

Circular Bridges in Midden-Delfland

Leiden, 31/01/2024

ERFGOED
KWARTIER
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Circular and sustainable bridges in Midden-Delfland

Leiden University
Minor Sustainable Development
31-01-2024

Group G:
Charley Beckers,
Marc de Bruijn,
Clara Pagliai &
Elena Weis

Executive summary

This report, commissioned by *Erfgoedkwartiermakers*, explores the application of a circular economic model to bridge infrastructure in the Midden-Delfland region. It emphasizes maintaining sustainability and environmental conservation through circular construction, with the focus of the research being the 15 bridges across the *Nieuwe Water* canal.

Erfgoedkwartiermakers, dedicated to heritage-inclusive area development, seeks to align maritime heritage preservation with sustainable practices. This involves the combination of various transformation strategies that emphasize economic, educational, recreational, and cultural benefits.

Midden-Delfland holds the distinction of being the first Dutch municipality to be awarded the Cittaslow hallmark, signifying a commitment to a slower, nature-focused city. Additionally, Midden-Delfland is recognized as a 'Bijzonder Provinciaal Landschap,' highlighting the significance of preserving the characteristic Dutch peat meadow landscapes situated between urban areas. The collaboration between *Erfgoedkwartiermakers* and our team aims to foster responsible infrastructure practices in Midden-Delfland.

Therefore, the circular economic model plays a significant role in advancing environmental sustainability goals. This model distances itself from the current "linear economy" narrative, where products are discarded after use, and new raw materials are extracted for production. The objective of this report is to demonstrate the potential implementation of a circular model in the development of bridge infrastructure in the Midden-Delfland area. The theoretical framework draws conclusions from previous studies addressing sustainable and circular materials in construction, providing insights for the research.

Our research introduces a sustainable and circular approach in bridge construction. Building upon the knowledge of Rinck and van der Blom (2020) and Geldermans (2016), our team forms a way of enhancing slow tourism by overcoming the barrier of bridges with low heights (<1.5m), under which small vessels cannot pass. Our research poses three essential questions: What constitutes circular and sustainable construction? Where do challenges lie in Midden-Delflands waterways? And how can existing bridges become circular? Through a combination of literature review, GIS-mapping, and Material Flow Analysis (MFA) on a simulated and a hypothetical bridge scenario, we set up a roadmap for *Erfgoedkwartiermakers* in attaining the circularity of the bridges. Our deliverables, a comprehensive research paper on sustainable bridge criteria, GIS-maps and simplified MFA pinpoints reconstruction priorities and concludes in an advisory report. This document not only highlights critical areas in Midden-Delfland but also provides actionable insights, guiding *Erfgoedkwartiermakers* to develop environmentally conscious bridge solutions.



**For circular development
and sustainability**

**GREEN
LOOP CONSULTANCY**

The Green Loop Consultancy Team



Charley Beckers

BA Linguistics



Marc de Bruijn

BSC Biologie



Clara Pagliai

BA International Studies



Elena Weis

BSC Architecture

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1 Introduction

1.1 Background

Economy, environment and society are the elements of a system that must necessarily use resources in efficient and sustainable management. It ensures that growth and well-being do not impoverish the natural heritage so that it can continue to provide environmental resources and services over time. A substantial help to achieve environmental sustainability objectives comes from the circular economic model: a production and consumption scheme that seeks to distance the economy from what is today defined as "linear economy", where the final output at the end of its use, is disposed and new raw materials are sought to produce a new one (Murray, 2017).

According to the Circularity Gap Report for the Netherlands, the Dutch economy is 24.5% circular. Targeted strategies especially in key sectors such as construction and infrastructure could triple the Circular Metric of the Netherlands by up to 70% (Netherlands- Circularity Gap Reporting Initiative, 2020). The Dutch government does have ambitious targets and plans to invest funds in the upcoming years to halve the consumption of raw materials by 2030 and achieve a fully circular economy by 2050. This plan aims at finding new efficient ways of using raw materials and to achieve a sustainable and waste-free economy (Waterstaat, 2019).

This report aims to illustrate the possible development and employment of a circular model applied to bridge infrastructure in the Midden-Delfland area. Of the bridges supporting the water-infrastructure of Midden-Delfland peat meadow landscape, this research will focus on fifteen, which are all situated across the *Nieuwe Water* canal. The intention is to analyse the current bridges and gain insights into the level of sustainability and circularity of the materials. These results and further analysis will serve as a foundational framework applicable to the design and development of new, sustainable bridges in the area.

1.2 Erfgoedkwartiermakers

As the commissioner of our project, the *Erfgoedkwartiermakers* cooperation deals with sustainability concerns which are of increasing importance and need to be considered when executing projects. With maritime heritage as its catalyst, the *Erfgoedkwartiermakers* cooperation is dedicated to fostering heritage-inclusive area development in port cities. They aim towards a sustainable, integrated concept for heritage port city development through combining different transformation strategies which focus on economic, educational, recreational and cultural benefits. The *Erfgoedkwartiermakers* cooperation has previously worked on many projects surrounding heritage infrastructure while focusing on maritime heritage areas. They achieved this by identifying sustainability challenges associated with these areas and systematically documenting cultural values while also promoting local economic development.

1.3 Executed and current projects

Some of the featured projects include the *Zeeuwse Groene Compagnie* consisting of five antique sailing vessels, aiming to be the first green fleet of historic vessels employed for the sustainable transport of local goods. These ships, used for tourist markets, will be repurposed with second-hand diesel engines. Furthermore, they will be given an electric motor to maintain their environmentally friendly propelling method for 20-30 years.

Additionally, *Erfgoedkwartiermakers* have participated in the '*Loods M*' initiative, a warehouse located in the Maassluis harbour in which various parties can work together on innovative and sustainable solutions for maritime heritage and the future of port cities. To develop creative solutions that withstand the complexities of everyday practice and real-life situations, a "real-life" setting is required in which civil society organizations and companies can work together.

1.4 Overview of the case study

This research report, on the project commissioned by *Erfgoedkwartiermakers*, focuses on the area Midden-Delfland with Maassluis (*figures 1 through 3*), situated between The Hague, Delft and Rotterdam, in the densely populated province of South-Holland in the Netherlands. The municipality of Midden-Delfland mainly consists of residential areas. There are fewer areas with industries and other activities. (Gemeente Midden-Delfland in Cijfers En Grafieken | AlleCijfers.nl, 2023).

Comprising the villages Den Hoorn, Maasland and Schipluiden, along with the hamlets ‘t Woudt, De Zweth and De Kapel (*figure 4*) (Wikipedia-bijdragers, 2023), Midden-Delfland attained the distinction of being the first Dutch municipality to receive the Cittaslow hallmark in 2008. Cittaslow, meaning “slow city,” serves as a hallmark for municipalities excelling in preserving their landscape, environment, infrastructure and cultural heritage. Midden-Delfland received the quality mark for its peat meadow area as well as its characteristic villages (Wikipedia-bijdragers, 2023a). Next to the Cittaslow hallmark, Midden-Delfland holds the designation of a ‘Bijzonder Provinciaal Landschap,’ a special provincial landscape. This status additionally highlights the importance of the conservation of these peat meadow landscapes between cities (Wikipedia-bijdragers, 2023).



Figure 1 : Bridge in Maassluis.



Figure 2: Sluice in Maassluis.



Figure 3: Old city centre of Maassluis.

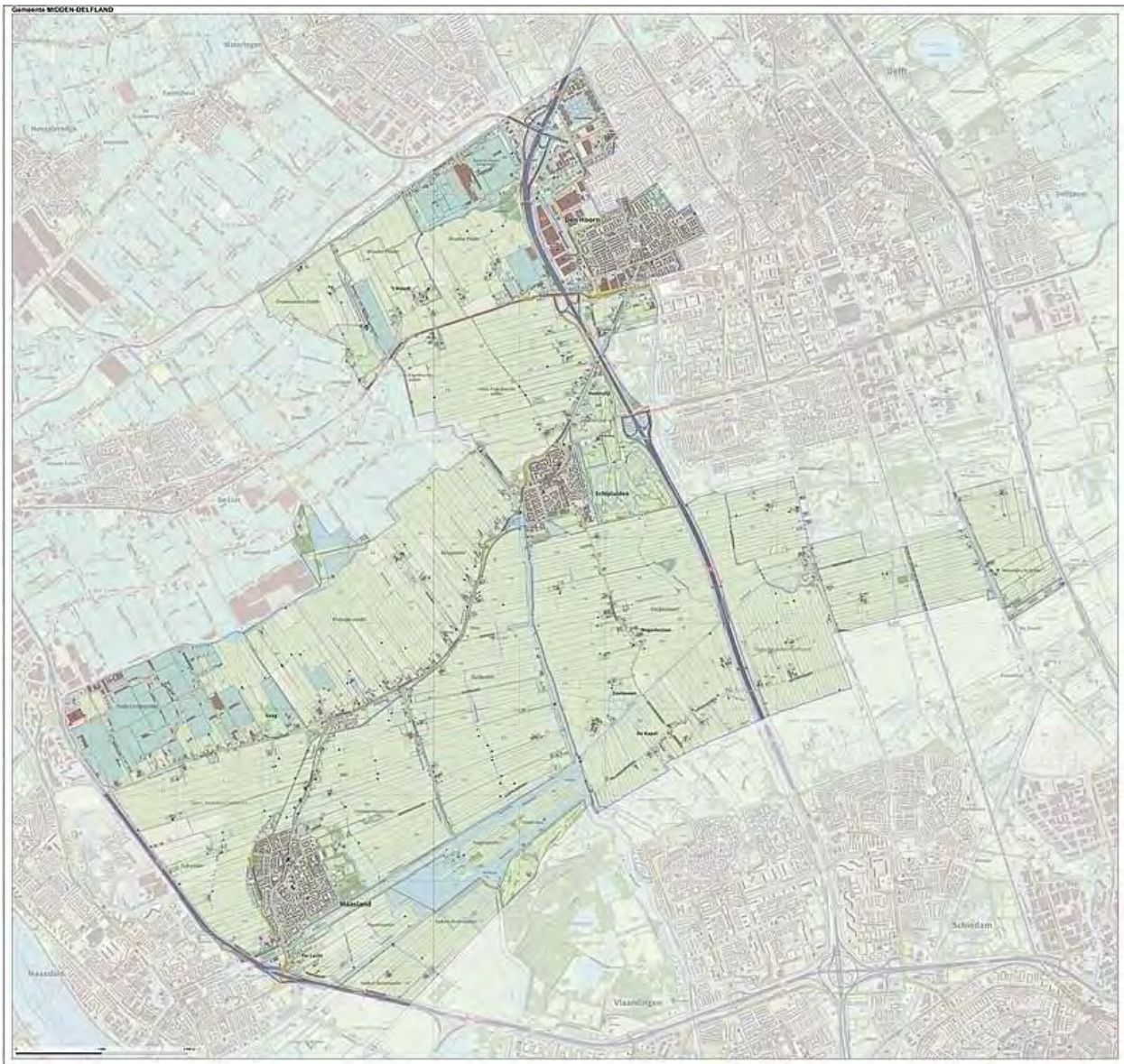


Figure 4: Topographic map of Midden-Delfland, surrounded by Maassluis (bottom left), Schiedam (bottom right), Delft (upper right) and The Hague (upper left). (<https://nl.wikipedia.org/wiki/Midden-Delfland>).

1.5 Structure of the report

This report is written in a concise and understandable manner to further enhance the reading flow and the understanding of sustainable bridges for its readers. The report starts with the key and relevant concepts and ideas that will be further explained to give clarity and insight into further use of these concepts. After this, an analysis of **important stakeholders** to the problem will be conducted, to give further clarity into the nature of the report. Following is a brief theoretical framework provided to enhance the understanding of the current state-of-art. This is followed by an explanation and listing of the research question and an overview to the objectives of the report. Thereafter, our **methodology** is explained, followed by the **results** of the report with an in-depth analysis of the results and what they represent. Following the results, is the conclusion and **discussion** in which the research questions are answered, and the results are further analysed to provide a full list of criteria for the critical areas of 'Het Nieuwe Water'. Finally, the recommendations are provided in which we outline our advice based on our results and discussion.

1.6 Key concepts

There are two key terms in this paper which are targeted towards bridges:

- Sustainability
- Circularity

Sustainability aims to meet the needs of the present without compromising the future, while the definition of a circular construction is less clear because there are no standard criteria which decide whether a construction is circular. The construction industry focuses most research on recycling at the micro-scale of materials, not taking the meso-scale of the building or construction into account (Anastasiades et al., 2020).

The European Commission states a **circular economy** “means rejecting the linear take-make-waste economy and adopting a regenerative model: using processes that restore, renew or revitalize their own sources of energy and materials and wasting as little as possible.” (*Circular Economy Strategy*, n.d.). A circular bridge construction thus refers to practices that align with the principles of a circular economy, emphasizing the regeneration and minimal waste of materials and energy throughout the bridge's lifespan (figure 5).

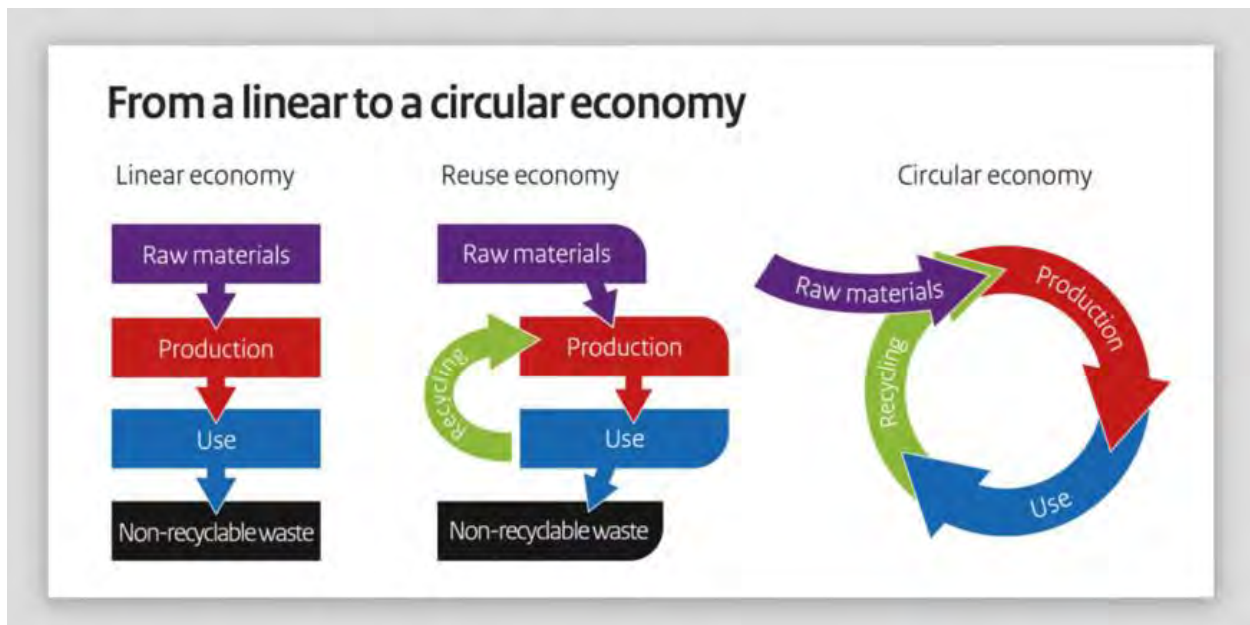


Figure 5: The difference in economic approaches when producing products (slidemodel.com, 2021)

In construction, sustainability and the circular economy are linked by practices that balance meeting present needs without harming the future. It emphasizes efficient resource use and minimal waste throughout the building process and the life cycle of structures.

1.6.1 Relevant concepts

Further relevant concepts in relation to the following report are listed below to further enhance the readability and understanding of the report.

Het Nieuwe Water is a long-stretched canal that connects Maassluis to surrounding municipalities, which can be used by small recreational boats to explore the surrounding areas. The canal is currently at a dead end within Maassluis, going away from Maassluis however is still partially possible.

Slow tourism is a relevant concept to this paper. It is defined as a sustainable approach to regular tourism in which tourists take in culture, history, and the characteristics of the area, through slower sustainable transportation such as walking, using recreational small vessels, cycling or other forms of non-combustion powered transportation (Barten, 2023). The concept of slow tourism has evolved as a response to the increasing demands of travel in more developed and industrialized societies. In recent years, slow tourism has shifted its emphasis from mere environmental sustainability to a broader focus on the practice of time and space, aligning with personal satisfaction and travel more ‘experience based.’ Slow tourism involves engaging in slower forms of travel, exploring local history and culture, and supporting the environment (Dickinson, 2017; Oh et al., 2014).

Micro-scale focuses on individual products or materials, such as recycling possibilities and circularity indicators for specific components.

Meso-scale encompasses the construction industry, including buildings and constructions. Emphasizes the importance of meso-scale circularity indicators that consider the entire construction as a system.

Macro-scale involves larger systems like cities or regions, examining material flows on a larger scale (Anastasiades et al., 2020).

Waterway infrastructure is identified as the combined rivers, canals, ponds, ditches, and all other bodies of water, as well as their relevant and attached structures or buildings such as bridges, sluices, and pumps.

Environmental quality as identified by the European Environment Agency can be defined as “*Properties and characteristics of the environment, either generalized or local, as they impinge on human beings and other organisms. Environmental quality is a general term which can refer to: varied characteristics such as air and water purity or pollution, noise, access to open space, and the visual effects of buildings, and the potential effects which such characteristics may have on physical and mental health (caused by human activities).*” (E.E.A., 2004)

1.7 Important stakeholders

Erfgoedkwartiermakers places a strong emphasis on conserving heritage in the Midden-Delfland area while actively promoting and attracting slow tourism.

Slow tourism aligns with the commissioner’s goal of preserving cultural heritage, as slow tourism encourages travellers to immerse themselves in local cultures and explore historical sites, thus engaging with cultural heritage. It further emphasizes environmentally and culturally sustainable tourism practices, which are less impactful on heritage sites and will be more sustainable soon.

Tourists are an important stakeholder to this project, as this project is executed to enhance the accessibility and experience for tourists in the Midden-Delfland area. The goals for tourists would be to be able to go through ‘Het Nieuwe Water’ so that they can more easily visit or pass through Midden-Delfland. These goals align with the goals of the project only further enhancing the importance of working with and pleasing the tourists that would visit the area.

Local inhabitants place an emphasis on the accessibility and appearance of the bridges and surrounding water ways. Their goals would be to reduce the time of construction to avoid hinderance over longer periods of time and for the bridges to be accessible to the locals their slow transport such as cycling or walking. This is an important stakeholder, as the uptake of our research and criteria by civil engineers would influence the local inhabitants, yet they don’t have much power to affect the outcomes of the research.

Landscape architects and engineers place a strong emphasis on producing residential areas and recreational areas using the available natural land in and around Maassluis. Their goal would be to increase the number of residencies and tourists in the area while maintaining an appealing appearance, which relates to the environmental quality of the area. This is to ensure new residents would want to live alongside ‘Het Nieuwe Water’ and tourists will visit the area. These are relevant stakeholders as they have the financial means and influence on the reconstruction of the bridges and therefore need to be informed on our proposal of doing this sustainably.

Industrial ecologists and scientists place a strong emphasis on the processes and execution of circular bridge construction, while focusing less on the aesthetics and sentiment surrounding these bridges. Their goal is to further use our results and methods for their own research to better understand and strengthen their understanding of the case-study. Their interest does not go further than the bridges and the environment itself and were therefore not carefully considered when producing our results. This stakeholder was considered during the formation of the methodology to ensure that reproducibility is possible for the research. These are relevant stakeholders as they have power and say when it comes to environmental projects and research and could influence the total power and effect that our results could have.

1.8 Current state of the project

Our commissioner, *Erfgoedkwartiermakers*, provided us with some background information on the area and its waterways. The following section is meant to highlight the current state of the project. It sets the foundation of our project and is relevant for the following chapter, in which we state our research question with its sub questions.

Rinck and van der Blom (2020) created an advisory report as a research project in their second year as students in ‘Ruimtelijke Ontwikkeling’ at the *Haagse Hogeschool*. The content focusses on many of the same problems as us, mainly the problems with accessibility of the waterways. Their objective was to give advice on how to make the waterways more accessible to benefit Maassluis and South-Holland. They did this through the question of: “*What is the added value (from an economic view and the attractiveness of the area) of restoring the potential of accessibility for smaller vessels by removing bottlenecks in the Nieuwe Water and connecting it to the existing small-scale network of waterways in Midden-Delfland and the Westland?*”. This literature states advice and methodologies which are sectioned into phases instead of one clear sweep of all structures to help increase the waterway efficiency.

A report of the ‘de Kracht van Water’ conference states how leading experts and professionals that work on the new waterway of Midden-Delfland came together to formulate their concerns and strategies surrounding the management and future projects in the area. Multiple problems are addressed in the report, yet it focusses on how to involve and convince authorities and the public to invest and participate in the new Waterway (“Verslag conferentie: De Kracht van Water,” 2019). This paper will contribute to our own research by providing inspiration for the methodology of creating our own criteria and improving the possibility of uptake by legislators and the public.

2 Research objectives and questions

2.1 Research objectives

This research aims to identify and address challenges related to Midden-Delfland and its numerous recreational waterways, aiming to enhance the appeal of slow tourism in the area. The primary challenge revolves around the presence of low bridges, rendering certain waterways inaccessible, and thereby hindering slow tourism. To solve this issue, our objective is to implement the concept of circular bridges, which are sustainable structures with minimal environmental impact, maintenance, and replacement costs. These bridges will allow better access for slow tourism in the area, therefore promoting and increasing slow tourism in the area. To implement these circular bridges, we aim to give a list of criteria, specifically for the Midden-Delfland area, to help instigate the future production and construction of these bridges. In these criteria we aim to include the research questions their answer and to give further insight into the circular construction of bridges and their materials in a form which is easily understandable to our commissioner and future readers.

2.2 Research questions

This research will focus on the question: **‘What criteria and factors contribute to the sustainable and circular adaptation or replacement of bridges in Midden-Delfland?’**

To help answer this question, the following sub questions will be addressed:

- a. What does a circular and sustainable construction look like?
- b. What does the current waterway infrastructure in Midden-Delfland look like and where do problems occur?
- c. To what extent are materials of existing bridges in Midden-Delfland sustainable or circular, and are there variations among them?

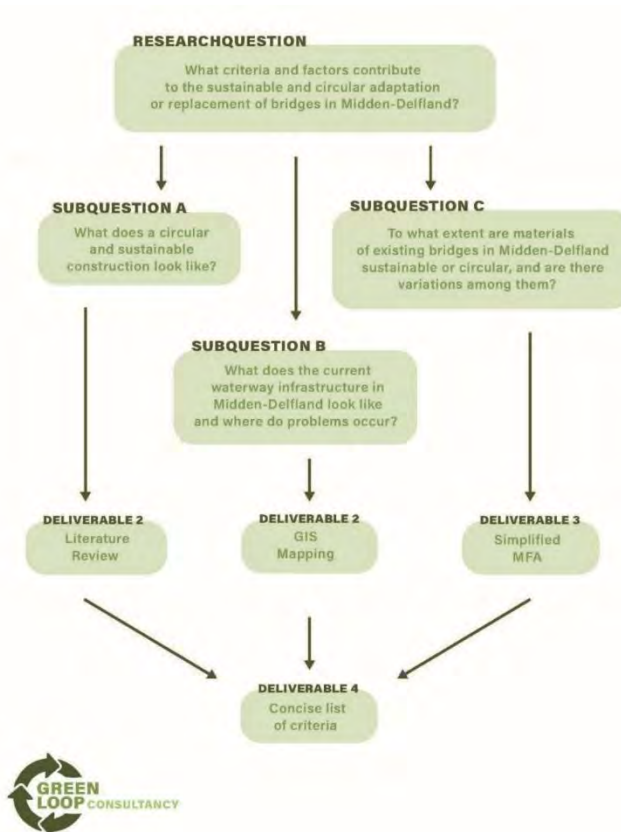


Figure 6: Flow chart of the research questions and relative deliverables

3 Methodology

3.1 Approach

Amidst the environmental issues contributing to the progressive deterioration of ecosystems, the central focus of this project is the demand for both enhanced environmental quality and greater efficiency of services and technological facilities, which makes it possible to gain economic opportunities, but also optimize products, companies and territories managed with strict criteria of environmental sustainability.

3.2 Method 1 – Literature review

To address sub question ‘a’, our first method involved a comprehensive literature review. The literature review aimed to identify key criteria for sustainability and circularity in construction. This step was crucial for formulating our own criteria and understanding potential weaknesses and strengths in circular designs, aligning with the goal of defining what constitutes a circular and sustainable construction. The literature was noted and identified as shown in *figure 6* below:

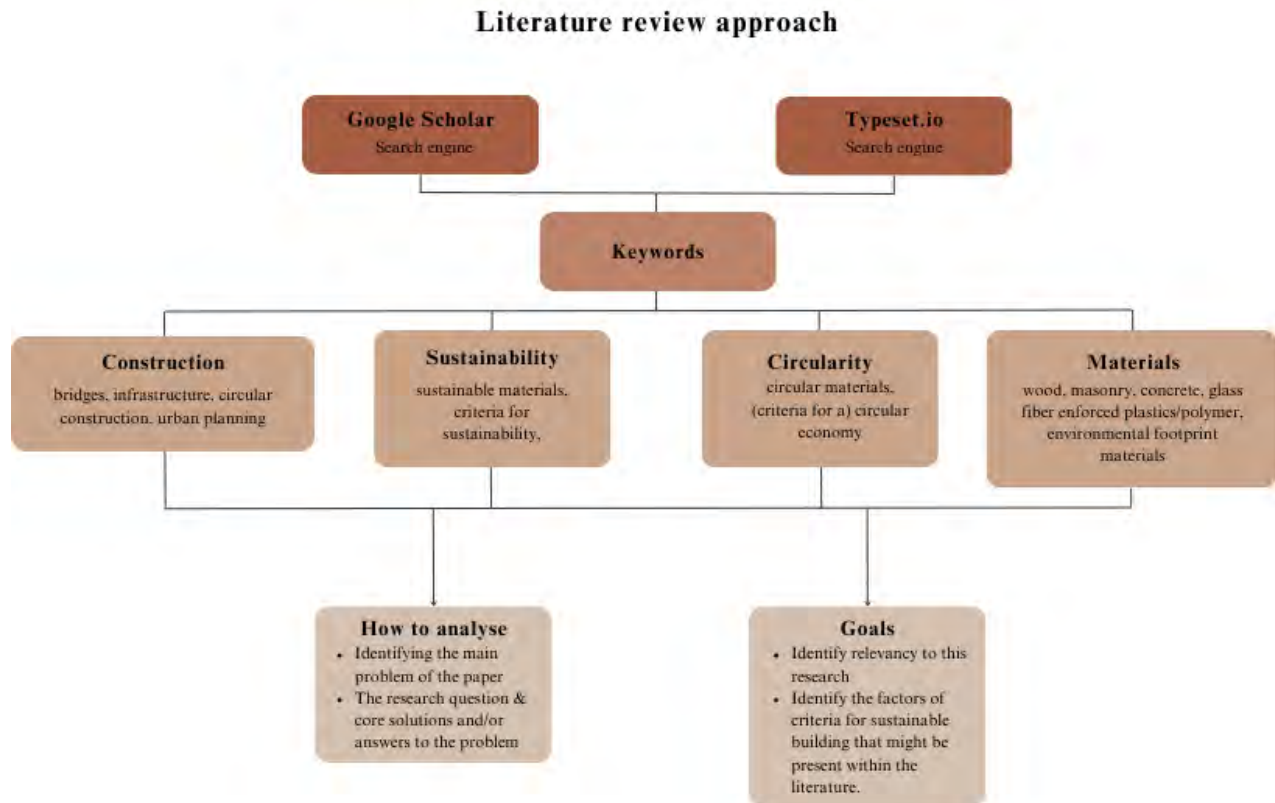


Figure 7: Explanation of methodology for the literature review.

These notes on the found literature were compared to each other. From these notes comprehensive summaries were formulated that contained a problem-solution relation of key factors and criteria. An example of the results section is the following: “A recurring problem within sustainable or circular construction, is ‘Problem A’. Several solutions, such as *x* and *y*, were given in ‘source A’ and ‘source B’.

3.3 Method 2 – Geographic Information System (GIS) mapping

To answer our research question, we had to chart part of the Midden-Delfland region and with it, answer sub question ‘b’. We mapped ‘Het Nieuwe Water’ canal, which goes from Maassluis to up North, along the Weverskade, including the selected fifteen bridges which stand over the canal, and we identified any problematic areas. With the findings from the previous sub question already acquired we planned a field trip and planned a list with goals regarding the type of data that would be gathered. These goals, in no specific order, consisted of:

- Identifying and writing down the main materials of all 15 bridges.
- Observations on how slow tourism functions in the area with bridges, paying attention to the public and the response of the tourists or residents to these bridges.
- Identifying the current state they are in.
- Checking the accessibility of the bridges per mode of transport.
- Taking photos of all 15 bridges.
- Listing down the complications of gathering the data.

This spatial analysis provided a detailed overview of the current bridge network over ‘Het Nieuwe Water’, highlighting specific locations that pose challenges to slow tourism. To visualize our spatial analysis, we used *ArcGIS*.

Erfgoedkwartiermakers provided us with some initial data. However, we integrated this data with additional sources and observations from the field to create a comprehensive map of the area that included all the necessary information for our study. We aimed to map not only the waterway and current infrastructure, but also categorize the bridges based on height, age, state, and materials. This categorization was based on the answers to sub question ‘a’, and our findings in the field.

This spatial analysis was crucial for obtaining a nuanced understanding of the existing bridge network, pointing out areas that pose challenges to slow tourism. GIS mapping forms a foundational step in addressing our research question, enabling us to visualise and analyse the waterway infrastructure in the Midden-Delfland region more thoroughly.

3.4 Method 3 – Simplified Material Flow Analysis (MFA)

The final method, to answer sub question ‘c’, was a simplified Material Flow Analysis (MFA). MFA is a systematic assessment of the **flows** and **stock of materials** within a **system** defined in space and time (Brunner & Rechberger, 2004). For our research, it is about the materials of the bridges along ‘Het Nieuwe Water’, starting from the building process until time of destruction.

MFA is coupled with the analysis of energy, economy, and urban planning. **Material** in MFA stands for both **substances** and **goods**, where substance is defined in a chemical manner and goods are (mixtures of) substances that have economic values assigned by markets (Brunner & Rechberger, 2004). The bridges thus solely contain substances.

Flows or **fluxes** are links between different processes. These **processes** can be defined as transport, transformation, or storage of materials. Processes can be natural, or manmade. Flows or fluxes entering a process are called **inputs**, while those leaving a process are called **outputs** (Brunner & Rechberger, 2004).

Stocks are defined as material reservoirs within the analysed system. The stocks have a certain mass and thus have the unit of kilograms. A stock is part of a process, comprising the mass that is stored in the process (Brunner & Rechberger, 2004).

MFA gives insight to the behaviour of a system. MFA has different purposes, but for our research we want to evaluate the circularity and sustainability of the current bridges and gain insights which could lead to an improved design for a bridge in the area.

Due to time constraints and lack of data, our MFA will be simplified, and a simulated, hypothetical bridge scenario. We assume there is one bridge, consisting of all materials identified in the field, because we want to evaluate all the different materials in the existing bridges. We do not know the weight of the bridges, nor how much of what material is used. So, we will work with a fixed unit, for example, the emissions of concrete are x grams of CO_2 per kilogram.

The steps for conducting an MFA are shown in *figure 8* below:

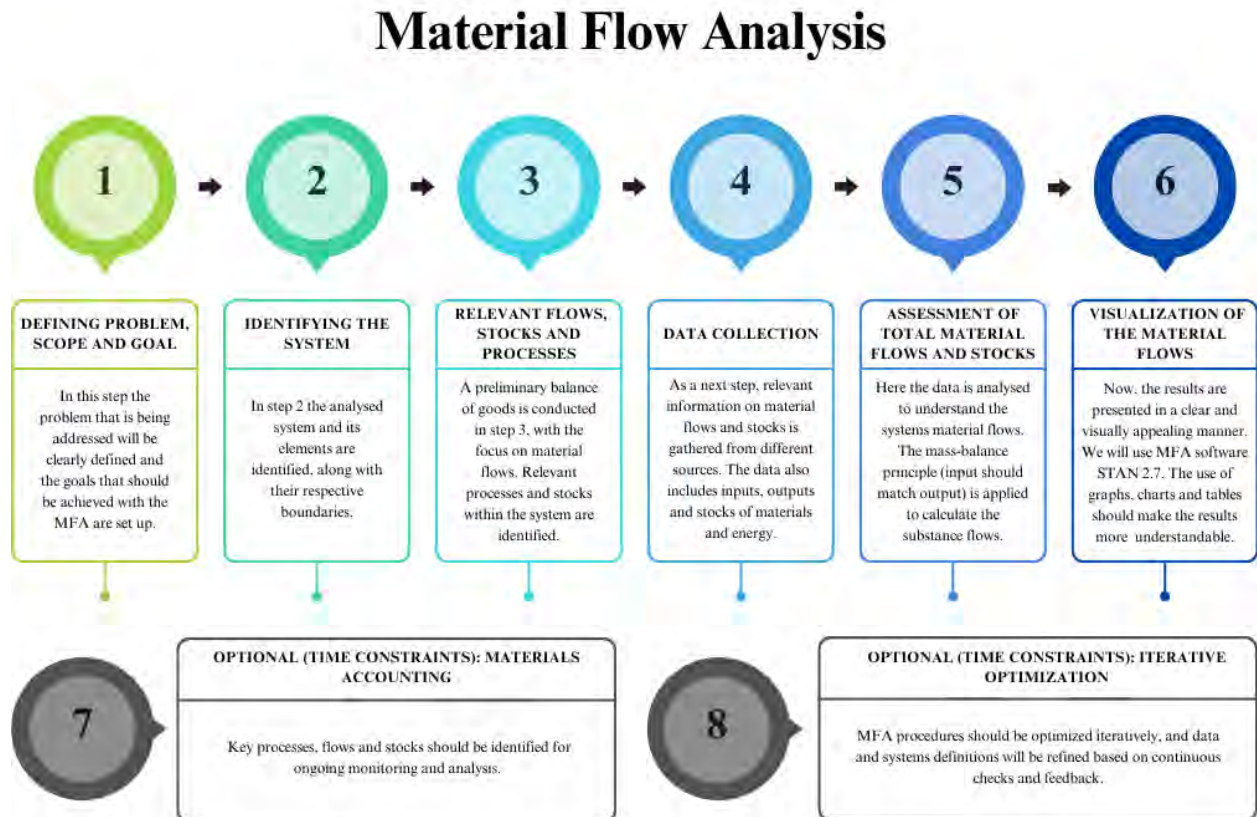


Figure 8: the 8 steps to conduct an MFA (steps 7 and 8 are optional due to time constraints).

After our MFA we can draw a conclusion for the current bridges and their materials. When these are interpreted with results from the first two methods, we can identify similarities, additional advice, and further insights from the data, to formulate a final strategy and advisory plan which can be used by the commissioners in future projects. The advice will consist of a ranked-order list of points in Midden-Delfland that are in most critical need of change plus a list of criteria that are important for a sustainable and circular bridge design. This last step aligns sub question ‘*a*’, sub question ‘*b*’, and sub question ‘*c*’, providing an integrated approach to addressing the research question.

4 Results

4.1 Literature Review

In the following section, several problems and key factors within our found literature are discussed and supported by combining several papers. This is to further strengthen the consensus and criteria that would be needed to formulate our own list of criteria. The structure of the following paragraphs begins with an introduction to a problem in our case study, after which we summarize relevant reviewed literature to the problem.

4.1.1 Circular construction

Defining what circular construction is, and what the factors related to it are, is a key problem to what a circular and sustainable construction looks like. Criteria and factors were distributed across the available literature; however, several ideas and management strategies were commonly discussed among various sources. The concept of infrastructure built on a sustainable development model has gathered widespread interest over time. This shift encompasses issues such as minimizing consumption in construction processes and embracing assessments rooted in a life cycle approach. In response, the sector has encountered growing governmental, social, and economic pressures (Munaro et al., 2020).

A Circular Economy (CE) involves managing material flows to create a closed-loop system, with emphasis on renewable materials, waste minimization, and maintaining product value. Design for Adaptability (DfA) and Design for Disassembly (DfD) are critical for facilitating Reuse, Reduce, and Recycle in CE. Key principles of DfA and DfD are summarized in *table 1*.

DfA	DfD
Modularity Designing products with modular components that can be easily replaced or upgraded.	Modularity Creating products with components that can be easily separated from each other.
Compatibility Ensuring that different generations of components or accessories are compatible with each other.	Standardized Fasteners Using common and easily removable fasteners to connect parts. Minimize use of glues and adhesives
Software Upgradability Designing electronic products with firmware or software that can be updated to accommodate new features or functionalities.	Material Identification Clearly marking and designing products with materials that are easy to identify for recycling purposes.

Table 1: Key principles of DfA and DfD ('Design for Assembly (DFA) Principles Explained', 2021; *Construction Principles and Design Rules in the Case of Circular Design*, n.d.).

The discussion on CE in construction covers micro-, meso-, and macro-scales, identifying a gap in meso-scale circularity indicators for the construction industry (Anastasiades et al., 2020). DfD and DfA in bridge construction face challenges such as negative perceptions of reused materials and a lack of industry-wide adoption of circular economy principles. Ghaffar et al. (2020) furthermore identified logistics (41%), cost (29%) and time/H&S regulations (12%) as the main bottlenecks in CE construction. Lack of standards, certification, and effective sorting pose additional challenges. Effective strategies include charges and enforcements on producers, legislation ensuring clients maximize material reusing/recycling, and laws specifying a percentage of new buildings' materials to be reused from previous projects. Legislation and regulations are emphasized as primary drivers for construction waste reductions, even though they may not be feasible in the current political context (Ghaffar et al., 2020). The success of a CE depends on a shift in user behaviour and ownership models, aligning with moderate sustainability goals (Anastasiades et al., 2020).

In summary, circular construction entails a paradigm shift in the building industry towards sustainable and circular practices. Ultimately, circular construction seeks to create a regenerative and environmentally responsible approach to building that minimizes waste and maximizes resource efficiency.

4.1.2 Modelling approaches

Modelling within a circular construction project seemed to be a limitation in the process of identifying what circular construction looks like. There is a research gap in the meso-scale of sustainable bridges. Various modelling approaches are essential for evaluating the sustainability of bridge construction. Physical models analyse material-, substance- and energy flows as well as life cycle, encountering limitations considering materials, energy, and land use.

Environmental models evaluate the environmental impact of construction materials and processes, using fate and exposure models to understand pathways and degradation. Micro-, meso-, and macro-economic models assess economic implications, resource inputs, labour, and capital, placing bridge technology within its macro-economic context (Heijungs et al., 2010).

Efficient Construction and Demolition Waste (CDW) collection, storage, and transport minimize environmental impacts. Selective demolition, use of secondary raw materials, pursuit of green building certifications, and life cycle assessment contribute to sustainable practices in construction (Zanni et al., 2018).

The examination of circular construction projects revealed limitations in understanding the meso-scale dynamics of sustainable bridges, prompting our decision to do a Material Flow Analysis (MFA). Comparing Life Cycle Analysis and Construction and Demolition Waste (CDW) management to MFA, coupled with the goals of our research project, further underscores the need for an analysis on the material flows and their level of sustainability and circularity, hence we decided on an MFA.

4.1.3 Materials and design

Identifying what materials and designs are sustainable, is a key factor and problem to our understanding of circular construction. Therefore, the main materials were identified in the field to use within the MFA. Concrete was identified as the primary material for bridge construction due to its strength, durability, and versatility (Hilton, 2013). However, concerns about finite resource depletion and environmental impact highlight the need for sustainable alternatives. Concrete, steel, aluminium, and blended cement are potential materials for sustainable bridge construction and design (Salonen, 2019; Puthiya, 2019; Asdrubali et al., 2023). The environmental impact of these materials should be considered in the selection process. Furthermore, CE scenarios based on the use of recycled coarse aggregates (RCA) show environmental and economic advantages over conventional concrete. Reduced transport distances, economic viability, and on-site production of RCA contribute to a more sustainable and efficient construction waste management system (Ruiz et al., 2022; Swamy, 2001).

The Integrated Structural and Material Design for Sustainable Infrastructures (ISMD-SI) paradigm connects material scientists with structural designers, emphasizing microstructural and macro-structural scales for sustainable infrastructure. This paradigm underscores the need for communication between sustainability experts and engineers in designing bridges (Lepech et al., 2005).

In conclusion, the pursuit of sustainable materials and designs in circular construction presents a crucial challenge, underscoring the significance of identifying suitable alternatives. Steel, aluminium, blended cement, and the innovative use of recycled coarse aggregates emerge as promising alternatives. These papers further highlight the importance of collaboration between material scientists and structural designers, emphasizing communication between microstructural and macrostructural scales for sustainable infrastructure.

4.1.4 Management of circular projects

The management of circular projects is an important factor to the success and completion of achieving circular construction. Therefore, management issues were a key problem to identifying what circular construction looks like by looking at the entire project. The many challenges are mainly related to decision making problems, the high environmental impact, cost or time impact, and material flow problems within the construction projects (Górecki J, Núñez-Cacho P, 2022). The main bottlenecks in relation to the management and execution of circular construction, as mentioned in 4.1.1, were identified as logistics (41%), cost (29%), time/H&S regulations (12%), and other issues (6%) in construction and demolition waste recycling. Suggestions for effective strategies include charges and enforcements on producers, and laws ensuring clients maximize reusing materials (Ghaffar et al., 2020). Circular economy also involves the management of material flows to create a closed-loop system, including different approaches for bio-based and non-bio-based products through strategies from a management approach (Anastasiades et al., 2020).

It is important to make information about the design process explicit. A lot of information, for example about sustainability, can get lost during the design- and realization processes. A reason for this is that the information is not transferred to the next phase, where there are different people working on the same project with different management (Van den Broek, 2012).

Furthermore, information about the materials should also be explicit. Engineers typically make decisions about materials based on their familiarity with the specific properties and capabilities of materials that they prefer. Explicitly stating information about the possibilities of various materials through, for example, Life Cycle Assessments (LCAs) can result in the development of more suitable and sustainable products for specific situations (Van den Broek, 2012).

In summary, effective management is integral to the success of circular construction projects. Ensuring information continuity through different management phases and promoting explicit material details is vital for fostering sustainability in construction practices.

4.1.5 Technological solutions and limitations

To further identify circular construction, we had to assess when something is fully integrated circular construction. For this technology must be set in place to help close the energy loop while constructing and re-using materials such as concrete and steel. Therefore, technological solutions and limitations were a key problem and factor to our research question.

Technological advancements can be unpredictable and have far-reaching effects for achieving sustainability (Heijungs et al., 2010). Yet most seem to have a positive effect on sustainability through methods such as integrating advanced sorting and processing technologies for C&DW Construction & Demolition Waste recycling, such as mobile robotic sorting with artificial intelligence to reduce waste and resource loss (Ghaffar et al., 2020). Another example would be the use of waste heat recovery systems, that can help capture and utilize the waste heat generated during cement and steel production, further improving energy efficiency within construction (Puthiya et al. 2019). Ideologies are also formed in relation to technological solutions from a sustainability view, as it is discussed that technological solutions could increase sustainability without reducing consumption. However, sustainability could also be increased without technological solutions by reducing consumption (Anastasiades et al., 2020). These conflicting ideas provide a further understanding into the role of technological solutions.

4.1.6 Sustainable bridge design

Van den Broek (2012) conducted a research project similar to ours, for her master thesis. She did a case study on sustainable bridges in Rotterdam and conducted a Life Cycle Analysis (LCA). Her findings were interesting for our research and the results are summarized as follows.

Ensuring sustainability in bridge construction involves considering both technical and functional lifetimes. The functional lifetime of a structure is the period during which it remains operationally effective and meets the intended functional requirements. The technical lifetime refers to the period during which a structure can physically exist without significant deterioration or failure (de Ridder, 2006). While a longer technical lifetime is generally deemed sustainable, it may lead to premature demolitions if it exceeds the functional lifetime. The challenge in Rotterdam is that overseers often demand extended technical lifetimes, influenced by political uncertainties every four years. An alternative approach involves aligning the functional and technical lifetimes through methods like re-use. However, the uniqueness of environments poses challenges in dismantling and rebuilding. Standardized and modular designs offer potential solutions, as they can be adapted for specific circumstances. Although these approaches may lead to some material inefficiencies, they can be beneficial if the added functionality will be utilized. Ultimately, the choice between tailored or standardized designs requires a careful consideration of longevity, adaptability, and cost-effectiveness in bridge construction (Van den Broek, 2012).

The LCA results of Van den Broek (2012) are the following. Wood, specifically *Azobe*, incurs high environmental costs due to its lower lifetime compared to other materials. In contrast, *Accoya* performs exceptionally well, boasting the best scores with a 25-year lifetime and maintaining high scores even with a 75-year lifespan (including two replacements). The environmental costs of steel bridges rise significantly, especially for longer spans. The costs increase notably when switching from IPE (a type of European standard steel I-shaped beam) to HEM beams (European wide flange beams, wider than IPE), particularly in the case of larger bridges. For shorter spans, approximately up to 7 meters, it is beneficial to use a statically determined bridge with a composite deck. Steel requires maintenance, which has a minimal impact on environmental costs when using a composite deck. Conversely, a wooden deck contributes more due to the necessity of interim hot dip galvanization every 25 years, as this requires bridge disassembly. Concrete performs excellently for middle and long spans, especially with wider bridges, though its weight demands substantial foundation support. In concrete bridges, the foundation's environmental costs overshadow those of the bridge components, and this relationship holds for bearing handrail bridges as well. However, the contribution of construction decreases for bearing handrail bridges, with the main bearing construction gaining importance for larger bridges at the expense of the foundation's contribution.

In conclusion, Van den Broek's (2012) research highlights the critical consideration of both technical and functional lifetimes in sustainable bridge construction. The challenge of aligning extended technical lifetimes with functional needs in Rotterdam underscores the importance of innovative approaches, such as re-use, standardized designs, and modular solutions. The Life Cycle Analysis (LCA) results emphasize the varying environmental costs associated with different materials and designs. Balancing longevity, adaptability, and cost-effectiveness is crucial in making informed decisions for sustainable bridge construction.

4.2 GIS Mapping

The following section covers the results and process of making and gathering the data for the GIS map. After establishing the data to be addressed and their collection, we started to compose a guideline to complete the project.

First, we found a ‘Topographic’ base map from Esri (2012), that was used as our basic ground map. From there, since there was no existing data on the issue and we weren’t granted full access to the official Midden-Delfland Esri database, with the information gathered we created several new layers to build on our map. For *figure 8* we opted to create six different feature layers to underline and categorize the bridges after our expedition; of all the 15 bridges we encountered we classified them based on accessibility to either bikes, boats or both and on their state based on the structure inspection, if the materials were worn out and, in case of a movable bridge, the state of the mechanisms. As shown in the legend the colours represent the state of the infrastructure, which was categorized as either good, partly good or bad. The shapes on the other hand represent the accessibility of each bridge. The symbol is a circle if the bridge is only bike accessible, a square if it is accessible by boat only and a triangle if it is accessible by both.

4.2.1 Outcome

From the GIS analysis resulted that 10 out of the 15 bridges that are built on the canal were found in overall good state with this feature highlighted by the green on the map, 3 out of 15 bridges were deemed structurally adequate but given that some parts and materials were damaged have been classified as in partially good state. Finally *bridges 12* and *13* were found in a detrimental state with most materials severely worn out (see *section 8.2*).

Concerning the accessibility of the infrastructure, given the importance in our commissioner’s demand to improve the transit for recreational vessels and the trade-off between boats and bikes, it was decided to only include the features that respond to the criteria for bike- and boat accessibility in the GIS mapping. Nevertheless, it is noteworthy to mention that except for *bridge 3*, which had architectural barriers, all the bridges are accessible by pedestrians and people with walking disabilities.

Concerning the overall accessibility of the waterway through recreational vessels, the field trip revealed navigating the canal directly is not practical, due to the *Westlandseweg*, which disconnects two portions of the canal (see *section 6.2*).

All the findings are summarized in *table 2*, considering all factors previously listed we categorized bridges based on the height we calculated at the highest point, age, main material composition, state and accessibility. For *bridge 6* and *bridge 9* we decided to include height measured at the lowest point as well. The table displays the 15 bridges and implements the data that *Erfgoedkwartiermakers* provided us, with the specifics that resulted from the field excursion.

	Height (m)	Age (years)	Main Materials	State	Bike Accessibility	Boat Accessibility
Bridge 1 "Wagenbrug"	0.40	21	Wood, steel, concrete, masonry	Good	yes	no
Bridge 2 "Fortegrachtbrug"	0.35		Wood, steel, concrete	Partly Good	yes	no
Bridge 3 "Karnemelkse brug"	1.65	10	Concrete, masonry, steel, asphalt	Partly Good	no	yes
Bridge 4 "Wedde brug"	1.36	8	Masonry, steel, stone	Good	yes	no
Bridge 5	1.5		Fibercore, asphalt, masonry	Good	yes	yes
Bridge 6 "Dijkpolder brug"	0.57-1.23	11	Asphalt, wood, fibercore	Good	yes	no
Bridge 7	1.29		Concrete, steel, asphalt	Good	yes	no
Bridge 8 "Arij van der Lely"	4	7	Asphalt, wood, steel, concrete, masonry	Good	yes	yes
Bridge 9 "Naamlozee brug"	0.93-1.39	8	Wood, fibercore, steel bolts, concrete	Good	yes	no
Bridge 10	1.6		Steel, weathering steel (corten steel), asphalt, concrete, masonry	Good	yes	yes
Bridge 11	1.6		Steel, weathering steel (corten steel), asphalt, concrete, masonry	Good	yes	yes
Bridge 12	1.16		Steel, concrete, asphalt	Bad	yes	no
Bridge 13	1.28		Concrete, masonry, steel	Bad	yes	no
Bridge 14 "Zevende brug"	1.5		Concrete, steel	Partly Good	yes	yes
Bridge 15 "Spartel brug"	1.3		Concrete, steel railing	Good	yes	no

Table 2: The summarized findings of the GIS analysis, the data is partly observational and partly received from the commissioner.



Figure 9: ArcGIS map showing the state and accessibility of 15 bridges along 'Het Nieuwe Water'.

4.3 MFA

4.3.1 Problem, Scope, and Goal of the Material Flow Analysis

As part of this project, some of the 15 bridges under examination are in poor condition and do not support slow tourism well, which means they will need replacing soon. Additionally, consideration must be given to their sustainability and recyclability, as they do not meet current standards.

A simplified **Material Flow Analysis (MFA)** will be used to assess how these bridges use materials and determine their sustainability. This analysis will provide insights into the different materials which the bridges along ‘Het Nieuwe Water’ are made of and will thus help to answer sub question ‘c’: To what extent are materials of existing bridges in Midden-Delfland sustainable or circular, and are there variations among them?

Eventually this will give a better understanding for designing bridges of improved quality that are more sustainable, circular and functional.

The found materials of the 15 bridges along ‘Het Nieuwe Water’ are wood, concrete, steel, fibre-core, asphalt and masonry.

4.3.2 The System and its boundaries

To simplify the analysis due to time constraints and lack of resources the **system** of this analysis will contain only one single hypothetical bridge, consisting of wood, steel, concrete, masonry, asphalt and glass fibre reinforced plastics.

To conduct an MFA, **temporal boundaries** must be set, including a **starting point** as well as an **ending point**. In the case of this bridge construction the starting point of the temporal boundary would be the date of construction of the oldest bridge (2002). From there a time span of 50 years can be chosen.

4.3.3 Relevant Flows, Stocks and Processes

As seen in *table 3* there is one overarching process within this system: the bridge construction. This process consists of different **subprocesses** which are mainly the production processes of all the different components of the bridge and the energy supply that goes into producing the different materials.

With an MFA there are different **inputs** going into the system and **outputs** leaving the system. All the materials of the bridge are seen as **inputs**. Other resources such as fuel, water and air which are used for production of the materials are inputs too. The finished bridge will be the **output** as well as all the construction and demolition waste and wastewater. What makes part of the output are the greenhouse gasses which were emitted during the production of the materials as well as the construction of the bridge.

Process	Subprocesses	Inputs	Output
Bridge construction	Concrete production, steel production, brick production, wood production, asphalt production, fibre-core production energy supply	Metal, wood, brick, concrete, asphalt, fibre-core, fuel, water, air	Bridge, construction and demolition waste, wastewater, greenhouse gasses

Table 3: Summary of bridge system, including construction process as well as its subprocesses, inputs and outputs (Brunner & Rechberger, 2004).

4.3.4 Data on Material Flows and Stocks within the System

Activity	Energy use (GJ/m ²)	CO ₂ emissions (kgC/m ²)
Concrete	0.62	19
Metals	0.82	13
Wood	1.51	4
Brick (Masonry)	0.62	19
Other materials	0.65	3
Transport	1.19	22
Construction activity	0.54	7

Table 4: Input-output results on primary energy use and CO₂ emissions for a detached building (Nässén et al., 2007).

Bridge component	Service life (years)
1. Asset in general	50-100
2. Wingwalls	50-100 10-15 (coating)
3. Slopes	25-50 20-30 (gabion and sheet piling)
4. Abutments	50-100 25-50 (facing) 10-15 (coating)
5. Piers, including foundations	50-100 25-50 (facing) 10-15 (coating)
6. Bearings	25-50
7. Load carrying superstructure	50-100 10-15 (coating of concrete) 25-40 (hot-dip galvanizing) 15-25 (coating of steel)
8. Waterproofing	30-50
9. Edge beams	30-50 (in-situ cast) 20-40 (prefabricated) 10-15 (joints and coating of concrete)
10. Parapet/railing	30-50 20-40 (hot-dip galvanizing) 10-20 (polymer surfacing)
11. Bridge surfacing	30-50 (asphalt base layer) 15-25 (asphalt top layer) 15-20 (polymer surfacing) 20-30 (tiles) 10-15 (bitumen joints) ≈30 (track and sleeper) 15-25 (ballast)
12. Expansion joints	30-50 (general)

	50-100 (cast-in parts) 15-25 (sealers) 10-15 (joints) 20-30 (grating) 10-15 (suspension)
13. Drainage	20-30 (grating) 10-15 (suspension) 25-50 (pump pit)
14. Other elements	20-23 (signals, lighting) 25-50 (stairs, sluice elements, etc.)

Table 5: Typical service lives for bridge components under normal operation (Jensen, 2019).

Material	Asphalt surface	Brick	Concrete deck	Fibre-core	Steel beams	Wood
Lifespan (y)	10-20	150	25-50	25	20-35	15

Table 6: Average lifespan of materials used in (hypothetical) bridge construction (Gervásio, 2010; Tao et al., 2023; Frequent Questions — Great Works Bridge, n.d.).

Material	Embodied energy (MJ/kg)	Embodied carbon (kgCO ₂ /kg)
Asphalt	2.6	0.045
Brick	3.00	0.22
Concrete (general)	0.95	0.130
Glass-reinforced plastic (fibre-core)	100	8.10
Steel (general)	24.40	1.77
Steel (recycled)	9.50	0.43
Steel (virgin)	35.30	2.75
Timber	8.50	0.46

Table 7: Typical embodied energy and embodied carbon values for some common construction materials (Zhang, 2010).

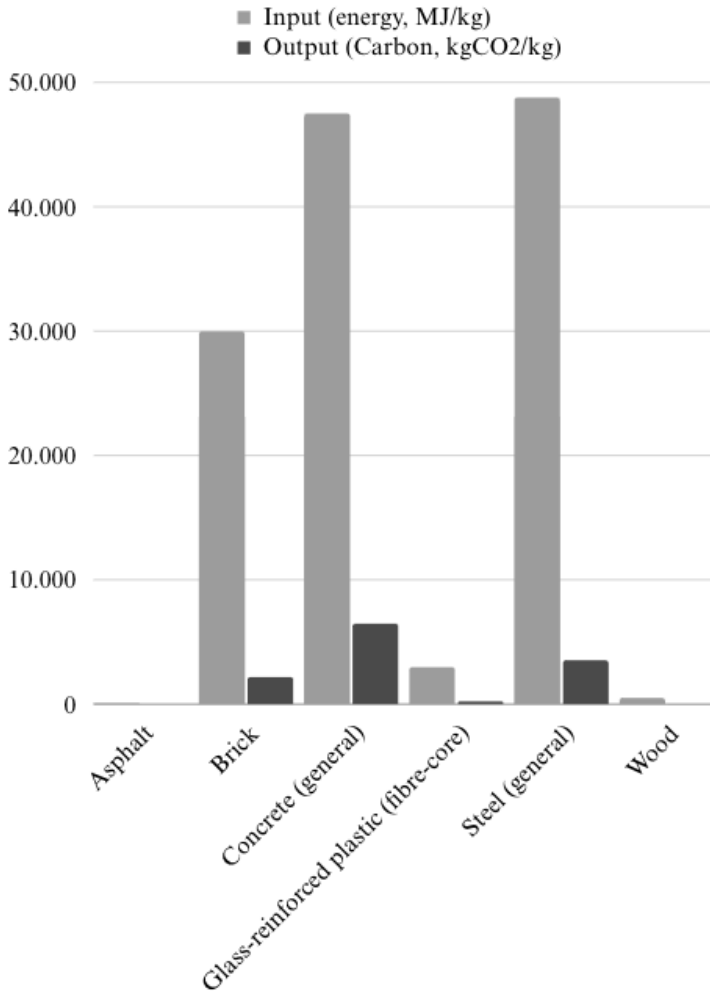


Figure 10: Values derived from Zhang (2010), calculated to fit our hypothetical bridge scenario (see 8.3).

Material	Energy (NW): GJ/t	Energy (Rec): GJ/t	GGE (NW): t-CO2 equiv./t	GGE (Rec): t-CO2 equiv./t
Steel-concrete composite bridge deck	9.95	5.66	0.87	0.5
Prestressed concrete bridge deck	3.48	3	0.41	0.36

Table 8: Energy consumption and greenhouse gas emissions (GGE) comparison with recycled (rec) and new-won (NW) materials (Martin, 2004).

4.3.5 Assessment of Total Material Flows and Stocks

Table 3 to 8 show data which could potentially be used in the MFA. To perform an in-depth MFA, more data would be necessary. To conduct an MFA, one specific location would have to be selected for there to be location specific data. What is missing here is data on **flows and fluxes**, meaning there is no information on how much mass per time interval flows in the system.

What can be told from the data in *table 4* and *7* is whether the materials have a high input and output.

Table 5 and *6* give more information on the life span of certain materials.

Figure 9 shows the amount of in- and outputs for the different materials used hypothetical bridge. This bridge consists of all materials encountered in the 15 bridges, and the calculations are further explained in 8.3.

4.3.6 Visualization of Material Flows

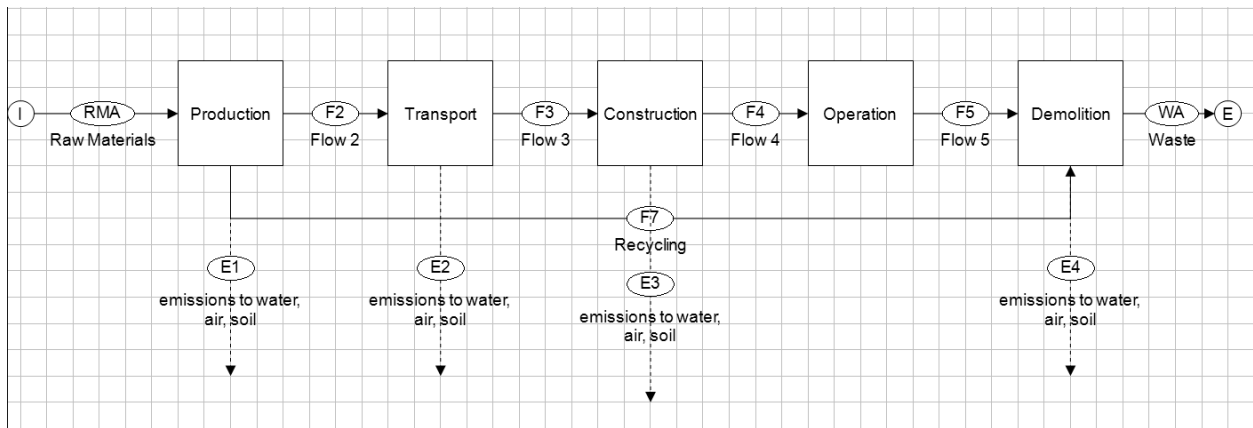


Figure 11: Visualization of the MFA, made with STAN 2.7.

5 Discussion and conclusion

5.1 Sustainable bridges for ‘Het Nieuwe Water’

From the literature review many important factors and key points were gathered and identified. The literature review does not contain numerical data or tables, but an interpretation and summary of the overlapping data. There was much literature found, including a similar case-study in Rotterdam, that relates to our main research question. However, there was a gap in the number of modern papers and research relating to the meso-scale of construction. From the literature several factors and problems were identified, with most being relevant to the future circular bridge construction in Maassluis. The factors within circular construction are highly relevant to our project as they provide key insight into when and how a constructed bridge would be circular for future design in Maassluis. The modelling approaches and their factors are closely related with circular construction. Furthermore, they help achieve a better understanding of the methods that could be implemented to analyse and consider whether a bridge is a circular construction. Also, the materials and design that are involved in circular construction were identified. While not directly relevant to the commissioners, the materials, designs and sustainability aspects that are involved with the bridges were necessary and crucial to the MFA methods.

Factors in relation to the management of circular construction projects were identified and are relevant to our commissioner and their future operations in circular construction. These factors provide a better understanding of errors and mismanagement that should be avoided when managing the construction of the circular bridges. It also provides insight into our commissioner and their future relations with structural engineers they might work with. While also providing feedback into ensuring that proper relations and information flow is maintained. The literature on technology and the solutions and limitations it brings is highly relevant to circular construction management, as the project will most likely make use of modern construction materials and machinery. These factors could provide insight into the use of modern technology and the side-effects that could occur due to their unfound risks that could have far-reaching effects. A change or insight into the ideology of the circular bridges could also be applicable for the commissioner through these technological factors. Finally, our found factors on sustainable bridge design focussed on the paper by Van den Broek (2012). This similar paper included multiple factors that are critical to sustainable bridges design for the bridges alongside ‘Het Nieuwe Water’. The factors include guidance into material selection for future bridges and general implications and problems that occur during a bridge’s lifetime. The main relevancy to our project lies within the factors of what and how a bridge will be handled during its lifetime. This is in relation to its environments and the material that it was constructed out of, therefore giving a clear image into what bridge designs are the most sustainable and how long they will last.

5.2 GIS data

Of the 15 bridges our research focused on we aimed at implementing and better visualizing the database since a valid and straightforward identification of the problem areas will be crucial for decision-making. The focus on the state of the infrastructures added new data to the picture which could help in identifying patterns, trends or anomalies if any; bridges 12 and 13 which were both in a bad state had not only similar structures but if we look at the materials’ composition, we understand how both bridges share the same main materials such as concrete. This creates a strong association between materials and resilience, which has previously been studied through the extensive literature review. Along those same lines a look at the bridges in a good state reveals that steel and FiberCore are the best performing materials when it comes to durability and make up two valid options for bridge construction.

The spatial patterns that have been identified within the research underscore that the middle section of *Het Nieuwe Water* performs better both in terms of accessibility and state of the infrastructure; this is due not only to the structural characteristics of the bridges, but the material composition plays a pivotal role.

5.3 MFA data

The primary goal of the MFA was to assess how the materials in the current bridges contribute to the overall sustainability and circularity among them. The MFA focused on a hypothetical bridge considering wood, steel, concrete, masonry and fibre-core (glass-fibre reinforced plastic), with a temporal boundary of 50 years.

When looking at the sustainability and circularity of the different materials, different aspects must be considered. Factors such as the production process, embodied energy, embodied carbon, lifespan, durability, and maintenance all play crucial roles in decision-making. Fibre-core, for instance, seems to have an extremely high embodied energy and a relatively high amount of embodied carbon compared to other materials. However, when looking at the lifespan, durability and lack of maintenance of this material, they seem to make up for all the energy that went into producing the product and the emitted greenhouse gasses (Van den Broek, 2012; Tao, 2023).

The MFA highlighted the significance of technical lifespan in material selection, emphasizing the need to factor in maintenance considerations. The comparison between brick and concrete revealed that brick, due to its recyclability and equal lifespan, is a more sustainable choice. If the bridge would be demolished, the bricks could be re-used if they were not damaged. Additionally, the analysis indicated that fibre-core could be a preferable alternative to steel due to its lower maintenance requirements, despite having a shorter lifespan. That choice is thus influenced by the number of years the structure is expected to be used.

In summary, the conclusion emphasizes the nuanced evaluation of materials. This includes production impacts, lifespan, and maintenance considerations as well as the technical lifespan, recyclability, and overall sustainability of materials in the form of energy use and emissions.

5.4 List of criteria

These criteria, grounded in literature, our GIS-analysis and MFA, provide a comprehensive framework for guiding sustainable and circular bridge construction along ‘Het Nieuwe Water’.

- 1) **Removal or replacement of bridges:** Multiple bridges require removal or replacement according to the GIS data and the requested requirements of the future bridges. The bridges that do not need removal or replacement are bridges 5, 8, 10 and 11 as these fit the requested criteria of 1.5m high and bike accessibility while still being in a good state.
- 2) **Effective management:** Communication of sustainability/circularity goals should be transparently conveyed from top-level decision-makers to all project stakeholders, including architects, engineers, and construction workers. Information continuity throughout different management phases is crucial for fostering sustainability (Van den Broek, 2012). Also Ghaffar et al. (2020) emphasize the importance of charges, enforcements, and laws to ensure clients maximize material reusing or recycling, highlighting management’s role in circular construction.
- 3) **Optimization of design:** The design should align with the specific characteristics of Maassluis, emphasizing adaptability, a long functional lifespan, and material reusability. Thinner bridge designs should be explored to reduce material usage and enhance the circular energy flow, promoting a long functional lifespan. In Maassluis several bridges consisted of a thick layer of masonry, so some were very wide and hefty. An optimized design for improving these bridges could be making them thinner. This will decrease the amount of material necessary for construction, which means less energy and less emissions. Anastasiades et al. (2020) discuss the need for Design for Adaptability (DfA) and Design for Disassembly (DfD) in circular construction, emphasizing material flows and circularity at different scales.

- 4) **Optimization of materials and modelling:** Selection of materials should consider factors such as function, size, and functional lifespan. Furthermore, materials should be durable and strong to maximize technical and functional lifespan. Plus, it is preferred for the materials to be reusable after demolition. To assess all of this, a full MFA, or even an LCA, should be done. Van den Broek's (2012) research underscores the significance of considering both technical and functional lifetimes when choosing materials for a sustainable bridge.
- 5) **Impact beyond the bridge:** Impact on the users and surrounding area of the bridge need to be acknowledged to determine if a future bridge is fully circular. Consideration of factors such as waste, pollution, and wear and tear in the surrounding area, is vital to determine the overall circularity of the construction. Munaro et al. (2020) highlight the shift towards sustainable development models, indicating a broader interest in minimizing consumption in construction processes. In Maassluis this can be done by looking at the surrounding environment of all private and commercial property that might be affected by a new flow of slow tourism.
- 6) **Proper waste management:** When repairs or demolition occur, the disposal and reuse of materials should be done according to pre-established circular and sustainable methods. Waste management practices are essential to prevent negative energy losses and promote recycling when that is feasible. Zanni et al. (2018) stress the importance of selective demolition, use of secondary raw materials, green building certifications, and LCA for sustainable practices in construction.
- 7) **Usage of best available technology:** The circular construction process should make use of established technology used in current sustainable construction. Experimental technology (e.g., A.I., experimental construction machinery, modern artificial materials) could pose risks to the future of the circular bridges due to unforeseen effects or far-reaching outcomes. Heijungs et al. (2010) highlight the unpredictable nature of technological advancements and the need for cautious integration to ensure positive effects on sustainability. While being cautious towards experimental technology, proven innovations that show clear benefits, such as recycled coarse aggregates (RCA) (Ruiz et al., 2022; Swamy, 2001), could be utilised. Research on new technology in this context is essential for staying at the forefront of circular construction advancements.

5.5 Addressing the research questions

Multiple criteria and factors were identified that contributed to the sustainable and circular adaptation or replacement of bridges in Midden-Delfland, therefore the research question has been answered. As for the sub questions, multiple criteria and factors were also identified for what a circular and sustainable construction looks like through material assessment and general management of circular construction. Through the field trip to Midden-Delfland, data was gathered on its current waterway infrastructure and several characteristics were defined within the GIS-figures. Using MFA, the materials of the existing bridges in Midden-Delfland were assessed and data was gathered on the sustainability and circularity of the materials. Therefore, all sub-questions were fully answered.

6 Recommendations

6.1 Limitation to the research

During the literature review we encountered a gap in research on the meso-scale of sustainable construction. Furthermore, most literature did not assess the commercial and private sector's processes that apply to circular construction.

Concerning the GIS analysis, as mentioned in 3.3, we worked with both the data provided by *Erfgoedkwartiermakers* and the information gathered by our team. Furthermore, most literature did not assess the commercial and private sector's processes that apply to circular construction and its management processes. A lack of recency of studies could also prove to create a lack of awareness on recent trends and findings. Therefore, this report could be missing new information that we are not aware of.

For what concerns the GIS analysis, as mentioned in the relevant section, we worked with both the data provided by *Erfgoedkwartiermakers* and the information gathered by our team. However, the inaccessibility to Midden-Delfland geoportal resulted in some missing figures on the table. The date of construction of 9 bridges were unobtainable and the materials' assessment of the infrastructures was a visual evaluation. To stem the latter issue, we decided to only list the main materials for each bridge so that the literature review and the MFA were consistent with our own findings.

Due to time constraints, only a hypothetical MFA was provided. In case of a longer research timeline and better accessibility to material flow information, a proper full MFA could be possible. Due to the hypothetical nature of the MFA, the results could be missing information that a full MFA could provide. A limitation that is not related to the performed methods or given results, but is related to the research, is the presence of the Westlandseweg. The Westlandseweg effectively cuts off het Nieuwe water making it a dead-end for recreational vessels. This research focussed on the bridges along '*Het Nieuwe water*', but as it stands now this waterway would still not be suited as a sailing route for recreational vessels due to this dead-end. This is a severe limitation to the possible effects and influence this research could provide and further research into solving this issue should be done along-side the previous report of 'Rinck and van der Blom (2020)'.

6.2 Possible impact

The decision if the materials of the current bridges in Midden-Delfland were sustainable needed referring to the results 4.3. However, a more in-depth MFA, or other modelling approach, on bridge materials is interesting for future research. The gathered data of the simplified MFA, as well as the approach for the different steps, can serve as a foundation for further research.

The criteria that were provided, were created with the intention of providing vital support and recommendations for future circular construction projects. These criteria impact these projects by broadening the scope and way of thinking on all production levels of the project. Especially in the formation and theoretical dimensions of a projects, these criteria could provide reference points and clear expectations. The GIS map impacts the future projects in Maassluis by the effective labelling of the bridges, to establish priority targets for replacements and reparations. This gives clear objectives to future projects for the Commissioner.

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8 Appendix

8.1 Agenda points

On December 16th, we had a meeting with our commissioner to delve into the project and understand their expectations. During the discussion, we communicated our inability to formulate a bridge design at that moment. However, we reached an agreement on the deliverables, a set of criteria for a sustainable bridge and an elaborate map of the problem area, which was defined as the ‘Het Nieuwe Water’ and its 15 bridges. Additionally, we requested and received data about the current bridges from Jan Stuij, a civil engineer working on the project.

Every Friday at 13:00, we held our weekly meeting with our supervisors, either online or in person. Occasionally, Nethmi would bring in master’s students conducting relevant research, providing us with an opportunity to seek advice related to our research project. The last two weeks, we engaged in two additional meetings with Nethmi, receiving further feedback on our report and practicing for upcoming presentations.

8.2 Field trip data

On the 17th of January, we embarked on a field trip to ‘Het Nieuwe Water’, where we explored and hiked along the canal. We were specifically focusing on observing and studying the bridges. Prior to the field trip, we had established goals to guide our research. Our goals were the following:

- Identifying and writing down the main materials of all 15 bridges.
- Observations on how slow tourism functions in the area with bridges, paying attention to the general public and the response of the tourists or residents to these bridges.
- Identifying the current state they are in.
- Checking the accessibility of the bridges per mode of transport.
- Taking photos of all 15 bridges.
- Listing down the complications of gathering the data.

We brought measuring tape to determine the height of the bridges, and a camera to take pictures of them. Because the field trip took place in winter, we acknowledge that the water level could be different in summer when tourists would sail here.

It was freezing, -1.5 °C, and there were not many people walking in the area. So, the second goal was not achieved. However, the rest of the field trip was a success. All the bridges, plus their respective pictures and notes, are listed in this section.

8.2.1 The bridges

Bridge 1



The identified materials are steel, wood, concrete, and masonry.

The bridge is in good condition. The bridge is still movable, so boats can pass underneath. If the bridge is closed, however, the height from the water up to the underside of the bridge is 0.40m, so too low for boats. It is accessible for bikers, pedestrians and cars, plus boats if the bridge is open.

Bridge 2



We identified wood, steel and concrete in the bridge.

The construction of the bridge is in good state, however, the movable parts are rusted, so it likely does not open anymore.

The height of the bridge makes it inaccessible for boats, with 0.35m from the water to the underside of the bridge.

It is, however, accessible for bikers and pedestrians.

Bridge 3



This bridge is made of concrete, masonry, steel and asphalt.

The state of the construction is good, but the asphalt top layer has worn off.

Its height is 1.65m, thus high enough for boats.

This bridge is accessible for pedestrians, but inaccessible for bikers and people with walking disabilities, because of the stairs.

Bridge 4



The materials of this bridge are masonry, steel and natural stone.

It is in good state.

The space underneath the bridge is only 1.36m, which makes it too low for boats to pass underneath. However, it is accessible for bikers and pedestrians.

Bridge 5



The identified materials are masonry, asphalt, fibre core (glass fibre enforced plastic), blocks of concrete and wood in foundation and steel bolts in the deck and railing.

The bridge is in a good condition.

The bridge is also high enough for boats, as it is 1.5m. Furthermore, the bridge is accessible for bikers and pedestrians.

Bridge 6



The materials of this bridge are asphalt, wood, fibre-core (glass fibre enforced plastic), steel bolts and concrete.

It is in good state.

This bridge varies in height, ranging from 0.57 to 1.23 meters, with one side being higher than the other. It is on both sides too low for boats. But accessible for bikes and pedestrians.

Bridge 7



The bridge consists of 3 materials: concrete, steel and asphalt.
The bridge is in good condition.
Its height is only 1.29m, so it is too low for boats to pass through.
But accessible for bikes, pedestrians, and perhaps cars.

Bridge 8



This bridge is not in direct proximity to the canal, it stretches over two waterways and is mostly built for cars.

It is made of steel, wood, masonry, asphalt and concrete.

It seems to be in a good condition and is 4m high.

It is thus accessible for cars, bikes, pedestrians and boats.

Bridge 9



The identified materials in this bridge are wood, fibre-core (glass fibre enforced plastic), steel bolts, and concrete.

It is in a good state.

The height ranges from 0.93-1.39m, so at its highest point it is accessible for boats, but it is definitely accessible for bikes and pedestrians.

Bridge 10



The 10th bridge is made of steel, specifically weathering steel (corten steel), asphalt, concrete and masonry.

We thought the steel was rusted in the first place, but then identified the specific steel type (weathering steel) and concluded it was in good state.

It is also 1.6m, so boats can pass underneath, while bikes, pedestrians and cars can cross the bridge.

Bridge 11



The materials are steel, weathering steel (corten steel), asphalt, concrete and masonry.
The condition of the bridge is good.

Its height is 1.6m, boats can pass underneath, and it is accessible for bikes, pedestrians and cars.

Bridge 12



This bridge is made of steel, concrete and asphalt.

The bridge is in a bad state, the railings are rusty railing falling apart, there are holes in top asphalt layer, and the steel and bolts in the foundation are also rusty.

The height is only 1.16m, so it is too low for boats.

It is however accessible for bikes, pedestrians and cars.

Bridge 13



The materials of the 13th bridge are masonry, concrete and steel.

The state of the bridge is not good, the masonry blocks in the foundation are falling apart; there were holes in the foundation.

It is just 1.28m, and too low for boats. For bikes, pedestrians and cars the bridge is accessible.

Bridge 14



This bridge is only made of two materials: concrete and steel.
It is in good state, but the top layer is a bit worn off, as you can see in the picture.
It is 1.5m, so high enough for boats. It is also accessible for bikes, pedestrians and cars.

Bridge 15



The railing of the last bridge is made of steel, and the foundation of concrete. It is only 1.30m high, so boats cannot pass underneath. However, it is accessible for bikes, pedestrians and cars.

8.3 Hypothetical bridge scenario

For the scenario building, we used ChatGPT 3.5. The prompt was: ‘If I design a pedestrian bridge, how much concrete, wood, steel, asphalt, brick and fibre-core would I need (in kg)?’ The answer is pasted below:

“The amount of concrete, wood, steel, asphalt, and fibre-core needed for a pedestrian bridge would depend on various factors, including the design specifications, dimensions, and intended load-bearing capacity of the bridge. To determine the quantities of each material, you would typically follow these steps:

Design the Bridge:

Define the dimensions, span, and load requirements of the pedestrian bridge.

Specify the structural elements and materials to be used in different parts of the bridge (concrete for foundations, wood for decking, steel for structural members, etc.).

Calculate Volume or Area:

Calculate the volume or area of each material needed based on the design specifications. For example:

Concrete: Volume of foundations, piers, or other structural elements.

Wood: Area for decking and other wooden components.

Steel: Length and cross-sectional area of structural members.

Asphalt: Surface area of the bridge deck if using asphalt.

Fibre-core: Quantity based on its intended use and structural requirements.

Convert the calculated volumes or areas to masses (in kilograms) using the densities of the respective materials:

Concrete density: Approximately 2,400 kg/m³.

Wood density: Varies by wood species.

Steel density: Approximately 7,850 kg/m³.

Asphalt density: Approximately 2,300 kg/m³.

Fibre-core density: Specific to the type of fibre-core material.

Consider Safety Factors:

Account for safety factors and allowances in your calculations to ensure the bridge meets required standards and can safely support the intended loads.

It's crucial to consult with structural engineers during the design process to ensure that the materials and quantities are appropriate for the specific conditions and requirements of your pedestrian bridge.

Keep in mind that precise calculations would require detailed engineering specifications, and a qualified structural engineer should be involved in the design process to ensure safety and compliance with regulations.”

The scenario was not specific enough, so we followed up with: ‘Can you design an example bridge, and calculate how much I would need of each material?’ The answer was the following:

“Certainly! Let's consider a simple example of a pedestrian bridge with the following specifications:

Span: 20 meters

Decking Material: Wood

Structural Members: Steel

Foundation: Concrete

Surface Coating: Asphalt (for the deck)

Additional Reinforcement: Fibre-core (for added strength)

Additional Structural Elements: Brick/masonry

Concrete (for Foundations):

Assume a standard foundation design, and based on that, calculate the volume of concrete needed.

Example: 50 cubic meters of concrete (this is a hypothetical value for illustration purposes).

Wood (for Decking):

Determine the area of the bridge deck.

Assume a standard wooden decking thickness.

Example: 60 square meters of wood decking.

Steel (for Structural Members):

Calculate the length and cross-sectional area of the steel beams required based on the bridge span and load requirements.

Example: 2000 kg of steel (this is a hypothetical value for illustration purposes).

Asphalt (for Surface Coating):

Estimate the surface area of the bridge deck that will be coated with asphalt.

Example: 40 square meters of asphalt (this is a hypothetical value for illustration purposes).

Fibre-core (Additional Reinforcement):

Depending on the design and engineering requirements, determine the quantity of fibre-core needed.

Example: 30 kg of fibre-core (this is a hypothetical value for illustration purposes).

Brick/Masonry (for Structural Elements):

Estimate the volume of bricks or masonry required for additional structural elements (e.g., pillars, supports).

Example: 10 cubic meters of brick/masonry (this is a hypothetical value for illustration purposes).

Remember, these values are hypothetical and based on a simplified example. Actual bridge design requires detailed engineering calculations and considerations for safety factors, local building codes, and specific material properties. It's crucial to work with a qualified structural engineer to ensure the bridge's structural integrity and safety.”

<https://chat.openai.com/c/3e98b6d4-dd30-4d3b-8e22-c72c8989ced5>

Based on these amounts, the table from Zhang (2010) was used for calculations of in- and outputs. The results are placed in a graph which is visible in section 4.3.4 (figure 9).