreviation references

Public sector	Abbreviation reference
Province of North Holland_A	[PNH_A]
Province of North Holland_B	[PNH_B]
Province of North Holland_C	[PNH_C]
Municipality of Amsterdam	[Mun_Ams]
Rijkswaterstaat_A	[RWS_A]
Rijkswaterstaat_B	[RWS_B]
CROW	[CROW]
Market parties	**Abbreviation reference**
Consultant Individual	[CI]
Arcadis Nederland B.V._A	[Arc_A]
Arcadis Nederland B.V._B	[Arc_B]
Contractor A_1	[CA_1]
Contractor A_2	[CA_2]
Contractor B	[CB]

5.1.2.1 Theme 1: Sustainability in maintenance

Sustainability is one of the main concepts central to the research. The concept is researched within academics and lately more integrated into policy documents and organizational goals. Sustainability is gaining more attention also in policies relevant to the civil engineering sector

in the Dutch context. The main goal of this theme was to gain practical insights into the definition of sustainability, the integration of the term within maintenance, and the relation between sustainability and circular economy.

Main takeaways from theme 1 "sustainability in maintenance" are:

- Defining sustainability in general is not as easy as the word is used in practice.
- Defining and considering sustainability in the maintenance stage is often also not easy.
- Sustainability is seen as an 'umbrella' term, whereby circularity is one of the few concepts how to achieve the overarching sustainability goal.
- Circularity within maintenance of civil engineering objects is often associated with materials.

Sub-theme 1.1. Defining sustainability

For this research, the most applicable definition of sustainability is as follows:

"The adoption of principles of sustainable development in infrastructure development projects execution, by striking a balance between environmental protection wellbeing and economic prosperity for the benefits of both the present and future generations"
(Munyasya & Chileshe, 2018)

It was researched how sustainability is defined by the interviewees. The reason for this is that to incorporate sustainability, it is necessary to set clear boundaries on the definition of the term. The question on defining sustainability was one of the starter questions of all the interviews. A few quotes retrieved from the transcripts on defining sustainability are:

"… You want to build and maintain structures in such a way that ***both life on the planet and future generations benefit from it.*** *This is then translated into actions such as circular building, materials flow, and impact on the future…"* [PNH_A]

"… Sustainability is often a ***very vaguely and broadly defined*** *term. So, this is organizational dependent…"* [Mun_Ams]

"…The term sustainability is a ***container term.*** *A reason for this could the that the term gained a large status very quickly..."* [RWS_B]

"… With sustainability you want to ***make it as concrete as possible*** *because that's the most important thing to get a foothold in the projects and with the people who have to deal with it. However, sometimes it is a bit of a search for how to apply sustainability due* ***to missing concreteness*** *in the definition of it…"* [Arc_A]

As the above quotes state, defining sustainability is not as easy as the term is being used in practice. The results of the analysis show that all participants were to a certain extent struggling with defining the term. Words such as "broadly defined", "vaguely", and "concreteness missing" were mentioned in the case of explaining sustainability. Whenever the participant did give a more elaborate definition of the term, the link was made with the protection of the environment. In literature, sustainability is linked to three (3) dimensions namely environmental, social and economic (Alhaddi, 2015; Heijungs et al., 2010; Liu et al., 2010; Sahely et al., 2005). However, all participants failed to include all dimensions of sustainability when asked to define the term.

In conclusion, the analysis shows that sustainability is not as easily definable for the actors. This could also lead to expectations. But, also not fully grasping and understanding what sustainability is about. This could be identified as one of the reasons why sustainability is not (always) easily incorporated or fully exploited in projects.

Sub-theme 1.2 Sustainable maintenance

The research at hand focuses on improving sustainable strategies within the maintenance of civil construction objects. The concept of sustainable maintenance within the civil construction sector is not yet fully explored. In some countries such as the UK, USA, and Australia they are a bit further in the process and are currently even exploring different mechanisms and tools how to do so. One of the follow-up questions asked to the interviewees after they elaborate on defining sustainability, was to define the term in the context of the maintenance of civil engineering objects. Some quotes retrieved from the transcripts are:

*"…Sustainability within the operational and maintenance stage is actually sometimes **already partly automatically considered.** The other part you try to stimulate as an organization…"* [PNH_C]

*"…it is about carrying out maintenance activities in such a manner that we **consider sustainability**…"* [PNH_A]

*"… works should be carried out as sustainably as possible. **Our clients expect** us as contractors to make both projects and objects as sustainable as possible…"* [CA_1]

*"…Within the operation and maintenance stage, sustainability is **maybe not considered to be that big of an aspect**. Important within maintenance is to carry out the maintenance works and be done, nothing extra. However, in my opinion, I've also seen reports that O & M by nature already considers the long-term, lifecycle costs, life extension. On the basis, you could maybe say that they are already including aspects that could lead to sustainability in the sense of prolonging the asset…"* [CI]

***"…Sustainability within O & M is often considered to be minimal**. Within this stage, it is important to preserve the object and longevity remains as well as the functionality of the object..."* [Arc_B]

It is concluded from the interviews that sustainability within this specific stage is not yet well embedded nor considered to be a standard aspect of maintenance. When asked for the reason, interviewees responded in different ways. These will be further elaborated on in theme 2, namely the barriers. Representatives of the market parties [CA_1/ CB/ Arc_1] mention that clients expect parties such as contractors to incorporate sustainable maintenance practices. Others [PNH_C] stated that without even really being aware of the aspect of sustainability in very broad perspectives, considerations that are made for maintenance activities somewhat already include the line of thinking linked to sustainability. However, these considerations are often indirect, and not explicitly emphasizing sustainability. Due to this, the full potential of integrating could be missed and overseen.

Sub-theme 1.3 Circular Economy

Another focus within the research is circular economy (*CE*) and circularity. The relationship between circular economy and sustainability is elaborately reserched (Geissdoerfer, Savaget, Bocken, & Jan, 2017; Mart & Aguayo-gonz, 2019). While circularity has a positive influence on certain aspects of sustainability, it does not integrate all dimensions, especially not the social one (Murray et al., 2015). This is one of the reasons for including circular economy explicitly.

With this sub-theme, more insights are to be gathered on the concept of CE, also within the maintenance stage.

"…within our organization (refers to Province of North Holland) ***sustainability is further translated into 6 goals where circularity is included*** *in as one of the six goals…"* [PNH_B]

"… ***circularity is one of the five pillars*** *of sustainability…"* [Mun_Ams]

"…Both sustainability and circularity are enormously linked together*. One cannot exist without the other. In most cases, people often pull both concepts (sustainability and circularity, red.) apart from each other. I never really understood that.* ***Circularity is an aspect of sustainability. It is important to move into a more integral picture.*** *It doesn't make much sense to sit hard core on circularity. It's important to have an integral view of sustainability in which circularity is then included…"* [CROW]

"… There are a few elements that you can use to make it (sustainability) more concrete, in which ***circularity is one of these elements…"****[* Arc_A]

Interviewees who were asked about the link between sustainability and circularity all somewhat made the relation with the latter being part of the first one. Sustainability is seen as an umbrella term, and circularity is under the umbrella. It is seen as a way of achieving sustainability together with others such as waste, energy, and CO_2 emissions.

Some participants also elaborated on circularity within the maintenance stage of existing civil construction objects:

"…In the case of circularity, we have to consider things in a different way. ***Materials should be considered circular*** *and then also sustainable. If you can think of doing this differently, you can also consider doing maintenance strategies in another manner…"* [PNH_B]

"…Circularity is mainly about using primary raw materials less and possibly no longer at all*, via the 4 R-ladder and dealing with them in the smartest possible way. So, look at what is already there and* ***can we use that before we use primary materials. Use secondary materials as smart as possible and therefore need fewer primary materials for carrying out maintenance activities…"*** [CROW]

" Circularity can be considered a ***relatively vague described term****. But* ***the material component*** *is of importance together with* ***secondary and renewable materials*** *and potential to* ***reuse*** *materials…"* [Mun_Ams]

"…It (circularity, red) has certain interfaces with sustainability. It is ***tremendously linked to your materials***" [CB]

"Circularity is ***more focused on material flows, resources flow"*** [CI]

There is often a link made between materials and circularity. It could be focused on the reuse of materials, using fewer primary materials, and smartly using the materials. Thus, circularity within the maintenance of civil engineering objects is often associated with materials.

5.1.2.2 Theme 2: Barriers for sustainable & circular strategies

As already mentioned in the first theme, follow-up questions were asked to the participants about the reasoning for not elaborately including sustainability to be part of the maintenance stage yet. This is one of the questions asked which resulted in identifying barriers for not fully considering sustainability within the maintenance stage. Next to that, it was explicitly asked if the interviewees can identify barriers for reasons why sustainable maintenance is not (often) considered.

Main takeaways from theme 2 "barriers for sustainable & circular strategies" are:

Analyzing the interviews, resulted in 5 main **categories of barriers**:

1. People involved
2. Financial resources
3. Procurement/ contracting stages
4. Maintenance transition
5. Others

The barriers are further elaborated on, described, and divided in **Appendix E**. Some quotes retrieved from the transcripts based on the categories are stated below.

People involved: *"**The people** who are involved may not see the relevance of it. But, that also holds something back. They have to accept that themselves first or somebody has to say to them that they need to do it differently. I am afraid that it only happens in the latter case…"* [Arc_A]

Financial resources: *"They also have **other budgets at O&M** compared to other parts that focus on other stages in the lifecycle, since the **budget for O&M is limited** to maintaining the asset and having it functioning…"* [CROW]

Maintenance transition: *"There are **practical obstacles.** People within the O & M **stages are often not really in favor of innovation** and with sustainability, you often need to consider innovation and innovative strategies…"* [CB]

Others: *" … lots of people who are very enthusiastic about it within our own organization. However, it is **hard to express everything in a number such as MKI**…"* [CA_2]

5.1.2.3 Theme 3: Enablers for sustainable strategies

With barriers, there are enablers and opportunities. In the case, participants mentioned barriers as described above, they were also asked to consider enablers to overcome the barriers.

Main takeaways from theme 3 "enablers for sustainable & circular strategies" are:

Analyzing the interviews, resulted in 5 main **categories of barriers**:

1. Procurement
2. After contracting stage
3. Project level
4. People involved
5. Others

As with the barriers, the enablers are further elaborated on, described, and divided in **Appendix E**. Some quotes retrieved from the transcripts based on the categories are stated below.

Procurement: *"… **the procurement and tendering really makes the difference**, in the end, it is about what the client asks…"* [CB]

Procurement: *"… **by bringing both sustainability and circularity as choices in contracts, for example, in the way we work**. As consultants, we have to suggest how we think something can best be done and what would be best for the client. In that way, we as consultants thus also have a role in this."* [Arc_A]

After contracting stage: *"… **Within O&M you also have long-term contracts, and it is important, though, to include developments in them**. Promoting new things in the contract, for example."* [RWS_B]

People involved: *" **More cooperation and promoting it through cooperation between the contractor, the client, and the knowledge institutions.** The requirements are set by the province and put them on the contractor who then must start coming up with solutions for this."* [PNH_B]

People involved: *" **People in the chain also must want it themselves and see the need.** If they also feel the urgency and show ownership for that transition, effort has to be put in it. Try, research, and make time and efforts. Another part also goes automatically…"* [PNH_B]

Others: *"…From the O & M side, initiatives can be implemented based on the problems encountered. **The O & M can serve as a base for innovations**."* [Arc_B]

5.1.2.4 Theme 4: Collaboration

Collaboration is a key enabler to identified barriers related to sustainability and circular economy (Arayici & Aouad, 2015; Placet et al., 2015). One of the ways of collaboration between these parties is currently via contractual agreements between the client and the contractor. With this theme, the interviewee is asked to elaborate on the contract type they have experience with for maintenance works.

Main takeaways from theme 4 "Collaboration" are:

- Performance-based contracts are mainly awarded by RWS for the maintenance works of civil construction objects
- RWS uses the concept of RAMMSHEEP to mainly steer on the functional requirements of assets, but sustainability is not fully embedded in this yet. Also confirmed by RWS self.

Sub-theme 4.1 Contractual agreements

Contracting is an important factor that sets the relationship between the client and the contractor for the works. It is important to mention that not all interviewees had experience with performance-based contracts. In some cases, for example, the municipality of Amsterdam and the province of North Holland were familiar with these types of contracts, yet, they are currently using and experimenting with other types of contracts for maintenance works such as "collaboration agreements" *(in Dutch: samenwerkingsovereenkomsten)* and/ or "framework agreements" *(in Dutch: raamovereenkomsten)*. Nonetheless, [RWS_A], [RWS_B], [Arc_A], [Arc_B], [CA_1], [CB_2], and [CB] do have experience with performance-based contracts. In the Dutch context, authority RWS uses the concept of "RAMSSHEEP", a risk-driven approach that also sets the requirements the asset must fulfill. The following statements below retrieved from the transcripts show an indication of the experiences on performance-based contracting:

"RAMSSHEEP as it is currently incorporated into the contracts is mainly focused on technical aspects, but when the focus on RAMSSHEEP was created several years ago, the ***concept of sustainability and the environment was not considered to be that important as now.*** *Within a short time, sustainability became very important and the impact on it is large, however, a big step may have been skipped. It is considered to take it more into account during the awarding (in dutch: gunning) stage. And with RAMSSHEEP, you put that in a document within the procurement stage, and then it might be considered read over it."* [RWS_B]

The above statement concludes that within the authority RWS, they might still search for possibilities to put more focus on the environmental dimension of sustainability for example. The same in some way goes for interviewee [Arc_A]: *"for myself, I find it quite challenging. In the role we are fulfilling as contract management department, it is hard to give sustainability a spot sometimes."*

Sub-theme 4.2 Collaboration between actors

Throughout the contract period for maintenance works, there is collaboration occurring between the client and contractor. The level and extent of that collaboration thus depend on how that is decided between involved parties and on a contractual level. Since achieving and considering sustainability and circularity requires more collaboration and stakeholder engagement, it is important to take the view of participants into account on this.

From the perspective of the public sector [CROW], [PNH_A], [PNH_B], [PNH_C], [Mun_AMS] the following quotes are retrieved from the transcripts:

*"… **More collaboration between the client and the contractor**. There is a movement of two-phase contracts and "bouwteams" within the civil engineering sector, especially in other phases of the lifecycle. Within the maintenance stage, there are especially performance-based contracts. **Here the role of the client and contractor are really delineated** (in dutch: afgebakend) and therefore makes collaboration quite difficult to achieve…"* [CROW]

"… RWS prescribes in a functional manner. And how the works are executed is up to the contractor. As RWS, we don't interfere with how a contractor does it. Unless it's of critical importance then we know sometimes we want to go toward prescribing. We do steer with the MKI. But the type of materials, ***how works are executed etc. is really dependent on the way the contractor wants to do this****…"* [RWS_A]

" I would prefer that ***the contractor stays engaged in sustainability throughout the whole project.*** *So have regular sessions and or exchange information about sustainability with the contractor. Unfortunately, we see that the contractor only does something if it makes them money…"* [RWS_A]

With the municipality of Amsterdam and the province of North Holland having experiences with other kinds of maintenance contracts, they might look at this from a different angle:

*"… **Working together** is also about making good agreements, and what we do when something goes wrong. Who is responsible, who do we talk to, and how does conflicts resolve themselves."* [Mun_ Ams]

"… at this type of contract type (samenwerkingsovereenkomst, red), the common goal is stated based on the best result and the goal(s) with the most impact. A joint plan is made for in the case of conflicts, interests of parties." [Mun_ Ams]

*"To **stimulate sustainability within maintenance, it is important to consider more collaboration since we cannot come up with everything by ourselves**…. In the case of "bouwteam- type" of contracts, we work together with the contractor as the client. Thinking together about ways to find sustainable alternatives for example. It is always better to include the market with this…"* [PNH_A]

Also, representatives from market parties such as [ID], [Arc_A], [Arc_B], [CA_1], [CA_2], and [CB] considered collaboration:

***"…** Collaboration creates more space to think about sustainability and maybe give ideas to do things differently… If you don't collaborate, but the contractor just executes that contract, then it stays as you conceived it…"* [Arc_A]

*"…There already is some kind of collaboration, but **not with the focus on sustainability always**…"* [CA_2]

5.1.2.5 Theme 5: Measuring sustainability

In case, more sustainable maintenance options should be considered, it is important to collaborate more among parties as described in the previous theme. However, it is also necessary to think about how sustainability can be incorporated. Interviewees were asked if they are familiar with ways to measure sustainability, and familiar with the concept of indicators. In the case, they said yes, it was then asked as a follow-up question what kind of indicators they consider within the maintenance stage, and how these are measured. **Table 12** shows the types of indicators respondents were working with/ familiar with for the maintenance stage. It can be concluded that the indicators mentioned by interviewees are mainly covering the environmental dimension of sustainability. The environmental cost indicator (*in Dutch: milieukostenindicator MKI)* is by far the most mentioned by participants. The reason for this could be that MKI is often used in practice.

Table 12 Indicators mentioned by interviewees

Indicators	No. of times mentioned during the interview
Environmental Cost Indicator (MKI)	8
CO_2 emissions	7
Circularity Index	3
Biodiversity	2
Material component	2
Energy usage	2
Air quality	1

4.1.3 Design brief – Defining the requirements

After analyzing the results from the literature and semi-structured interviews, the requirements could be set to solve the identified problem. This led to the design brief. To recap, **the need based on the identified problem**: The analysis of the literature review and interviews identified that there is a need to develop a tool to stimulate and monitor sustainable and circular actions as part of the maintenance strategies.

Having a description of the requirements will answer the fifth sub-research question (**SQ5**): '*What are the requirements for developing a tool that could be used to stimulate sustainable maintenance strategies?'*

The following **requirements** to solve the identified problem are formulated based on the results of conducting the literature review and semi-structured interviews:

- **Collaboration**: Throughout the discovery phase of the "Double Diamond Method", it was concluded that sustainability is not yet elaborately considered in the maintenance stage of existing civil construction objects. There have been various barriers identified for this, but "collaboration" is identified as a key enabler to barriers related to sustainability and circular economy (Arayici & Aouad, 2015; Placet et al., 2015). The importance of collaboration between actors during the maintenance stage is researched (Hauashdh et al., 2022). To meet the needs and demands of sustainable maintenance practices, strategic approaches should be considered together with the actors involved. Nonetheless, the current state is that the focus is too much on shifting risks to parties rather than seeking collaboration among parties to achieve common goals and objectives (Engebø et al., 2020). There is a need to enhance collaboration and engagement between actors since this is considered to be an important aspect to put more emphasis on stimulating sustainability and circularity. This is not only confirmed by the literature but also mentioned by participants during the interviews.
- **Indicators**: An identified way to assess, communicate and monitor the progress toward sustainability is via indicators (Balasubramanian, 2020; Lyytimäki, 2012). Various indicators could be useful to stimulate that sustainability and circularity in the maintenance strategies of existing civil construction objects. Via literature review, a set of applicable indicators are identified that could be useful for this research, see **Table 7, Table 8, Table 9,** and **Table 10**. The tool should be able to stimulate the use of more sustainable and circular interventions with the help of indicators (Mart & Aguayo-gonz, 2019).
- **Monitoring**: Within the Dutch civil engineering sector, RWS awards mainly performance-based contracts to contractors to execute maintenance works. These contracts are often for periods between 5-10 years. Throughout this period, data is

gathered in various ways to apply maintenance strategies. Gathered data can help steer processes, but also considerations of sustainability.

These above requirements, lead to the decision to **design a tool** that could be used throughout the maintenance period of existing civil construction objects. To design the tool, it is important to first define what a tool is. The most common definition found for a "tool" is:

" a piece of equipment that you use to help you do a job"

For this research, **a tool** should be designed in such a way that it can "help" actors involved in the maintenance process, to **collaborate** in such a way that with the help of **indicators,** maintenance strategies for existing civil construction objects will be reviewed, **monitored** and stimulated with sustainable and circular interventions.

The next section will elaborate on the design, the verification, and the validation processes eventually delivering the end result.

4.2 Part II: Insights – Develop & Deliver results

The second part of the "Double Diamond Method" covers the stage in which the tool will be designed and developed according to the requirements. As explained in the methodology, this part furthermore includes the systems-engineering line of thinking integrated into the process via the "verification and validation (*V&V*) model".

This section is two-folded. The first part will cover the development of the tool, including the design process and demonstration of the tool. The second part will cover the stage of testing the tool via validation sessions with experts.

4.2.1 Developing the tool- Verification

The design process of the tool is iterative. The requirements set at the end of the discover stage, are used as a guideline throughout the design process. Throughout the design process, the content and layout of the tool became more specific. This is a result of the iterative character of the "Double Diamond Method" research methodology. Next to the requirements set at the end of the discover stage, the following aspects are also important to consider for the development of the tool:

- **Applicability in two phases**: The tool should be designed in such a way that it could be applicable in the following two phases:
  - **Pre-contractual stage**: Reviewing of contracting procedures for obtaining maintenance contracts shows that the client currently does not include nor steer on incorporating sustainability and circularity as requirements in the necessary documentation and throughout the procurement process. It could be of interest to apply the tool in the pre-contractual stage to stimulate the client to consider sustainability and circularity within the specifications of the contract and other associated documents.

- **Execution stage**: With maintenance contracts often being awarded to a contractor for periods of approximately 5 years, considering sustainability throughout the maintenance activities can be more explored than the current situation. Depending on the contractual relationship between the client and contractor, it could be of interest to apply the tool in such a manner that the contractor has more guidance on exploring sustainable maintenance strategies. Hereby the client could to a certain extent also steer the contractor.

- **Civil engineering objects within the 'HVWN- network' managed by RWS**: It was chosen to solely focus on two types of civil construction objects, namely **bascule bridges** (*in Dutch: beweegbare bruggen)* en **sluices**. From a more general point of view, it is found that there is more focus on optimal maintenance strategies for civil engineering objects such as bridges (Almomani & Almutairi, 2020; Huang et al., 2004; Sun et al., 2015). Furthermore, bridges are considered to be key components of public transportation infrastructure in modern society (Sun et al., 2015). Next to that, the elements and way of conducting maintenance of bascule bridges and sluices correspond reasonably, whereas other objects for example tunnels have other components as well as other applicable policies.
- **Collaborative character**: Throughout the research, it is mentioned several times that collaboration and stakeholder engagement are considered important to stimulate sustainability and circular economy. This is also the case for the maintenance stage. The tool needs to be able to accommodate collaboration and stimulate interactiveness between the actors involved.
- **Indicators**: For this research, it was decided to measure sustainability and circularity via the use of indicators. It is important to understand the definition and objective of the indicators. A strategy can be measured on sustainability with an indicator. With the iterative process, the indicator can then afterward be used as a "steering tool" to adjust the strategy.
- **Maintenance strategies**: There are various maintenance strategies (Abbassi et al., 2022) for civil engineering assets. With the research being conducted in the Dutch context and more specifically focusing on certain objects managed by RWS, it is found that a risk-driven approach is applied. The risk-driven approach is based on the concept of FMECA *(Failure Mode, Effects & Criticality Analysis)* which is considered to be a quantitative failure analysis on the element level of an object. The focus maintenance strategy for the development of the tool is mainly on day-to-day maintenance activities to keep the object and its related systems functioning for the users. The day-to-day maintenance activities are in practice referred to as "standaard verzorgend onderhoud" (*SVO*).
- **Asset management approach**: Asset management is focused on coordinating and optimizing activities such as planning, asset development, asset care (or maintenance), asset life extension, asset decommissioning, and asset disposal. It regards decision-making through the total life cycle of the physical asset from its creation or acquisition,

use, maintenance, and renewal or disposal. As maintenance is part of the asset management principle, there have been researches emerging that incorporate maintenance management processes with the ISO-55000 asset management standard (Okoh, 2019; Parra, 2020). For this research and the development of the tool, it is therefore of interest to see how existing maintenance management processes can be incorporated into existing standards.

- **Interface**: The tool needs to be developed in a user-friendly program. It is chosen to use "**Microsoft Excel**" for this.

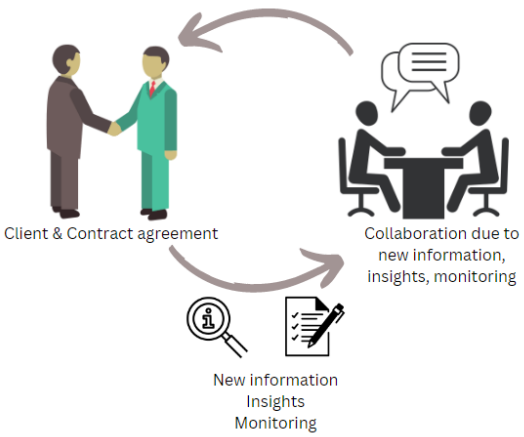
The ultimate point to take into account when designing the tool is, incorporating sustainability and circularity also requires exploring the creativity of the actors to come up with suitable solutions. The content of the tool is based on the scientific knowledge gained throughout the literature review part of the research. To make the tool useable for practice, it is decided to deliver the tool in Dutch.

4.2.1.1 Designing the tool

This section will explain the various design steps that are taken to deliver the final version of the tool. The tool is titled: *"Maintaining Sustainably & Circularly in a collaborative way"*; the title speaks for itself since the main objective of this tool is to consider the concepts of sustainability and circularity throughout the maintenance of existing civil objects whereby collaboration could be playing an important role to achieve that. The basis for designing the tool is according to the adapted FSSD framework as shown in **Figure 25**.

Start of the project

Comparing the results of the findings led to barriers encountered in both literature review and semi-structured interviews such as (1) the lack of knowledge on concepts such as sustainability and circular economy, (2) the industry being relatively uncollaborative, (3) the lack of collaboration, and (4) insufficient use of collaboration tools. Considering these barriers, led to designing the tool that will enhance (a) collaboration between parties involved in the maintenance phase and (b) deal with the lack of knowledge currently on the concepts of sustainability and circular economy integrated within the maintenance stage.



It was mentioned among participants of the interviews that trust plays an important role during the collaboration between the client and contractor. For that reason, it can be helpful to make information visible, have access to information, and together explore the options for sustainability in the maintenance strategies.

As mentioned earlier, the tool is developed in **MS Excel** and consists of various working sheets. Each sheet has a certain objective. **Table 13** shows an overview of each sheet within the tool, including a description of the objective(s) per sheet. Each sheet will be further explained afterwards.

Table 13 Overview of the various sheets in the tool including their objective(s)

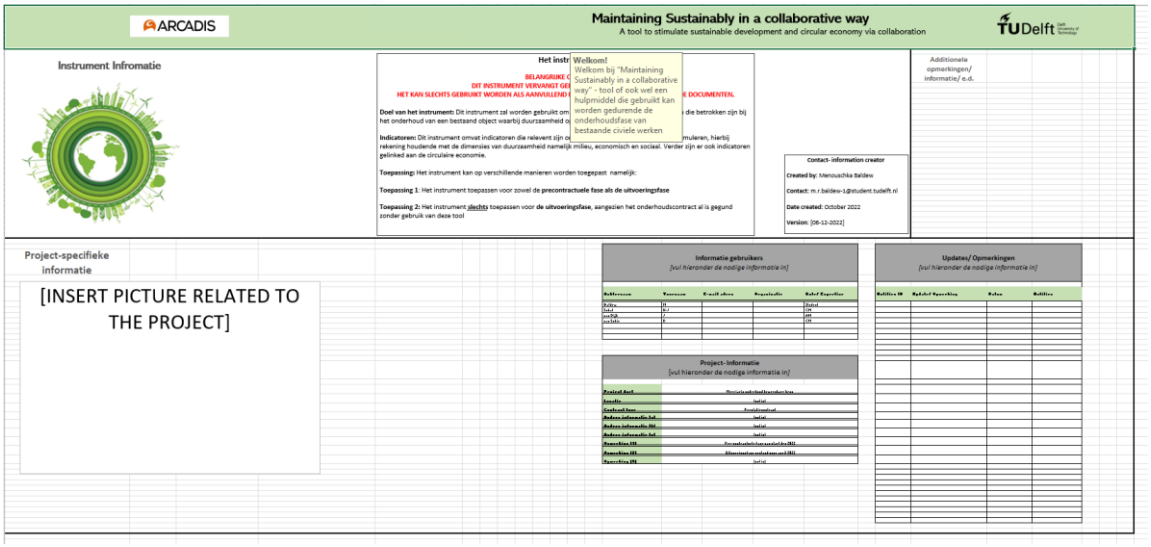
Sheet no.	Sheet title (*Dutch*)	Sheet objective
0	Cover page (*Voorpagine*)	Necessary information about the tool and project-related information.
1	Decomposition (*Decompositie*)	Decompose the management object according to the NEN standard.
2	Dashboard	Dashboard with information.
3	Theme + Category ambitions (*Thema + categorie ambities)*	The client determines the importance of relevant categories linked to four themes; The "importance" or ambition with regard to sustainability and circularity is determined by means of four levels ranging from 0 to 3.
4A	Pre-contractual stage (*Pre-contractuele fase)*	Before tendering takes place, the client should prepare documents for this process. An important document here is "demand specification requirements." This tab sheet focuses on the aspect requirements.
4B	Execution stage (*Uitvoeringsfase)*	During the execution phase, the responsibility regarding the execution of maintenance work lies with the contractor. Since maintenance contracts in most cases have a relatively long contract term, sustainable options for maintenance can be devised.
5	Definitions (*Definities)*	Several terms are used in this instrument. Here are further explanations and meanings of various terms.

The cover- page of the tool includes all the necessary information about:

1. **Project-specific information**: Each project is unique and therefore has other requirements. The information provided and necessary is in most cases also project-dependent.
2. **Collaborators**: Stakeholder engagement is considered to be an important aspect of collaboration between the client and contractor to stimulate sustainability. Depending on the various characteristics of a project such as period, and its complexity, it could be that different stakeholders are involved. Next to that, it is important to include the stakeholders when considering sustainability within the maintenance stage. Throughout the projects, collaborators could be added or even replaced. It is important however to keep track of who is participating, and their expertise. In some cases, certain expertise(s) could be of added value to the project, and in this way, the missing expertise(s) can be easily identified.

3. **Monitoring**: The length of setting up the procurement strategy is often a process of a few months. The same goes for the contract time for maintenance works, which is in most cases between 5 and 10 years. Throughout the period, things can change and/or be updated. For that reason, it is important to keep track of changes within the projects and within the tool. With sustainability and circular economy being emerging topics, research & development are also ongoing. In some cases, there might arise questions and specific remarks throughout the use of the tool and collaboration with the need to further research those and a reminder remark might be helpful to keep track of that.

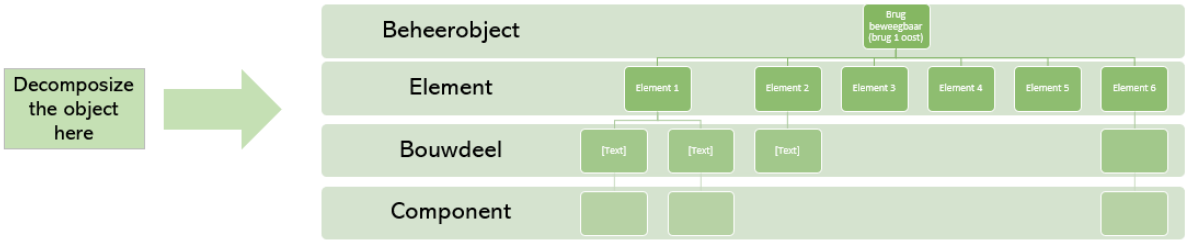
Below two impression pictures of the cover page are shown. Throughout the tool, there are also notes and explanations given within certain cells, in case the user wants more information. *Due to the size, the pictures might appear to be unclear, please zoom in for clarity.*

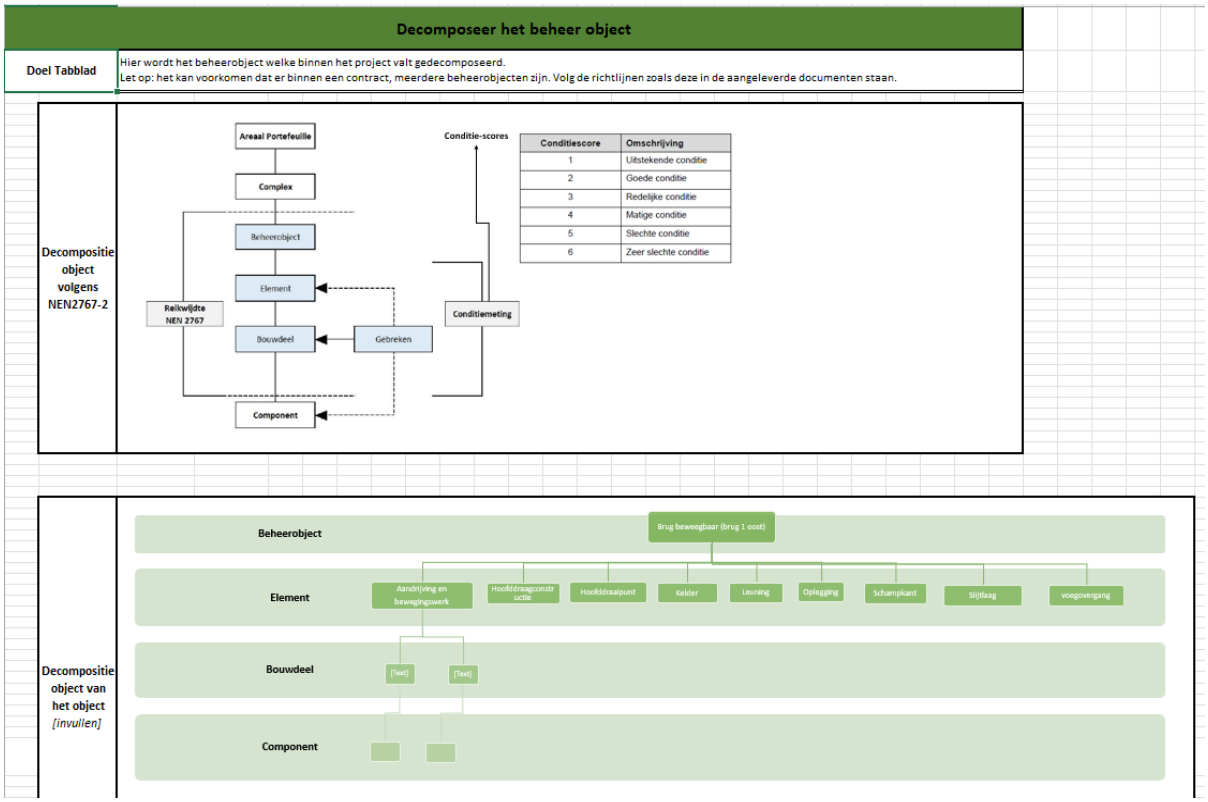


The tool allows the user to select or use certain sheets depending on the reason for using the tool. The picture below shows the second part of the cover page whereby a short explanation is given of each sheet including a button to click.

Hoe kan dit instrument gebruikt worden?	Tab-blad no.	Tab-blad titel	Doel tab-blad	Verwijzing
	0	0.VOORPAGINA	Nodige informatie over het instrument en project	Hier ben je al
	1	1. DECOMPOSTIE	Decomposeer het beheer-object volgens de NEN norm	Decompositie
	2	2. DASHBOARD	Dashboard aan informatie	Dashboard
	3	3. THEMA + CATEGORIE AMBITIES	De opdrachtgever bepaalt hier de belangrijkheid van relevante categorien gekoppeld aan 4 themas; De "belangrijkheid" of te wel de ambitie m.b.t. duurzaamheid en circulariteit wordt bepaald door middel van vier cijfers variend tussen 0 en 3	Thema & Categorie ambities
	4A	4A. PRECONTRACTUELE FASE	Voor dat de aanbesteding plaatsvindt, dient de opdrachtgever documenten klaar te maken voor dit process. Een belangrijk document hier is "vraagspecficatie eisen". Dit tab-blad legt de focus op de aspect-eisen	Pre-contractuele fase
	4B	4B. UITVOERINGSFASE	Tijdens de uitvoeringsfase ligt de verantwoordelijkheid m.b.t. uitvoeren van de onderhoudswerkzaamheden bij de opdrachtnemer. Gezien onderhoudscontracten in de meeste gevallen een relatief lange contract-tijd hebben, kunnen duurzame mogelijkheden voor onderhoud worden bedacht.	Uitvoeringsfase
	5	5. DEFENITIES	In dit instrument worden er diverse termen gebruikt. Hier vindt men nader uitleg en betekenissen van diverse termen.	Definities
	NIET GEBRUIKEN	DROPDOWNLIST	Programeren van de dropdownlist. ALLEEN BEWERKEN INDIEN NODIG	Dropdownlist
	NIET GEBRUIKEN	REKENSHEET	Programeren van de dashboard. ALLEEN BEWERKEN INDIEN NODIG	Rekensheet
	NIET GEBRUIKEN	ACHTERGROND	Nodige achtergrond informatie/	

The decomposition- page of the tool allows the user to decompose the object on the element level (*in dutch: element)*, the section level (*in dutch: bouwdeel)*, and the component level (*in ducth: component)*. The decomposition is executed according to the NEN2767-2 standard. For setting up the maintenance strategies, it is important to decompose an object since in the majority of cases, the maintenance works are carried out and described on the element level. Currently, the decomposition of the object is not linked to other sheets. However, it is considered to be useful to have an overview of the maintenance object in the tool. *Due to the size, the pictures might appear to be unclear, please zoom in for clarity.*





Applicable phases for the tool

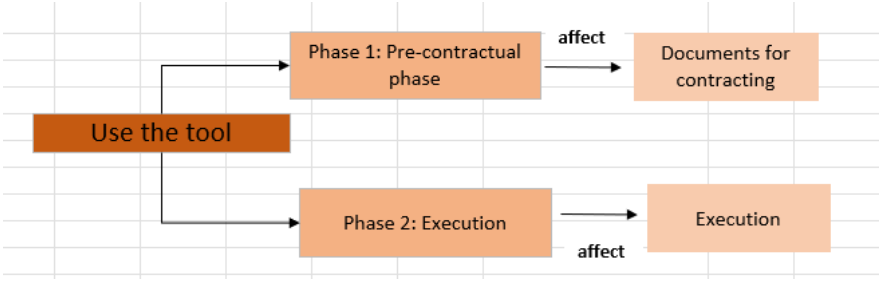
In the requirements, it is set that stimulating sustainable and circular maintenance strategies is a continuing process. There are two phases whereby this can be considered namely:

(1) The period/ stage before putting the procurement online, the **pre-contractual stage**
(2) The period/ stage after obtaining the maintenance contract, the **execution stage**

Analyzing these phases, procedures, and necessary documents, resulted in a list of aspects that differ for each of the two phases and should be taken into account for designing the tool:

- The difference in roles of the client and contractor;
- The procedure;
- The activities to carry out;
- Where to steer, implement sustainability and circularity to create that difference.

The picture below indicates the use of the tool for the various phases. Important to acknowledge here is that it's the decision of the user in which phase the tool should be applied. The current version of the tool covers the process in which the pre-contractual phase is linked to the execution stage. However, other options are also possible to use the tool only for one specific phase.



The definition- page of the tool includes the description, explanation, and additional information on indicators and other terms within the tool. Findings from both literature and semi-structured interviews concluded that terms are often defined in various ways. To achieve and implement sustainability, it is also important to set the right definitions. Setting definitions and boundaries of terms might also enhance collaboration among involved actors.

The theme + category ambitions- page

Sustainability is based on three dimensions; the environmental dimension, the economic dimension, and the social dimension. It was decided to create therefore three main themes that cover these aspects of sustainability. Next to that, circular economy is covered by another theme. This resulted in four (4) main themes (*in Dutch: hoofdthemas)* based on sustainability and circular economy:

- Main theme 1: Environmental impact
- Main theme 2: Social impact
- Main theme 3: Economical impact
- Main theme 4: Circularity impact

Each main theme consists of a range of indicators. The indicators are based on the list of indicators derived from the literature review and shown in **Table 7, Table 8,**

Table 9, and **Table 10**.

Each project is different, which means there is no standard way of including sustainability and circular economy in the maintenance strategies. On this page, the client can decide on the importance of certain main themes and indicators by assigning a certain numerical value, or level to the theme and/or indicator. Ambitions do not necessarily mean that this is what should be applied instantly in the rest of the process. It is an ambition, it is working towards that ambition. Especially since these maintenance contracts are awarded for 5+ years, the contractor and client can work together towards their ambitions.

The importance is indicated by a level. Since the tool is developed in the Dutch context, it is decided to apply to a certain extent the existing levels according to the "Ambitieweb" developed by Platform Duurzaam GWW (CROW, 2019):

Level 0	No modifications
Level 1	Minimal sustainability applications

Level 2 Significant improvements
Level 3 Added value/ "the extra mile"

The levels as shown above could be interpreted in various ways. It is therefore decided to include in the tool two examples for each level. There is however a "thin" line between level 2 and level 3. But that is up for discussion throughout collaboration.

		voorbeeld 1	voorbeeld 2
Ambitie- levels	Level 0: Geen aanpasingen	Geen afval scheiding	Geen verandering
	Level 1: Minimale duurzaamheidstoepassing	Afval scheiding	Energie besparing
	Level 2: Significante verbetering/ Concrete reductie/ meetbaarheid	Recycling	Energie opwekking
	Level 3: Toegevoegde waarde bieden	Recycling met energie opwekking	grote investeringen, totale levenscyclus meenemen

The pre-contractual phase- page

The pre-contractual phase is defined as the stage before the procurement of the maintenance works is published on the open-access platform 'TenderNed'. During the pre-contractual stage, the client is setting up documents that will be published on TenderNed. These documents are used by the contractors in order to make a bid for the works during the tendering phase.

The following documents that are at least published by the client in the case of procuring for maintenance works for civil engineering objects are:

- Basic Agreement (*in Dutch: Basisovereenkomst)*
- Demand specifications (*in Dutch: Vraagspecificties)*. This is further divided into:
    - Demand specifications General (*in Dutch: Vraagspecificties Algemeen)*
    - Demand specifications Requirements (*in Dutch: Vraagspecificties Eisen)*
    - Demand specification Processes (*in Dutch: Vraagspecificties Proces)*
- Appendices (*in Dutch: Bijlagen)*
- Annexes (*in Dutch: Annex)*

Reviewing above documents published by the clients showed that there are still opportunities to consider and stimulate sustainability and circularity via these documents. The obstacle here however is that currently mainly performance-based contracts (*PBCs)* are awarded for maintenance works of existing civil objects managed by RWS. With these contract types, the contractor has the freedom to execute the works, however, to a certain extent he needs to fulfill requirements.

In the pre-contractual phase sheet, the client can explore the options to include sustainability via the aspect-requirements (*in Dutch: aspect- eisen)* as part of the Demand specifications Requirements (*in Dutch: Vraagspecificties Eisen).* The tool that is now developed, allows the client to steer more on these aspect requirements by considering sustainability and circularity in a more concrete sense with the help of the indicators. Next to exploring the indicators, the tool also includes the verification methods and objectives per indicator. Important to mention

is that the tool has the opportunity to be expanded in such a way that the user can also in the future explore sustainability and circularity for other requirements than the aspect requirements.

The picture below shows a part of the pre-contractual phase sheet. Within this sheet, new aspect requirements (*in Dutch: aspect-eisen*) are formulated based on the chosen indicator. The verification method is also described for the indicator. This can now be part of the "Demand Requirment documents" (*in Dutch: Vraagspecificties Eisen)* that the client publishes as part of the procurement stage. Doing this exercise will result in more specific aspect requirements and verification methods to stimulate sustainability and circularity, rather than generically described ones. **Due to the size, it is a bit unclear in some cases, please zoom in for clarity.*

Themes	Indicator Categorie	Indicator	Parameter / wat wordt er gemeten (metriek)/ doel	Eis van opdrachtgever [vul in slechts sub-categorie]	Formulering specifieke aspect-eis [Maak hierbij de aspect-eis zo specifiek mogelijk mbv kernwoorden]	Verificatie methode [Hoe zal de aspect eis worden gecontroleerd]
Environmental Impact	Climate			2		
		Estimation of carbon dioxide associated with activity	Method of calculation based on calculating (CO2) for example: mass of material x transport distance x transport emissions factor *note: Hutchins UK Building Blackbook (Franklin + Andrews, 2009) as a reference to calculate (CO2)	1	Berekening maken van alle activiteiten waarbij CO2 (mogelijk) wordt uitgestoten a.h.v. voorgeschreven berekeningsmethode	Controle van de berekeningsmethode a.d.v. activeiten uitgevoerd

Collaboration during the pre-contractual phase

As one of the reasons for developing the tool is to stimulate collaboration, this should then also be considered in the pre-contractual phase. During this phase, the client often has a team working together. The team in most cases consisting of people from various disciplines and backgrounds, can now with the help of the tool collaborate more. The tool can help to (1) review the current aspect requirements and (2) use the tool to stimulate more on sustainability and circular economy via the indicators. In this phase, the collaboration is mainly internal with the client. Big organizations such as RWS have in-house knowledge in various departments. In some cases, the client also collaborates with market parties such as contractors, and consultancy agencies throughout the pre-procurement stage to finalize the requirements. The tool can also be applicable here.

The execution phase- page

After the contract is awarded to the contractor, the object needs to be maintained. This research solely puts focus on the maintenance strategies linked to daily maintenance activities, or (*SVO*). Maintenance activities focused on repairing and replacement work for elements are part of the corrective maintenance part. However, repairing and replacing works are not happening that frequently compared to daily maintenance.

For daily maintenance, the contractor carries out the work according to the maintenance strategy assigned to an element. This maintenance strategy often referred to as "Standaard Verzorgend Onderhoud (*SVO*)" describes very generic how maintenance is executed. From the analysis of documents on maintenance strategies, referred to as "prestatie gestuurde

instandhoudingsplannend" (*P-IHP)*, it is concluded that there are possibilities to include sustainability and circularity with the help of indicators.

In the execution phase sheet, the main goal is to explore the options for sustainability and circularity for the "Standaard Verzorgend Onderhoud (*SVO*)". The sheet should be used according to the following order:

(1) Section A: The first step, is to fill in the sheet according to existing information in regard to the maintenance activities on the element level. This is then information based on standard activities within maintenance and can often be found in the P-IHP. The information in most cases is from the contractor since they are responsible for making the maintenance plans (*in Dutch: onderhoudsplannen).*

(2) Section B: The second step is where the collaboration part comes into play, more on that later in the section. Here the option is given to the user(s) if it is preferred to explore the sustainable/ circular options for that element. In the case of yes, certain points need to be given attention to sustainability. Of course the user also has the option to not explore the sustainability/ circularity options.

Duurzaamheid als middel voor mogelijke aanpassingen in SVO					
de kolommen hier kan je invullen tijdens de samenwerking					
Duurzaamheids opties verkennen	Points of attention [which parts of maintenance can be explored]	Dimensions	dicator categor	Doel van de indicator categorie	Eis van de opdrachtgever [DOEL INDICATOR CATEGORIE]
Ja	*Afval tijdens smeren*	*Environment*	*Waste*	*Waste Recycling*	1

(3) Section C: The third step will only be taken if it decided to explore sustainable/circular options in the previous step. Exploring sustainability and/ or circularity can be done by considering themes and related indicators. This might lead to adjusting or modifying the current maintenance strategy, or *SVO*. The user should fill in the new maintenance strategy and key aspects that should receive attention.

Implementation measures
Describe SVO with sustainable measure [adhv eis]
De uitvoerder moet aantoonbaar kunnen maken: - Alle afval die bij het smeren wordt gegeneerd - Afval scheiding; hoe doet hij dat e.d

(4) Section D: The last step is very important and covers the monitoring part. This part is based on the verification (*in Dutch: controle)* and the check of the aiming level per indicator. Monitoring is very important and should always be considered. Only then,

it could be shown if the sustainability measures do or do not work and the effect of these. Monitoring also gives transparency to the user(s).

Collaboration during the execution phase

As mentioned in point 2 (section B) above, collaboration between actors is also enhanced with the use of the tool. Within the execution phase, the contractor is the main responsible actor. Collaboration during the execution phase can occur in several ways. The collaboration is mainly dependent on what the actor(s) decide on beforehand. Or, the relationship between the client and contractor. Various ways that the tool can be used to stimulate collaboration during this phase are:

- Alternative 1: The contractor has a team consisting of internal employees. The team uses the tool to explore sustainable/ circular alternatives for maintenance strategies.
- Alternative 2: The contractor has a team consisting of internal employees and parties outside the organization such as sub-contractors. Both internal and external parties collaborate to explore.
- Alternative 3: The contractor and the client collaborate during the execution phase. The client steers to a certain extent the contractor based on their ambitions, or the contractor can use the tool as a way to inform the client regarding the works.

The link between the pre-contractual & execution phase

Above, the pre-contractual phase and execution phase are considered to be two separate phases. However, the tool that is designed is developed in such a way that the two phases are linked to one another. The content of the pre-contractual phase can then be used as information to be verified within the execution phase. Thus, in summary, the tool can be used in the following ways:

- Option 1: Use the tool **solely** for the **pre-contractual phase**. The client uses the tool to explore and specify aspect requirements and verification methods (*in Dutch: aspect-eisen)* within the Demand requirement document. The collaboration during this phase is mainly internal within the client's organization. It could be that the client uses the support of a consultancy.
- Option 2: Use the tool **solely** for the **execution phase.** Since the tool is developed, it could be that the pre-contractual phase and awarding phase are already passed. Due to the lengthy period of maintenance contracts, the tool can be applied to explore now the possibilities regarding the current daily maintenance activities (*SVO*).
- Option 3: Use the tool for the **pre-contractual phase** & **execution phase**. In the case, a new project starts, the tool can be used throughout the whole process.

Furthermore good to acknowledge that the collaboration in all three options can differ.

The tool - Maintaining Sustainably & Circularly in a collaborative way

The tool gives the user(s) the ability to explore and **consider sustainability and circularity options** with the help of main themes, indicator categories, and indicators. These options can be considered in various ways and are dependent on the phase(s) in which the tool will be applied, thus in the (1) pre-contractual phase, (2) execution phase, or both. The tool can be made project-specific and expanded. Figure 26 shows the process overview of using the tool. This can be considered a simplified framework.

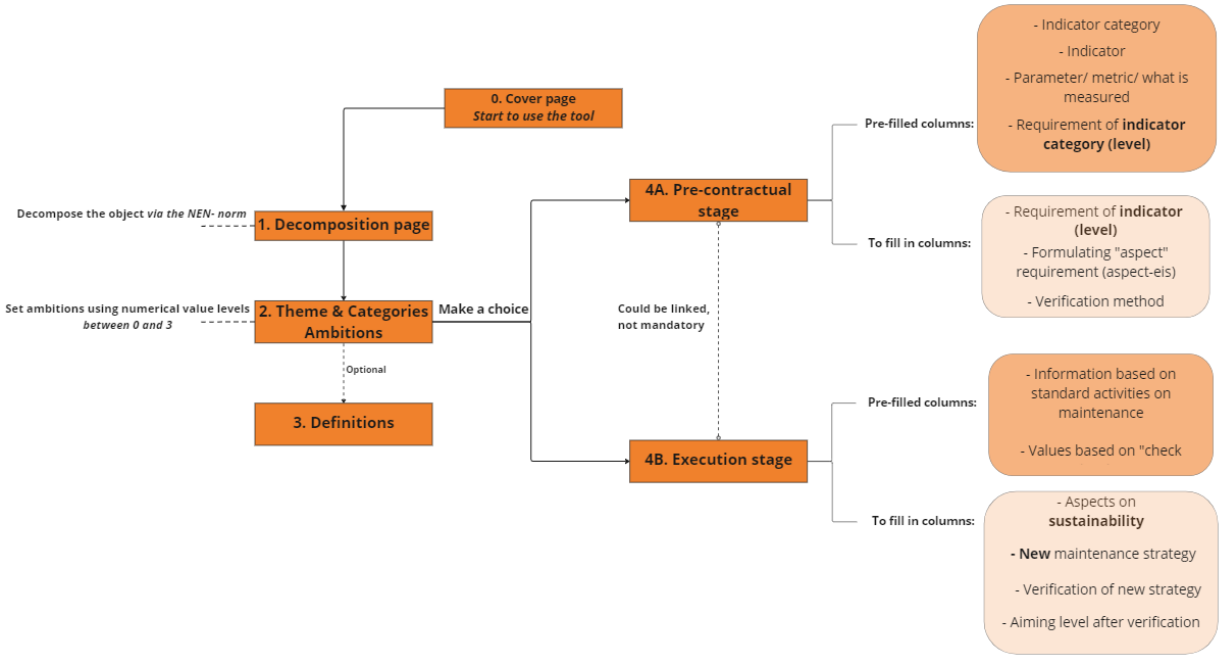


Figure 26 Simplified overview of the content of the tool and the processes applicable to the tool

4.2.1.2 Demonstration of the tool

As part of the research, the tool will also be demonstrated. In order to show how the tool works in practice, it is decided to use material from a case provided by Arcadis Nederland B.V. This section will elaborate on the application of the case material in the tool.

4.2.1.2.1 Case description

To test the tool, it was decided to fill in case-relevant information. Arcadis Nederland B.V. provided the case material of the following project: "*Performance-based contract for maintenance of HoutribComplex*". This project was part of the SHERPA project, whereby Arcadis Nederland together with other parties was involved in the maintenance of this complex. The project has already been completed several years ago, but the content is considered to be relevant to test the tool due to similarities with other cases.

The Houtribcomplex is divided into 5 management objects (*in Dutch: beheerobjecten)*. To test the tool, the following 2 objects within the complex are taken into account namely: a floodgate (*in Dutch: Spuisluis*) and a bascule bridge (*in Dutch: beweegbare brug*). The following case documents are reviewed and used as input for the tool:

- Pre-contractual documents
    - Demand specifications Requirements (*in Dutch: Vraagspecificties Eisen)*
- Performance-based Maintenance plans (*P-IHP*): The focus was on mainly corrective maintenance strategies, referred to as "Standaard Verzorgend Onderhoud (*SVO*)" in the case material.

Since the project is already done, it is decided to include some extra assumptions to the case to demonstrate the tool better. These assumptions are fictional:

- There are 4 people involved in the project. Two are representatives from the client's side, a consultant working for the client, and a representative from the contractor's side.
- The following project: "*Performance-based contract for maintenance of HoutribComplex*" is in the pre-contractual phase. The client has decided to involve a consultant during this phase due to the missing expertise within the client's organization.
- The project will also cover the execution phase. A representative from the contractor's side is now also involved in the project.
- Throughout the execution phase, the client's representatives are still involved in the project.

4.2.1.2.2 Start page of the tool

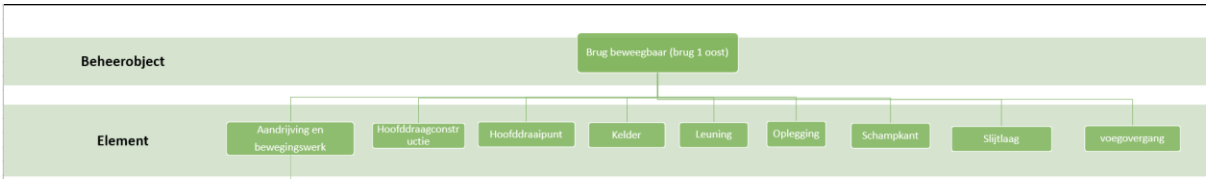
The first sheet that opens when the tool is started is the cover page. On the cover page, information related to the project, and the collaborators are filled in. For privacy reasons, the information on this page is fictional and solely filled in for demonstration purposes. The sheet also includes more general information about the tool that could be useful for the users.

Informatie gebruikers *[vul hieronder de nodige informatie in]*				
Achternaam	**Voornaam**	**E-mail adres**	**Organisatie**	**Rol/ Expertise**
AA	BB		Cleint	
CC	DD		Cleint	
EE	FF		Consultant (client)	
GG	HH		Contractor	

Project- Informatie [vul hieronder de nodige informatie in]	
Project doel	Meerjarig onderhoud beweegbare brug
Locatie	[vul in]
Contract type	Prestatiecontract
Andere informatie [a]	[vul in]
Andere informatie [b]	[vul in]
Andere informatie [c]	[vul in]
Opmerking (1)	Pre-contractuele fase van start dec 2022
Opmerking (2)	Uitvoeringsfase gepland voor april 2022
Opmerking (3)	[vul in]

4.2.1.2.3 Decomposition of the object(s)

The decomposition of the object is only of importance for the execution phase since the current maintenance strategies are based on the element level. As a demonstration, a bascule bridge is decomposed according to the NEN 2767. In most situations, the decomposition of an object is given in the maintenance plans. Even though according to the NEN-2767 an object can be decomposed on element, section, and component level, it is decided as a demonstration to decompose a bascule bridge within the Houtribsluis solely on element level. The tool does have the ability to decompose the object on element, section, and component levels. Good to acknowledge is that the decomposition of an object is not automatically done since this is object dependent. There is also currently no link between the decomposition of an object and information in the other sheets in the tool. The main reason to include the decomposition of the object in the tool is that the user(s) has all information that might be considered necessary at his disposal.



4.2.1.2.4 Ambitions sustainability & circularity

Before applying and considering sustainability and circular economy, it is important to set ambitions. As described earlier, the project is in the start-up phase. Before focusing on the pre-contractual phase and execution phase, the client must set ambitions in regard to his view on sustainability and circularity for this project specifically. It could also be that the ambitions set in the tool, are more related on an organizational basis. In this case, this should be clearly stated in the tool after discussing that. Nevertheless, in this case, it is decided to set the ambitions for each of the main themes and related indicator categories on the project level, thus specifically for the performance-based contract for the Houtribsluiscomplex.

The ambition level is decided based on choosing a value between 0 and 3. The two representatives from the client together with the consultant collaborated and set the ambitions. The decision concerning the ambition levels is based on chosen fictively. The ambitions must be set by the client for the following 2 aspects:

1) Main theme
    a. Main theme 1: Environmental impact
    b. Main theme 2: Social impact
    c. Main theme 3: Economical impact
    d. Main theme 4: Circularity impact

Main themes	vul in*
hoofdthema 1: Environmental Impact	2
Hoofdthema 2: Social Impact	0
Hoofdthema 3: Economical Impact	0
Hoofdthema 4: Circularity Impact	0

2) Indicator category for each main theme

Main theme	Indicator Category	vul in*
hoofdthema 1: Environmental Impact	Climate	2
hoofdthema 1: Environmental Impact	Resources	0
hoofdthema 1: Environmental Impact	Waste	2
hoofdthema 1: Environmental Impact	Biodiversity	0
hoofdthema 1: Environmental Impact	Materials	0
hoofdthema 1: Environmental Impact	Ecotoxicity	0
hoofdthema 1: Environmental Impact	Energy	0
hoofdthema 1: Environmental Impact	Water	0
hoofdthema 1: Environmental Impact	Soil	0
Hoofdthema 2: Social Impact	Actors	0
Hoofdthema 2: Social Impact	Users	0
Main theme 2: Social Impact	Integration	0
		0
Hoofdthema 3: Economical Impact	Costs	0
Hoofdthema 3: Economical Impact	Technical	0
Hoofdthema 3: Economical Impact	Service-tariff	0
Hoofdthema 4: Circularity Impact	Strategies	0
Hoofdthema 4: Circularity Impact	Redesign	0
Hoofdthema 4: Circularity Impact	Reduce	0
Hoofdthema 4: Circularity Impact	Reuse	0
Hoofdthema 4: Circularity Impact	Refurbish	0
Hoofdthema 4: Circularity Impact	Recycle	0
Hoofdthema 4: Circularity Impact	Recover	0

For this project, the decision is made to solely focus on the main theme 1, environmental impact. Even though the other main themes are also important for sustainability, it was decided by the client that at least for this round/ session, only the environmental theme will be given attention.

4.2.1.2.5 Pre-contractual phase

After the ambitions are set, the pre-contractual phase will be given attention. From the ambition sheet, it is concluded that the client focuses on indicator categories "climate" and "waste". The other categories will be neglected for this round. As a demonstration of the tool, the following shows an example of how the necessary columns are filled in.

During the pre-contractual phase, the user fills in the following columns for the chosen indicators:

- "eis van de opdrachtgever" (*in English: requirement of the client)*: This is the ambition level that the client assigns to the specific **indicator** within an indicator category. The ambition levels can range from a numerical value between 0 and 3 and are defined in the same manner as on the ambition sheet.
- "Formuliering specifieke aspect-eis" (*in English: formulating specific aspect requirement)*: The user should formulate the aspect requirement. The formulation of this requirement can be done with the guidance of the information found in the column "parameter/ wat wordt er gemeten/ doel" (*in English: parameter/ what is measured/ objective)*
- "Verificatie methode" (*in English: verification method)*: The user should formulate the verification method. The verification method for a specific indicator can be formulated according to information found in the column "parameter/ wat wordt er gemeten/ doel" (*in English: parameter/ what is measured/ objective)*

The decision regarding the content of the above columns is decided based on collaboration between the representatives of the client and consultant.

Indicator category "climate": Within the indicator category "climate", the only indicator available is "estimation of carbon dioxide associated with activity". The client assigned the following to the columns that need to be filled in as seen in the impression picture below.

Themes	Indicator Categorie	Indicator	Parameter / wat wordt er gemeten (metriek)/ doel	Eis van opdrachtgever [vul in slechts sub-categorie]	Formulering specifieke aspect-eis [Maak hierbij de aspect-eis zo specifiek mogelijk mbv kernwoorden]	Verificatie methode [Hoe zal de aspect eis worden gecontroleerd]
Environmental Impact	Climate			2		
		Estimation of carbon dioxide associated with activity	Method of calculation based on calculating (CO2) for example: mass of material x transport distance x transport emissions factor *note: Hutchins UK Building Blackbook (Franklin + Andrews, 2009) as a reference to calculate (CO2)	1	Berekening maken van alle activiteiten waarbij CO2 (mogelijk) wordt uitgestoten a.h.v. voorgeschreven berekeningsmethode	Controle van de berekeningsmethode a.d.v. activeiten uitgevoerd

The same approach can be done for each indicator. After all necessary columns are filled in, the sheet gives a complete overview of indicators, aspect- requirements, and verification methods that could be integrated into the Demand specifications Requirements document (*in Dutch: Vraagspecificties Eisen)* as part of the set of documents for the performance-based contracting.

4.2.1.2.6 Execution phase

After the contract for the maintenance work is awarded, the tool can be used throughout the execution phase. Currently, the maintenance strategies for each element per object are stated in a performance-based maintenance plan (*P-IHP).* This document is set up in most cases by the contractor and used as a basis to conduct the maintenance works.

During the execution phase, the main objective of the tool is to steer on sustainability and circularity via the current daily maintenance strategy (referred to as SVO in the sheet) per element.

As a demonstration of the tool, the bascule bridge (*in Dutch: beweegbare brug)* is chosen. In the case of decomposition, the bridge consists of various elements. Here it is chosen to focus on the drive and motion element *(in Dutch: Aandrijving en bewegingswerk,elektromechanisch)*.

Below a description is given of the steps taken in the tool during the execution phase.

Step 1: Fill in the necessary columns as part of section A. The information for these columns can always be found in the performance-based maintenance plan (*P-IHP)*. The picture below shows that columns are filled in with the necessary information.

Section A: Information based on standard activities within maintenance							
fill in beforehand based on standard approaches							
ID - reference [project dependent]	Beheerobject	Element	Werkgebied	Faaloorzaak	Standaard Verzorgend Onderhoud (SVO) - Onderhoud strategie	Frequentie (SVO)	Onderhoudsplan
20D-001.04.03.1.A.2	Beweegbare brug west	Aandrijving en bewegingswerk, elektromechanisch	Werktuigbouw (WTB)	Falen / veroudering / bereiken technische levensduur van aandrijving en bewegingswerk ophaalbrug	smeren, inspecteren + functioneren testen van de aandrijvingsonderdelen	6x/ jaar	• Smeermiddel XX • Het smeren geschiedt met een doekjes die worden na gebruik in de ton gegooid. • Inspectie geschiedt door sub-aannemer B uit Vlissingen • Het testen van functioneren geschiedt met een apparaat op diesel

Step 2: Sustainability and circularity are now considered. During this step, also the part of the collaboration between the actors involved will happen. An overview of the filled columns is shown in the picture below. The following columns need to be filled in:

- "Duurzaamheids opties verkennen"(*in English: exploring sustainability options):* Here the users need to decide if sustainability or circularity will be explored for the specific element. In the case "no" is chosen, then there is nothing to add further. In the case "yes" is chosen, then the next columns need to be filled in. In the case of the example below, it is chosen to explore sustainability for the element.
- Points of attention/ which parts of the maintenance can be explored: In this column, the user has to indicate for which specific aspects of the current maintenance strategy, sustainability options should be explored. In the case of the example, it is stated that during lubrication, waste management should be considered.
- Dimensions: Here the user should assign which main theme gets to be focused on. In the case of the example, it is chosen to focus on the environmental impact.
- Indicator category: The user should choose the indicator category based on the main theme chosen in the previous column. The options that appear are linked to the chosen

main theme in the previous column. For the example below, it is chosen to focus on the indicator category of waste.

- Indicator: The user should choose an indicator. The options that appear are linked to the chosen indicator category in the previous column.
- "Eis van de opdrachtgever" *in English: requirement of the client)*: This column is **pre-filled**. The value appearing in this column is based on the requirement the client set in the pre-contractual phase for the specific indicator category. This should give the user guidance to formulate the new maintenance strategy (new SVO) with the sustainable measure in the next step.

Section B Duurzaamheid als middel voor mogelijke aanpassingen in SVO					
de kolommen hier kan je invullen tijdens de samenwerking					
Duurzaamheids opties verkennen	Points of attention [which parts of maintenance can be explored]	Dimensions	Indicator category	Indicator	Eis van de opdrachtgever [DOEL INDICATOR CATEGORIE]
Ja	*Afval tijdens smeren*	*Environment*	*Waste*	*Waste Recycling*	1

Step 3: This step focuses on formulating the new maintenance strategy (new SVO) with sustainable measures included. The user should fill in the new maintenance strategy and key aspects that should receive attention. In the case of the example, it is stated that for the new maintenance strategy, the contractor should be able to demonstrate which sorts of waste are generated during the lubrication of the element, and how waste will be separated and deposed.

Section C: Implementation measures
Describe SVO with sustainable measure [adhv eis]
De uitvoerder moet aantoonbaar kunnen maken: - Alle afval die bij het smeren wordt gegeneerd - Afval scheiding; hoe doet hij dat e.d

Step 4: The last step is focused on the monitoring part. This part should be updated as soon as a maintenance activity is carried out. This part is based on the verification (*in Dutch: controle)* and the check of the aiming level per indicator. The example shows that as a verification of the maintenance strategy, a report should be delivered stating the type of waste and how the waste is separated including images and proof. ONLY after this is delivered and checked, the monitoring is ok.

Section D: Monitoring		
Controle van SVO	**Behaalde level na controle**	**Check levels**
Controle van rapportage afvalscheding dmv bijv beeldmateriaal	*1*	*Check*

The same approach can be done for each element of the object. After all necessary columns are filled in, the sheet gives a complete overview of the new maintenance strategies for each element.

The previous sections show how the developed tool can be used throughout the various phases. It is important to acknowledge that with the demonstration, only one simple example is shown. The tool is developed in such a way that it can be expanded for more objects. The focus for this research was only on objects within the 'HVWN- network' managed by RWS. As demonstrated in the previous sections, the tool is applicable for sluices and bascule bridges. However, the tool also has the possibility to be expanded in such a way that it could be useful for other objects managed by RWS. However, due to time constraints, this was not considered to be part of the research.

It is furthermore described in the previous section how collaboration could be stimulated via the use of the tool. However, this is just a simple case. Collaboration is dependent on various factors, but also group dynamics play an important role. It is important to therefore take into account that the collaboration part with the help of the tool can differ each time. However, the tool does stimulate collaboration to a certain extent.

4.2.2 Delivering the tool – Validation

After the design and development of the tool were done, it was time to see how the tool will function in practice. As described in the methodology, the tool is validated according to a validation protocol. In the end, there were two (2) sessions, in which experts could give feedback on the tool. The main takeaways from these sessions are elaborated on below. After the second session, the tool was accepted. The validation protocol is elaborated

The main idea of the tool is that it can be used as an additional tool next to the existing and applied documents and processes within the maintenance phase.

4.2.2.1 Validation protocol

The validation of this research will be done via a focus group session with a set of experts working in both contracting and maintenance management. The aim of the validation session is to gain insights and input in regards to the tool made

The following set up was used during the validation session:

- Short introduction about the research (show methodology)
- Demonstration of the tool according to the case applied
- Feedback:
    - Identified changes
    - Suggested changes
    - Input on the design of the tool
- Suggestions

4.2.2.2 Validation results

Since there were two test rounds carried out, it is good to mention that the version presented in this thesis, and in the previous chapter, was also the version that was presented in the second test round after incorporating improvements of the first version presented.

Test round #1

The first session was held on the 25th of November 2022. The session was hybrid, and there were in total four (4) experts invited to participate in this session. All the experts have a seniority level either within the department of Contract Management or Asset Management within Arcadis.

During this session, the first version of the tool was presented. Below the main takeaways from this session are described:

- The tool has potential, the idea is clear to all
- Some of the participants are familiar with the "ambitieweb", a tool developed by another platform, but the story should be a bit more clear why "ambitieweb" and the developed tool "Maintaining Sustainably in a collaborative way" have differences and added value

- The "execution stage" sheet of the tool is clear but could use some improvement. Currently, the FMECA maintenance strategies are applied, however, these are more related to predictive maintenance. The activities related to FMECA are not as often carried out as the corrective maintenance works.
- The tool should be made more user-friendly. Now the user could be easily lost in what the possibilities are in the tool. Also, a more clear overview is required.
- The "pre-contractual stage" is not complete, explore a bit more how this can be integrated.

The feedback of the first test round led to improvement of the tool in various ways. It was decided to have another feedback session. The case material of the "HoutRibsluis" was filled in the tool for the second test round.

Test round #2

The second test round was held on the 6th of December 2022 via an online session. During this session, three (3) experts participated. All participants have a seniority level either within the department of Contract Management or Asset Management within Arcadis.

During this session, the second version of the tool was presented after taking feedback from the first version into account. Below the main takeaways from this session are described:

- The tool and story are clear
- Every participant sees the added value of the tool and how it can be used in the maintenance stage
- It is clear to the participants what the added value of the developed tool is compared to existing tools such as "ambitieweb" (CROW, 2019)
- It would be interesting to look if it is possible to link the elements in the decomposition stage to the sheet "execution stage". Currently, other than giving an overview, the decomposition of the object is not of too much-added value
- Costs are very important in every project. Now there are no costs included. Maybe adding 2 columns to the sheet of the "execution stage" to give an overview of the costs for the current maintenance strategies, and the influence of the sustainability aspect to the maintenance strategy, leading to a new cost indication.
- Within Arcadis they are going to search for the possibilities to use the tool for projects

5. Discussion & Limitations

In the previous chapter, the results of the literature review and semi-structured interviews formed the basis for the design requirements of the tool. At the end of chapter 4, the tool is finalized and delivered. At the end of this chapter, an answer will be given to sub-research question six (SQ6): *What procedures can help practitioners effectively implement and integrate sustainability and circularity in the maintenance stage?*

5.1 Discussion

This section will discuss the findings of the research.

Sustainability & circular economy as terms

In the scope of the research, it is established that finding appropriate definitions for terms such as sustainability and circular economy in the context of the research is important. From this research, it is concluded that in order to stimulate concepts like sustainability and circular economy, it is extremely important to define these and set the boundaries for the definitions. If a term is defined, it can be more easily understood, applied, and safeguarded. The same applies to sustainability and circular economy in the context of maintenance.

Barriers & enablers

Barriers and enablers to stimulate sustainability and circular economy line-of-thinking within the maintenance stage were explored and identified via both literature review and by conducting semi-structured interviews with experts. From the literature (Giesekam et al., 2018) (Larsson, 2020) (C. Z. Li et al., 2022) (Arayici & Aouad, 2015; Bal et al., 2013) (Placet et al., 2015) barriers have been identified. However, since it could not always be traced if these barriers applied to stimulating sustainability and circular economy in the maintenance stage of an object, it was then concluded from the interview analysis that there are barriers identified by experts similar to several ones found in the literature. The data found on barriers from the interviews thus may suggest that there are similarities but also differences in perspectives on barriers.

Next to barriers, there were also enablers identified from literature such as “collaboration”, “procurement strategies“, “leadership”, “and designing tools”. From the semi-structured interviews, however, most enablers to the barriers were either linked to the “procurement strategy”, or to “people involved in maintenance”. In literature, there is a lot of emphasis on considering collaboration to stimulate sustainable practices. However, from the interviews, the “people” component was not directly traced back to collaboration among parties. To a certain extent, it was confirmed by the market parties that the public sector should put more focus on sustainability, but not specifically mentioned the aspect of collaboration. This comes as no surprise, since also confirmed in the literature, the civil construction sector is a relatively un-collaborative sector. What was interesting is that one interviewees mentioned that the people within maintenance will more likely consider sustainability within the maintenance,

in the case it is made easier for them. This enabler can be linked to one found in literature, designing tools.

Indicators

Within literature, however, it was not always clear to what extent a certain sustainability indicator was linked to one of the three dimensions of sustainability. The identification steps taken did help with sorting the indicators in the themes linking to the sustainability dimensions and circular economy. There is a debate going on within the literature regarding the sustainability score of indicators in the case more than one dimension of sustainability is addressed. Normalization is considered to be a method to aggregate values with different units into a dimensionless index score (Arya et al., 2015). Another way to do so is by weighing or developing schemes based on analytical hierarchy processes (AHP) (Akhtar et al., 2015 ; Hossaini et al., 2015) However, there is some discussion going on about aspects here such as "individual preferences" which could be then subjectively and even negatively influence (Agarski et al., 2016 ; Schmidt and Sullivan, 2002) but this could be solved by applying, for example, probability components such as sensitivity analysis.

For the research, this eventually led to indicator categories that could be divided into the three dimensions of sustainability and the circular economy. The indicators for the circular economy are based on the strategies as part of the 9R framework. Throughout interviews, it was also explored from the practice side, the knowledge about indicators that could be of relevance to stimulating sustainability. The most mentioned indicator is MKI (*in Dutch: Milieu Kosten Indicator).* This comes as no surprise since MKI is widely applied within the practice for a few years now. In total, 8 different indicators were mentioned by all interviewees, in which they were all linked to the environmental dimension of sustainability. On the other hand, literature included 9 indicator categories for the environmental dimension, 3 indicator categories for the social dimension, 3 indicator categories for the economical dimension, and 8 indicator categories for the circularity dimensions. The various indicator categories further consisted of indicators. One conclusion then goes back to the definition that most interviewees had regarding sustainability. In practice, sustainability is often seen as an environmental aspect. Another conclusion is that indicators are often seen as a quantitative way of gaining insights. However, the literature shows that there are also qualitative and mixed types of indicators. Thus, from the research it is concluded that the use of indicators within the practice must be further applied and used in order to include all dimensions of sustainability.

The tool

Literature on enablers for sustainability barriers also shows that tools can be used as a way to stimulate sustainability. Initially, the approach was taken to design the tool in order to be applicable for objects within the 'HVWN-network' managed by RWS. Throughout the design and development stage of the tool, it was concluded that the tool is designed in such a way that there are possibilities to explore and apply the tool to other types of objects such as roads and tunnels. The tool is thus a combination of how several aspects found in literature such as indicators and collaboration can be integrated into a tool, in such a way that the aim to achieve sustainable maintenance can be considered.

Throughout the research, it was found that there is another tool becoming increasingly popular in the Netherlands lately, namely the "Ambitieweb" (CROW, 2019). The "ambitieweb" is a tool that can be used to stimulate sustainability via certain indicators. However, the tool is not specifically set up for the maintenance stage, nor does the tool have a monitoring aspect related to it. The "ambitieweb" is more of a general tool that can be useful for various projects. The tool developed in this research on the other hand is considered a more practical solution integration of practical aspects (such as the current maintenance strategies) and theoretical research (such as indicators). The developed tool is specifically developed based on the maintenance process for existing civil objects. This part also answers the sub-research question six (SQ6): *What procedures can help practitioners effectively implement and integrate sustainability and circularity in the maintenance stage?*

Is the maintenance part of the civil construction sector ready for change?

On a scientific level, this research puts more focus on the specific stage of maintenance within the lifecycle of existing objects by exploring the literature on that. But, with the research also considering the practical relevance, one could ask, what the views of the maintenance sector are on incorporating more sustainability within both the contractual part and execution phase. From a variety of perspectives, the interview results show that people involved in the maintenance sector are focused on maintaining the object as it is always done. Sustainability might introduce risks and uncertainties. But, with this research, with the development of this tool, a first step is made to help the actors involved in this stage of the lifecycle. Instead of prescribing what must be done, the tool gives freedom to the user to what extent they want to consider sustainability in the maintenance by assigning values to these aspects. The tool allows exploring what are ambitions, but also what is possible. It also stimulates collaboration both internally and externally with the actors involved. Collaboration is one thing, but trust and communication are also important to take into account. With options such as its monitoring aspect, the tool also offers transparency to all. With a positive outcome on the validation, the tool is ready to be applied within the practice and tested more!

5.2 Limitations

It is also necessary to discuss the limitations of the research. Although the research was conducted in such a way resulting in answers to the research questions, some limitations were taken into account and should be mentioned. It is worth mentioning that the limitations are a result of the choices that are made throughout the research.

Literature review based on existing documentation

The focus of this research was on sustainability and circular economy integrated into the specific stage of the lifecycle, namely the maintenance stage, of existing civil construction objects. Throughout the period, the researcher was often confronted with the limited resources available within the scientific world on this specific aspect. In some cases, extrapolation of existing results was conducted, for example in the case of exploring the options for sustainable indicators, it was decided to also expand the research to indicators applicable to the maintenance of buildings. However, due to time limitations, extrapolation was not considered in all cases.

Interviewee sampling

For the semi-structured interviews, there were 13 participants chosen based on expertise within the Dutch civil construction sector, especially within maintenance, asset management, and contract management. However, in the literature, there are more elaborate research methods discussed regarding the choice of participants and the most suitable options (Ivlev et al., 2015). Unfortunately, due to time limitations and limited access to people, it was not possible to explore these research methods. Nevertheless, the current participant sample did include both the public and market perspectives.

Indicator ranking

Currently, the approach for the indicator choice is based on certain requirements and the "importance" of the indicators is not taken into account in the analysis. The "importance" can be decided when the tool is being used in practice by including or not including the indicator in the process. However, in more elaborate scientific research on indicators, scientists use different decision-making methods and probability methods as ways to rank indicators, such as the analytical hierarchy process (*AHP*), and grounded theories (Chen et al., 2020). Based on requirements, a selection of indicators is made. However for this research, the AHP method is not applied, but solely chosen the indicators based on more generic and applicable requirements. There was no ranking or questionnaire method used and sent to experts to gain insights into their opinion on the importance of the indicators, because the maintenance sector does not really consider sustainability on a high level yet. Due to limited experience with sustainable and circular indicators, the decision was made that for this research the focus will first be on gathering data, and developing a tool with the indicators. After people are more

familiar with and used to these indicators within the maintenance stage, more in-depth research can be done on ranking these.

Choice of focus for civil construction objects

RWS manages different kinds of objects, however, for this research, the focus for developing the tool was mainly on existing objects managed by RWS within the HVWN network. This led to the focus only being on two types of structures namely bascule bridges and floodgates.

Maintenance focus

As described throughout the thesis, there are various maintenance strategies. However, for this research, the focus was solely on the corrective maintenance strategies, which are also referred to as "daily maintenance activities". The reason for this is, is that predictive maintenance is based on the probability calculations, FMECA. This means that predictive maintenance is not as often carried out as corrective maintenance activities and the process is different.

Tool validation

Part of the "Double Diamond Method" was validating the tool. There was one validation session organized in which experts from both the contract management department and asset management department gave their feedback on the tool. Some individuals within the group also had experience working from both the client's and contractors' points of view. However, However, due to time-constraints, it was not possible to test the tool in practice and validate it with other stakeholders involved in the maintenance stage.

6. Conclusion

The main idea behind this research was to analyze the current maintenance applications in relation to sustainability and circularity and in what way these 2 concepts can be stimulated.

This research covered various key aspects and explored different complexities and challenges linked to the research. Due to the complexities, the research became quite broad and covered different aspects. Important to acknowledge is that all these aspects are linked together. The various complexities that were researched are:

(i) Terminology: Sustainability and circular economy are key aspects within this research. It was however a challenge to find suitable definitions for these terms in the context of the research. It is also concluded from both literature and practice, that mainly the environmental dimension of sustainability is considered. This means that sustainability is not always fully taken into account, even though it is mentioned;

(ii) Sustainability in maintenance neglected: Currently, the focus within science and practice is mainly on stimulating sustainability and circular economy in 'early' stages of the lifecycle such as design and construction. This shows that a lot of attention is given to new to built assets, however, in the Netherlands most of the large civil engineering assets were built after the second world war and need to be maintained daily. There is little to no attention really given to the maintenance stage, however, it is proven that maintenance is an important aspect to achieve a fully circular economy (Ellen MacArthur Foundation, 2013; Ferreira, 2018);

(iii) Barriers & enablers for sustainable and circular practices: Due to the limited research in the context of sustainability and circularity incorporated in the maintenance stage, it was not easily found what kind of barriers and enablers exist in this context. Extrapolation of literature was necessary. This resulted in barriers such as "lack of knowledge" and enablers such as "collaboration".

(iv) Indicators: As indicators are a way to measure sustainability, it was considered to research which indicators could be applicable to the maintenance stage to stimulate sustainability and circular economy.

The various complexities as stated above together with challenges resulted in connecting the scientific and practical relevance of the research. At the end of the research, a solution was proposed to trigger systematic change and stimulate sustainability and circular economy in the maintenance phase. In total 6 research questions were answered to dissect the problem in order to arrive to the proposed solution in the form of a tool. This tool should enhance collaboration, knowledge dissemination, and integration of sustainability into the maintenance of existing civil objects.

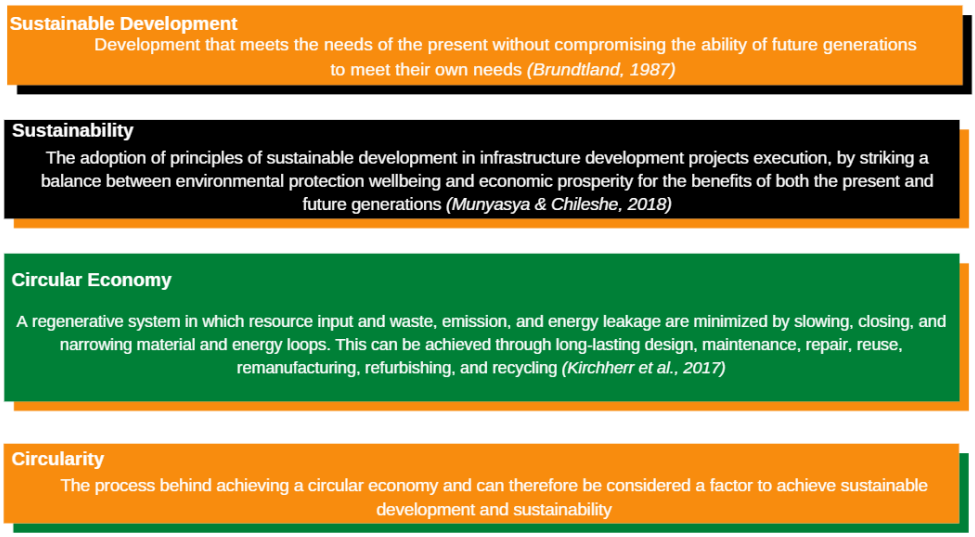
It should furthermore be highlighted that the developed tool is designed for assets within the 'HVWN network' such as sluices and bridges. However, the tool can be expanded and also applied to other civil engineering assets.

6.1 Conclusion sub-research questions

This section of the chapter will provide answers to the sub-research question. The answer to the sub-research questions eventually lead to answering the main research question.

1) What are applicable definitions for sustainability and circularity in the context of maintenance?

As sustainability and circular economy are key aspects, it is important to define these terms in the research context. The terms are often used interchangeably and defined by authors in various ways. Throughout the research, various scientific articles were reviewed on finding suitable definitions for sustainability and circularity in the context of the maintenance of civil engineering objects. In the figure below, an overview is shown of definitions for sustainable development, sustainability, circular economy, and circularity. All these four terms are defined in the context of this research.



2) What methodology can be applied to design and develop a tool to stimulate sustainability and circular economy in the maintenance stage?

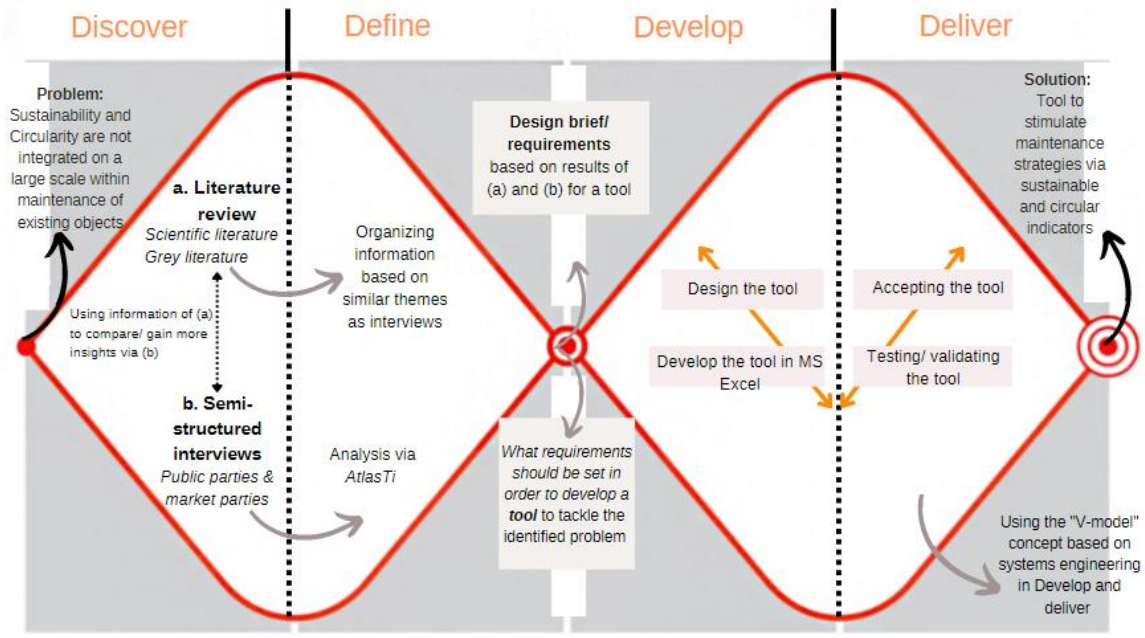
With this research, an attempt is made to incorporate concepts of sustainability and circularity in the process of (1) the pre-contractual stage of maintenance contracts and (2) the execution stage of the maintenance activities for assets within the 'HVWN' network managed by RWS. Furthermore, there is the aim to fill the gap and identified problems described in previous sections by understanding the reason behind the missing elements of sustainability currently incorporated in the maintenance stage. A suggestion to do so is by developing a tool, that could not only stimulate the integration of sustainability but next to that also enhance

collaboration, decision-making, and monitoring processes between the client (*in Dutch: opdrachtgever)* and the contractor (*in Dutch: opdrachtnemer)*.

It is characterized as a step-by-step iterative process that can be applied to carry out the research in a structured manner. Furthermore, it's in the line of thinking covering design research which is to produce scientific knowledge, as well as helping actors solve real problems (Feng & Hannafin, 2011).

Considering this aim of the research, an appropriate research methodology to apply is design-thinking principles. Within the scientific field, there are various design-thinking research methods. After considering various design-thinking research methods, it was decided to apply the Double Diamond Methodology as a research method. In the figure below, an overview is shown of the double diamond method adapted to the research at hand.

The double diamond research method consists of 4 main phases, discover, define, develop and deliver. Each of these phases consists of other research methods. As an example, the discover stage consists of conducting literature review and semi-structured interviews. Within the develop and deliver phases as part of the Double Diamond, the theory behind the "Verification & Validation" (V&V) is incorporated into these phases. The develop phase is mainly focused on the verification part, whereby the tool is designed and developed in MS Exce. The deliver phase of the Double Diamond on the other hand is focused on the validation part, in which the tool is tested and eventually delivered.



3) What are the barriers and enablers for stimulating sustainability and circular economy within the maintenance stage?

The answer to sub-research question three could be found in **Figure 14** as this gives a complete overview of the barriers and enablers identified for sustainability and circular economy within the maintenance stage. On the one hand, the barriers are clustered within five (5) levels. For the research at hand, all barrier clusters are relevant however for this research it is not doable to overcome all barriers. On the other hand, the enablers are not clustered since one enabler could be linked to various barriers. The enablers are therefore identified on a more general level. Eventually, the main enablers that will be focused on for this research are "collaboration", "stakeholder engagement" and "designing tools". It could be that throughout the research, certain enablers could be indirectly relevant.

4) What is the effect of collaboration on stimulating sustainability and circular economy within the maintenance stage?

Collaboration is seen as an important enabler to sustainability and circular economy in the maintenance stage. Sustainable practices also require effectiveness and innovation which are facilitated by collaboration (Larsson, 2020). Previous research on collaboration (Engebø et al., 2020; Larsson, 2020; Shelbourn et al., 2007) shows that there are various types and ways to enhance collaboration. Collaborative 'partnering' arrangement is one type of collaboration that has shown the potential to improve business in various contexts (Larsson, 2020), thus also within the civil construction sector. With collaboration, aspects such as communication, trust, processes, and technology are important to consider (Shelbourn et al., 2007). Achieving collaboration is furthermore strongly dependent on the engagement between the stakeholders involved. Stakeholders can influence projects through decision-making (Kordi et al., 2021). It is important to also recognize that the collaboration between involved actors is also dependent on the contract type. However, the focus is currently too much on shifting risks to parties rather than seeking collaboration among parties to achieve common goals and objectives (Engebø et al., 2020). Within maintenance projects, contract agreements apply for longer periods between a public client and contractor/supplier. If sustainability and circular economy then want to be achieved within the maintenance stage, it is important to enhance and work towards more collaborative partnering arrangements and actor involvement.

5) What are the requirements for designing and developing a tool that could be used to stimulate sustainable maintenance strategies?

Findings of literature and semi-structured interviews on various concepts led to the requirements of the tool. These requirements in summary are:

- **Collaboration:** throughout the discovery phase of the "Double Diamond Method" it was concluded that sustainability is not yet elaborately considered in the maintenance stage of existing civil construction objects. The importance of collaboration between actors during the maintenance stage is researched by authors (Hauashdh et al., 2022).

To meet the needs and demands of sustainable maintenance practices, strategic approaches should be considered together with the actors involved. Nonetheless, the current state is that the focus is currently too much on shifting risks to parties rather than seeking collaboration among parties to achieve common goals and objectives (Engebø et al., 2020). However, there is a need to do so. Collaboration and engagement with stakeholders could be considered an important aspect to put more emphasis on and stimulating that sustainability;

- **Monitoring:** maintenance contracts are often for periods between 5-10 years in the Dutch context. Throughout this period, data is gathered in various ways to apply maintenance strategies. Gathered data can help steer processes, but also considerations of sustainability.
- **Indicators:** indicators are considered to be a way to measure sustainability and circularity. Various indicators could be useful to stimulate that sustainability and circularity in the maintenance strategies of existing civil construction objects.

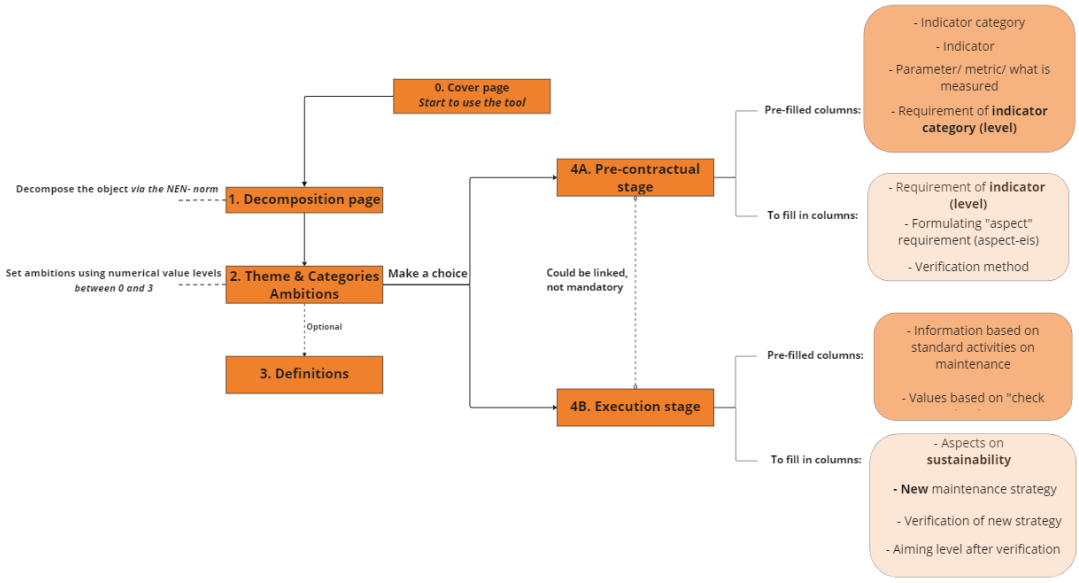
6) **What procedure can help practitioners effectively implement and integrate sustainability and circularity in the maintenance stage?**

As part of the research, a tool in excel is developed that should help practitioners collaborate and stimulate more sustainable and circular practices within the maintenance stage of existing objects. The tool, "Maintaining Sustainably & Circularly in a collaborative way", can be used in two phases, namely (i) in the pre-contractual phase, and/ or (ii) in the execution stage. Ideally, the tool should be applied in both (i) and (ii), however, the user of the tool is free to make that decision.

In the pre-contractual phase, the tool is developed to steer on the aspect requirements (*in Dutch: aspect-eisen)* by formulating more specific aspect requirements and verification methods with the help of indicators.

In the execution phase, the main idea is to consider the current corrective (daily) maintenance strategies. This current maintenance strategy can be adjusted/ modified by exploring the opportunities with the indicators categories. There is also a monitoring and verification aspect added here.

The figure below shows a simplified overview of the content of the tool and the processes applicable to the tool.



6.2 Conclusion main research questions

This graduation thesis aims to answer the following main research question:

In what way can the dimensions covering sustainability and circular economy be integrated during the pre-contractual stage and throughout the execution of maintenance works for existing civil engineering objects?

To answer the main research question, the Double Diamond Method was applied. This design-thinking method led to the development of a tool, "Maintaining Sustainably & Circularly in a collaborative way" which is a step towards considering sustainability within the maintenance stage of existing civil construction objects. Getting to this point, meant researching various aspects based on the identified problem.

Sustainable and circular economy line of thinking is more important than ever to include throughout the lifecycle of civil construction objects (TNO, 2021). However, lately focus within science has been mainly on researching possibilities to integrate sustainability in more early stages of the lifecycle such as procurement and construction (Coenen et al., 2021) (UNEP, 2021). The maintenance stage, also part of the lifecycle, is in a more general sense seen as an important stage to achieve circular economy (Ferreira, 2018) (Ellen MacArthur Foundation, 2013), due to its service-prolonging character (Scope et al., 2021). With the focus on existing civil engineering objects within this research, it is found that not a lot of attention has been given to sustainable and circular maintenance strategies for existing civil engineering objects within the field of science. Evaluating strategies with the use of indicators (Arya et al., 2015; van Breugel, 2017) can help achieve and consider sustainability and circular economy throughout the maintenance stage.

Thus, the way to stimulate the dimensions of sustainability, namely the environment, the social and economic dimensions, together with circular economy, can be exploring indicator

categories based on these four aspects, which are then also linked to the four main themes within the tool: environmental impact, social impact, economic impact, and circularity impact.

Having the indicators and information on that is one thing, but another very important aspect to further integrate that sustainability is via collaboration. Collaborating between the actors involved, especially the client and contractor plays an important role. Trust and communication are then also important aspects that should be considered. By developing and delivering the tool, aspects such as collaboration, communication, and trust can be enhanced due to the transparency of the tool for all participants.

The tool can be applied in two phases, namely the pre-contractual phase and the execution phase.

In the pre-contractual phase, the client can explore the options to include sustainability via the aspect-requirements (*in Dutch: aspect- eisen)* as part of the Demand specifications Requirements (*in Dutch: Vraagspecificties Eisen).* The tool that is now developed, allows the client to steer more on these aspect requirements by considering sustainability and circularity in a more concrete sense with the help of the indicators. Next to exploring the indicators, the tool also includes the verification methods and objectives per indicator. Important to mention is that the tool has the opportunity to be expanded in such a way that the user can also in the future explore sustainability and circularity for other requirements than the aspect requirements.

In the execution phase, the main goal is to explore the options for sustainability and circularity for the "Standaard Verzorgend Onderhoud (*SVO*)" with the use of the tool. For daily maintenance, the contractor carries out the work according to the maintenance strategy assigned to an element. This maintenance strategy often referred to as "Standaard Verzorgend Onderhoud (*SVO*)" describes very generic how maintenance is executed.

7. Recommendations

Having a critical look at the research, the results, and the overall process is also part of conducting the research. With the complete research being done in roughly 6 months, it was important to set strict boundaries. This led to specific things not being included in the research due to factors such as time limitations. This chapter will cover the recommendations for future research.

Noteworthy is that sustainability within the maintenance stage for existing civil construction objects is not yet fully explored, both within the scientific field and practice. There are numerous reasons for this which are elaborated on in this thesis research. Nonetheless, this research is a step in exploring and giving more attention to the maintenance of existing civil construction objects. Some future research recommendations are:

Including the VenR-opgave

In the Dutch context, a large number of civil structures are currently reaching the end of their life. Therefore more and more large repair works are needed to be considered. It could be of interest to research how daily maintenance activities affect(ed) this.

Performance-based contracts

Since the research was conducted in the Dutch context and with the focus on existing civil construction objects managed by RWS within the 'HVWN-network', it was decided to solely focus on Performance-based contracts since these are most applied by RWS for maintenance. However, recent research showed that within RWS there might be experiments going on with other types of contracts for maintenance works. It is worth exploring other kinds of contracts that are used for maintenance and how the content of these new contracts can be used in the developed tool.

Perspective of the research

The research is conducted at a consultant agency in the Netherlands. Both the view of the public and the market party was taken into account throughout the research by involving experts in various ways working in the maintenance stage. However, with the current way of carrying out maintenance activities, the contractor has far more responsibilities. The contractor can influence the processes and has access to more data. It could be of interest to see what kind of data contractors allot, and how these data can be used within the tool, to make the tool even better.

Including "MKB" bedrijven

Sustainability also goes together with (large) innovations. Large contractors often have various resources to exploit options for considering sustainability and circularity. However, in the Netherlands, there are also smaller companies operating as contractors. It could be relevant to research how smaller companies, in the Dutch context, referred to as "MKB"

(middel klein bedrijven) can also be included in the transition towards sustainable maintenance within the civil engineering sector.

Developing and ranking indicators

This research reviewed and analyzed only **existing** indicators. With the limited research within science done on indicators specifically applicable to the maintenance stage of civil engineering objects, it might be considered of interest to explore the possibilities of these indicators more thoroughly specifically for the maintenance stage. Next to that, options could be considered to send out questionnaires among users (of the tool/indicator) to see their ranking and experience with these indicators within the maintenance stage.

Procurement

The developed tool can be used as an additional, but not mandatory tool throughout the procurement phase from the perspective of the client. However, the tool only includes the aspect of sustainability and circularity as requirements. There are more requirements that a prospective contractor has to comply with for the tendering. However, currently, these are not included. It could be of interest to look into setting up the procurement in such a way that sustainability and circularity are as important as other aspects. Also, exploring the possibilities of including more sustainability indicators in the "BPKV".

Since the tool is now most applicable from the clients' perspective to steer more on sustainability, options could be explored from the contractors' point of view on how they can explore more sustainability options for the submitted tenders.

European Union (EU) wide

Since sustainability is not only considered to be important for the Netherlands, it could be explored how other countries with the European Union (EU) can consider more legislation and standards on sustainable maintenance of existing civil objects. Other researchers (Fernández-sánchez & Rodríguez-lópez, 2010) found that within legislation also indicators can play an important role to be included.

Finance

The financial aspect is a very important component for both the client and the contractor. Looking into financial models with the concept of sustainability and circularity integrated might be interesting. It could explore what options there are for incorporating financial models and their effect on sustainability within the maintenance stage.

Bibliography/ References

Abadi, M., Moore, D. R., & Sammuneh, M. A. (2021). A framework of indicators to measure project circularity in construction circular economy. *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, *175*(2), 54–66. https://doi.org/10.1680/jmapl.21.00020

Abbassi, R., Arzaghi, E., Yazdi, M., Aryai, V., Garaniya, V., & Rahnamayiezekavat, P. (2022). Risk-based and predictive maintenance planning of engineering infrastructure: Existing quantitative techniques and future directions. *Process Safety and Environmental Protection*, *165*(July), 776–790. https://doi.org/10.1016/j.psep.2022.07.046

Ahern, T., Leavy, B., Byrne, P. J., Andersen, E. S., Armstrong, J. R., Wade, J. P., BAM, H. S. E., Biddix, J., Componation, P. J., Dorneich, M., Hansen, J. L., Elm, J. P., Goldenson, D., Neisa, A., Estefan, J. A., Haskins, C., Hermans, L. M., Naber, A. C., Enserink, B., … Westerveld, E. (2015). De samenhang centraal. *International Journal of Project Management*, *44*(8), 1395–1410. http://www.sciencedirect.com/science/article/pii/S0263786315001945%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Managing+Large+Infrastructure+Projects:+Research+on+Best+Practices+and+Lessons+Learnt+in+Large+Infrastructure+Projects+in+E

Ahlin, E. (2019). Semi-Structured Interviews With Expert Practitioners: Their Validity and Significant Contribution to Translational Research. *Semi-Structured Interviews With Expert Practitioners: Their Validity and Significant Contribution to Translational Research*, *November*. https://doi.org/10.4135/9781526466037

Ahmed, G., Nacu, C. B. Ă., & Bou, R. (2020). *the Impact of Infrastructure Development for a Circular Economy: the Case of Sustainable Development of Iraq*. 608–614. https://doi.org/10.24818/imc/2020/03.13

Alhaddi, H. (2015). Triple Bottom Line and Sustainability: A Literature Review. *Business and Management Studies*, *1*(2), 6. https://doi.org/10.11114/bms.v1i2.752

Alizadeh, J. (2016). *Circular Economy and Civil Infrastructure Systems - Applying the principles of circular economy into the design and engineering process of the civil infrastructure systems*. 145.

Almomani, H., & Almutairi, O. N. (2020). *Life-Cycle Maintenance Management Strategies for Bridges in Kuwait*. *8*(4), 1556–1562.

Alsharqawi, M. (2018). *Integrated Decision Support Methodology for Bridge Deck Management under Performance-Based Contracting Mohammed Alsharqawi In the Department of Building , Civil , and Environmental Engineering Presented in Partial Fulfillment of the Requirements for the D*. *April*.

Arayici, Y., & Aouad, G. (2015). *BUILDING INFORMATION MODELLING (BIM) FOR CONSTRUCTION LIFECYCLE*. *October 2010*.

Arya, C., Amiri, A., & Vassie, P. (2015). A new method for evaluating the sustainability of bridges. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, *168*(6), 441–453. https://doi.org/10.1680/STBU.14.00069

Bakker, J., Blom, M., Van den Bogaard, J., Bruggink, G., Dietvorst, B., Klanker, G., Nagtzaam, G., Souw, R., Vermeulen, B., Van der Worp, J., & Zwanenbeek, T. (2010). *Leidraad RAMS - Sturen op prestaties van systemen*. *9*, 124.

Bal, M., Bryde, D., Fearon, D., & Ochieng, E. (2013). *Stakeholder Engagement: Achieving Sustainability in the Construction Sector*. *i*, 695–710. https://doi.org/10.3390/su5020695

Balasubramanian, A. (2020). *Environmental indicators*. *April*.

https://doi.org/10.13140/RG.2.2.28305.79200

Balogun, T. B., Tomor, A., Lamond, J., Gouda, H., & Booth, C. A. (2020). Life-cycle assessment environmental sustainability in bridge design and maintenance. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, *173*(7), 365–375. https://doi.org/10.1680/jensu.19.00042

Basiago, A. D. (1995). Methods of defining 'sustainability.' *Sustainable Development*, *3*(3), 109–119. https://doi.org/10.1002/sd.3460030302

Bina, O. (2013). The green economy and sustainable development: An uneasy balance? *Environment and Planning C: Government and Policy*, *31*(6), 1023–1047. https://doi.org/10.1068/c1310j

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Braha, D., & Reich, Y. (2003). Topological structures for modeling engineering design processes. *Research in Engineering Design*, *14*(4), 185–199. https://doi.org/10.1007/s00163-003-0035-3

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Brooks, M., Abdellatif, M., & Alkhaddar, R. (2021). Application of life cycle carbon assessment for a sustainable building design : a case study in the UK ABSTRACT. *International Journal of Green Energy*, *18*(4), 351–362. https://doi.org/10.1080/15435075.2020.1865360

Brundtland, G. H. (1987). Our common future - Call for action. *Environmental Conservation*, *14*(4), 291–294. https://doi.org/10.1017/s0376892900016805

Byrne, D. (2022). A worked example of Braun and Clarke's approach to reflexive thematic analysis. *Quality and Quantity*, *56*(3), 1391–1412. https://doi.org/10.1007/s11135-021-01182-y

Canadian International Development Agency (CIDA). (1997). *GUIDE TO GENDER-SENSITIVE INDICATORS*.

Carson, J. S. (2002). *Model Verification and Validation*. 52–58.

Case, C., & Jarosław, G. (2022). *applied sciences Decision-Making Problems in Construction Projects Executed under the Principles of Sustainable Development — Bridge*.

Chen, D., Xiang, P., Jia, F., Zhang, J., & Liu, Z. (2020). An indicator system for evaluating operation and maintenance management of mega infrastructure projects in China. *International Journal of Environmental Research and Public Health*, *17*(24), 1–24. https://doi.org/10.3390/ijerph17249589

Coenen, T. B. J., Santos, J., Fennis, S. A. A. M., & Halman, J. I. M. (2020). *Development of a bridge circularity assessment framework to promote resource efficiency in infrastructure projects*. https://doi.org/10.1111/jiec.13102

Coenen, T. B. J., Santos, J., Fennis, S. A. A. M., & Halman, J. I. M. (2021). Development of a bridge circularity assessment framework to promote resource efficiency in infrastructure projects. *Journal of Industrial Ecology*, *25*(2), 288–304. https://doi.org/10.1111/jiec.13102

Corona, B., Shen, L., Reike, D., Carreón, J. R., & Worrell, E. (2020). Towards sustainable development through the circular economy — A review and critical assessment on current circularity metrics. *Resources, Conservation & Recycling*, *151*(May 2019), 104498. https://doi.org/10.1016/j.resconrec.2019.104498

Creswell, J. W. (2013). *Qualitative inquiry and research design*.

CROW. (2019). *Ambitieweb Levels*.

Diaz-sarachaga, J. M., Jato-espino, D., Alsulami, B., & Castro-fresno, D. (2016). Evaluation of existing sustainable infrastructure rating systems for their application in developing countries. *Ecological Indicators*, *71*, 491–502. https://doi.org/10.1016/j.ecolind.2016.07.033

Du, G., Safi, M., Pettersson, L., & Karoumi, R. (2014). Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. *International Journal of Life Cycle Assessment*, *19*(12), 1948–1964. https://doi.org/10.1007/S11367-014-0797-Z

Ek, K., Mathern, A., Rempling, R., & Brinkho, P. (2020). *Life Cycle Sustainability Performance Assessment Method for Comparison of Civil Engineering Works Design Concepts : Case Study of a Bridge*.

Ellen MacArthur Foundation. (2013). *Transitioning to a circular economy business | Report*. https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Engebø, A., Lædre, O., Young, B., Larssen, P. F., Lohne, J., & Klakegg, O. J. (2020). *COLLABORATIVE PROJECT DELIVERY METHODS : A SCOPING REVIEW*. *26*(3), 278–303.

Faber, M. H., & Sorensen, J. D. (2002). Indicators for inspection and maintenance planning of concrete structures. *Structural Safety*, *24*(2–4), 377–396. https://doi.org/10.1016/S0167-4730(02)00033-4

Faris, H., Gaterell, M., & Hutchinson, D. (2022). *Developing a collaborative framework for construction projects in emerging economies economies*. https://doi.org/10.1108/SASBE-10-2021-0186

Feng, W., & Hannafin, M. (2011). Design-Based Research and Technology-Enhanced Learning Environments. *Instructional and Cognitive Impacts of Web-Based Education*, *53*(4), 241–261. https://doi.org/10.4018/978-1-878289-59-9.ch016

Fernández-sánchez, G., & Rodríguez-lópez, F. (2010). *A methodology to identify sustainability indicators in construction project management — Application to infrastructure projects in Spain*. *10*, 1193–1201. https://doi.org/10.1016/j.ecolind.2010.04.009

Ferreira, L. (2018). *The Importance of Reliability and Maintenance for the Circular Economy : The Importance of Reliability and Maintenance for the Circular Economy : from Consumers to Users*. *November*, 0–10.

Ganeshan, B. R., Grobler, F., Coimbatore, V., & Member, S. (2001). *CITYWORK: APPLICATION OF COLLABORATIVE TECHNOLOGIES FOR INFRASTRUCTURE MANAGEMENT*. *15*(January), 74–80.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/J.JCLEPRO.2016.12.048

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Jan, E. (2017). The Circular Economy e A new sustainability paradigm ? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Giesekam, J., Densley, D., Adams, N., Stief, P., Dantan, J., Etienne, A., & Siadat, A. (2018). ScienceDirect ScienceDirect Barriers and drivers in a circular economy : the case of the built France of the built Barriers and drivers circular economy : the case environment environment b analyze the functional A new and physical architecture Katherine . *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Glavič, P., & Lukman, R. (2007). Review of sustainability terms and their definitions. *Journal of Cleaner*

Production, *15*(18), 1875–1885. https://doi.org/10.1016/J.JCLEPRO.2006.12.006

Griffiths, P. I. J., Smith, R. A., & Kersey, J. (2003). *Resource flow analysis : measuring sustainability in construction*. *September*.

Guo, H., Li, H., & Skitmore, M. (2010). *Life-Cycle Management of Construction Projects Based on Virtual Prototyping Technology*. *1*(January). https://doi.org/10.1061/(ASCE)0742-597X(2010)26

Hajian, M., & Kashani, S. J. (2021). 1 - Evolution of the concept of sustainability. From Brundtland Report to sustainable development goals. In *Sustainable Resource Management*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-824342-8.00018-3

Hatchuel, A., & Weil, B. (2003). A New Approach of Innovative Design: An Introduction to C-K Theory. *International Conference on Engineering Design*, *19*, 1–15.

Hauashdh, A., Jailani, J., Abdul, I., & Al-fadhali, N. (2022). Strategic approaches towards achieving sustainable and effective building maintenance practices in maintenance-managed buildings : A combination of expert interviews and a literature review. *Journal of Building Engineering*, *45*(October 2021), 103490. https://doi.org/10.1016/j.jobe.2021.103490

Heijungs, R., Huppes, G., & Guinée, J. B. (2010). Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. *Polymer Degradation and Stability*, *95*(3), 422–428. https://doi.org/10.1016/j.polymdegradstab.2009.11.010

Hofmann, F. (2019). Circular business models: Business approach as driver or obstructer of sustainability transitions? *Journal of Cleaner Production*, *224*, 361–374. https://doi.org/10.1016/J.JCLEPRO.2019.03.115

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, *130*, 109948. https://doi.org/10.1016/J.RSER.2020.109948

Hristov, I. (2019). *The Role of Sustainability Key Performance Indicators (KPIs) in Implementing Sustainable Strategies*.

Huang, Y.-H., Adams, T. M., & Pincheira, J. A. (2004). Analysis of Life-Cycle Maintenance Strategies for Concrete Bridge Decks. *Journal of Bridge Engineering*, *9*(3), 250–258. https://doi.org/10.1061/(asce)1084-0702(2004)9:3(250)

Hussain, C. M., Paulraj, M. S., & Nuzhat, S. (2022). Source reduction and waste minimization in the mining industries. *Source Reduction and Waste Minimization*, 169–176. https://doi.org/10.1016/b978-0-12-824320-6.00011-3

Ivlev, I., Kneppo, P., & Barták, M. (2015). Method for selecting expert groups and determining the importance of experts' judgments for the purpose of managerial decision-making tasks in health system. *E a M: Ekonomie a Management*, *18*(2), 57–72. https://doi.org/10.15240/tul/001/2015-2-005

Johnston, P., Everard, M., Santillo, D., & Robèrt, K. (2007). *Discussion Articles Reclaiming the Definition of Sustainability*. *14*(1), 60–66.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(April), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Klerk, W. J., & Den Heijer, F. (2017). A framework for life-cycle management of public infrastructure. *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure - 5th International*

Symposium on Life-Cycle Engineering, IALCCE 2016, *November*, 477–484. https://doi.org/10.1201/9781315375175-63

Koo, D., Ariaratnam, S. T., & Jr, E. K. (2009). *Development of a sustainability assessment model for underground infrastructure projects*. *776*, 765–776. https://doi.org/10.1139/L09-024

Kordi, N. E., Belayutham, S., Khairil, C., & Che, I. (2021). Mapping of social sustainability attributes to stakeholders ' involvement in construction project life cycle. *Construction Management and Economics*, *39*(4–6), 513–532. https://doi.org/10.1080/01446193.2021.1923767

Kylili, A., Georgali, P., & Christou, P. (2022). *An integrated building information oriented framework for sustainable building design design*. https://doi.org/10.1108/CI-02-2021-0011

Larsson, J. (2020). *Integration , Application and Importance of Collaboration in Sustainable Project Management*. 1–17.

Laurett, R., & do Paço, A. (2019). Sustainability Barriers. *Encyclopedia of Sustainability in Higher Education*, 1–7. https://doi.org/10.1007/978-3-319-63951-2_188-1

Lenferink, S., Tillema, T., & Arts, J. (2013). Towards sustainable infrastructure development through integrated contracts : Experiences with inclusiveness in Dutch infrastructure projects. *JPMA*, *31*(4), 615–627. https://doi.org/10.1016/j.ijproman.2012.09.014

Li, C. Z., Guo, Z., Su, D., Xiao, B., & Tam, V. W. Y. (2022). *The Application of Advanced Information Technologies in Civil Infrastructure Construction and Maintenance*.

Li, T. H. Y., Ng, S. T., & Skitmore, M. (2016). *Modeling Multi-Stakeholder Multi-Objective Decisions during Public Participation in Major Infrastructure and Construction Projects : A Decision Rule Approach*. *142*(3), 1–13. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001066

Lingegård, S., Havenvid, M. I., & Eriksson, P. E. (2021). Circular public procurement through integrated contracts in the infrastructure sector. *Sustainability (Switzerland)*, *13*(21). https://doi.org/10.3390/su132111983

Liu, G., Rasul, M. G., Amanullah, M. T. O., & Khan, M. M. K. (2010). AHP and fuzzy assessment based sustainability indicator for hybrid renewable energy system. *AUPEC 2010 - 20th Australasian Universities Power Engineering Conference: "Power Quality for the 21st Century," January*.

Lyytimäki, J. (2012). *Evaluation of sustainable development strategies and policies : The need for more timely indicators*. *36*, 101–108.

Mahmoodian, M., Shahrivar, F., Setunge, S., & Mazaheri, S. (2022). Development of Digital Twin for Intelligent Maintenance of Civil Infrastructure. *Sustainability (Switzerland)*, *14*(14). https://doi.org/10.3390/su14148664

Marlow, D. R., & Burn, S. (2008). Effective use of condition assessment within asset management. *Journal / American Water Works Association*, *100*(1), 54–63. https://doi.org/10.1002/j.1551-8833.2008.tb08129.x

Mart, A., & Aguayo-gonz, F. (2019). *Standardization Framework for Sustainability from*.

Ministerie van Economische Zaken. (2013). *Vaststelling van de begrotingsstaat van het Diergezondheidsfonds voor het jaar 2014; Memorie van toelichting*. *2*, 1–13.

Ministerie van Infrastructuur en Waterstaat. (2022). *Uitvoeringsagenda Klimaatbestendige Netwerken*. 52.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., de Meester, S., &

Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, *146*(January), 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045

Munyasya, B. M., & Chileshe, N. (2018). Towards Sustainable Infrastructure Development: Drivers, barriers, strategies, and coping mechanisms. *Sustainability (Switzerland)*, *10*(12), 1–18. https://doi.org/10.3390/su10124341

Murray, A., Skene, K., & Haynes, K. (2017). *The Circular Economy: An interdisciplinary exploration of the concept and application in a global context*. *140*, 369–380.

Navarro, I. J., Yepes, V., & Martí, J. V. (2021). Sustainability life cycle design of bridges in aggressive environments considering social impacts. *International Journal of Computational Methods and Experimental Measurements*, *9*(2), 93–107. https://doi.org/10.2495/CMEM-V9-N2-93-107

Nicolai, R. P., & Klatter, H. E. (2015). Long-term budget requirements for the replacement of bridges and hydraulic structures. *Safety and Reliability of Complex Engineered Systems - Proceedings of the 25th European Safety and Reliability Conference, ESREL 2015*, 969–974. https://doi.org/10.1201/b19094-129

Oberkampf, W. L., & Trucano, T. G. (2008). Verification and validation benchmarks. *Nuclear Engineering and Design*, *238*(3), 716–743. https://doi.org/10.1016/j.nucengdes.2007.02.032

Okoh, P. (2019). *AMMP : a new maintenance management model based on ISO 55000 AMMP : A new maintenance management model based on ISO 55000*. *May*. https://doi.org/10.1680/jinam.14.00042

Olawumi, T. O., & Chan, D. W. M. (2018). A scientometric review of global research on sustainability and sustainable development. *Journal of Cleaner Production*, *183*, 231–250. https://doi.org/10.1016/J.JCLEPRO.2018.02.162

Olsina, L., Tebes, G., Peppino, D., & Becker, P. (2020). Approaches used to Verify and Validate a Software Testing Ontology as an Artifact. *2020 IEEE Congreso Bienal de Argentina, ARGENCON 2020 - 2020 IEEE Biennial Congress of Argentina, ARGENCON 2020*. https://doi.org/10.1109/ARGENCON49523.2020.9505430

Parra, C. (2020). *Integration of a maintenance management model (MMM) into an asset management process*. *October 2019*. https://doi.org/10.13140/RG.2.2.13779.40483

Placet, M., Anderson, R., Fowler, K. M., Placet, M., Anderson, R., & Fowler, K. M. (2015). *Strategies for Sustainability*. *6308*(2005). https://doi.org/10.1080/08956308.2005.11657336

Platform CB '23. (2022). *Meetmethode voor circulariteit in de bouw*. 1–3.

Rackwitz, R., Lentz, A., & Faber, M. (2005). Socio-economically sustainable civil engineering infrastructures by optimization. *Structural Safety*, *27*(3), 187–229. https://doi.org/10.1016/j.strusafe.2004.10.002

Raworth, K. (2017). *Why it's time for Doughnut Economics*. *24*(3), 216–222. https://doi.org/10.1111/newe.12058

Razzouk, R., & Shute, V. (2012). *What Is Design Thinking and Why Is It Important ? Author (s): Rim Razzouk and Valerie Shute Source : Review of Educational Research , September 2012 , Vol . 82 , No . 3 (September Published by : American Educational Research Association Stable URL : ht*. *82*(3), 330–348.

Renuka, S. M., Umarani, C., & Kamal, S. (2014). A Review on Critical Risk Factors in the Life Cycle of Construction Projects. *Journal of Civil Engineering Research*, *4*(2A), 31–36. https://doi.org/10.5923/c.jce.201401.07

Rijksoverheid. (2019). Klimaatakkoord 2019. *Den Haag: Rijksoverheid*.

https://www.rijksoverheid.nl/documenten/rapporten/2019/06/28/klimaatakkoord

Rijkswaterstaat. (2022). *Circulair durven en doen Circulair durven en doen*.

Romero, D., Flores, M., Vallejo, C., & Molina, A. (2009). *Towards a Novel Living Lab Model for Sustainable Innovation in the Construction Industry*.

Ruggerio, C. A. (2021). Sustainability and sustainable development: A review of principles and definitions. *Science of the Total Environment*, *786*. https://doi.org/10.1016/j.scitotenv.2021.147481

Sahely, H. R., Kennedy, C. A., & Adams, B. J. (2005). Developing sustainability criteria for urban infrastructure systems. *Canadian Journal of Civil Engineering*, *32*(1), 72–85. https://doi.org/10.1139/l04-072

Sartori, S., Da Silva, F. L., & De Souza Campos, L. M. (2014). Sustainability and sustainable development: A taxonomy in the field of literature. *Ambiente e Sociedade*, *17*(1), 1–22.

Scerri, A. (2009). *Accounting for sustainability Implementing a residential emissions reduction strategy using an approach that combines qualitative and quantitative "indicators."* https://doi.org/10.1108/14777831011010900

Scope, C., Vogel, M., & Guenther, E. (2021). Greener, cheaper, or more sustainable: Reviewing sustainability assessments of maintenance strategies of concrete structures. *Sustainable Production and Consumption*, *26*, 838–858. https://doi.org/10.1016/j.spc.2020.12.022

Selim, A. M., & Saeed, D. M. (2021). Infrastructure projects for green cities between implementation challenges and efficiency indicators. *Civil Engineering and Architecture*, *9*(2), 347–356. https://doi.org/10.13189/cea.2021.090208

Shani, P., Chau, S., & Swei, O. (2021). All roads lead to sustainability: Opportunities to reduce the life-cycle cost and global warming impact of U.S. roadways. *Resources, Conservation and Recycling*, *173*. https://doi.org/10.1016/j.resconrec.2021.105701

Shelbourn, M., Bouchlaghem, N. M., Anumba, C., & Carrillo, P. (2007). *Planning and implementation of effective collaboration in construction projects*. *7*(4), 357–377. https://doi.org/10.1108/14714170710780101

Skjott Linneberg, M., & Korsgaard, S. (2019). Coding qualitative data: a synthesis guiding the novice. *Qualitative Research Journal*, *19*(3), 259–270. https://doi.org/10.1108/QRJ-12-2018-0012

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*(March), 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Steenwinkel, M. S. (2006). *Het belang van onderhoud voor de aannemer Werken aan onderhoud*.

Stranges, M. K. W., Ul Haq, S., & Dunn, D. G. (2014). Black-out test versus UV camera for corona inspection of HV motor stator endwindings. *IEEE Transactions on Industry Applications*, *50*(5), 3135–3140. https://doi.org/10.1109/TIA.2014.2306979

Strauss, A., Spyridis, P., Zambon, I., Sattler, F., & Apostolidi, E. (2022). Quality Control Method for the Service Life and Reliability of Concrete Structures. *Infrastructures*, *7*(2), 1–23. https://doi.org/10.3390/infrastructures7020024

Sun, X.-Y., Dai, J.-G., Wang, H.-L., Dong, W.-W., & Wang, J. (2015). Decision Support System for Optimizing the Maintenance of RC Girder Bridge Superstructures in Consideration of the Carbon Footprint. *Journal of Bridge Engineering*, *20*(12), 04015022. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000774

Tennakoon, W. D. N. S. M., & Janadari, M. P. N. (2022). Measuring Economic Sustainability: Are we doing it Right? *Sri Lanka Journal of Social Sciences and Humanities*, *2*(1), 21. https://doi.org/10.4038/sljssh.v2i1.53

TNO. (2021). *Instandhouding civiele infrastructuur. Proeve van landelijk prognoserapport vervanging en renovatie*. 1–37.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *British Journal of Management*, *14*(3), 207–222. https://doi.org/10.1111/1467-8551.00375

UNEP. (2021). *International Good Practice Principles for Sustainable Infrastructure Integrated, Systems-Level Approaches for Policymakers First Edition*. https://wedocs.unep.org/bitstream/handle/20.500.11822/34853/GPSI.pdf

van Breugel, K. (2017). Ageing Infrastructure and Circular Economy: Challenges and Risks. *Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering*, 1–8. https://doi.org/10.11159/icesdp17.1

Vilutiene, T., & Ignatavičius, Č. (2018). Towards sustainable renovation: Key performance indicators for quality monitoring. *Sustainability (Switzerland)*, *10*(6). https://doi.org/10.3390/su10061840

Wong, G., Greenhalgh, T., Westhorp, G., Buckingham, J., & Pawson, R. (2013). RAMESES publication standards: Meta-narrative reviews. *Journal of Advanced Nursing*, *69*(5), 987–1004. https://doi.org/10.1111/jan.12092

Xu, G., & Guo, F. (2022). Sustainability-oriented maintenance management of highway bridge networks based on Q-learning. *Sustainable Cities and Society*, *81*, 103855. https://doi.org/10.1016/J.SCS.2022.103855

Xu, S., Wang, J., Wang, X., & Shou, W. (2019). Computer vision techniques in construction, operation and maintenance phases of civil assets: A critical review. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*, *May*, 672–679. https://doi.org/10.22260/isarc2019/0090

Frangopol, D. M., & Estes, A. C. (1997). Lifetime bridge maintenance strategies based on system reliability. *Structural Engineering International*, *7*(3), 193-198.

Appendices

Appendix A: The total lifecycle of civil construction assets

The total lifecycle of civil construction works consists of various stages. This research focuses mainly on the maintenance stage, however, it is relevant to provide the reader with background information regarding the other stages and their relation to the maintenance stage.

Life-cycle management (*LCM*) is considered to be an overarching term that focuses on the management of the processes within different sectors, thus also within the civil construction sector (Guo et al., 2010). One of the models found in the literature that elaborates on the lifecycle stages within construction projects is based on the six lifecycle phases of the international standard ISO/IEC 15288 Systems Engineering.

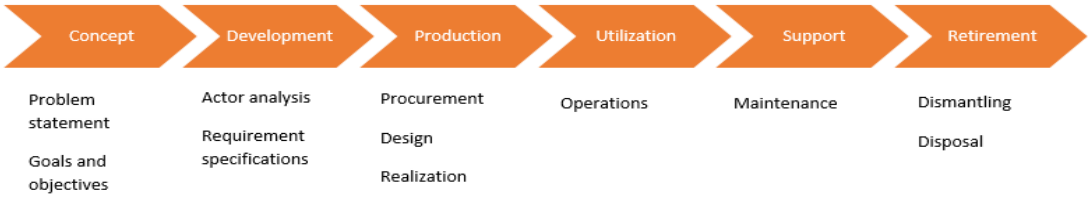


Figure 27 The normal construction project steps related to the six life cycle phases

Figure 27 shows a linear progression of the various stages in the lifecycle of a construction project. Even of greater interest, is the cyclic process between the stages of the lifecycle of a construction project as seen in Figure 28. The phases are influenced both by their preceding and succeeding stages (Guo et al., 2010). Next to that, there is also forward and backward information flow occurring, which also concludes the involvement and interaction between actors (Kordi et al., 2021). Due to its cyclic character and the stages being dependent on one another, it can create opportunities for aspects such as the re-use of information (Guo et al., 2010). There is also a strong connection found between lifecycle stages, lifecycle costs (*LCC*), and lifecycle assessment (*LCA*) for planning, constructing, and maintaining infrastructure objects and therefore then evaluating environmental impact (Shani et al., 2021).

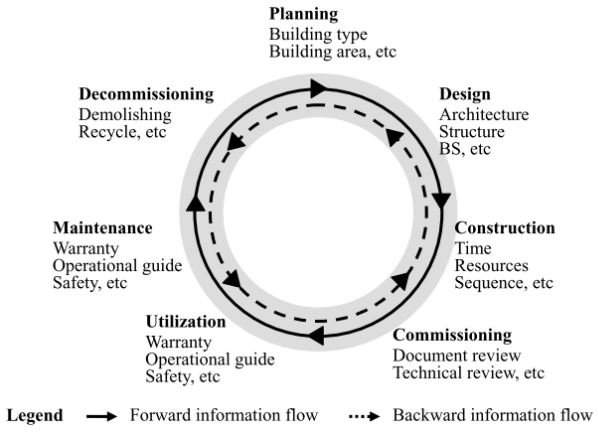


Figure 28 Life-cycle stages in a construction project (Guo et al., 2010)

The environmental concerns within the civil construction industry show that it is important to be aware of the fact that the sector is also undergoing some metamorphosis concerning existing processes, and stages within the lifecycle (Romero et al., 2009). For that reason, it is necessary to understand the cyclical character of the life-cycle stages in a construction project.

The civil construction sector is considered to be one of the most important sectors within the practice that can help to achieve sustainable development throughout the complete lifecycle (Romero et al., 2009), this is also claimed by global institutions such as the UN Environment Programme (UNEP, 2021). Sustainability can be achieved in different ways throughout the lifecycle (Kordi et al., 2021).

Appendix B: The journey of finding fitting definitions

Finding the right definitions applicable to the terms at hand isn't an easy task. For that reason, this appendix walks the reader through the process of eventually finding the fitting definitions.

Terms are often used interchangeably and defined in various ways by authors. Considering the research at hand, boundaries must be set for the definitions of terms such as sustainability, sustainable development, and circular economy.

Defining: Sustainable Development & Sustainability

From reviewing numerous articles on the terms '*sustainability*' and '*sustainable development (SD)*', it is concluded that these two terms are often used interchangeably; this is also confirmed by others in the scientific field (Glavič & Lukman, 2007; Olawumi & Chan, 2018; Sartori et al., 2014). To successfully apply, integrate, and create support for sustainable implications, it is necessary to (i) understand relations between terms and (ii) set out clear definitions (Glavič & Lukman, 2007). Before understanding the relationship between 'sustainability' and 'sustainable development' better, it is important to define the terms separately.

Sustainable Development

The definition of this term published for the first time in the Brundtland Commission report in 1987 is referred to numerous times in several publications (Basiago, 1995; Hajian & Kashani, 2021; Johnston et al., 2007; Olawumi & Chan, 2018). The definition sounds as follows:

"development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987)

The term however is often interpreted in different ways and there is even discussion going on concerning this (Tennakoon & Janadari, 2022).

Sustainability

The term 'sustainability' is often linked to 'sustainable development'. The concept of sustainability is based on three (3) dimensions, namely (1) the environmental/ecological, (2)the economic, and (3) the social (Brundtland, 1987). These three are somewhat linked to one another and their relation to one another evolved.

Evolution of three dimensions of sustainability

Figure 29 shows the relation and the change between the three dimensions of sustainability throughout the evolvement of theories.

- **"Pillars of sustainability"** -
  The three pillars are studied separately. There is no integration whatsoever between the pillars (Tennakoon & Janadari, 2022)
- **"Circles of sustainability"** –
  This theory is linked to the popular "Triple Bottom Lines model of Sustainability (*TBL*)". In literature, there are also references made to "ecology, economy, and equity" (Mart & Aguayo-gonz, 2019) or the Triple-P namely "people, planet, and profit" (Larsson, 2020) as synonyms for the TBL. This model originates from J. Elkington and is researched by others such as (Alhaddi, 2015; Heijungs et al., 2010; Liu et al., 2010; Sahely et al., 2005). In the ongoing debate regarding the evolution and interaction between the pillars of sustainability, the 'TBL' is considered a "weak" model, often referred to as "weak sustainability". The reason for this is due to the limited intersection area between the 3 pillars to stimulate sustainability (Tennakoon & Janadari, 2022). However, a more in-depth review of the concept shows that the "weak sustainability" emphasis on economic systems as being the subject. Furthermore, in more recent years there has been the concept of circular economy emerging within the concept of 'TBL' (Bina, 2013). This focuses on sustainable development and posing that environmental issues can be solved by technological and scientific advancement (Ruggerio, 2021).
- **"Spheres of sustainability"** -
  Lastly, theorists then also view "strong sustainability"(Beckerman, 1994). Within strong sustainability, the priority is conserving nature in the purest state possible.

However, the view of "strong sustainability" is not considered to be the dominant view within the field of engineering. With the various views of "weak sustainability" and "strong sustainability" argued by scientists, it could be considered to use the theory behind "weak sustainability"/ "circles of sustainability" as guidance throughout the research. Other relevant reasons to do so are that with "weak sustainability" emphasis is put on all three pillars of sustainability. Furthermore, there is also the concept of the circular economy considered to be part of weak sustainability which also shows great potential for this research.

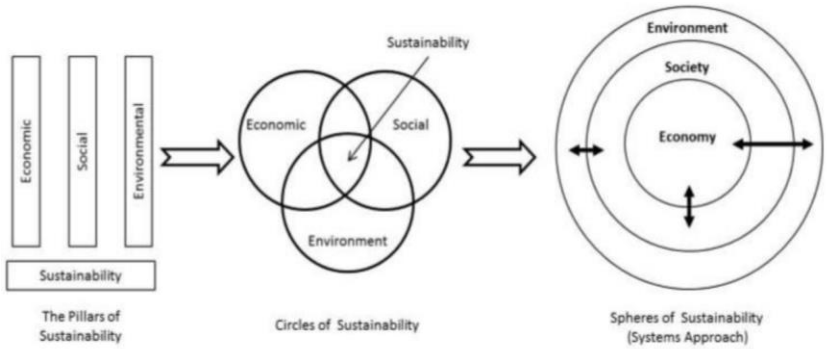


Figure 29 Evolution of sustainability based on research conducted by Saharum et. al (Tennakoon & Janadari, 2022)

Definitions for Sustainability

Various definitions of sustainability found in the literature relevant to the research are summarized in **Table 14**. There is still discussion going on among scientists and practitioners regarding the broadness of the definition of the term. Many often view sustainability from the environmental/ ecological lens, while few apply the concept across all three dimensions. The important aspect of sustainability is that all three dimensions should be included and considered in an integrated manner.

Table 14 Various sets of definitions for sustainability found in the literature that are considered to be of relevance to the research

Definition of Sustainability	Referenced by
Sustainability implies the provision of more efficient services that maintain public health and welfare, are cost-effective, and reduce negative environmental impacts today and into the future.	(Sahely et al., 2005)
The quality of causing little or no damage to the environment and therefore able to continue for a long time.	Cambridge Dictionary (2021)
The sustainability paradigm is generally viewed as a multi-objective optimization problem; there can be different objectives that are optimized such as minimal operating costs, energy use, maximizing useful products, and accessibility.	Sahely et al. (2005)
Sustainability is framed as the balanced and systemic integration of intra-and intergenerational economic, social, and environmental performance.	(Geissdoerfer, Savaget, Bocken, & Jan, 2017)
The adoption of principles of sustainable development in infrastructure development projects execution, by striking a balance between environmental protection well-being, and economic prosperity for the benefit of both the present and future generations.	(Munyasya & Chileshe, 2018)

Sustainable Development & Sustainability

The terms "sustainability" and "sustainable development" are often interchangeably used (Glavič & Lukman, 2007; Olawumi & Chan, 2018; Sartori et al., 2014). Within the literature, there have been attempts made to clarify the distinction between terms.

One way to distinguish these terms from one another is by considering sustainable development as the many processes and pathways to achieve the goal, namely sustainability. Another way to make the distinction is by considering sustainability to be a paradigm for considering the future in which environmental, societal, and economic aspects are balanced in the pursuit of improved quality of life; sustainable development is then considered to be the overarching paradigm of the United Nations.

Defining: Circular Economy & Circularity

Within academics, the concepts of 'circular economy (*CE)*' (*Dutch: Circulaire Economie*) and 'circularity' (*Dutch: circulariteit*) are nowadays widely researched and applied (Geissdoerfer, Savaget, Bocken, & Jan, 2017). CE can be described via a loop economy to tackle problems within the civil engineering sector (Bocken et al., 2016). Also, on policy and national levels, the CE is getting attention. The Dutch government aims to incorporate the concept of CE nationwide and within all sectors (Rijksoverheid, 2019). Understanding CE and circularity is therefore relevant to this research.

Circular Economy

Just as the case with sustainability, there are also various definitions found for CE within the literature. **Table 15** gives an overview of relevant definitions of CE.

Table 15 Various sets of definitions for Circular Economy found in literature that are considered to be of relevance to the research

Definition of CE	Referenced by
An industrial economy that is restorative or regenerative by intention and design.	(Ellen MacArthur Foundation, 2013)
Design and business model strategies [that are] slowing, closing, and narrowing resource loops.	(Bocken et al., 2016)
A regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.	(Geissdoerfer, Savaget, Bocken, & Jan, 2017)
An economic model wherein planning, resourcing, procurement, production, and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being.	(Murray et al., 2017)
An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.	(Kirchherr et al., 2017)

Appendix C: The Interview Strategy (Dutch version)

Semi-gestructureerde interview set-up

**Opmerking: Interviewvragen / reeks vragen kunnen variëren, afhankelijk van de persoon die wordt geïnterviewd. Dit document bevat alle vragensets. Thema 1,2, en 3 zullen aan alle geinterviewde worden voorgelegd.*

Het interview bestaat uit 3 delen namelijk:

a) **Introductie**
b) **Onderwerpen, vragen en vervolg vragen met 3-4 thema's**
    - *Thema 1: Rol/ expertise van geïnterviewde binnen organisatie in relatie tot onderzoeksonderwerp*
    - *Thema 2: Duurzaamheid en circulariteit geintegreerd in plannen en contracten*
    - *Thema 3: Eindproducten van het onderzoek*
    - *Thema 4: Rijkswaterstaat als asset owner, de rol binnen beheer en onderhoud GWW*
c) **Toekomstperspectief + aanvullende opmerkingen van geïnterviewde(n) zijde**

Ad. A. Introductie (+- 5 min)

A.1 Introductie onderzoek

Voor mijn Master Thesis Research vanuit de TU Delft, opleiding Construction Management and Engineering (CME) onderzoek ik de mogelijkheden om duurzaamheid, waaronder ook circulariteit te incorporeren in beheer en onderhoud van kunstwerken in Nederland.

Voor mijn onderzoek, richt ik mij daarom op de huidige onderhoudsplannen en onderhoudscontracten. Het laatste zijn meestal prestatiecontracten. In de onderhoudsplannen zijn er verschillende onderhoudstrategieën meegenomen. Echter blijkt dat het aspect van duurzaamheid daar weinig tot niet in wordt meegenomen. Hetzelfde geldt voor de onderhoudscontracten (prestatiecontracten voornamelijk).

Het eind doel van mijn thesis is om een raamwerk en tool op te zetten die gebruikt kan worden op die duurzaamheid via een set van KPI's (Kritieke Prestatie Indicatoren) te stimuleren in de onderhoudsplannen en onderhoudscontracten. Hierbij is belangrijk te vermelden dat uit de literatuur is gebleken dat duurzaamheid vooral te stimuleren is door samenwerking met betrokken partijen.

Door middel van deze semigestructureerd interviews af te nemen met verschillende experts uit de praktijk en wetenschap, waaronder u, wil ik informatie verzamelen om: i. een beeld te kunnen vormen omtrent de huidige stand van zaken betreffende integratie van duurzaamheid binnen onderhoud en beheer en ii. Informatie verzamelen om mijn eindproduct(en) verder vorm te geven. Uiteraard zal het eindresultaat met u gedeeld worden.

Interessant om erbij te vermelden: het idee achter semigestructureerde interviews is dat ik vooraf wat vragen heb opgesteld, maar dat de antwoorden die u geeft ook sturend zullen zijn voor de conversatie. Goed om erbij te vermelden, er zijn geen foute en slechte antwoorden. Uw mening en informatie zal slechts voor wetenschappelijk onderzoek worden gebruikt.

A.2 Privacy en gegevens

Vanuit privacy regels wil ik u op het volgende attenderen: Ingeval u akkoord gaat zal dit interview opgenomen worden. Na ons gesprek, zal ik dit interview transcriberen. Hierna ontvangt u deze ook. Pas na uw goedkeuring zal ik de informatie uit het interview voor mijn onderzoek gebruiken. Verder zal al het videomateriaal worden verwijderd na dat de transcriptie is goedgekeurd. Het interview zal ook worden geanonimiseerd. Het analyseren van de informatie geschiedt slechts vanuit perspectief van de functie/ rol binnen een organisatie die de persoon vervult.

<<start recording>>

Kunt u graag de volgende informatie aangeven:

- Uw naam, functie/ rol binnen het bedrijf/ instelling die u vandaag representeert.
- Ook graag aangeven als u akkoord gaat met het opnemen van dit interview.

B. Onderwerpen, vragen en vervolg vragen (~45/50 min)

Voorafgaan dit interview, ben ik vooral de literatuur ingedoken. Op basis van de opgedane theoretische kennis, heb ik diverse hoofdthema's bedacht. Het idee is om een conversatie met u te hebben op basis van verschillende hoofdonderwerpen die ik in kaart heb gebracht. Voor elk thema, heb ik vooraf wat vragen geformuleerd, maar er is zeker flexibiliteit om gedurende het interview af te wijken van deze vragen ingeval de reactie(s) vanuit de geinterviewede daar meer informatie om vragen.

Voor dit interview zijn de volgende thema's opgesteld:

- Thema 1: Rol/ Expertise van de geinterviewde in relatie tot het onderzoeksonderwerp *- voor iedereen*
- Thema 2: Duurzaamheid en circulariteit geintegreerd in plannen en contracten-*voor iedereen*
- Thema 3: De eindproducten (raamwerk en interactieve tool met KPI's en eisen)-*voor iedereen*
- Thema 4: Rijkswaterstaat en markt partijen- *voor RWS/ partijen direct gelinked aan RWS*

<<start nu met het interview>>

Thema 1: Rol/ expertise van geïnterviewde binnen organisatie in relatie tot onderzoeksonderwerp
Zoals reeds in mijn inleiding aangegeven richt ik mij tijdens het onderzoek op het ontwikkelen van een raamwerk en tool die gebruikt kan worden om KPI's in onderhoudsplannen en onderhoudscontracten van kunstwerken mee te nemen. Vanuit de literatuur is er onderzoek gedaan naar beschikbare

indicatoren die gericht zijn op duurzaamheid, tevens circulariteit. Met het raamwerk en de tool zal dan duurzaamheid meer gestimuleerd worden in de plannen en contracten, mogelijk via strategien.

De vragen binnen dit thema zijn gebasseerd op de rol en expertise van u met betrekking tot duurzaamheid, beheer en onderhoud van kunstwerken, beheer plannen en beheer contracten welke voornamelijk prestatiecontracten zijn.

- *Thema 1.1 Ervaringsdeskundigheid*
    - Betrokkenheid en ervaring omtrent duurzaamheid, circulariteit, beheer en onderhoud kunstwerken, beheerplannen en beheercontracten
    - Projecten/ cases binnen GWW kunstwerken waaraan gewerkt in recente jaren waaruit de betrokkenheid en ervaring voortvloeid van de geinterviewde

- *Thema 1.2 Duurzaamheid en circulaire economie binnen GWW – Aanbesteding, operationele en beheer processen.*
  Het begrip duurzaamheid en circulariteit/ circulaire economie horen we de laatste tijd heel veel. Ook binnen onze sector (de GWW industrie). De volgende vragen zijn gericht op het aspect van duurzaamheid binnen de aanbestedingsprocedure voor beheer en onderhoud contracten, maar ook duurzaamheid binnen beheer en onderhoud processen zelf.

  Intro vragen:
    - Hoe omschrijft u de volgende begrippen: duurzaamheid (binnen GWW), circulaire economie en circulariteit (met name de sector/ vanuit de perspectiefrol waarin de geïnterviewde werkt)
    - Wat is uw mening omtrent de integratie van deze (3) concepten binnen uw vakgebied/ beheer& onderhoud kunstwerken?
    - (De Rijksoverheid heeft meerdere doelen, een van deze doelen is om primaire materialen in 2030 met 50% te verminderen en in 2050 een volledige circulaire economie te hebben)
      Gedachten over de duurzame en circulaire doelen van de Rijksoverheid met betrekking tot beheer en onderhoud van bestaande kunstwerken. (haalbaar/ realistisch?)
        - Welke barrières signaleert de GWW-sector om duurzaamheid, duurzame ontwikkeling en circulariteit binnen de beheer-enonderhoudsfase verder te verbeteren?
        - *Onderhoudscontracten en onderhoudsplannen:* Er worden onderhoudsplannen opgegesteld en na de aanbesteding krijgt de winnende partij een prestatiecontract waarbij het beheer en onderhoud wordt toegewezen aan deze partij.
    - Ervaring mbt huidige prestatiecontracten

- Gedachten over het integreren van duurzaamheid en circulariteit in de aanbestedingsprocedure / prestatiecontracten/ beheerplannen – Noodzaak/ ontbrekenede zaken/ stimulerende zaken?

Thema 2: Duurzaamheid en circulariteit geintegreerd in plannen en contracten

Deze studie legt de nadruk op het concept van duurzaamheid en circulaire economie binnen onderhoud en beheer van kunstwerken. Een manier op deze 2 zaken te stimuleren is via beheerplannen en contracten. Dit thema legt de focus dan ook daarop.

- *Thema 2.1: Duurzaamheidsbeoordelingssystemen (sustainability assessment rating systems in GWW)*

BREEAM/ LEED etc. zijn duurzaamheidsbeoordelingssystemen/beoordelingsinstrumenten voor de gebouwde omgeving. In het Verenigd Koninkrijk, de VS en Australië zijn er reeds duurzaamheidsbeoordelingssystemen specifiek onderzocht voor de civiele techniek / infrasector. Er is echter geen equivalent van die in Nederland.

- Zie je de noodzaak om er een te creëren? Zo ja/nee, waarom?

- *Thema 2.2: Indicatoren gericht op sustainable development duurzame ontwikkeling (milieu, economisch en sociaal) en circulariteit*

Sustainable development is gericht op het principe van people-planet-profit of te wel milieu, sociaal en ecomische waarde. Willen we duurzaamheid meer in de prestatiecontracten en onderhoudsplannen meenemen, dan zal je die duurzame ontwikkeling gaan moeten stimuleren. Vanuit de literatuur wordt er gestuurd op indicatoren.

- Is het belangrijk voor u om: eerst een indicator te hebben en dan de strategie of juist eerst de strategie en dan de indicator? Waarom
- Willen we duurzaamheid echt stimuleren dan is het belangrijk om die balans te vinden tussen indicatoren gericht op milieu, economie en sociale aspecten. Zijn deze alle 3 belangrijk voor u binnen onderhoud en beheer? Hoe ziet u dat?
- In Nederland wordt MKI toegepast als een van de milieu indicatoren, bent u nog bekend met andere? Zo ja, welke zijn dat.
- De huidige eisen worden nu gesteld binnen de 'basispecificatie' of 'vraagspecificatie'.
  - Het aspect duurzaamheid: nu gericht op energiebesparende besparingen, LED, gebruik van oliën/vet (vetten) / beton ontkisting (beton ontkisting), olie hydraulische bewegingsapparaten (olie hydraulische bewegingswerken) –
    - Zijn er mogelijkheden/suggesties voor meer aspecten?
  - Het aspect circulariteit: nu is er geen focus/vermelding van van circulariteit/ circulaire economie in strategieën/ prestatiecontracten
    - gedachten hierover?
    - Kansen/ suggesties?

- Binnen prestatiecontracten is er ook het aspect 'prestatie meten'. Dit betreft de samenwerking tussen betrokken partijen. Wat vindt de geïnterviewde ervan om hier sociale indicatoren in op te nemen?
- Besluitvorming: nu wordt EMVI gebruikt als een vereiste voor het gunnen van contracten. De aannemer die het contract krijgt, krijgt ook veel vrijheid om de werken uit te voeren. Deze vragen hebben zowel betrekking op de fase van (1) aanbesteding als (2) het bepalen van strategieën.
    - Kan het besluitvormingsproces worden verbeterd? En hoe?
    - Huidig besluitvormingsproces voor het beslissen over de juiste aannemers en strategieën? Stimuleert dit duurzaamheid en circulariteit binnen de uitvoering?

Thema 3: Eindproducten van het onderzoek

Het eindresultaat van de thesis is (1) een raamwerk en (2) een interactieve tool. Deze 2 zullen worden gebruikt gedurende de gehele beheer en onderhoudsfase van kunstwerken in Nederland. De 2 producten zullen van toepassing zijn tijdens bijv. de aanbestedingsfase, maar ook in fases later waarbij de klant en aannemer strategien moeten voorschrijven en toetsen. Het kan dan nuttig zijn om indicatoren te gebruiken ter stimulans van duurzaamheid en circulariteit. Verder is vooral het gebruik van de tool om de samenwerking tussen de partijen onderling te stimuleren en de kennis te gebruiken.

Dit onderdeel van het interview richt zich op het vormgeven van de eindproducten.

- Naar aanleiding van de introductie betreft de eindproducten, hoe staat u hier tegenover?
- Denkt u dat de eindproducten als nuttig/ relevant zullen worden ervaren?
- Wat zou u graag terug willen zien in de tool? Bijvoorbeeld wat voor type indicatoren.
- Zijn er nog andere aspecten waarmee ik rekening moet houden tijdens ontwerpen van de tool?
- Is het haalbaar om zo'n tool te implementeren en zal het nuttig zijn om de tool te gebruiken?

Thema 4: Rijkswaterstaat als asset owner, de rol binnen beheer en onderhoud GWW

Rijkswaterstaat is een hele belangrijke partij binnen de GWW sector. Deze vragen zijn gerelateerd aan deze organisatie.

- *Thema 4.1 : RWS binnen beheer en onderhoud*
- RWS heeft nu een bepaalde rol binnen beheer en onderhoud van de bestaande structuren, gedachten over de huidige rol?
    - Zijn er veranderingen/verbeteringen nodig? Suggesties voor
    - In de levenscyclus zijn er ook verschillende rollen. In de praktijk is dit vaak een obstakel voor de implementatie van lifecycle management, omdat verschillende organisaties verschillende rollen en dus verschillende belangen hebben?

        - Gedachten hierover?
        - Suggesties voor verbetering
    - RWS stuurt nu vooral op RAMSSHEEP
        - hoewel in de documentatie van RWS de nadruk ligt op betrouwbaarheid en beschikbaarheid (de R en A in RAMSSHEEP), wat is de belangrijkste reden hiervoor?
        - Hetgaat vooral om kwantitatieve risicoanalyses bij de R en A. Hoe wil RWS haar doelstellingen op het gebied van duurzaamheiden circulariteit bereiken?
    - Stimulansen
        - Moet RWS meer prikkels creëren voor de contracten om duurzaamheid en circulariteit te stimuleren?
        - Hebben aannemers meer hulp nodig?
        - Wat is nou voor hun bepalend om bepaalde kansen en maatregelen te nemen?

c. Toekomstperspectief op duurzame en circulaire operationele en onderhoudsstrategieën (+-5min)

Het einde van het interview

- Hoe kijkt u aan tegen dit onderzoeksonderwerp?
- Onderwerpen/ opmerkingen die je nog wilt maken over het onderzoeksonderwerp/ interviewinhoud

Bedankt voor uw tijd en de moeite die u heeft genomen om te participeren aan mijn onderzoek. Zoals ik in het begin aangaf zal ik het interview transcriberen en voor uw opsturen. Voor ik afsluit: voor mijn onderzoek wil ik graag nog een keer samen zitten met experts om het eind resultaat te presenteren en voor eventuele input. Bent u geïnteresseerd hierin?

Extra vragen (ingeval nodig)

Duurzame en circulaire strategieën.

- Wat zijn de vereisten hiervoor?
- Hoe kunnen deze gestimuleerd, opgenomen, gemeten en geëvalueerd worden?

Om CE-strategieën te incorporeren en te bedenken, is het noodzakelijk om belanghebbenden, het bedrijf te betrekken bij circulaire economische plannen en teamwerk voor het ontwikkelen van deze strategieën en doelen.

- Gedachten hierover
- Haalbaarheid

Data gerelateerde vragen

- Gegevens in O &M
    - Weet de geïnterviewde wat voor soort gegevens worden gegenereerd/verkregen gedurende de operationele en onderhoudsfase van de levenscyclus van bruggen/sluizen?
        - Type gegevens/gegevenscategorieën
        - Manieren om gegevens te verkrijgen
        - Manieren om data te analyseren/gebruiken voor toekomstige strategieën (binnen huidige/andere projecten?)
        - Soort gegevens gekoppeld aan duurzame ontwikkeling/ circulaire economie?
        - Zijn er uitdagingen geïdentificeerd door de geïnterviewde met betrekking tot het verkrijgen / analyseren van gegevens , enz.?
        - Soorten gebruikte software?

RWS als organisatieen beleidsdoelstellingen

- Wat zijn deze beleidsdoelen?
- Hoe worden deze gemeten (lange en korte termijn)
- Hoe willen ze mij zijnen deze doelen?
- Haalbaarheid van de doelen op basis van de huidige manier van werken etc.

Appendix D: The list of indicators

Measuring sustainability demands the applicability of indicators. The developed tool gives transparency, since that is needed within the application of applying sustainability indicators.

The table below will show the final list of indicators, including the type and objective.

Theme: Environmental Impact		
Indicator Category	**Indicator**	**Goal/ what does it do/ measure/**
Climate	Estimation of carbon dioxide emissions (CO_2) associated with activity	Method of calculation based on calculating (CO_2) for example: mass of material x transport distance x transport emissions factor **note:* *Hutchins UK Building Blackbook (Franklin + Andrews, 2009)* as a reference to calculate (CO_2)
Resources	Resources measured and minimized - Energy	- Promoting energy efficiency based on data - estimation on energy use
Resources	Resources measured and mminimized– Materials	Consider the total weight of the virgin material(s)
Resources	Resources measured and mminimized– Land	- Minimize total land required - Take into account: • Total land take • Quality of land • Adverse affect on surroundings
Resources	Resources measured and minized - Water	- Encourage effective water use - Minimize risk of contamintation - Take into account: • total volume of potable water required • risk of contamination of water courses • past performances such as complaints.
Waste	Waste Recycling	Recycle materials by including recycling processes
Waste	(design/ implement) for deconstruction	- Is deconstruction considered? - What happens in the case of dismanteling?
Waste	Quality Recycled materials	- Ensuring the quality of recycled materials - Create/ Stimulate towards secondary use
Waste	Waste treatment	- Type of waste treatment
Waste	Waste production	- Quantifying waste and type
Waste	Waste management	- Process for waste management
Biodiversity	Protection flora and fauna	- Value of biodiversity - number of habitats effected
Biodiversity	Natural heritage	Conservation of non-renewable resources due to added value to quality life
Materials	Equipment and materials with ecological labels	Materials and equipment with threshold on ecological labels
Materials	Use of regional materials	Distance from supplier to project-site
Materials	use of durable materials	Executing durability tests
Materials	Reused/ recycled materials	Assess the quality of recycled material
Materials	Product footprint	- LCA - MKI

Ecotoxicity	Air quality	Measuring the air quality index (aqi)
Ecotoxicity	Dust	Calculating Dust Impact
Ecotoxicity	GHG	- emissions of industrial soot and dust - CO2 emissions and Co2 equivalent - Gas cleaning before releasing into the atmosphere
Energy	Renewable energy	- Effect of nonrenewable energy - input of renewable energy
Energy	Energy consumption	Energy efficiency
Energy	Energy efficient drivers	Use of practices and appliances aiming at reduction of energy consumption
Energy	Energy recovery	- energy generation through incineration of high caloric potential materials - In the form of electricity, heating and/ or gas
Energy	Light pollution	Night sky brightness (NSB) quantifying the brightness usingSky Quality Meters (as an example)
Water	Water Saving	Use of water efficient techniques and technologies
Water	Water consumption	Water useage
Water	Protection of water resources	Water quality
Water	Water leakage	Inspection
Soil	Erosion and sedimentation control plan	Risk assessment of soil errosion
Theme: Social impact		
Indicator Category	**Indicator**	**Goal/ what does it do/ measure/**
Actors	Participation	- Assess engagement - Assess experience
Actors	Multidisciplinary	- Diversify team
Actors	Communication	- # of complaints when works executed
Users	Noise	- Frequency of noise events (noise intensity) - Number of affects - Effects on surroundings
Users	Accidents	- # of accidents during works
Users	Communication	- # of complaints about works
Users	public safety	- # injuries during works
Users	Vibrations	- Vibration dose - Frequency - Effects on surroundings
Users	Dust	- Calculating dust impact - Examination of control measures
Integration	Local workers during maintenance	- Amount of local workers/ organizations participating
Integration	Raising levels of training and information	- sufficient engaging eduction through staff training, green training and development programs - Educational tools such as training in sustainability
Integration	Safety and health of workers	- # injuries during works
Theme: Economical impact		
Indicator Category	**Indicator**	**Goal/ what does it do/ measure/**
Costs	CBA	Executing CBA
Costs	LCC	Executing LCC
Costs	Local economy	Percentage stimulating the local economy
Costs	Investment costs	- Financial investment - Return on investments - Profitability index

		- Investment planning
Costs	Material costs	Weighing material alternatives via costs
Costs	Inspection time	Time inspection takes for activities
Costs	Labor time	Labor expressed in money
Technical	Research & Development	Cost R&D
Theme: Circularity impact		
Indicator Category	**Indicator**	**Goal/ what does it do/ measure/**
Strategies	Technologies for circularity	- creating and incorporating new circular economy friendly technologies - BIM, BAMB, VR tools, interactive nature of technologies
Strategies	Closed loop systems	- implement recycling and policies on waste reduction - waste minimization
Strategies	Circularity awareness and skills among employees	stakeholders are necessary to develop circular economy concepts
Strategies	Maximize economic impact	implies delivering revenues for implementation of CE
Strategies	Secondary market mechanisms	different mechanisms in recycled materials market to stimulater recycled material usage
Redesign	Prolongation of use phase	- design for longevity and durability - Design for ease of maintenance and repair
Redesign	Circular-end-of life	- material choice enables recycling - biodegradation
Redesign	Circular logistics	- Circular packing - Weight and volume of return materials - Sourcing and collection strategies throughout value chain
Redesign	Innovation	- Promote innovation in business models, processes, products and services - Establish networks and partnerships
Reduce	Reduce quantity	- Resources used in the production process of materials etc - Reduction of waste and leakages - Consumption of raw material, mineral and fossil-based resources
Reduce	Reduce depedency	- Reduce consumption and imports of critical and scarce raw materials. Elements and minerals - Use of secondary materials
Reduce	Reduce complexity	- Dematerialisation (reduction of quantity and variety of materials) - Optimisation of packaging strategies
Reduce	Reduce impact	- sustainable procurement - Traceability and use of certified resources
Reuse	Reparability and maintainability	Eabled through warranty, maintenance and repair schemes and services
Refurbish	Refurbishment and upgradability of products	- product designed for upgradability and refurbishment - Systems in place exist and are low in labour, energy, material and costs
Refurbish	Accessibility and reusability of components	- inspection and testing of components and assembly of approved parts - Properties of components are preserved after disassembly and configuration facilitates detachment and reincorporation to next product

		- Disassembly, fitness for reuse, adaptability, and longevity on components level is considered from design and applied at system level.
Recycle	Material composition and separability	- physical capabilities of a product to be separated into material types
Recycle	Properties for recycling	- material' capability to be recycled one or more times without losing their Quality - Material properties to be cascaded down into materials and products
Recycle	Used of recycled material	- percentage of recycled material from total - Energy used to produce recycled materials of same quality as raw ones v.s. their counterparts produced from primary material inputs only - Material use rate in cascading alternatives
Recover	Waste to energy	- combustion/ incineration of waste to obtain and use heat and energy in urban or industrial applications - Composition, biodegration or incenratation to reintegrate minerals in biological cycles or to obtain specific minerals for industrial or agricultural applications.

Appendix E: Elaborate results semi-structured interview Analysis

The analysis of the interviews was carried out according to the 6-step Framework by Braun and Clarke. This appendix will give an overview of the results extracted from analyzing the interviews. In summary, a thematic analysis will be conducted.

In the maintenance stage of civil engineering objects, different actors are involved in the process. These actors have a certain relationship due to collaboration. The way of collaboration depends on different factors such as the contractual agreement between actors. In general, two main perspectives are considered throughout the maintenance phase namely the perspective of the client, in this research the client is (a representative of) the public sector. Another perspective that is considered to be important throughout the maintenance stage of civil engineering objects is the perspective of the market party. For this research, the market parties only consists of contractors. Other market parties also relevant for the maintenance stage were excluded from this research, since in practice these parties are working as sub-contractors for the main contractors. In this way, these parties are indirectly linked to the contractors interviewed. Thus, the interviewees/ respondents who participated in the interviews were then categorized into either the public sector or market parties. The analysis of the results are also compared from both perspectives. In total 13 participants all active in the Dutch civil engineering sector were interviewed throughout the period between September 2022 and October 2022. The duration of each interview was between 45-60 minutes max.

Table 16 gives an overview of all involved interviewees including a reference abbreviation for each interviewee. These references will be used as a basis throughout the analysis.

Table 16 All interviewees participated in the research including their abbreviation reference and date of interview

Public sector	**Abbreviation reference**	**Interview Date**
Province of North Holland_A	[PNH_A]	27th of September 2022
Provincine of North Holland_B	[PNH_B]	6th of October 2022
Provincine of North Holland_C	[PNH_C]	13th of October 2022
Municipality of Amsterdam	[Mun_Ams]	3rd of October 2022
Rijkswaterstaat_A	[RWS_A]	30th of September 2022
Rijkswaterstaat_B	[RWS_B]	30th of September 2022
CROW	[CROW]	26th of September 2022
Market parties	**Abbreviation reference**	**Interview Date**
Consultant Individual	[CI]	25th of September
Arcadis Nederland B.V._A	[Arc_A]	29th of September 2022
Arcadis Nederland B.V._B	[Arc_B]	6th of October 2022
Contractor A_1	[CA_1]	17th of October 2022
Contractor A_2	[CA_2]	17th of October 2022
Contractor B	[CB]	18th of October 2022

The interview protocol from the semi-structured interview shows that there are certain key concepts that must be discussed and starter questions. These key concepts are considered beforehand since these are based on concepts and theories found in the theoretical framework in the previous chapters. Throughout the interview, there was room to deviate from the standard questions if the interview took that approach. The following key concepts were discussed:

1. Sustainability and Circularity in operation and maintenance
2. Barriers to implementing sustainability and circularity in operation and maintenance
3. Opportunities to implement sustainability and circularity in operation and maintenance
4. Collaboration (between parties)
5. Indicators in O & M
6. Future perspectives

In the end, it is also important to keep in mind what the goal is of doing these interviews. The reason for conducting these semi-structured interviews lies in the fact that the information obtained from the interviews will be part of the data analyzed that form the basis for setting the requirements/ design brief for integrating sustainability and circularity in the maintenance stage of civil engineering objects.

Analysis

After transcribing the interviews, each transcript was reviewed and:

- Applied initial coding
- Transcripts with initial coding were screened again, to see which initial codes can be combined to come up with some codes representing more initial codes
- From the set of codes, various themes were set up.
- The relationship between themes, sub-themes, and connections were shown in a thematic map.

Since the interviews were analyzed using the software Atlas Ti 22 version, it is shown in the table below the process from initial coding (first cycle of coding) to coming up with the themes. The interview analysis was in the end based and coded in such a way that these main themes flowed out it. Below is a description found on the main themes.

Theme 1: Sustainability in maintenance

Sustainability is one of the main concepts that is central to the research. Both concepts are researched among different scholars and integrated in policy documents and organizational goals lately. This is also the case for policies related to the civil engineering sector in the Dutch context.

For the semi-structured interviews, it was for this theme mainly the goal to get insights into definitions of sustainability, circularity and the operational and maintenance stage of civil engineering structures from the perspectives of the different interviewees.

Sub-theme 1.1 Defining sustainability

it is concluded from desk research that the terms are (i) often too broadly defined, (ii) integrated mainly in the design and construction stage of civil engineering structures and less within the operational and maintenance stage. Before terms can be widely implemented it is important to understand how terms are defined by actors within various organizations. Within this research, the definition on sustainability as defined in the Brundtland report is guiding. With this question, the researcher wants to research how the term is defined within organizations. Some of the interesting definitions on the term quoted during the interviews are:

> You want to build and maintain structures in such a way that both life on the planet and future generations benefit from it. This is then translated into actions such as circular building, materials flow, and impact on the future. [PNH_A]

> Sustainability is often a very vaguely and broadly defined term. So, this is organizational dependent. [Mun_Ams]

> The term sustainability is a container term. A reason for this could the that the term got a large status at once. [RWS_B]

> With sustainability you want to make it as concrete as possible, because that's the most important thing to get a foothold in the projects and with the people who have to deal with it. However, sometimes it is a bit of a search how to apply sustainability due to missing concreteness in the definition of it. [Arc_A]

> The works should be carried out as sustainable as possible [CA_1]

Conclusion: As the above quotes state, defining sustainability is not as easy as we use the word in practice. The question on defining sustainability was one of the starter questions of the interview. The reason for this, is that sustainability is a key concept of the research at hand. The results on the analysis of defining sustainability show that all participants/ respondents were a bit struggling with defining the term. Words such as “broadly defined”, and “vaguely”, and “concreteness missing” was often mentioned at the start of explaining the definition of the term. In the case, the participant did give a definition to the word, it often

included the link with protecting the environment and future generations. Within literate, the term sustainability is often linked to the triple bottom line of "environmental considerations, social and economic". However, all participants failed to really include all aspects of sustainability when asked to define the term. From this it is concluded that the definition of the term is not as easy definable for the actors. This could also lead to expectations and not really understanding what sustainability is about. This can then also make it harder to integrate and incorporate in projects one could say.

Sub-theme 1.2 Sustainable maintenance

This research specifically focuses on improving sustainable strategies. Literature review shows that in literature scientists mention that the concept of sustainable maintenance is not yet really explored. In some countries such as the UK, USA, and Australia they are a bit further in the process and are currently even exploring different mechanisms and tools how to do so. One of the follow-up questions asked to the respondents after asking to define sustainability, was based on defining the term in the context of the operational and maintenance stage of civil engineering objects. Below some quotes on this are shown:

Sustainability within B&O is actually sometimes already partly automatic. The other part you try to stimulate as an organization. [PNH_C]

We can say it is about carrying out maintenance activities in such a manner that we consider sustainability [PNH_A]

The works should be carried out as sustainable as possible. Our clients expect from us as contractors to make both projects and objects as sustainable as possible [CA_1]

Within O & M sustainability is maybe not considered to be that big of an aspect. Important within maintenance is to carry out the maintenance works and be done, nothing extra. However, in my opinion, I've also seen reports that O & M by nature already considers the long term, lifecycle costs, life extension. At the basis, you could maybe say that they are already including aspects that could lead to sustainability in the sense of prolonging the asset. [ID]

Sustainability within O & M is often considered to be minimal. Within this stage, it is important to preserve the object and longevity remains as well as functionality of the object [Arc_B]

Conclusion: The concept of sustainable maintenance is defined within literature as: From the analysis of the interviews, it is concluded that sustainability within the maintenance phase does not really found its place yet. In follow-up questions about the reasons for this, interviewees responded in different ways. These will be later further explored and explained in the form of the theme "barriers to obtain sustainable maintenance". However, defining sustainable maintenance was not yet really a concept the interviewees were too familiar with. From the PoV of contractors, it is said during the interviews that the clients who the

contractors work for, expect them to incorporate sustainable maintenance practices in their works. Others also say that without even really considering the aspect of sustainability in very broad perspectives, the considerations made for maintenance activities somehow already consider sustainability. However, these considerations are often indirect, not really emphasizing too much on sustainability and without really mentioning and considering sustainability, full potential of integrating could be missed and overseen.

Sub-theme 1.3 Circular Economy

Within the theoretical framework of the research, the concept of circular economy/ circularity is broadly researched. Review shows that the definition of circular economy by is most applicable to the research. In theory, the relation/link between sustainability and circularity is also considered. Within literature it is found that there are some discussions going on among researchers themselves how sustainability and circularity are linked to each other. With this sub-topic more insights wanted to be gathered on how interviewees see this since both concepts, sustainability and circularity are considered to be important for the research. Also in the context of O&M was considered to be of relevance. With circularity also being a key point of focus in the research, throughout the interview, it was also asked to the respondents, there thoughts on circularity, and the link between circularity and sustainability and how it is perceived within practice. Below some quotes on this are shown:

> Within our organization (refers to Province of North Holland) sustainability is further translated into 6 goals where circularity is included in as one of the six goals. [PNH_B]

> In the case of the municipality, circularity is one of the five pillars of sustainability. [Mun_Ams]

> I see circularity as part of sustainability. We once signed the Green Deal and "duurzaam GWW". In both of these, circularity was one of the indicators and a very important one [PNH_A]

> Both sustainability and circularity are enormously linked together. One cannot exist without the other. In most cases, people often pull both concepts (sustainability and circularity, red.) apart from each other. I never really understood that. Circularity is an aspect of sustainability. It is important to move into a more integral picture. It doesn't make much sense to sit hard core on circularity. It's important to have an integral view of sustainability in which circularity is then included. [CROW]

> There are a few elements that you can use to make it (sustainability) more concrete, in which circularity is one of these elements.[Arc_A]

Conclusion: Respondents who were asked about the link they see between sustainability and circularity all some what made the relation between sustainability and circularity as the latter one being part of the first one. Sustainability is seen as an umbrella term, and circularity is

under the umbrella, an indicator, a pillar of achieving the sustainability together with Co2 uitstoot etc.

Next to asking interviewees how they see the link between sustainability and circularity. Some were also asked how they see circularity in the maintenance stage, what kind of aspects to consider, below some quotes on this are shown:

In the case of circularity we have to consider things in a different way. Materials should be considered circular and then also sustainable. If you can think of doing this differently, you can also consider doing maintenance strategies in another manner. [PNH_B]

Circularity is mainly about using primary raw materials less and possibly no longer at all, via the 4 R-ladder and dealing with them in the smartest possible way. So, looking at what is already there and what is coming and can we use that before we use primary materials. In particular, use secondary materials as smart as possible and therefore need less primary materials for carrying out maintenance activities [CROW]

Circularity can be considered a relatively vague described term. But the material component is of importance together with secondary and renewable materials and potential to reuse materials [Mun_Ams]

It has certain interfaces with sustainability. It is tremendously linked to your materials [CB]

Circularity is more focused on material flows, resources flow [IC]

Conclusion: In the case it was asked to the interviewee how they see the circularity in the maintenance stage of civil engineering objects it was concluded that for circularity the link was often made to materials. It could be related from reusing materials, to using less primary materials and using these in a smart way.

Overall conclusion on theme 1- Sustainability in maintenance shows that:

- Defining sustainability is not as easy as the word is spread and used in practice.
- Defining and considering sustainability in the maintenance stage is often also not easy.
- Sustainability is seen as an umbrella term, where circularity is under the umbrella as one of the few pillars/ concepts how to achieve the overarching sustainability goal.
- Circularity within maintenance of civil engineering objects is often associated with materials.

Theme 2: Barriers for sustainable & circular strategies

Next to defining sustainable maintenance, it was also asked to respondents if they see barriers for reasons why sustainable maintenance is not often directly considered. Or even considered on a large scale. Here insights are observed on analyzing reasons for not elaborately considering sustainability in O & M. How do parties perceive this, do they see barriers and in the case of yes, what kind of barriers do they see. Below a few quotes on these can be found:

Within O&M, its main objective here is to maintain the functionality of the object. Then you assume a certain situation that is already there anyway in order to maintain it as much as possible. Less **degrees of freedom (**vrijheidsgraden) to do something with sustainability in O &M [CROW]

They also have other **budgets** at O&M compared to other parts that focus on other stages in the lifecycle, since the budget for O&M is limited to maintaining the asset and having it functioning. [CROW]

other type of management, more standardization within O & M. There is also not a lot of room for experiments to innovate within O&M. Availability of infrastructure is an important aspect. Within O & M, it is important to organize activities in the same manner. The activities are often of repetitive character, such as the same materials, same kind of machineries. With introducing sustainability, it can introduce risks. If the current way of carrying out activities work, is it then worth it to change it and introduce uncertainty. [CROW]

Incorporating sustainability is quite tempting. However, in practice I see that we cannot make final choices yet. One is always researching, and working out more and more in detail, because there is so much uncertainty in it and not a lot is really implemented in projects in practice. [CROW]

Focus mostly on new-to-be built constructions for integrating sustainability. O&M of existing infra is not yet deserving the attention it needs to get. [PNH_A]

Currently data capturing is not yet done on a large scale. This can be seen as a barrier to exploit and reuse of materials. [PNH_A]

Finance can be a barrier for integrating sustainability and circularity. It might cost more to be circular instead of doing it in the same manner as we do now due to the processes and the supply chains involved. It might cost more money and time to changes these including training personnel. [PNH_A]

You have to get the right people together who are all positive about integrating and open for sustainability. It also sounds a bit perhaps derogatory to the people involved in that. But a manager is from his culture, someone who wants to maintain it and is not so much always

looking for innovation, and preferably not to do crazy things. There is a change necessary in that, I think in order to achieve the sustainability. [PNH_A]

unfamiliarity with sustainability. And then there is also the resistance which has to do with unfamiliarity and the resistance to change, because you have to try new things. A manager (*in Dutch: beheerder)* is usually a bit more conservative. This actor is focused on managing and preserving the asset to say so and then if you apply a sustainable aspect or material or whatsoever, you don't know how this will impact the asset. [PNH_B]

Sustainability involves innovation and that comes with risks [PNH_B]

Sustainability can also cost more. [PNH_B]

Terminology of sustainability is hard to understand often and then also hard to include in O&M. That's because when talking about sustainability everyone instantly thinks about solar panels and windmills and green electricity and much less about resource depletion for example. [Mun_Ams]

The civil engineering sector is an enormously material-intensive sector and that's why I think it's really necessary to change it. So, it is mainly because it is just not understood or that there is still a knowledge gap. [Mun_Ams]

Sustainability has become very important very quickly. Due to this, organizations themselves are still in transition and then you run into walls. [Mun_Ams]

Sustainability is hard to measure. That's where the biggest barrier is. How is that done and can it be verified? [Mun_Ams]

We're still dealing with critical infrastructure. Or infrastructure that has an availability requirement. You want to avoid that contractors will say: you have high demands in regard to availability. So we do not dare to use remanufactured or reused materials. Since that might not meet that lifetime requirement or that availability requirement. The availability requirement must always be met, that is a given, and then there is no room for experimentation [RWS_A]

We struggle quite a bit with circularity and how to get that right in contracts without being super specific, but specific enough that you get circularity and a reduction in primary material use. [RWS_A]

Within the procurement there are basic procurement principles (proportional guide) that must be followed. With sustainability in the tendering phase, depending on how you steer, it might exclude certain parties. [RWS_B]

Although everyone would love to join, but there is the need for an alternative revenue model [RWS_B]

The people working in O & M are quite conservative, because it is also a relatively conservative side of the industry. O&M is status quo. “If I don't have to do anything, I don't have to do anything that idea.” [IC]

Within O&M, the most important thing is that it functions and that is what you want. Things like innovation and research are less important, which are part of sustainability. You can say in summary: “a conservative person in a conservative part in a conservative sector.” [IC]

They don't know very well what sustainability means. And somehow there is also a certain urgency to do so missing. [IC]

I think the culture in the O&M is more conservative than in the construction sector. [Arc_A]

People within the sector also have to be open to it. If there are only people involved who say: “this is how we have done it for ages”, then this will not lead to sustainability. [Arc_A]

There is also the aspect of uncertainty that comes with sustainability. Also, you also have to consider innovations. [Arc_A]

The people who are involved may not see the relevance of it. But, that also holds something back. They have to accept that themselves first or somebody has to say to them that they need to do it differently. I am afraid that it only happens in the latter case. [Arc_A]

You see that contractors are very keen to come up with sustainable solutions, to work them out in detail, and then hear from the client that there are no resources for this. As a result, there is not much drive from the contractors to keep doing it. [Arc_B]

Within O&M functionality is important. So, if in the preliminary stage something with sustainability is incorporated, then it is operated and maintained with that in mind. But adding sustainable things makes it more difficult. [Arc_B]

It is not intended that an awful lot of money goes to maintenance. In practice this is also the case. [Arc_B]

Rijkswaterstaat organized it in such a way that maintenance is really meant for maintaining the asset. It is not meant to fund new things and new initiatives. [Arc_B]

What we see in practice, but also from my own experience when I was at a contractor is that a lot of those contractors want to put in sustainability initiatives in projects. Also after awarding. They research those, put effort into that and then show it to the client. However, they then often “get a lid on the nose” by the client stated that there is no money [Arc_B]

Often clients do not extensively address sustainability in the tendering/ procuring stages. [CA_1]

You see the client's contracting team is willing to go the extra mile sometimes with sustainability, but their own management organization is a little less open [CA_1]

From our experiences, sustainability costs more than traditional business as usual approaches. [CA_1]

A few years ago, you could describe your measures in a plan and that was then rated. But lately that has mostly gone back to just do an MKI calculation and then I (the client) can just compare that and then no more whining about ratings. [CA_1]

Lack of clarity. [CA_2]

We do find ourselves in constant splits now, what can something cost and what does it yield. [CA_2]

The culture within the client but also in the Netherlands. Here we want the tight little lawns and that is actually not good for nature at all and not at all sustainable [CA_2]

we try to bring it to a number because it is difficult for our customers to judge it on the soft side. As Heijmans we obviously want a lot for sustainability, and there are a lot of people who are very enthusiastic about it within our own organization. However, it is hard to express everything in a number such as MKI [CA_2]

Yes, there is much more focus on impact, you can still include the measures. But then we have to demonstrate what that measure does with the MKI [CA_2]

The team that focuses on the procurement and tendering stage from the client's side is a few steps further than the traditional maintenance method. [CB]

There are practical obstacles. People within the O & M stages are often not really in favor of innovation and with sustainability you often need to consider innovation and innovative strategies. [CB]

Conclusion: When asked to explain/elaborate on barriers that hold back on sustainable/ sustainability integration/ consideration/ strategies some participants made the link/ comparison to other stages within the lifecycle such as design, built/ construction.

Based on analyzing the interviews on barriers, a poule was made to categorize the barriers based on how often they are mentioned.

1. People involved
2. Financial resources
3. Procurement/ contracting stages
4. Maintenance transition
5. Others

Barrier category	Sub- category
Finance Related	Budgets are restricted
	Costs are more
	No alternative revenue model
	No resources available from client, but contractors are keen to do
	No money from clients side available for it
	Costs are more
People active in maintenance	Personnel
	People who are in it
	"culture" within maintenance is traditional and not open to innovate
	Understanding problems with terminology/ knowledge gap
	Unfamiliarity with sustainability
	Resistance to change
	Manager are conservative
	Conservative people
	Definition of sustainability is unclear
	Urgency to consider sustainability is missing
	The culture is conservative
	People have to be open to it
	People involved may not see the relevance
	Not everyone is open
	The culture
	Conservative side of the industry
	The culture
Transition	No Space for innovation/ experiments
	Sustainability introduces risks/ uncertainties
	Don't want to introduce risks/ uncertainties
	Innovations must be done but come with risks
	Innovation and research seem to be less important, but are important in sustainability
	Uncertainty in innovations
	Focus not too much on new innovations
	Not too much in favor of innovations
	Sustainability quickly got a certain status, still in transition
	Lack of clarity
Contracting	Hard to be specific and put it into contracts
	Basic procurement principles/ proportional guide must be met
	Sustainability is not extensively and standard addressed in procurement and tendering
Measuring	Sustainability is hard to measure
	Sustainability is mostly asked in the form of calculations via MKI, but that is not always possible
	Hard to express all measures in MKI/ numbers/ quantify it

Extra	Availability is an important requirement that must be met, no room for experiments
	Maintenance is status quo
	Functionality is most important
	Constant split between costs and what it yields
	More Standarization/ same way of carrying out activities
	Degrees of freedom
	Not yet deserving the attention it needs to get

In the end, the barriers from the interviews somehow overlap with some barriers found in the literature.

Theme 3: Enablers for sustainable & circular strategies

With barriers there also come opportunities. In the case, respondents mentioned some kind of barriers as described above, it was then also asked as a follow up, what they consider to be opportunities. Next to the barriers listed by the interviewees, it was also important to ask if they see opportunities at all to include the aspects in O&M. And if they see opportunities, what can these be? Are there even opportunities possible with these barriers that they mentioned. Below some quotes can be found on that:

1. Procurement
2. After contracting stage
3. Project level
4. People involved
5. Others

Enabler **category**	**Sub-category**
Procurement stage	One way to include sustainability in the process, is to have a portfolio approach and then include more projects at ones
	Sustainable procurement
	Materiaal, materieel en bij inkoop kan je daarom scoren
	to think about procurement requirements.
	The procurement strategy (tendering), what the client asks is a very important component to improve the sustainability in practice
	by bringing both sustainability and circularity as choices in contracts, for example, in the way we work
	procurement and tendering
	the procurement and tendering really makes the different
	Within O&M you also have long-term contracts, and it is important, though, to include developments in them
After contracting	More cooperation and promoting it through cooperation between the contractor, the client and the knowledge institutions
	more focus on the end of life cycle/ phase
	a bit of a shift towards in own initiative, I think from Contractors
	But if the market (contractors) develops something, then the clients such as RWS should be more open to it, cooperate, research and invest in it if they can
Project level	Research is going on and on, instead of implementing and learning more. Pilot projects are executed but, maybe more should be done.

	Reusing as many of the existing materials
	Creating spaces and logistics for material storage after useage
	I think you have to be concrete in your proposals to give sustainability and circularity a place in the projects and also in contract.
	Social Impact of sustainability is important and even more important than people realize
People	People in the chain also must want it themselves and see the need
	Some how sustainability is already automatically applied on some level
	When it seems to be made easier, then people are more likely to take action in interventions and could stimulate the sustainability
	You also notice that if you get the people from O & M on board with sustainability, then you have taken some steps.
	When it seems to be made easier, then people are more likely to take action in interventions and could stimulate the sustainability
Extra	Asset management thinking
	The sustainable solution should be standard.
	with data you have knowledge and then you know what's in it
	In case sustainability is not automatic, can you encourage it by policy aspects, by setting new frameworks, strategies.
	The O & M can serve as a base for innovations.
	Existing measurements and data obtained from that can help with sustainable innovations
	Open and transparency can create opportunities for sustainability
	If clients specifically ask that out. And also have the budget to actually go

within O&M it is hard to take sustainability into account as a business-as-usual activity, due to the complexity. One way to include sustainability in the process, is to have a portfolio approach and then include more projects at ones. [CROW]

Research is going on and on, instead of implementing and learning more. Pilot projects are executed but, maybe more should be done. [CROW]

use as many of the existing materials as possible. This is both an opportunity and a barrier, because to do this you also need logistics, knowledge and a platform. [PNH_A]

People in the chain also must want it themselves and see the need. if they also feel the urgency and show ownership for that transition, effort has to be put in it. Try, research and make time and efforts. Another part also goes automatically. [PNH_B]

But if the market (contractors) develops something, then the clients such as RWS should be more open to it, cooperate, research and invest in it if they can [Arc_B]

the choice moment for replacement should perhaps be brought forward in the process. [CB]

Sustainable procurement of materials during B&O is important [PNH_A]

Reusing as many of the existing materials as possible and retain their value. [PNH_A]

creating indeed a space for example for the storage of materials in the phase when it has been taken out of an object that it has temporarily no new use. Then it must be stored

somewhere and that is also an important aspect. Currently we do not have a space to do so. [PNH_A]

I do think Asset Management can also contribute to thinking ways to do more effective management and maintenance. And in doing that, you actually make it more sustainable as well [PNH_A]

So then you also have the front runners who have to keep stimulating and at a given moment that market is going to move and it becomes the standard. [PNH_B]

More cooperation and promoting it through cooperation between the contractor, the client and the knowledge institutions. The requirements are set by the province and put them on the contractor who then must start coming up with solutions for this. [PNH_B]

Materiaal, materieel en bij inkoop kan je daarom scoren [PNH_B]

When it seems to be made easier, then people are more likely to take action in interventions and could stimulate the sustainability. we will never get to one hundred percent circularity if indeed we don't reuse the existing. if we just design that new construction circular. That, of course, is a very good way. You have to start with that anyway, but by reusing the existing. [Mun_Ams]

sustainability is special now. The sustainable solution should be standard. There should just be no concrete, no more fossil products offered at all and preferably no new material, but reuse materials or an existing material or taken apart, something that comes back again, or in other words primary raw materials and a mode of production produces basically no waste. That should actually be standard. It's special now and that's how we treat it. In other words, extra sustainability. No, that what you do should actually be sustainable. [RWS_B]

We do have to be realistic in what market parties can do, where of course we as government parties can push. [RWS_B]

Within O&M you also have long-term contracts, and it is important, though, to include developments in them. Promoting new things in the contract, for example. [RWS_B]

Although everyone would love to join in, but need an alternative revenue model. [RWS_A]

with data you have knowledge and then you know what's in it. And then you can start thinking in advance about where you can use existing material or whatsoever. It also stimulates material passports [PNH_B]

In case sustainability is not automatic, can you encourage it by policy aspects, by setting new frameworks, strategies. How do you get there in the end? Then you have to think about procurement requirements. so if you set requirements around for example that the asphalt you apply that that has to be sustainable. [PNH_B]

if you do proper management and maintenance, then also your object will remain sustainable as well [PNH_C]

The procurement strategy (tendering), what the client asks is a very important component to improve the sustainability in practice. [CA_2]

The people involved should be more open to it and be acceptable of sustainability more. [Arc_A]

I think you have to be concrete in your proposals to give sustainability and circularity a place in the projects and also in contract. But the clients, they put their stamp on it. So there has to be support there as well. [Arc_A]

by bringing both sustainability and circularity as choices in contracts, for example, in the way we work. As consultants we have to suggest how we think something can best be done and what would be best for the client. In that way we as consultants thus also have a role in this. [Arc_A]

If there would be more focus on the end of life cycle/ phase, then this will open up chances for sustainability within O & M. [IC]

You also notice that if you get the people from O & M on board with sustainability, then you have taken some steps. [IC]

the existing structures were built at a time when sustainability was not literally included, but they are still these robust structures that do require less maintenance I think that is quite sustainable in that concept of the time. We build sturdy objects that need a lick of paint once in a while. Sometimes a polish. [Arc_B]

From the O & M side, initiatives can be implemented based on the problems encountered. The O & M can serve as a base for innovations. [Arc_B]

If you figure it out right at the Tender then you come up with a kind of pressure cooke to figure some things out once and then we look for the breadth again as well. [CA_1]

Because it shouldn't cost too much, so to speak. but We do have something to do and we want to. [CA_1]

You do see now a bit of a shift towards in own initiative, I think from Contractors. [CA_1]

Very often it depends on the procurement and tendering and what is asked from the client's side [CA_1]

With our type of clients, everything has to be done openly and transparently, and you also create sustainability opportunities with that [CA_2]

we do measurements within maintenance and you could use that data for sustainable measures. [CA_2]

Social Impact of sustainability is important and even more important than people realize [CB]

If clients specifically ask that out. And also have the budget to actually go and do that. Yes, then we will be happy to do that. [CB]

the procurement and tendering really makes the different, in the end it is about what the client asks. [CB]

But as long as that it is financially cheaper To fly on a traditional boss out of the masses your project and is not specifically asked to do it more sustainably. Actually, people will still always go to the common cheaper alternatives. [CB]

capturing properly [CB]

Conclusion:

Based on analyzing the interviews on barriers, a poule was made to categorize the barriers based on how often they are mentioned.

Opportunities Client's side
One way to include sustainability in the process, is to have a portfolio approach and then include more projects at ones
Research is going on and on, instead of implementing and learning more. Pilot projects are executed but, maybe more should be done.
People in the chain also must want it themselves and see the need
Some how sustainability is already automatically applied on some level
But if the market (contractors) develops something, then the clients such as RWS should be more open to it, cooperate, research and invest in it if they can
Sustainable procurement
Reusing as many of the existing materials
Creating spaces and logistics for material storage after useage
Asset management thinking
More cooperation and promoting it through cooperation between the contractor, the client and the knowledge institutions
Materiaal, materieel en bij inkoop kan je daarom scoren
When it seems to be made easier, then people are more likely to take action in interventions and could stimulate the sustainability
The sustainable solution should be standard.
Within O&M you also have long-term contracts, and it is important, though, to include developments in them
with data you have knowledge and then you know what's in it
In case sustainability is not automatic, can you encourage it by policy aspects, by setting new frameworks, strategies.
to think about procurement requirements.
Opportunities market parties side
The procurement strategy (tendering), what the client asks is a very important component to improve the sustainability in practice
I think you have to be concrete in your proposals to give sustainability and circularity a place in the projects and also in contract.
by bringing both sustainability and circularity as choices in contracts, for example, in the way we work
more focus on the end of life cycle/ phase

You also notice that if you get the people from O & M on board with sustainability, then you have taken some steps.
The O & M can serve as a base for innovations.
a bit of a shift towards in own initiative, I think from Contractors
procurement and tendering
Open and transparency can create opportunities for sustainability
Existing measurements and data obtained from that can help with sustainable innovations
Social Impact of sustainability is important and even more important than people realize
If clients specifically ask that out. And also have the budget to actually go
the procurement and tendering really makes the different

In the end, the barriers from the interviews somehow overlap with some barriers found in literature.

Theme 4: Collaboration

Sub-theme 4.1 Contractual Agreements

Collaborating between parties is considered to be a very important aspect within O & M. It is done in various manners. One of the ways collaboration between parties is done is via contract agreement between the client and the contractor. By reviewing literature, it is found that there are various contract types given from contractors to the client. The performance-based contracts (*in Dutch: prestatiecontracten)* are awarded for maintenance works in relatively most of the times to the contractors. The type of agreement also sets the relationship between the parties, the involvement and the responsibilities. With this theme, the interviewee is asked to elaborate on the contract type they have experience with for O & M works, and ways to consider to stimulate sustainability and circularity in the O & M stage.

Contracting

As explained in the previous section, contracting is an important factor that sets the relation between the client and the contractor for the works. It is important to mention that not all interviewees had experiences with the performance-based contracts. In some cases, for example at the level of the municipal and province, they know what the performance based contracts are. Yet, they use other types of contracts for maintenance works such as "samenwerkingsovereenkomsten, and "raamovereenkomsten" or in the case of the province of North Holland, they are more familiar with maintenance contracts for assets based on their division areas. The province of North Holland is divided into 7 areas, whereas assets within each area are maintained by 1 contractor who as the full responsibility of that.

Nonetheless, **[RWS_A], [RWS_B], [Arc_A], [Arc_B], [CA_1], [CA_2], [CB]**have experience with these performance based contracts. In the Dutch context, authority RWS uses the concept of "RAMSSHEEP", a risk-driven approach which also sets the requirements the asset has to fulfill. One of the "**e"** within RAMSSHEEP focusses on environment. Reviewing of documentation on RAMSSHEEP integrated in the procuring phase and contacting shows that not a lot of attention has been given to all elements of RAMSSHEEP. The following statements

below give an indication on the current situation in regard to their experiences on performance-based contracting for O & M of civil engineering objects in the Netherlands:

[RWS_B] state the following during the interview: "RAMSSHEEP as it is currently incorporated into the contracts is mainly focused in technical aspects, but when the focus on RAMSSHEEP was created several years ago, the concept of sustainability and the environment was not considered to be that important as now. Within a short time, sustainability became very important and the impact on it is large, however a big step may have been skipped. It is considered to take it more into account during the awarding (in dutch: gunning) stage. En with RAMSSHEEP, you put that in a document within the procurement stage and then it might be considered read over it."

The above statement concludes that within the authority RWS, they might still search for possibilities to put more focus on the environment for example.

The same in some way goes for interviewee **[Arc_A]**: "for myself, I find it quite challenging. In the role we are fulfilling as contract management department, it is hard to give sustainability a spot sometimes."

Relationship client-contractor

Relationships between client and contractor are important to consider. Here the interviewee was asked to elaborate on the collaboration in relation to sustainability.

> Working together is also about making good agreements, and what do we do when something goes wrong. Who is responsible, who do we talk to and how does conflicts resolve themselves. [MAms]

> At the municipality of Amsterdam, they work more with "samenwerkingsovereenkomsten" rather than a specific contract type. At this type of contract, the common goal is stated based on the best result and the goal(s) with the most impact. With the "samenwer"ingsovereenkomst", a joint plan is made for in the case of conflicts, interests of parties. [MAms]

> More collaboration between the client and the contractor. There is a movement of two-phase cotnracts and bouwteams within the civil engineering sector. especially in other phases of the lifecycle. With O&M, there are especially performance based contracts. Here the role of the client and contractor are really delineated (*in dutch: afgebakend)* and therefore makes collaboration quite difficult to achieve. [CROW]

> In order to stimulate sustainability within O & M, it is important to consider more collaboration since we cannot come up with everything by ourselves. That is why in the case of "bouwteams" type of contracts, we work together with the contractor as the client. Thinking together about ways to find sustainable alternatives for example. It is always better to include the market with this. Because if we all have the same sets of requirements then the

market parties also have incentive to invest and can move to make it efficient. Because if there is only one organizations setting these sustainable requirements, they have lesser chance that the market is going to move. But you also have to make sure that the market makes demands that the market can meet. [PNH_A]

RWS prescribes in a functional manner. And how the works are executed are up to the contractor. As RWS, we don't interfere with how a contractor does it. Unless it's of critical importance then we know sometimes we want to go toward prescribing. We do steer with the MKI. But type of materials, how works are executed etc. is really dependent on the contractor. [RWS_A]

I would prefer that the contractor stays engaged in sustainability throughout the whole project. So have regular sessions and or exchange on information about sustainability with the contractor. Unfortunately, we see that the contractor only does something if it makes them money. [RWS_A]

The goals in regard to circular economy are on a national level, not specifically only by RWS. So also for market parties this is a goal they have to work towards. [RWS_B]

cooperation between governments and market participants [PNH_C]

Collaboration creates more space to think about sustainability and maybe give ideas to do things differently. If you don't collaborate, but contractor just executes that contract, then it stays as you conceived it. From that collaboration you can for sustainability. You can also take a look in between from that contractor, he might have ideas to do things more sustainably. Maybe there are developments in the industry or in the field that offer opportunities to do things differently. The moment you work together and are in discussion, it is much easier to give it a place than when you don't work together. And you can adjust it in the interim. [Arc_A]

You have to give collaboration a place in the contract, but it also goes on a voluntary basis. But that you cooperate with each other that you have an eye for each other's interests. And I don't think you can enforce that contractually. People have to be open to it. [Arc_A]

And I think you have to look much more at on base. What is technologically possible to add were again with repairs. Reform is to in this cetera then though. That you really have to certain, you can now say completely open. Now we have to put down the news. And that based on that you have a realistic strategy so about Yes, then again you're going to look about those gentlemen there several decades and therefore going to send and. And that it's less of Well, we've always done it this way [CB]

Theme 5: Measuring sustainability

Sub-theme 5.1 Indicators

Indicator	No. Times mentioned
MKI	8
Co2 uitstoot	7
Circularity Index	3
Biodiversiteit	2
Material component	2
Energie verbruik	2
Luchtkwaliteit	1
Lifecycle costs	1