Feasibility and Environmental Implications of Reusing Steel Bridges

Including a Case Study design process reusing the Keizersveerbrug

Msc Thesis

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by

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Preface

Before you lies the result of my final assignment for my master's studies in Civil Engineering. This thesis represents an accumulation of knowledge from all the courses, lectures, and exams I have completed since starting my Bachelor's in Civil Engineering in 2018 and my master's track in Structural Engineering in 2022. Interestingly, my fascination with structures—particularly bridges—has been a common thread throughout these years, accompanying me to the very end. As my interest in sustainability grew, both professionally and personally, I felt a strong responsibility to apply my engineering knowledge, time, and energy to this cause.

We are constantly reminded in the news of the urgency of climate action, and within our faculty, it is well known that the building and construction sector accounts for a significant share of global pollution. As engineering students, we are often excited to design new buildings and structures, yet it is sobering to realize that the most sustainable option is, in many cases, not to build at all (to Refuse). However, some new structures remain necessary in modern society, making it crucial to find ways to create them as sustainably as possible. The concept of reuse caught my interest, and through this thesis research, I expanded the traditional design cycle to incorporate reuse and explored its potential environmental impact savings—specifically for steel bridges in the Netherlands.

I am incredibly grateful for the support I received during this research from the architecture and engineering firm NEY & Partners. My supervisor at the company, Stijn Joosten, has been invaluable, and I would like to sincerely thank him for his time, ideas, enthusiasm, knowledge, and guidance throughout the project. I felt truly welcomed at the company, where I had the opportunity to work at their Delft office and take part in shared moments such as Christmas celebrations, birthdays, and NEYDay. Thank you, Joris, Helene, Tom, Jacoba, Gaby, Rafail, and Yilin, for making me feel part of the team!

I also want to extend my gratitude to my university committee for their guidance, support, and advice. The chair of my committee, Trayana Tankova, provided invaluable insights into steel structures and the graduation process. For questions regarding life cycle assessments and sustainability, I could always rely on Marc Ottelé. Both of them made a great effort to listen, think along with me, and challenge me during our meetings—something I deeply appreciated.

Finally, my time at the Civil Engineering faculty would not have been the same without my friends, especially those from U-BASE. Learning from everyone's thesis experiences helped shape my own research. The support of my family was also essential, with one particularly devoted supporter from beginning to end—my grandmother—who shared my enthusiasm so much that we even visited the case study bridge together.

I hope you enjoy reading my thesis and that it inspires you to take action toward greater sustainability in the field of civil engineering!

Deborah Dekker
Delft, March 2025

Abstract

To achieve sustainability goals, the Dutch government is striving toward a circular economy, which necessitates changes in the building and construction sector—responsible for 34% of global carbon dioxide emissions in 2022. Steel production contributes significantly, accounting for 7.2% of global greenhouse gas emissions (United Nations Environment Programme, 2024). Reuse, a key strategy within the circular economy, holds great potential but remains underutilized in infrastructure projects. This research investigates the feasibility and environmental impact of reusing a Rijkswaterstaat bridge, addressing the central question: *What are the feasibility and environmental implications of reusing the Keizersveerbrug, a steel truss bridge, on an object-level basis, as assessed through a comprehensive case study design process?*

A donor structure file, following the technical guideline NTA 8713 for the reuse of steel elements, is developed to assess the feasibility of reusing the Keizersveerbrug. A visual inspection confirms that the bridge is in good condition, with minimal corrosion and damage. The truss bridge aligns well with the design criteria of the new application, allowing for multiple feasible design options for both the approach ramps and the main span. An evaluation based on environmental impact, user comfort, and integration into the surroundings leads to a preliminary design. This design incorporates three 100-meter truss bridge elements from the donor structure, with adaptations including a new deck and a fresh paint layer.

An environmental impact assessment, conducted using Environmental Product Declarations and in accordance with NEN-EN 15804+A2, demonstrates significant environmental cost savings. When considering all life cycle stages, a reduction of 0–66% is observed, while excluding life cycle stage D results in a 25–60% reduction compared to variants constructed from other materials. Additionally, this research adapts the traditional design cycle to integrate reuse considerations, providing a structured approach for engineers addressing the challenges of reusing steel bridges. These findings underscore the potential of reuse to contribute to sustainable infrastructure that aligns with the principles of a circular economy.

Contents

1 Introduction

1.1. Research context

The need for sustainable practices in the built environment has never been more urgent since the United Nations Environment Programme's report indicates that the world is not on track to achieve the Paris Agreement goals. The buildings and construction sector is a major contributor to global climate change. In 2022, this sector was responsible for 34% of global energy demand and 37% of energy and process-related carbon dioxide (CO_2) emissions (United Nations Environment Programme, 2024). There has been progress in reducing operational carbon emissions created by heating, lighting and cooling of structures. However, there is a lack of solutions to reduce embodied carbon emissions due to the design, production and deployment of building materials like aluminium, cement and steel. After concrete, steel is the second most used material in the building and construction sector, thus a big contributor. The embodied emissions of the iron and steel industry creates 7.2% of global greenhouse gas emissions (United Nations Environment Programme, 2023).

According to the United Nations Environment Programme, a strategy to decarbonise is to avoid the extraction and use of raw materials, which is also one of the main principles of a circular economy. The circular economy principles offer a framework to reduce waste and minimise environmental impact by keeping materials in use for as long as possible. According to the Ellen MacArthur Foundation, reuse is one of the key strategies to achieve circularity, alongside maintaining, refurbishing, re-manufacturing, and recycling (Ellen MacArthur Foundation, n.d.).

On national level, the Netherlands has committed to achieving a fully circular economy by 2050, as outlined in its Circular Economy Programme (Rijksoverheid, 2022). Additionally, Rijkswaterstaat (RWS), the executive agency of the Ministry of Infrastructure and Water Management, has set the goal of working circularly by 2030 (RWS, n.d.). A key part of this strategy is the reuse of elements, components, and materials from existing infrastructure projects. Rijkswaterstaat's approach to reuse follows the principle of 'High-quality reuse, unless…', meaning that where technically and economically feasible, high-quality reuse is prioritized over downcycling. The most desirable form of reuse is at the object level, where a structure retains its original function. If this is not possible, reuse at the component level is considered, followed by recycling as a last resort. Feasibility is determined by factors such as financial costs, technical constraints, stakeholder responsibilities, and potential disruptions (Copper 8 and Witteveen+Bos, 2023).

In the coming decade, RWS plans to replace eight steel bridges, consisting of 20 individual bridge spans. Figure 1.1 shows these bridges. These structures will be offered for sale on a digital platform called the 'Nationale Bruggenbank' to encourage reuse within the sector. According to research (Copper 8 and Witteveen+Bos, 2023), reusing these bridges together has a potential environmental gain between 0-4.8 million ECI and a reduction of approximately 34.100 tons of CO_2 emissions. However, while the circular economy framework is widely discussed in building construction, its application to infrastructure, particularly steel bridges, is still underdeveloped.

Figure 1.1: Overview of bridges of RWS that will be replaced in the near future.

1.2. Research problem

Research and real-life examples demonstrate the possibilities of reusing structural steel elements in buildings. One good example is the temporary courthouse building in Amsterdam, which was fully dismantled and relocated to be reused in Enschede after five years of use (Rijksvastgoedbedrijf, 2021). A notable example of research is the elaborate document on the assessment, testing and design principles of structural steel reuse published by the Steel Construction Institute (D.G. Brown et al., 2019). However, this guide and the recently published Dutch regulation on steel reuse, NTA 8713, explicitly exclude cyclically loaded structures such as traffic bridges from their application. This exclusion highlights a significant gap in technical knowledge regarding the reuse of steel bridges.

While RWS has commissioned studies on the reuse potential of steel bridges, these analyses lack detailed insights into environmental impact, leaving the benefits of reuse compared to recycling or new construction uncertain. Besides technical concerns like fatigue and corrosion, practical challenges, such as transportation, storage, design constraints, and stakeholder responsibilities further complicate reuse (B. van Offenbeek-Kuipers et al., 2021). An advisory report by Copper 8 and Witteveen+Bos classifies steel bridge reuse into four phases: Phase 1 (Start), Phase 2 (Competition), Phase 3 (Critical Mass), and Phase 4 (Institutionalization). The sector currently remains in Phase 1, with limited practical experience but growing awareness. Advancing to the next phases requires further research, pilot projects, and small-scale initiatives to refine methodologies and demonstrate feasibility (Copper 8 and Witteveen+Bos, 2023).

This research aims to address these gaps by systematically evaluating the feasibility, environmental impact, and practical challenges of steel bridge reuse, providing insights that contribute to advancing the field from Phase 1 to subsequent phases. Findings from this study can support future updates to regulations like NTA 8713 by offering insights on the viability of steel bridge reuse.

1.3. Research objectives

The primary objective of this research project is to evaluate the feasibility of reusing steel bridges in the Netherlands. This is done at the object level by conducting a conceptual design process using a case study. Specifically, the case study will focus on reusing the Keizersveerbrug to design a cycle, pedestrian bridge, and wildlife passing over Highway A13, South of Delft, the Netherlands. More specifically, the objectives of this research consist of three parts, for which an overview is given in Figure 1.2. The objectives are to obtain the following products:

1. **Detailed Overview of Costs and Benefits**: To provide a comprehensive analysis of the environmental implications of reusing the Keizersveerbrug in a new context, compared to constructing new infrastructure in that same context.
2. **Inspiring Design Example**: To develop a creative and practical design proposal for the Keizersveerbrug as a reused object. This demonstrates innovative possibilities for bridge reuse.
3. **Elaborate Description of the Design Process**: To document and present the step-by-step design process of reusing a steel bridge on the object level. Both theoretical insights and practical challenges will be presented.

These objectives aim to contribute to the development of guidelines for the effective reuse of steel bridges.

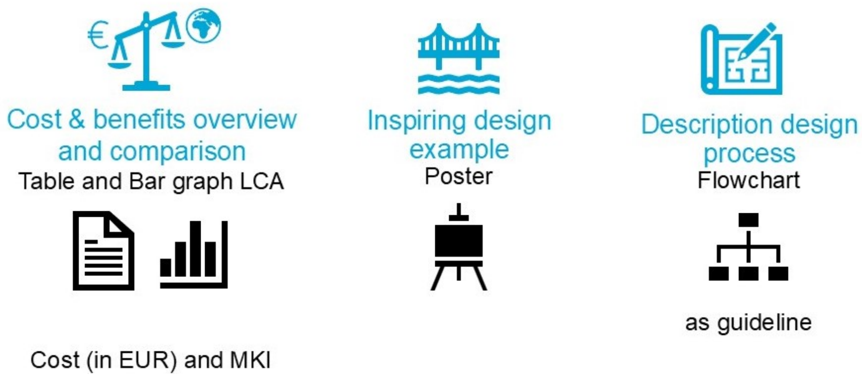

Figure 1.2: Overview of the three research objectives.

1.4. Research questions

1.4.1. Main research question

The research question that will be answered as a result of the thesis is as follows:

What are the feasibility and environmental implications of reusing the Keizersveerbrug, a steel truss bridge, on an object-level basis, as assessed through a comprehensive case study design process?

1.4.2. Sub research questions

Sub-questions are defined to arrive at an answer to the main research question. The sub-questions are:

1. How can the reuse potential of a steel bridge be assessed?
2. How can reuse be implemented in the design cycle/steps of preliminary design?
3. What are the environmental implications of the design from reuse compared to similar bridges built with new materials?

1.5. Research method and scope

This research can be categorised as an Engineering Means-End Knowledge project, which is generally used to prescribe how to act to achieve a specific goal within a particular context. With no prescribed methodology, it has been chosen to approach the project using the Design Cycle Methodology. A more detailed description of the method and scope per research objective can be found in the following paragraphs.

1.5.1. Design cycle steps

The design steps of the preliminary design phase are shown in Figure 1.3. This framework originates from the book of Roozenburg (N.F.M. Roozenburg, 1998) and is one of many similar frameworks. It is an iterative cycle with the key steps of analysis, synthesis, simulation, evaluation and decision. This research uses the steps of the design cycle as a guide during the design process using reused steel bridge objects.

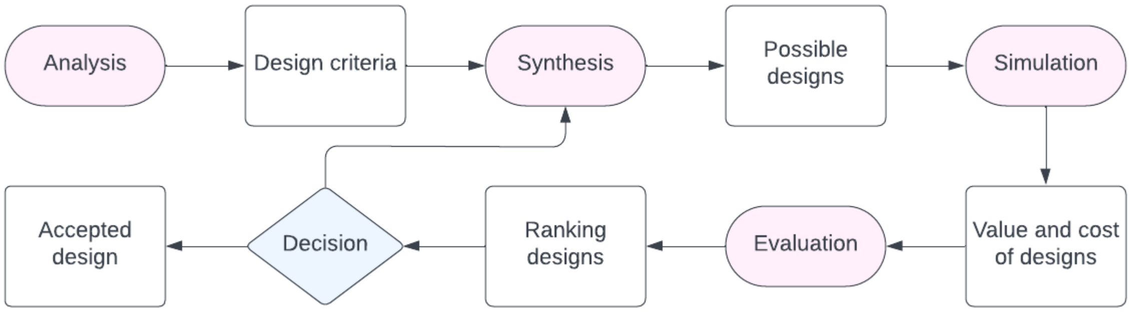

Figure 1.3: Preliminary design cycle (adapted from N.F.M. Roozenburg, 1998).

- Analysis: This step gathers relevant information on the design problem. This includes information such as user requirements, technical constraints and environmental factors. This step aims to fully understand the design problem before generating solutions.
- Synthesis: Potential design solutions are generated based on the insights from the analysis step. In this creative step, sketching and modelling can be used to explore different design considerations.
- Simulation: The proposed designs are tested and analysed in this step by modelling and structural analysis to predict the performance, feasibility and impact of different design choices.
- Evaluation: The designs are evaluated based on the initial design criteria and ranked based on their effectiveness in solving the design problem.
- Decision: Based on the evaluation, a decision is made on which design to proceed. A design could also be iterated back through the cycle if necessary.

1.5.2. Detailed overview of environmental costs

The environmental impact for all life cycles of a structure is found using existing Environmental Product Declarations (EPDs) for different materials. These documents provide the environmental impact per kg or m^3 product for the 13 main environmental impact categories by NEN-EN 15804+A2 ("NEN-EN 15804:2012+A2:2019 en", 2019). These can be multiplied by their weighting factor to obtain environmental costs. The total environmental impact of different design scenarios is obtained by multiplying these values by the weight of the main load-bearing superstructure of the designs.

The environmental impact of the design, including reuse, can then be compared to the impact of other design scenarios. These scenarios are: a similar design from recycled steel, virgin steel, a steel bridge design to be reused, a plate steel bridge and a concrete design variant.

1.5.3. Inspiring design example

A preliminary design is developed for the Ackerdijkse Bridge, a cyclist and pedestrian bridge South of Delft, the Netherlands. It includes a part of the Keizersveerbrug as a reused object and is verified using the technical guidelines on reuse, extended with knowledge from literature. The requirements program is established in agreement with the municipality of Delft. The focus lies on the design of the superstructure and a rough estimation of the dimensions of the substructure (foundations).

1.5.4. Elaborate description of the design process

The design steps that are carried out to arrive at an inspiring design example, including reuse, are documented to achieve this objective. This includes an extension beyond the original design cycle steps. Other bridge engineers can use this description as a guide in including reuse in their projects.

1.6. Research outline

This research document has the following structure. An overview of relevant background information regarding the reuse of steel is given in Chapter 2. This includes guidelines on structural steel reuse, background information on fatigue and corrosion, guidelines on environmental impact assessment and current state-of-the-art market supply and demand. The case study is introduced in Chapter 3, both the donor structure Keizersveerbrug as well as the new design situation of Ackerdijksebrug. This information forms the basis of the analysis step. The next three steps, design criteria, synthesis and possible designs can be found in Chapter 4. Here, the first design possibilities that include reuse are shown. These are modelled and evaluated in Chapter 5, and after some iterations, the final design is presented.

The environmental impact analysis is performed, and the results can be found in Chapter 6. This results in a comparison of the environmental costs of the final design compared to other design scenarios. In Chapter 7, an overview of the design cycle steps, including reuse, is given and discussed. This includes general notes on the methodology and case study-specific remarks. In the chapter, the limitations of the research are also discussed. A conclusion is drawn by answering the research questions, and recommendations for different stakeholders and further research are given in Chapter 8. Some other detailed information is provided in the Appendices, to which references are shown within the main text.

2

Literature review: structural steel reuse and environmental considerations

This literature review covers key topics addressing the theoretical and practical aspects of steel structure reuse, forming the foundation for this research. Each topic is selected to provide the necessary context and knowledge for understanding and advancing reuse practices.

First, guidelines for reuse are examined to evaluate their applicability to steel bridges and outline practical steps within the design cycle. Next, the critical challenges of fatigue behaviour and corrosion are explored, as both significantly could impact the durability and safety of steel structures. A theoretical foundation on assessment methodologies is necessary to evaluate the environmental impact of reuse. Finally, the topic of supply and demand contextualises the research, adding to knowledge of the practical implications of reusing steel bridges.

2.1. Guidelines for reusing structural steel

There are multiple guidelines concerning structural steel reuse, such as the NTA 8713, RTD1006, and the SCI Structural Steel Reuse guide. An overview of relevant aspects of these guidelines will be given in this subchapter.

2.1.1. NTA 8713 - Reuse of structural steelwork

In June 2023, a new Dutch regulation on reusing structural steelwork was published. This “NTA 8713” (2023) is developed by researchers and engineers from different companies and instances. The aim is to facilitate the reuse of structural steel and reduce the environmental impact of steel structures. The document describes the procedure to determine the geometrical and material properties of steel profiles dismantled from a donor structure to be reused in another structure. However, the document does not apply to:

- Steel from before 1955;
- Steel from a donor structure from outside of the Netherlands;
- Steel structures that are loaded on fatigue, like bridges, cranes, machinery or masts;
- Plastic-deformed steel, for example, deformed by overloading, dismantling work, extraordinary loads like fire, explosion or collision;
- Corten steel/weathering steel, stainless steel, cast iron;
- Bolts, rivets and prestressing bolts.

Although officially not applicable to steel bridges, the document provides valuable information on how to approach structural steel reuse. More specifically, it covers topics such as demounting, determination of material properties, structural design and manufacturing. The following paragraphs will summarise this information and highlight relevant aspects for this research. The following definition for reuse is used in the guideline: 'the reuse of a construction product previously applied for the same or a similar function' ("NTA 8713", 2023). Figure 2.1 gives an overview of the files that should be produced and the steps necessary for reusing a steel element, according to the technical agreement.

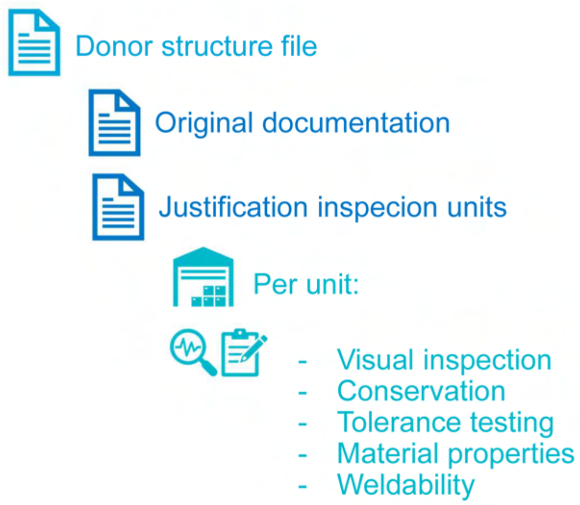

Figure 2.1: Summary of the NTA-8713.

Donor structure file

Chapter 5 of the NTA 8713 describes what information on the existing steel profiles should be recorded before dismantling to facilitate reuse. Technical information about the steel profiles of the donor-object should be defined in a 'Donorbouwwerkdossier', which can be translated as a 'Donor structure file'. This file is based on information from the original documentation on the structure. The available original documentation should be included in this file. The type of available documents will give the information a certain 'status'. Figure 2.2 shows the different types of documents and their status. A status one is a more useful document than a status two document.

Status	Document
1	Inspection document, CE marking or DoP
2	Fabrication drawing
3	Execution-ready design drawing
4	Tender drawing/calculation
5	Design drawing/calculation

Figure 2.2: Document status for donor structure, based on "NTA 8713" (2023).

Inspection units

The next step is for the structure to be split up into inspection units. A unique code is given to each steel profile within the unit. These inspection units can weigh a maximum of 20 tonnes and should have the same profile. A suggested way of grouping would be for elements with the same structural application, location, condition or load. A justification for choosing these inspection units is necessary. To reuse an object, the object is physically not split into units, which would become a theoretical step.

Inspection document

An inspection document is drafted for each inspection unit. This document contains the following aspects:

- Results of the visual inspection
- Assessment of conservation
- Material properties and explanation
- Examination class
- Explanation of weldability

Visual inspection
The visual inspection focuses on several key aspects, including any damages and repairs, holes, welded-on parts, and varying levels of corrosion, which may range from light to heavy. Additionally, attention is given to any cross-section loss in the structural elements. For each of these aspects, it is important to note whether they are present or absent and to document the findings with accompanying photographs. An example of a fillable inspection sheet is provided in the figure below.

Subject of inspection	Assessment	Findings/observations
Damage, repair	Present Not present	
Holes	Present Not present	
Welded parts	Present Not present	
Corrosion	Light Moderate Heavy	
Loss of cross-section	Present Not present	

Figure 2.3: Visual inspection table (Adapted from “NTA 8713”, 2023).

Assessment of preservation
The conservation method and its condition should be qualitatively assessed and documented. This assessment should specify the type of preservation, which may include options such as non-preserved, organic coating, hot-dip galvanised, or duplex coatings. Additionally, any relevant details, such as the thickness of the preservation layer, should be noted in the comments, along with any suspicion of toxic substances. An example of a fillable assessment sheet can be found in Figure 2.4.

If there is reason to believe that the existing coating contains hazardous substances—such as lead, chromium-6, other heavy metals, or PAHs (Polycyclic Aromatic Hydrocarbons)—there are two possibilities: to refrain from further investigation and report the suspicion since there are duty-to-report regulations, or conduct a formal inquiry to confirm the presence of toxic substances in the organic coating.

Should toxic substances be confirmed, there are two possible steps; one must be implemented: blast the structural steel to Sa 2.5 by NEN-EN-ISO 8501-1 standard or repurpose the structural steel in another application, where it cannot pose a hazard. Both actions must be done in consultation with the client and according to applicable laws and regulations.

Subject of inspection	**Assessment**	**Findings/observations**
Type of conservation	Not conserved organic coating hot-dip galvanised duplex	
Toxic substances?	Yes No Not researched	

Figure 2.4: Example preservation inspection table (Adapted from “NTA 8713”, 2023).

Tolerance testing
For each inspection unit, the dimensions of the cross-section and straightness of the steel profiles

should be measured and recorded. These dimensions should not exceed the standardised maximum tolerances recorded in other Eurocodes.

If the cross-section dimensions meet the tolerances, then the cross-sectional properties (A, I and W) may be read from the tables in dictations and books. However, if the cross-section dimensions do not meet the tolerances, the dimensions should be specified according to Figure 1.1 of NEN-EN 1993-1-1+C2+A1:2016 and the cross-sectional properties determined using mechanics. This figure can be found in Appendix A.

Material properties
For new steel, a Declaration of Performance (DoP) is issued. For reused steel, an inspection report based on this NTA replaces this. Reporting on the steel grade is mandatory, and reporting on the steel quality is optional. Three ways to determine the material properties are using archive information of the donor structure and old standards, the lower bound approach, or testing. In all cases, the year of steel production should be assumed to be no more than 2 years earlier than the year of construction of the donor structure.

- Based on archive information and old standards: Appendix C of the NTA contains tables that refer to the product norms of steel elements in different years between 1955 and 2014. It can be used when the original type of steel is known. Figure 2.5 shows this table. Since the standard is applicable for steel from 1955 and older, the table also starts from this year.
- Based on the lower bound approach: Steel produced over a specific time may show variations in composition and strength. The lower limit of known strength values is taken instead of an average or typical value to ensure safety. This avoids overestimating the steel in calculations, leaving a safe margin. NTA 8713 bases these values on historical data and material characteristics of steel produced in specific periods. For different construction years, the minimum yield strength and tensile strength have been determined based on known steels of that time. This means that a safe assumption for strength properties can be made even if the exact steel grade is unknown. Figure 2.6 shows the table from the NTA.
- Based on testing: The required testing depends on the research class and, thus, the consequence class. A summary of the required tests can be found in the table below, in Figure 2.7. It includes references to Appendix E of the NTA, an appendix on testing. E.2 is about non-destructive tests like the Vickers Indentation Fracture Test. Appendix E.3 on destructive testing, such as the tensile strength test. For tests on the chemical composition necessary for welding, appendix E.6 gives a procedure. This can also be non-destructive, such as by Optical Emission Spectrometry or a X-ray fluorescence Instrument. Destructive tests are performed in the laboratory using chips of the structure obtained by drilling.

Tabel C.1 — Norm voor het ontwerpen van een constructie en productnorm en introductie CE-markering (1955–heden)

	Norm voor het ontwerpen van constructies	Productnorm	Tabel
1955-1972	N 1055:1955 (TGB 1955)	V 1035 deel IV	C.2
1972-1990	NEN 3851:1973 (TGB 1972)	Euronorm 25-72	C.3
1990-1997	NEN 6770:1991 (TGB 1990)	NEN-EN 10025:1991 NEN-EU 113:1986	C.4
1997-2005	NEN 6770:1997 (TGB 1990)	NEN-EN 10025:1993 NEN-EN 10113:reeks (1993)	C.5
2005-heden [a]	NEN-EN 1993-1-1	NEN-EN 10025-1:2004 NEN-EN 10025-2:2019 NEN-EN 10025-3:2019 NEN-EN 10025-4:2019+A1:2022	C.6

[a] Sinds 2014 is CE-markering verplicht en is een DoP geleverd bij het staal die mogelijk nog beschikbaar is.

Figure 2.5: Construction design and product standards and introduction of CE marking (1955-present) ("NTA 8713", 2023).

Tabel D.1 — 1955-heden: ondergrensbenadering voor de treksterkte en vloeigrens

Periode	Aanname staalsoort voor ondergrens	f_y N/mm²			f_u N/mm²		
1955-1972	Gewalst staal H	235			335		
1972-1990	Fe 310 / Fe 33	$t \leq 40$ mm			40 mm $< t \leq 100$ mm		
		f_y	f_u		f_y	f_u	
		200	310		180	280	
1990-1997	Fe 360 / FeE 235 [a]	$t \leq 40$		$40 < t \leq 100$		$100 < t \leq 250$	
		f_y	f_u	f_y	f_u	f_y	f_u
		235	360	215	340	175	320
1997-2005	S235	$t \leq 40$		$40 < t \leq 100$		$100 < t \leq 250$	
		f_y	f_u	f_y	f_u	f_y	f_u
		235	360	215	340	175	320
2005-heden	S235	$t \leq 40$		$40 < t \leq 100$		$100 < t \leq 250$	
		f_y	f_u	f_y	f_u	f_y	f_u
		235	360	215	340	175	320

[a] NEN-EN 10025:1991 geeft nog Fe 310-0. Omdat NEN 6770:1991 deze staalsoort niet noemt, wordt aangenomen dat Fe 310-0 in deze periode niet is toegepast in gebouwen.

Figure 2.6: lower limit approach for tensile and yield strength (“NTA 8713”, 2023).

Examination and consequence class

The consequence class for which the elements from one inspection unit can be reused depends on various aspects. Table 2.1 summarises the relation between the consequence class, the research class, the available documents and the visual inspection.

Consequence class	Research class	Available documents	Visual inspection
CC1 – low consequences	Research class 1,2,3	Any document status	Everything allowed
CC2 – normal consequences	Research class 2,3	Document status 1,2,3,4	Loss of cross section and damage/repair not allowed
CC3 – high consequences	Research class 3	Document status 1,2	Loss of cross section and damage/repair not allowed

Table 2.1: Summary of requirements for consequence classes (adapted from “NTA 8713”, 2023).

2.1.2. RTD 1006 - Richtlijn Beoordeling Kunstwerken

The RTD 1006 is a document by Rijkswaterstaat containing additional requirements, guidance, and information for assessing the structural safety of their civil engineering structures (J. Doorgeest and H. Sliedrecht, 2022). It is relevant in the context of reuse because assessment of the structure’s current state is part of assessing the reuse potential of a structure.

2.1.3. SCI - structural steel reuse

The SCI, Steel Construction Institute published a document on structural steel reuse assessment, testing and design principles in 2019 (D.G. Brown et al., 2019). This institute has been a leading, independent provider of technical expertise for over 30 years. The scope of the document is similar to the NTA 8713, excluding steel from before 1970 or that has been subjected to fatigue. Furthermore, the protocol anticipates the reclaimed steelwork to be plain members, excluding connections and the reuse of a complete structure. Still, the document is consulted because it provides relevant information and advice.

Research class	Required testing
1	Based on a document of status 5, the steel grade should be determined according to Annex C in combination with at least three non-destructive hardness measurements according to E.2. If structural welding is to be performed on the inspection unit, the chemical composition should be determined based on one destructive test according to E.6, or the maximum CEV shall be taken as the lower limit according to Annex D.
2	All steel profiles in the inspection unit should be non-destructively tested with a hardness test according to E.2 in combination with one destructive tensile test according to E.3; Or, based on a document of status 4 or higher, according to Table 3, the steel grade should be determined according to Annex C in combination with one destructive tensile test according to E.3. If structural welding is to be performed, the chemical composition of the inspection unit shall be determined based on one destructive test according to E.6.
3	All steel profiles in the inspection unit should be tested non-destructively with a hardness test according to E.2 in combination with at least three destructive tensile tests according to E.3; Or, based on a document of status 2 or higher, the steel grade should be determined according to Annex C in combination with at least three destructive tensile tests according to E.3. If structural welding of the inspection unit is required, the chemical composition should be determined based on three destructive tests according to E.6.

Figure 2.7: Research class and its required testing procedure, based on "NTA 8713" (2023).

Overall process

An overview of the process of reusing structural steel and the involved stakeholders shows similarities with the process described in the NTA 8713. The difference is the addition of stakeholders and mentioning the costs of the processes. The process is described as follows:

1. When a building is offered to reclaim its steel elements for reuse, important considerations are the quality of the source material, the structure's ease of disassembly, and the additional costs of careful demolition.
2. A business agreement is established between the steel stockholder and the demolition contractor.
3. Crucial details about the reclaimed steel are documented.
4. The stockholder receives the reclaimed steel, categorised and listed accordingly. This significantly influences the required extent of testing.
5. Each steel member is inspected and tested, with results added to the stock database. Testing may involve non-destructive and/or destructive methods with conservative assumptions about specific material properties. The seller must declare the required characteristics when the material is sold.
6. Then, the material can be sold, and the declaration accompanies the declaration of the material characteristics.
7. Lastly, the structural design and member verifications are completed using certain modifications.

Design Recommendations

The SCI document gives some design recommendations for reuse. Standing out are the recommendations about buckling resistance and connections. For buckling resistance of reclaimed steel, a modified value of $\gamma_{M1,mod} = 1.15\gamma_{M1}$ should be used (in the UK). This is because of the additional insecurities of the cross-sectional properties, dimensional and straightness tolerances and other possible imperfections.

With regards to connections, the protocol anticipates that they are not reused. If welds are reused, it states that the strength of the weld is at least equal to the base steelwork. It advises to inspect and test the welds carefully. Riveted connections, which are often used in older steel bridges, are not mentioned in the document. A check needs to be performed for bolt holes if they reduce the cross-section by more than 15%. In that case, the net cross-section properties should be used when verifying the members. Furthermore, a recommendation is given to avoid new connections within 100 mm of existing holes.

2.2. Material challenges: fatigue and corrosion

Fatigue and corrosion are phenomena that influence the performance of steel structures. How to design new structures accounting for these phenomena has become a common practice nowadays. However, accounting for it when reusing steel structures is more challenging. This section first explains the phenomena's basics, after which their role within the reuse subject is discussed.

2.2.1. Fatigue of steel structures

Basics of fatigue

Fatigue leads to a lowering of the strength or even failure of a material due to repetitive stress. It occurs in load-bearing components or structures and even in consumer products like shoes (Donald R. Askeland et al., 2011). The loading is below the static strength of a structure; thus, a single application does not cause any damage. However, when repeated many times, it does, and could even induce a complete failure (Schijve, 2009). Fatigue was a known problem in the 19th century but remained a mysterious phenomenon. Starting from the 20th century, more research into it led to the understanding of the mechanism. Now, structures are designed and produced in a way that during the design life of the structure, fatigue failure does not occur.

The failure mechanism of fatigue occurs in three stages. This can also be seen in Figure 2.8. First is the crack initiation stage, which usually happens around areas with maximum stress and surface defects. Then, the crack propagation stage occurs when the load occurs in cycles. Lastly, the material suddenly fractures. This happens when the remaining cross-section cannot support the applied load anymore. The figure 2.9 shows this fatigue fracture in a steel shaft.

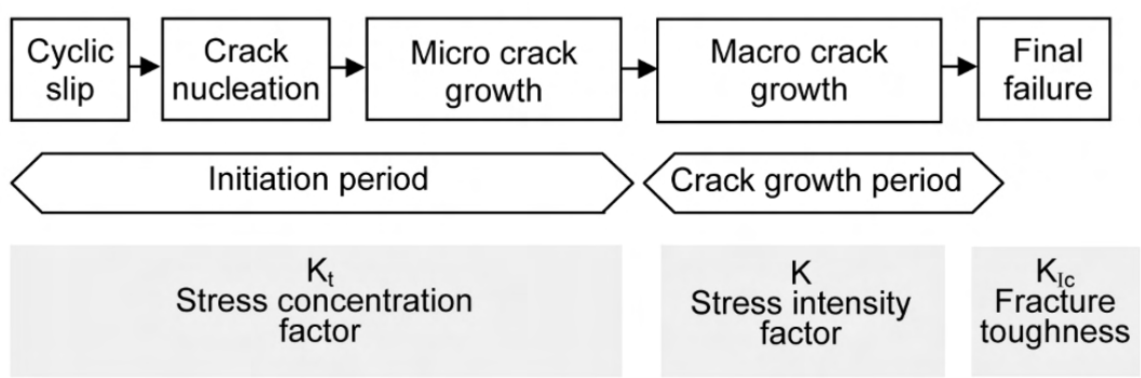

Figure 2.8: Different phases of fatigue life and relevant factors (Schijve, 2009).

The phenomenon of fatigue depends on a lot of aspects. Figure 2.10 summarises the aspects to be considered when designing for fatigue. It takes design aspects, basic information and the structure in service as inputs. The wide variety of input factors shows that the phenomenon is a multi-disciplinary problem. As output, it predicts the fatigue limit, fatigue life, crack growth and final failure (Schijve, 2009).

The **Design aspects** are:

- The structural concept: which is the overall design of a structure. Differences are, for example, a continuous span, which experiences lower stress ranges than a simply supported structure. The fatigue behaviour of box girders is different from that of open-truss structures, also due to reduced stress concentrations.

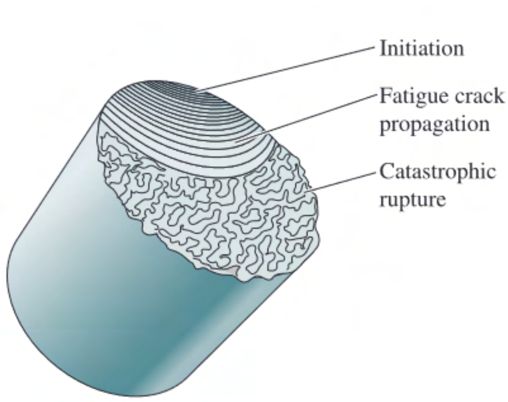

Figure 2.9: Fatigue fracture in steel shaft (Donald R. Askeland et al., 2011).

- The joints: different joints, such as welds, bolts and rivets, behave differently under cyclic loading. In many historic steel bridges, rivets are used, which may experience fatigue cracking at the holes.
- The material selection: different steel grades perform differently on fatigue, for example, higher toughness steel grades perform generally better.
- The material surface condition: Fatigue resistance can be influenced by surface roughness and residual stresses from manufacturing processes.
- Production variables: Different production techniques, such as welding and heat treatments, can influence fatigue behaviour. Fatigue resistance is lower when there is poor quality control, mis-alignment and welding defects.

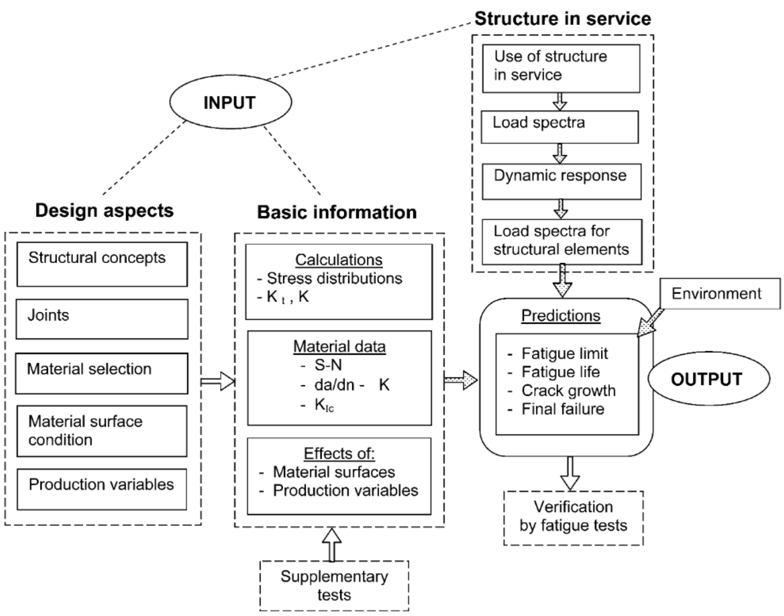

Figure 2.10: Aspects relevant to fatigue design (Schijve, 2009).

The structure in service aspect of the input focuses on the use of the structure, which is for bridges determined by the bridge users. Traffic bridges can be designed for trains, car traffic, cyclists and pedestrians. The different users lead to varying loads on the structure, thus different load spectra and the dynamic response of the bridge. This leads to the load spectra specifically for each structural element. A load spectrum can change over time if the use of the structure changes. The history of the load spectrum is relevant in the predictions of the fatigue performance of a structure. A load spectrum can either be predicted by analysing the use of the structure, or when a (similar) structure already exists, it can be measured.

The basic information consists of:

- The calculations of the stress distribution in the structure. This can be expressed as the stress range, $\Delta\sigma$: the difference between the minimum and maximum stress value. For stress concentrations, the stress concentration factor K_t is used, which is defined as the ratio between peak stress at a notch and the nominal stress without a concentration.
- Material data is information such as S-N curves. Those are obtained by experimental investigation of different specimens loaded until failure. They show the maximum load cycles a material can withstand (x-axis) under a specific constant stress range (y-axis). Both axes are logarithmic. A constant stress range results from cyclic loading with a constant amplitude and mean load, like sinusoidal loading. An example of an S-N curve is shown in Figure 2.11. Other relevant data is the fatigue crack growth resistance of a material da/dN, which is obtained from fatigue crack growth tests.
- The effect of material surface and production variables. Different processes, such as the production and assembly of steel structures, can lead to residual stresses. This is a stress distribution that is present in an element without an external load applied. Tensional residual stress can have a negative effect on fatigue resistance. Measuring residual stresses is not simple, however, an estimation can be made by calculation (Meijer, n.d.).

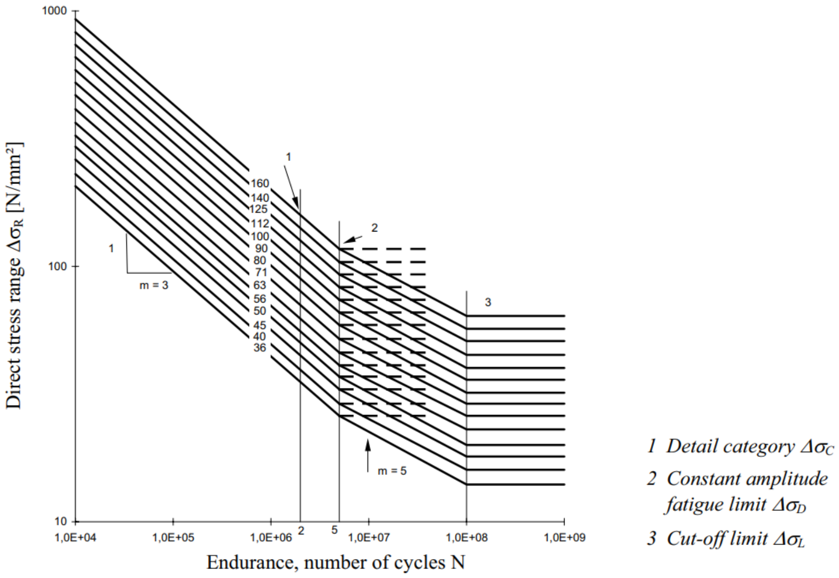

Figure 2.11: Fatigue strength curves for direct stress ranges ("NEN-EN 1993-1-9+C2", 2012).

Output predictions provide information on the fatigue behaviour of the structure. This can be based on different calculation approaches, such as the nominal stress approach and the modified nominal stress approach. One of the outputs is the fatigue life, which is expressed as the number of stress cycles the structural member or detail can withstand before it fails.

Nominal stress approach
This approach is based on S-N curves, which are specific for a particular part of the structure, called detail category. The category is numbered by the value of $\Delta\sigma_c$ for fatigue strength at 2 million cycles. In Figure 2.11, this is marked by 1. Point 2 shows the fatigue limit for a constant amplitude $\Delta\sigma_D$, and the third point stands for the cut-off limit $\Delta\sigma_L$.

Structures are usually not subjected to a constant amplitude loading since traffic loading results in variable amplitude loading with a complex load-time history. The "NEN-EN 1993-1-9+C2" (2012), Annex A, prescribes how to obtain the fatigue load parameters using the stress history and suggests calculating damage summation using the Palmgren-Miner Rule. $\Sigma n/N = 1$, with n cycles and N fatigue life.

However, Schijve (2009) questions the validity of this approach, pointing out its principal inconsistencies. The approach ignores the contribution to fatigue damage of cycles below the fatigue limit, while these can contribute to an increase in existing fatigue damage. The writer concludes that the Miner rule gives, at best, a rough estimation of the fatigue life.

Modified nominal stress approach
Construction details are especially prone to fatigue cracks because of the stress concentrations in the geometrical notches. This phenomenon is not included in the S-N curve, and a modified stress approach must account for it. This is done using a stress concentration factor k_f to obtain a modified stress value: $q_{mod} = k_f \cdot \sigma_{nom}$. Figure 2.12 shows examples of specimens with holes or notches and their corresponding stress distribution.

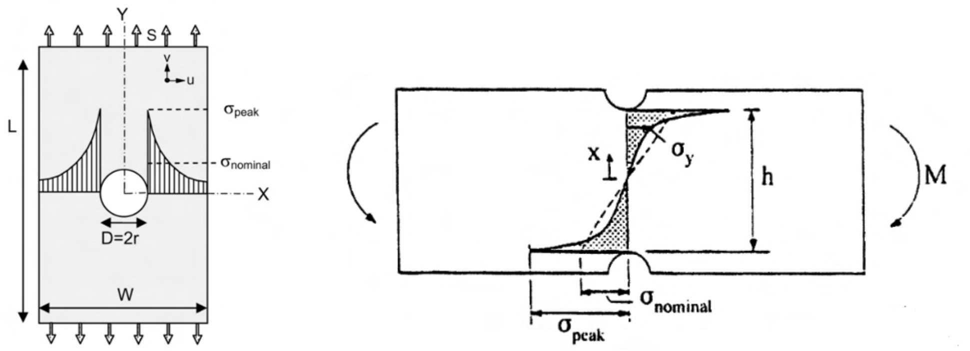

Figure 2.12: Example of specimen with non-linear stress distribution due to hole (left) or nothes (right) (Schijve, 2009).

Fatigue in riveted connections
The fatigue behaviour of riveted connections is relevant since it is applied in many steel bridges constructed in the early-to-mid 1900s. The Eurocode EN 1993-1-9 provides some detail categories for assessing fatigue in connections (“NEN-EN 1993-1-9+C2”, 2012). The focus lies mainly on beams from build-up cross-sections (Reijers, 2024). More complex loading situations, like joints of riveted structures, are barely incorporated. Other advanced assessment methods can capture the fatigue response of complex joints, like the local strain-life approach and fracture mechanics. These have not yet been adapted to the Eurocodes.

Reijers (2024) analysed the fatigue behaviour of a complex riveted joint using a shell-element-based FE model. He compared different approaches: the Smith-Watson-Topper’s adaptation (SWT), the maximum shear strain criterion (MSSC) Methods and the Stress concentration factor method (SCF). He concluded that the results show a wide variety by comparing the resulting stress- and strain-life curves and resulting fatigue-life estimation. SCF results in a conservative estimation, with orders two smaller than SWT and three smaller than MSSC. This difference between SWT and MSSC is likely due to the mechanics behind truss structures, which act with limited multiaxial loading. Furthermore, prestressing in rivets has a limited effect on the S-N curve and ε-N curve but can increase the estimated fatigue life by a factor of two. This is because the stress range is lower, which increases local stress and strain at low loads and increases with high loads. Regarding applicability (ease of use and time), SWT scores best, followed by MSSC and SCF. So, it can be advised, when assessing the remaining fatigue life of steel bridges with riveted connections, to use the Smith-Watson-Topper’s adaptation approach.

Fatigue assessment of existing steel bridges
A well-known literature source on fatigue in steel structures is a document by the Joint Research Centre and ECCS cooperation (Kühn et al., 2008) called ’Assessment of existing steel structures: Recommendations for estimation of remaining fatigue life’. It illustrates the general assessment procedure for fatigue and the method for existing steel bridges.

The illustration summarising this procedure can be found in Appendix A, figure A.2. The method consists of four phases (Kühn et al., 2008):

1. Preliminary Evaluation: using available documents combined with site visits to assess the safety based on the current codes.
2. Detailed Investigation: to make a more precise assessment of critical members. Qualitative inspection methods like easy-to-use, low-tech, non-destructive test methods are used.
3. Expert Investigation: In cases with high consequences, assessment should be improved using specific tools like high-tech NDT, probabilistic, and fracture mechanics.
4. Remedial measures are proposed to update the structure to a sufficient safety level.

Especially the first two phases show similarity with the process of assessment for reuse as explained in 2.1. Thus, combining the approaches to include a basic fatigue assessment in setting up a report for reusing steel bridges is advised.

Inspecting fatigue cracks
Visual inspection is a way to assess the current state of the structure. A crack found during an inspection could be an unloaded defect/crack that resulted from the original fabrication process. This is harmless because there will be no crack propagation. Alternatively, it could be a fatigue crack, which can be recognised by its opening and closing under cyclic loading. The location of this fatigue crack influences its acceptability. It is less dangerous if it occurs in a secondary structural element (Kühn et al., 2008). Furthermore, rubbing of the sides of the crack can create a fine steel powder. This will oxidise when exposed, leading to decolourisation/rust staining, making the crack easier to observe. Other methods to detect fatigue cracks are listed in the table in Figure 2.13 below.

N°	Short cut	Method	Application	Costs of equipment
1	MT	Magnetic particle inspection	Surface cracks	low
2	PT	Colour penetration test	Surface cracks	low
3	RT	Radiographic inspection	Surface and subsurface cracks also in sandwiched elements	moderate
4	UT	Ultrasonic inspection	Material thickness, in some special cases crack detection possible: ▪ in riveted sections using low-angle sound transmitter ▪ in rolled sections, e.g. between flange and web	moderate
5	ET	Eddy current technique	Crack detection in rivet holes after rivets were removed, cracks in thin plates	moderate
6*	AE	Acoustic emission techniques	Surface cracks, subsurface cracks, identification of "active" cracks only	not fully applied and approved
7	FOS	Fibre optical sensors	Monitoring during the crack propagation	high

* Range of applicability not evident. Large testing, particularly in field tests is necessary.

Figure 2.13: Available Non-Destructive Tests for fatigue inspection of steel bridges (Kühn et al., 2008).

Measures against fatigue
A possible measure is to drill a hole (stop hole) in the crack path to reduce the stress concentration. The stress can be redistributed. However, it could make the material prone to other failure modes (Guijt, 2023).

Other possible remedies are strengthening using pre-stressed bolts or injection bolts. Structural members could be added, like filler plates, cover plates or fibre-reinforced plastic strips. Repair welding is also a possibility. Other, more general measures are to intensify the monitoring or reduce the amount of traffic using the bridge (Kühn et al., 2008).

2.2.2. Corrosion of steel structures

Basics of corrosion

Corrosion is a process that deteriorates materials like metals by a chemical or electrochemical reaction with their environment. This could negatively affect material properties, like ultimate yield and tensile strength. Different types of corrosion and classification can be done by visual inspection or grouping by the reaction taking place on the metal (Reijers, 2024). The types of corrosion based on appearance can be uniformly or locally present and are summed up below and schematised in Figure 2.14.

- Uniform or General corrosion: corrosion spreads homogeneously over the material's surface, proceeding at the same rate. It results in a decrease in the thickness of the cross-section and weight loss. Due to its good predictability, it is used in most predictive corrosion models.
- Pitting corrosion: formation of local pits/holes. It can cause harm to an element but is more challenging to detect.
- Crevice corrosion: formation of local erosion damage close to an area of the metal that is protected.
- Galvanic corrosion: corrosion due to the presence of a more noble metal.
- Erosion corrosion: due to the flowing of a corrosive material past the metal.
- Cavitation: bubbles and vacuums may be present on the metal due to fluids, and their collapse can impact the surface. It erodes protective layers and causes pits.
- Stress corrosion: stresses could cause brittle cracking of the material.
- Fatigue corrosion: cyclic loading could induce cracking of the material.

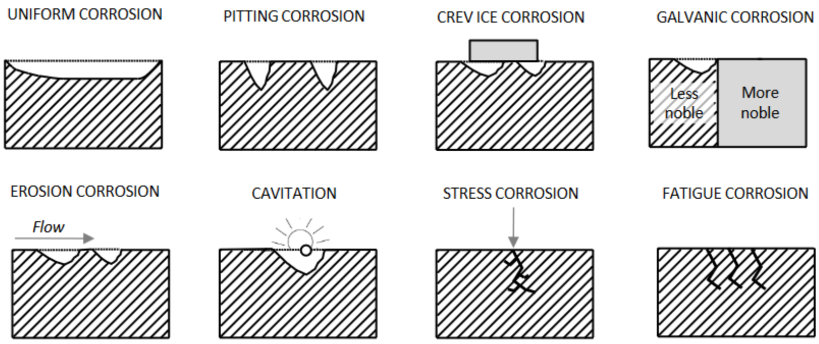

Figure 2.14: Main corrosion forms of metal structures (Landolfo et al., 2010).

Corrosion of steel bridges

The loadbearing capacity of structural members in a steel bridge can be reduced due to corrosion. Local deterioration can affect the structural behaviour of a member, which can affect the behaviour of the bridge (Guijt, 2023). An assessment of the current state regarding corrosion is necessary when considering a bridge object to be reused.

The document 'Guidelines for evaluating corrosion effects in existing steel bridges' (Kulicki and National Research Council (U.S.), 1990) shows many examples for different scenarios and has a clear guide on the assessment steps.

- Phase 1 - Preparation of the corrosion analysis by collecting bridge data, understanding the structural behaviour of the bridge, and coordinating the purpose of the inspection, thus clarifying what information is necessary from the inspection.
- The field investigation takes place.
- Phase 2 - Initial qualitative evaluation based on the field investigation results. The criticality of the conditions is identified, to provide a fast initial assessment of the bridge's condition. Critical members that should be examined in more detail are identified.
- Phase 3 - Quantitative evaluation to determine the residual capacity of the bridge, to determine the effect of corrosion on the overall member strength and the effect on the bridge structure as

a whole. Tension, compression and bending members can have a different response to material loss (Kulicki and National Research Council (U.S.), 1990). It should be determined if a more refined evaluation is necessary, which could be costly.

A field investigation is necessary as a basis for evaluation of corrosion damage. The information that should be documented is:

- The location of the damage, which members or details suffer from damage and where on those members.
- The nature of the damage, which could be material loss, deformed components, shifting members or misalignment.
- The geometry and the amount of the corrosion damage;
- The extend of damage, how many members or elements are affected;
- The environmental conditions of the structure, which could be humid, coastal, or industrial.

Effect of corrosion on fatigue
As mentioned in the subchapter on fatigue, areas with a change in cross-section are sensitive to fatigue problems. Pitting corrosion forms local pits or holes and can thus be a sensitive area for fatigue cracks. This is shown in Figure 2.15

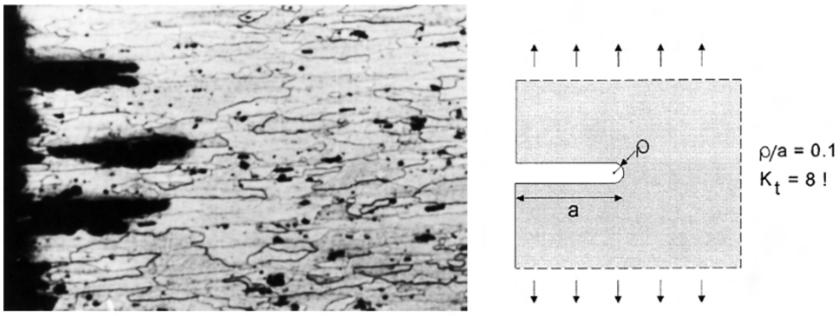

Figure 2.15: Corrosion pits and schematisation (Schijve, 2009).

One of the quantification possibilities for the corrosion damage is to express it as a percentage of section loss, which relates the amount of section loss to the original section of the member. In his thesis, Guijt (2023) explores the reuse potential of a Dutch steel bridge based on a fatigue and corrosion damage evaluation. Using the above stated procedure, he used the section loss as the main quantification of corrosion damage and uses the reduced cross section as an input in the fatigue assessment. This is shown in his flowchart of the assessment method for fatigue and corrosion, in Figure 2.16.

Measurements against corrosion
When corrosion is detected on elements of the donor structure, it should be removed. There are multiple methods, for example, abrasive blasting, chemical cleaning, electrochemical cleaning or grinding and sanding (Kulicki and National Research Council (U.S.), 1990). After this removal procedure, the element's surface should be inspected for any remaining corrosion or damage. If it is necessary, repairs can be performed, after which the steel can be treated with a protective coating (Guijt, 2023).

The type of corrosion protection necessary depends on the atmospheric conditions of the structure's location. The environments can be categorised from C1 (mild environmental) to C5 (very high exposure, such as offshore or coastal areas) (Adsetts et al., 2023). A coat system can consist of different layers from different materials. Commonly used coating systems for infrastructure are zinc-based coatings, non-zinc coating systems, metallising systems, and hot-dipping galvanising. An example of how a three-layer zinc-based coating works, is shown in Figure 2.17. It consists of a zinc primer, a polymer midcoat and a polyurethane topcoat. The topcoat repels water and absorbs light. The midcoat prevents the flow of ions and gases and the bottom layer is higher galvanic and thus corrodes instead of the steel.

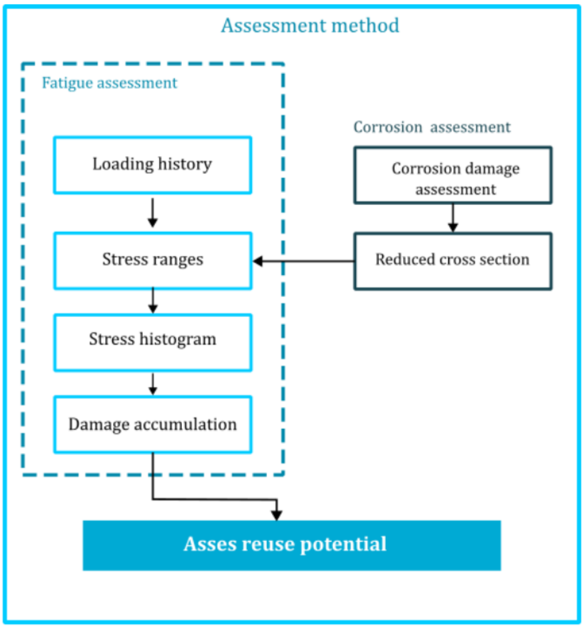

Figure 2.16: Steps assessment fatigue and corrosion steel bridges (E.A. van de Grift, 2017).

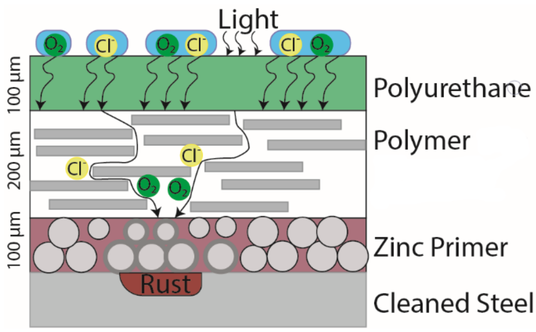

Figure 2.17: Basic mechanism for a three layer zinc coating system (Adsetts et al., 2023)

2.3. Assessing the environmental impact of reuse

2.3.1. The circular economy

Multiple well-established models concerning sustainability apply to the construction sector, like the butterfly diagram of the circular economy from the Ellen MacArthur Foundation, shown in Figure 2.18. Reuse is one of the possible processes to keep products and materials in circulation and to create a circular economy. Besides reuse, possibilities are maintaining, refurbishing, re-manufacturing and recycling (Ellen MacArthur Foundation, n.d.). In line with the R-strategies, reuse is preferred before recycling. Refusing, rethinking, and reducing are preferred strategies to create a waste-free world (Larae Malooly and Tian Daphne, 2023). A graph summarising the R-strategies can be found in Appendix A, in Figure A.3.

2.3.2. Design from End-of-Life

The main principles of the circular economy are eliminating waste and pollution, regenerating nature and circulating products and materials at their highest value. To be able to circulate products at their highest value, it is critical to design products with this circulation in mind. This 'Design **for** End-of-Life' principle is often mentioned in papers and other literature. What is less mentioned, however, is how to design with recycled elements/structures, so 'Design **from** End-of-Life'.

Martínez Leal et al. (2020) presents a structured approach to design from recycling, which is divided

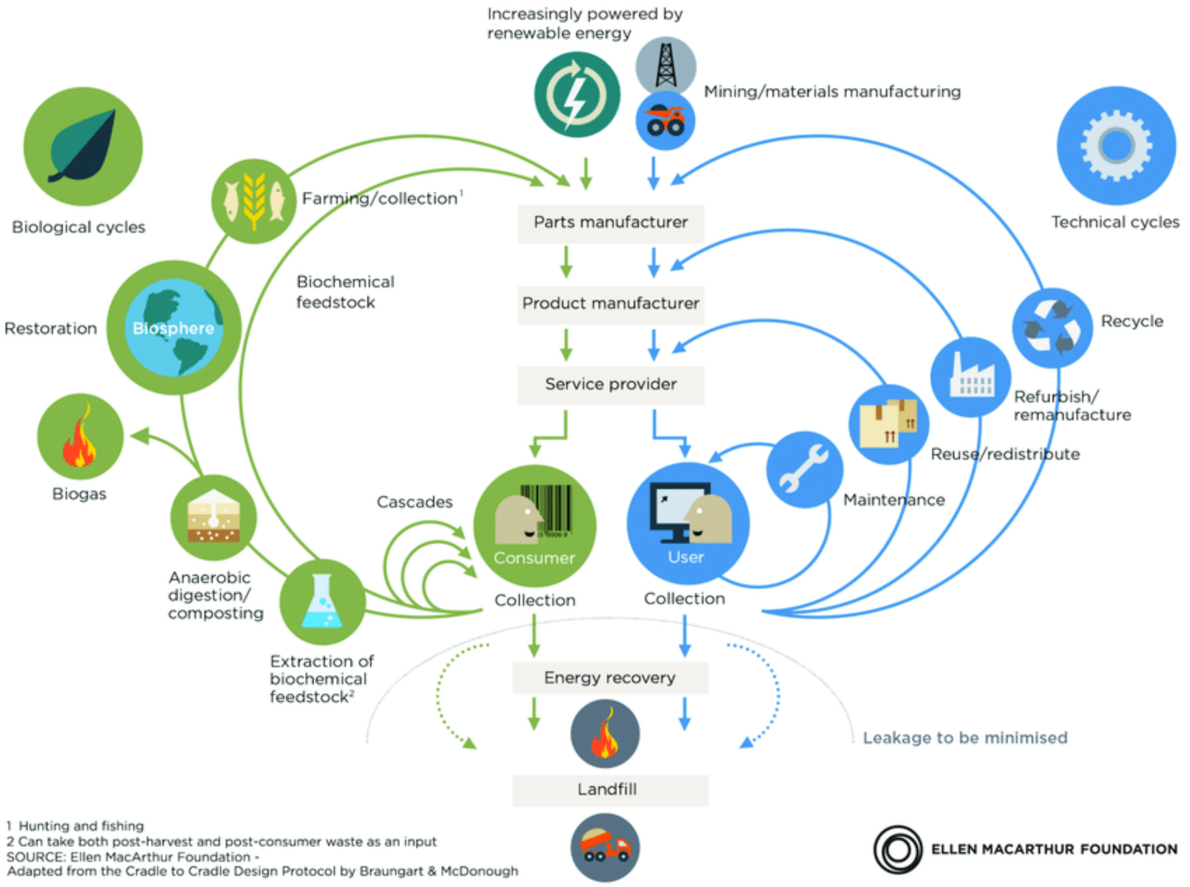

Figure 2.18: The circular economy (Ellen MacArthur Foundation, n.d.).

into three primary steps: the selection of recycled material, the evaluation of convenience indicators and the evaluation of convenience index. Although the methodology is not tailored to the construction sectors, it offers valuable insights applicable to the design in this thesis. The framework for assessing the convenience of recycling incorporates three key indicators:

- Technical convenience: This involves verifying the material's technical quality and evaluating its supply's reliability.
- Economic convenience: This assesses the economic feasibility of recycling compared to using raw materials.
- Environmental convenience: This evaluates the environmental impact of recycling relative to using raw materials.

This comprehensive evaluation framework provides a robust basis for comparing recycling scenarios to new production. In the context of this thesis, the framework is particularly relevant for assessing steel reuse compared to recycling. The research methodology primarily focuses on evaluating environmental convenience. While technical convenience is considered to a limited extent, economic convenience falls mainly outside the scope of this study.

2.3.3. NEN-EN 15804+A2 - Sustainability of construction works

The "NEN-EN 15804:2012+A2:2019 en" (2019) is titled 'Sustainability of construction works Environmental product declarations - Core rules for the product category of construction products'. It is a standard to ensure that all construction products, services and processes have a reliable Environmental Product Declaration (EDP). This declaration document provides quantified information on the environmental impact of a product during the different phases of its life cycle. It is a product for performing a Life Cycle Assessment (LCA). The liability and responsibility for an EDP lies with the manufacturer. The format of the document should be following the “NEN-EN 1766” (2021).

Life cycle assessment (LCA)
The method of performing a life cycle assessment can be split into four stages, which are:

1. Goal and Scope Definition: A description of what is being analysed, the system boundaries, and the functional/declared unit.
2. Life Cycle Inventory (LCI): An inventory of all resources consumed (input) and emissions generated (output) across the life cycle.
3. Life Cycle Impact Assessment (LCIA): Description of the environmental impact of the inputs and outputs of the LCI.
4. Interpretation: An evaluation of the LCI and LCIA, including recommendations.

Life cycle stages
In an EDP, certain life cycle stages are considered. The different stages are subdivided into modules A1–A3, A4–A5, B1–B7, C1–C4 and module D, as shown in Figure 2.19.

- A1-A3: Product stage
- A4-A5: Construction process stage
- B1-B5: Use stage, building fabric
- B6-B7: Use stage, operation of building
- C1-C4: End-of-life stage
- D: benefits and loads beyond the system boundary

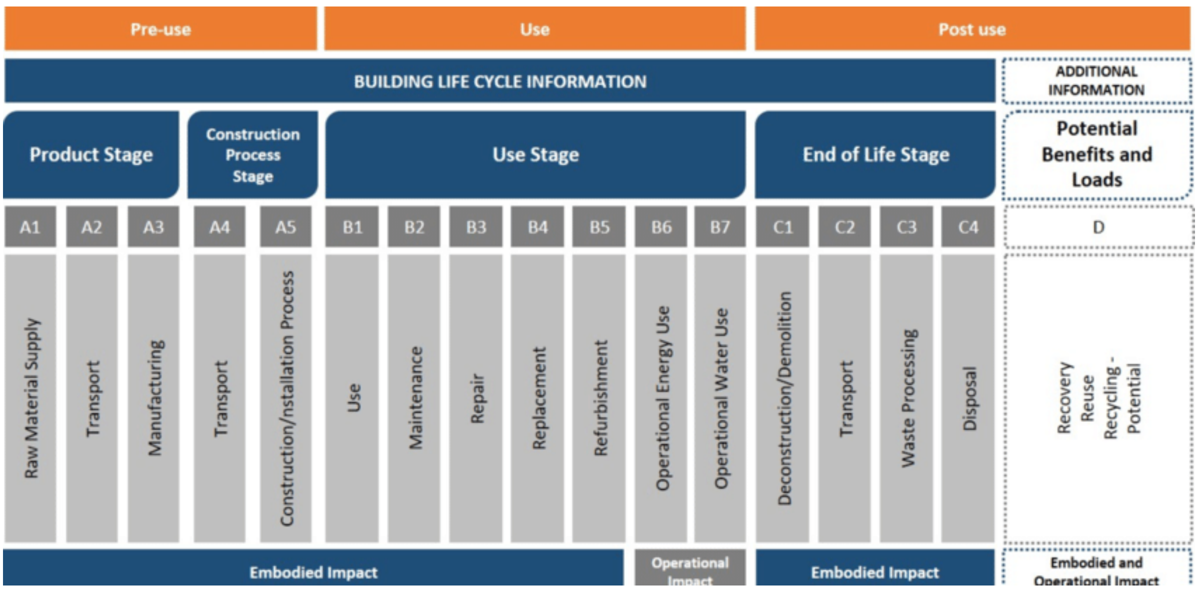

Figure 2.19: Overview of Life Cycle stages (L.M. Pulgrossi and V. Silva, 2020).

System boundaries
The system boundary is defined in the first step of the LCA, and the life cycle stages are decided upon in the analysis. The choice of a boundary influences the accuracy and relevance of the assessment. The possibilities are:

- Cradle-to-Grave: all stages, so a comprehensive LCA.
- Cradle-to-Gate: stages A1-A3, focus on production-related impacts.
- Cradle-to-Site: stages A1-A4, production and delivery to the construction site.
- Gate-to-Gate: only A3, so a focus on a product's production or processing phase.
- Cradle-to-Cradle: all stages, including recycling or reuse, focus on a circular economy.
- Gate-to-Grave: stages A4 up and including D, which is useful when interested in the impact during product installation, use and disposal.
- End-of-Life: stages C1-C4, used to assess the impact of a product after its useful life ends.

An example of the process for each life cycle stage for steel products, including recycling or reuse, can be found in Figure A.4 in Appendix A.

Functional unit and declared unit
The Environmental Product Declaration of different products can be used to compare them. A functional or declared unit should be defined to make comparison possible. The functional unit reflects the quantity (amount of product) and the quality (durability, strength) required to deliver the specified function. For example 1 kilogram of structural steel with a lifespan of 50 years. A declared unit can be used if the product's function is unknown, like for raw materials. For example, 1 kilogram of structural steel.

Life Cycle Impact Assessment
A life cycle Impact Assessment is the third step of the LCA. It involves classifying, characterising and sometimes normalising and weighting the environmental burdens associated with the product's life cycle.

The various inputs (raw materials, energy) and outputs (emissions, waste) are assigned to impact categories during classification. For example, CO_2 emission is classified as Global Warming Potential. During characterisation, the total impact per impact category is calculated. It is optional but possible to normalise the impact results. For example, the global warming potential might be expressed as a percentage of a country's total annual emissions, giving a sense of the relative scale of the product's environmental burden. Furthermore, weighting could be done to assign weights to different impact categories based on their perceived importance. For example, climate change might be given more weight than eutrophication if that is seen as the more pressing issue in the context of the study.

There are different approaches to doing the LCA, with varying boundaries of the system. These should be clearly defined in the first step of the process.

1. The Cut-off Approach (100-0) is also known as the recycled content method. It only considers the benefits of material recycling on the input side (module A). It neglects recycling at end-of-life (World Steel Association, 2017).
2. The End-of-life Approach (0-100) expands the boundary of the study to include another product system. It credits recycled material at the end of life as it avoids a burden for the next life cycle of production from virgin material. This is also known as the closed material loop method and is relevant for steel(World Steel Association, 2017).
3. The 50:50 approach is a compromise approach between the previously explained approaches. It credits both recycled content and end-of-life recycling (World Steel Association, 2017).
4. The market-based method is similar to the End-of-life approach but includes an extra factor to account for the market supply and demand. This factor should be determined by, for example, considering the financial value of the non-reused end-of-life product compared to a new product. This is, however, not a well-established method (World Steel Association, n.d.).

5. Lastly, there is the multiple reuse method, which considers the number of times the product is reused before it is recycled. The burdens from manufacture and end-of-life recycling are equally shared between the life cycles (World Steel Association, n.d.).

Environmental impact categories and indicators
The impact of a product or process can be expressed in different ways, for which impact categories and indicators are created. Each category also has a standardised unit. The table in Figure 2.20 is from the NEN-EN 15804+A2 and shows the core environmental impact indicators. Note that since 2019, there has been a transition from other indicators from a so-called A1 set, to this A2 set.

Figure 2.20: Core environmental indicators (blue) and optional indicators (gray) of the EN 1804-A2 set.

2.3.4. Stage D for structural steel

The potential for recovery, reuse and recycling and its environmental impact is related to life cycle stage D. A recent article in the journal of 'Bouwen met Staal' sheds some light on stage D with regards to structural steel (J-P. den Hollander, 2024). There are three production routes for structural steel:

1. The primary production process is the production of steel in a Blast Furnace (BF) from raw materials iron ore and coal. It has a recycled content of 10 to 20 percent for cooling. The environmental footprint in terms of CO_2 production is $2kg[CO_2 - eq]/kg$ steel.
2. The secondary process is the production of steel in an Electric Arc Furnace (EAF) entirely from scrap steel, so with a recycled content of 100 percent. The environmental footprint in terms of CO_2 production is $0.5kg[CO_2 - eq]/kg$ steel.
3. Lastly, steel from an existing structure can directly be reused, resulting in a percentage of steel that can be called reused content. The environmental footprint in terms of CO_2 production is $0.1kg[CO_2 - eq]/kg$ steel.

It should be noted that in Module D, for steel from the secondary process, some carbon emission from the primary production is accounted for as well. This is because all steel is produced first through the primary production process. For example, ArcelorMittal's heavy structural steel is called XCarb. XCarb is made with 100% scrap in an electro-furnace powered by sustainable electricity. CO2 emissions for module A1-A3 are $0.333 kg[CO_2 - eq]/kg$ steel and CO2 emissions for module D are $+0.214 kg[CO_2 - eq]/kg$ steel.

How much heavy structural steel can be reused depends heavily on the building design. In other words, is the building designed to be dismantled. If it is not, dismantling proves difficult and time-consuming, steel profiles are damaged and the demolisher often decides to sell the steel as scrap after all. Therefore, the end-of-life percentage of reuse is generally lower than the end-of-life percentage of recycling.

Calculation example module D
In Figure 2.21, there is a calculation example of module D, according to Annex D of the NEN-EN 15804 and more specifically on D1. It shows the positive environmental impact in terms of CO2-equivalent for the case of a steel building that is reused for 80 percent. It takes into account that 16 percent of the steel input was recycled, which is an average value for steel produced in the Netherlands (J-P. den Hollander, 2024).

$$e_{module\ D} = e_{module\ D1} + e_{module\ D2} + e_{module\ D3} + e_{module\ D4}$$

$e_{module\ D1}$	Loads and benefits related to the export of secondary materials
$e_{module\ D2}$	Loads and benefits related to the export of secondary fuels
$e_{module\ D3}$	Loads and benefits related to the export of energy as a result of waste incineration
$e_{module\ D4}$	Loads and benefits related to the export of energy as a result of landfilling

$$e_{module\ D1} = \sum_i \left(M_{MR\ out}\big|_i - M_{MR\ in}\big|_i\right) \cdot \left(E_{MR\ after\ EoW\ out}\big|_i - E_{VMSub\ out}\big|_i \cdot \frac{Q_{R\ out}}{Q_{Sub}}\bigg|_i\right)$$

$M_{ER\ out}$	Output flow of material that will be recycled or reused
$M_{ER\ in}$	Input flow of material that reached end-of-waste state and enters the system as secondary fuel
$E_{MR\ after\ EoW\ out}$	Emissions and resources consumed from material recovery (recycling and reusing) processes
$E_{VMSub\ out}$	Emissions from primary material that would replace the secondary material in the next production system
$Q_{R\ out} / Q_{Sub}$	Quality ratio between outgoing recovered material (recycling and reusing) and the substituted material

2.3.5. Environmental impact assessment in practice

To achieve becoming climate-neutral and circular by 2030, Rijkswaterstaat has developed strategies, called transition paths (transitiepaden). These tackle the processes with the biggest climate impact, like road pavement, shoreline care, waterway maintenance, engineering structures, construction sites and construction logistics (Frederieke Knopperts, 2020).

Part of the strategy is to reward sustainability by taking into account a calculation of the Environmental Cost Indicator (MKI) of tenders. In line with their 'Best Value approach' offers with a lower MKI value are awarded an advantage. They developed their own calculator tool, DuboCalc (Duurzaam Bouwen Calculator), that can be used to calculate the MKI value.

Situation Demountable steel structure with 80% end-of-life reuse

$M_{ER\ out}$ 80% = 0.8

$M_{ER\ in}$ Reused content is 16% in NL so =0.16

$E_{MR\ after\ EoW\ out}$ Emissions of reuse = 0.1 [kg CO2-eq]

$E_{VMSub\ out}$ Emissions of elektro-oven = 0.5 [kg CO2-eq]

$Q_{R\ out} / Q_{Sub}$ No quality loss so = 1

$$e_{module\ D1} = \sum_i \left(M_{MR\ out}\big|_i - M_{MR\ in}\big|_i \right) \cdot \left(E_{MR\ after\ EoW\ out}\big|_i - E_{VMSub\ out}\big|_i \frac{Q_{R\ out}}{Q_{Sub}}\bigg|_i \right)$$

= (0.8 – 0.16) * (0.1 * 0.5*1) = -0.256 kg [CO2-eq]

Figure 2.21: Calculation of module D1 for 80 percent reused steel

2.4. Market Dynamics: Supply and Demand

2.4.1. Supply

Bruggenbank.nl

Set up from an idea of Royal HaskoningDHV in the 1980s, the bruggenbank acts as a marketplace for bridges. An example of a successful project at the time is the swing bridge at Kiesterzijl - a bridge that originated in South Holland. After demand diminished over the years, the Bridge Bank was revived in October 2019. It facilitates the matching of supply and demand, including the initial contact and the placement and preparation for the use of the bridge at the new location. Foundation and substructure design can also be carried out by the Bruggenbank, aiming to contribute to a smooth buying and selling process ("de Bruggenbank, over ons", n.d.). A screenshot of the webpage can be found in Figure 2.22.

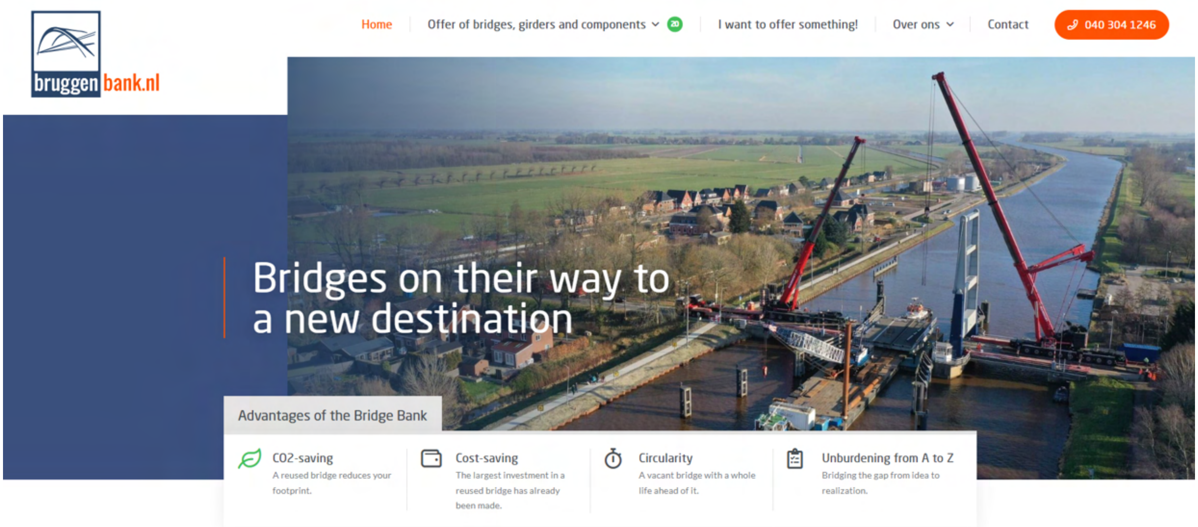

Figure 2.22: Screenshot webpage bruggenbank.nl (translated).

Nationale Bruggenbank

Launched in March 2021, the Nationale Bruggenbank is an initiative of AmRoR, a collaborative alliance between Rijkswaterstaat and the municipalities of Amsterdam and Rotterdam, and the Bruggenstichting. The goal of this initiative is to stimulate the reuse of bridges, resulting in less energy and materials necessary for the construction of new bridges. Besides complete bridge structures, the platform is developing and also offering parts like bridge girders and railings (Barbara Kuipers, n.d.)

2.4.2. Demand

Within the Netherlands, a large amount of existing civil engineering structures are nearing their end of life and should be replaced. A study performed by TNO (A.N. Bleijenberg, 2021) states that there is EUR 1 billion a year spent on civil infrastructure renewal, an amount that will rise to EUR 3-4 billion in 2040-2050. It can be concluded that there is a big demand for new structures that can potentially be designed including donor structures.

2.5. Conclusions

This chapter has reviewed essential topics related to the reuse of steel bridges that will be used to answer the research questions and complete the research objectives. The following conclusions can be drawn.

The **guidelines for reuse**, such as NTA 8713, provide a structured approach for creating a donor structure file during the analysis step of the design cycle. However, these guidelines lack detailed provisions for connections and use impractical inspection units for complex cases involving varied cross-sections. Despite these limitations, the steps in NTA 8713 align well with those in SCI and are robust enough for preliminary designs, particularly for applications like cyclist or pedestrian bridges that are not susceptible to fatigue.

The discussions on **fatigue** and **corrosion** emphasise their intertwined nature. There is a need for protective coatings against corrosion and inspection strategies to detect fatigue. Additional calculations are necessary for applications with significant fatigue loading, as highlighted in step 3 of the JRC procedure.

The **environmental impact assessment** section establishes a clear guideline for evaluating reuse. From different approaches, the cradle-to-grave approach should be used for comprehensive analysis. Starting with the 50:50 method and comparing it to the cut-off approach can offer valuable insight into the effect of Module D on the analysis. Furthermore, valuable benchmarks for CO_2-equivalent emissions in steel production have been stated in the section.

Finally, the exploration of **supply and demand** highlights platforms like the Nationale Bruggenbank and Bruggenbank as promising tools for simulating reuse in practice.

3

Analysis: reuse case study

The bridge that is considered as the donor structure in the case study for this thesis is the Keizersveerbrug. Originally, the elements of which this bridge consists were part of another bridge; the Moerdijkbrug. A more elaborate overview of the structure's history is given in subsection 3.1.1. The current state of the structure is described in Subsection 3.1.2, presented as a donor structure file, in accordance with the NTA 8713. The new implementation for this donor structure will be the Ackerdijkse brug. An overview of this site analysis is given in Subsection 3.2. Furthermore, the logistics of transport and storage of the donor structure are discussed in Subsection 3.3. Both three locations of this bridge are highlighted in the Figure 3.1.

3.1. Reusability of the existing structure (Keizersveerbrug)

3.1.1. History of the bridge

The Moerdijkbrug was constructed in 1936, spanning over the Hollandsch Diep in the province of Zuid-Holland. This steel truss bridge for car traffic was opened by the Queen of the Netherlands, Queen Wilhelmina. It was the second bridge between the Island of Dordrecht and Noord-Brabant, the first being a railway bridge. Design and construction was done by local construction company Penn and Bauduin. A picture of the opening can be seen on the left of Figure 3.2.

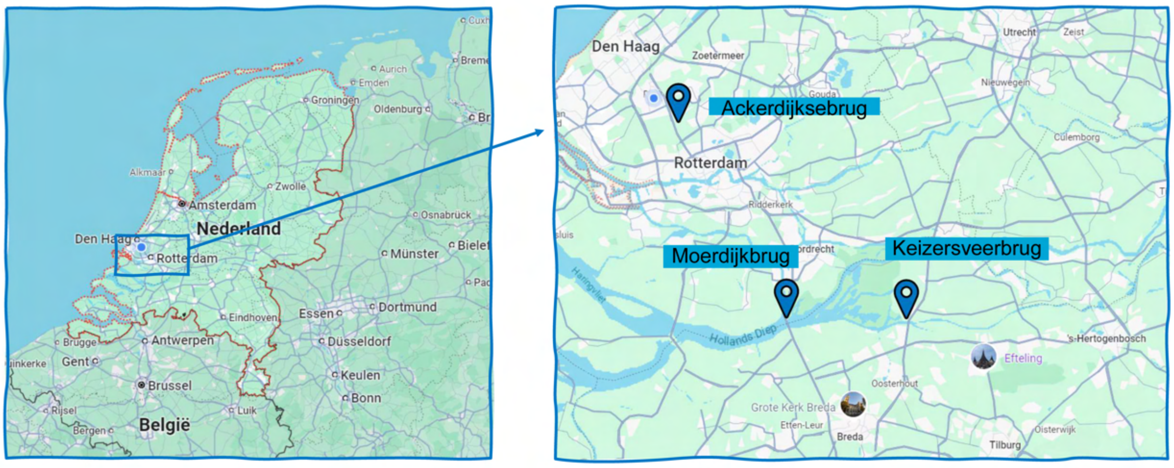

Figure 3.1: Map showing three locations of applications of the bridge from the case study.

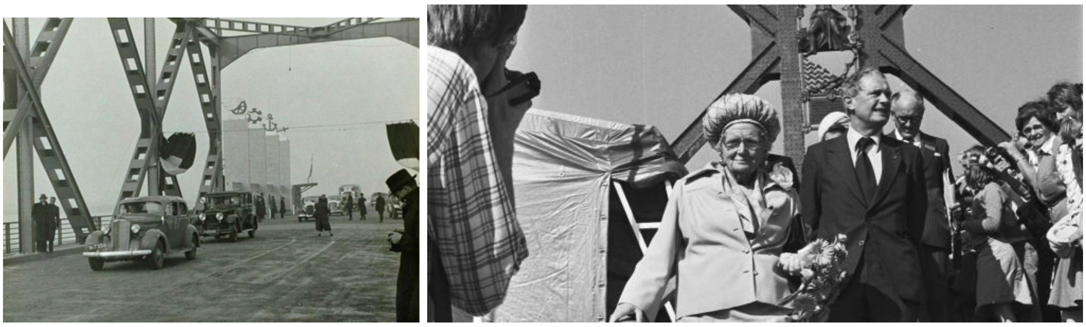

Figure 3.2: Historic images of the opening of the first traffic bridge, Moerdijkbrug 1936 (Wiel van der Randen, n.d.) and the second bridge in 1978 by Queen Juliana ("Koningin Juliana opent de Moerdijkbrug", 1978) .

The bridges were destroyed by the Germans in 1944, during WWII, to prevent the Allies from using them. They could be repaired and were opened again by Prince Bernard in 1946. Due to the increase in car use and thus traffic, the Moerdijkbrug soon became a critical junction and was replaced by a new bridge in 1987. The new bridge was opened by Queen Juliana, as can be seen on the right of Figure 3.2. In the background of this picture, a monument consisting of elements from the old bridge can also be seen.

At the location of Keizersveer, named after a ferry connection across the Bergsche Maas, the first traffic bridge was constructed in 1931. This bridge was blown up during the Second World War but restored after. A picture of this bridge is shown in figure 3.3. However, the bridge had to be replaced in 1978 to accommodate more traffic due to increased traffic. For this, six trusses from the old Moerdijkbridge were used.

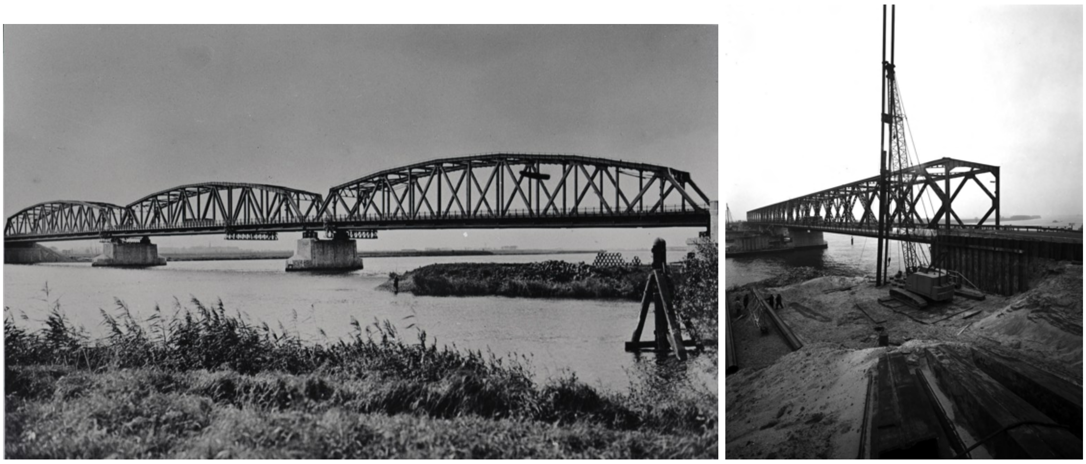

Figure 3.3: Historic images old Keizersveerbrug ("Keizersveerbrug jaren 30.jpg - Wegenwiki", 1930) and construction second bridge 1978 using old Moerdijkbrug (Beeldbank RWS, n.d.).

This is one of the only examples of a steel bridge in the Netherlands that has been given a second life on the object level. From 1978 up until now, the bridges have functioned very well. They consisted of 2x2 car lanes and an emergency lane, with a lane for slow traffic in between. On both sides, there is a lane for bicycles (Wegenwiki, 2024). Four trusses have a length of 100 meters, and two have a length of 87.5 meters. They all have a width and height of 12.5 meters (Ir. C.J.F. Hulsebosch et al., 2023). More exact measurements can be found in Figure 3.4.

3.1.2. Current function and state of the Keizersveerbrug

At the moment, Rijkswaterstaat has plans to replace the Keizersveerbrug since traffic has increased even more. Two new bridges with three lanes and an emergency lane will replace the Keizersveerbrug (Wegenwiki, 2024). Since the replacement plans have become public, the idea of reusing the bridge

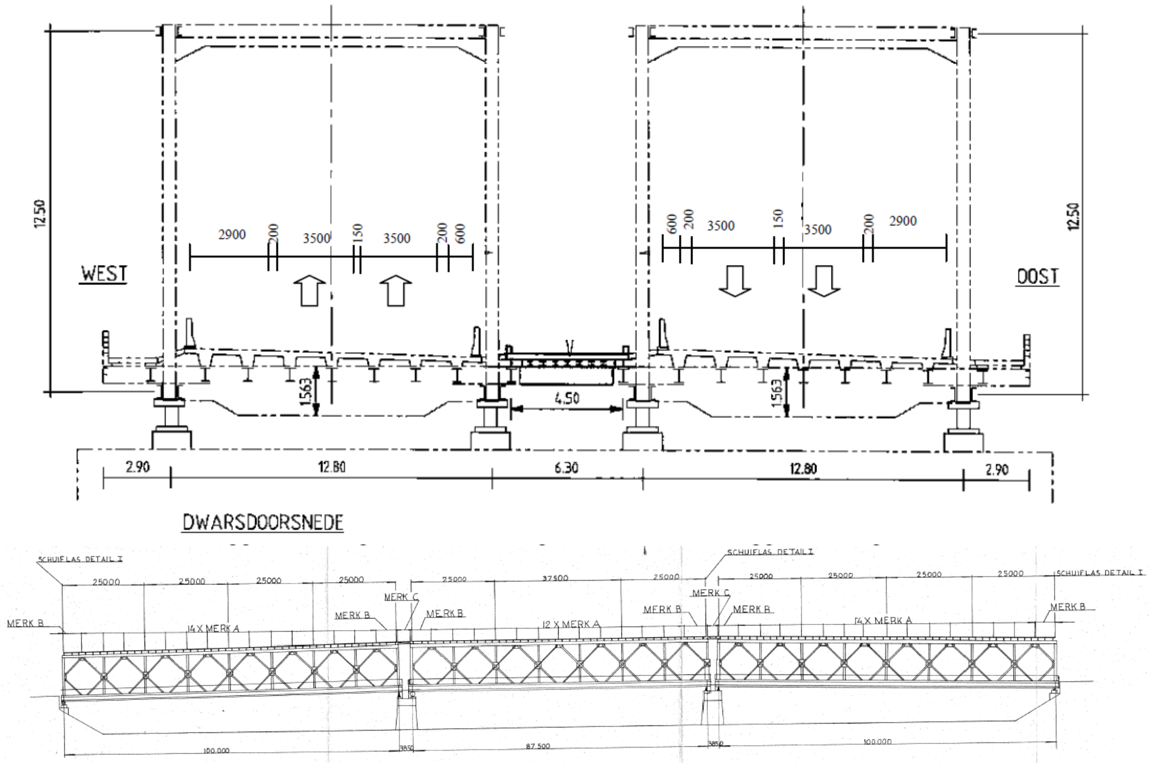

Figure 3.4: Original documentation of cross-section of Keizersveer (Movares, 2016b).

for a second time has been discussed. The topic has been covered in some news articles and studies, including the challenging possibilities of transport, storage, and reuse of the bridge(elements). For example, an article by Rijkswaterstaat discusses the necessity of finding a storage place for the bridge (elements) to give it a third life (Rijkswaterstaat, 2023).

Figure 3.5: Pictures of the current Keizersveerbrug (Rijkswaterstaat, 2023) (left) (Wegenwiki, 2024) (right).

Overall structural performance

According to a study by AmRor (B. van Offenbeek-Kuipers et al., 2021), the bridge is currently in good technical condition. It has been assessed under the NEN8700/8701. It can be concluded that the main load-bearing structure meets the strength requirements and is suitable for a residual lifespan of at least 30 years at its current location. This residual lifespan will be longer if the bridge is relocated to an area with lower traffic intensity (and lighter freight traffic composition). The concrete driving floor complies with NEN8702. However, it should be mentioned that although the road surface complies with NEN8702, it does not comply with hefty axle loads, as in Load Model 2 of NEN-EN 1991-2. This should be considered through a use restriction (not allowing permanent exemptions) or a deck replacement.

3.1.3. Donor structure file

A preliminary donor structure file is set up in accordance with Chapter 2.1. The following documents about the design of the Keizersveerbrug are available:

- Overview drawing Keizersveer 1974 ("Dwarsdoorsneden bruggen over de bergse maas bij Keizersveer verbouwing 1974", 1975);
- Cross-sections after renovation 1974 ("Samenstelling bruggen bij Keizersveer uit overspanningen van de brug bij Moerdijk", 1974);
- Drawing transport 1976 ("Het verhalen van brug van eind-naar midden overspanning", 1976);
- Archeological assessment (D. Schaars, 2018).
- Fatigue and fracture toughness assessment (H. Slot and J. Maljaars, 2016).

However, reports that are available refer to other source materials, so it is assumed that there is more information in the archives of Rijkswaterstaat, of at least document status two or higher.

Inspection units
Figure 3.6 shows the categorisation of the types of elements in the Keizersveerbrug. The following different types of elements can be categorised:

- Main load-bearing beam bottom / Bottom cord
- Main load-bearing beam top / Top cord
- Vertical truss elements / Columns
- Diagonal truss elements
- Longitudinal girders
- Crossbeams
- Cross bracings

However, for each category, there is a large variety in the different cross-sections (Movares, 2016b). In practice, this will result in a large amount of small inspection units. For this preliminary assessment, it is sufficient to use the categorisation as units and assume all sections within these categories are the same.

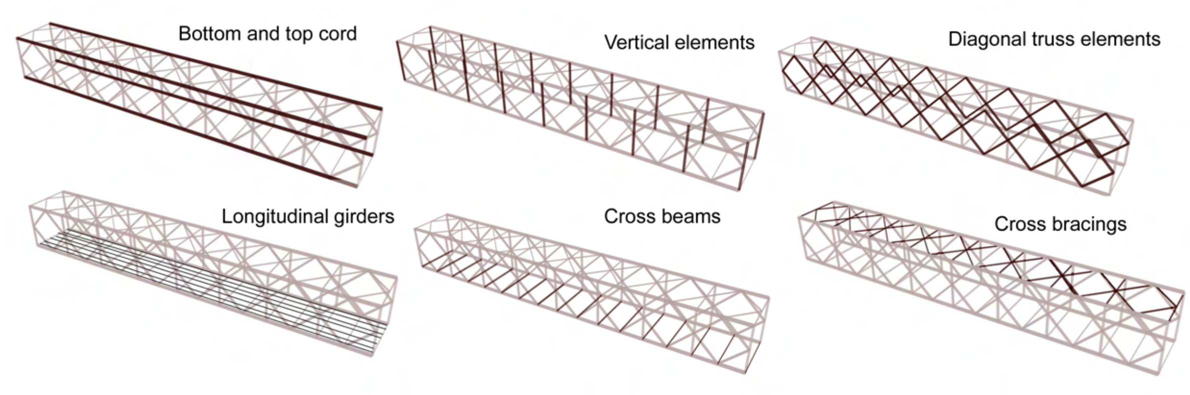

Figure 3.6: Different element categories of the load-bearing structure of the Keizersveerbrug.

Visual inspection
Based on an available inspection report from 2015 (Movares, 2016b), the inspection table, as can be seen in Figure 3.7, is found. There are some damages, holes, welded-on parts, corrosion and losses of cross-sections found. However, the report also concludes that those do not influence the structural performance of the bridge.

Assessment of preservation
Preservation was assessed in 2022, and it is concluded that the current preservation does not contain

Subject of inspection	Assessment	Findings/observations
Damage, repair	Present	Replacement of some rivets by bolts. There are some local deformations in the upper flange of the upper chord. Some deformations of cross beams.
Holes	Present	Holes are found in the upper cord of one of the bridges.
Welded parts	Present	New material is added to recover holes.
Corrosion	Light	Light corrosion on longitudinal girders' top flanges. Corrosion of reinforcement of concrete deck of bike lane.
Loss of cross-section	Present	At the location of corrosion, max 3 mm loss of cross-section.

Figure 3.7: Report visual inspection Keizersveerbrug.

Chromium-6 or other heavy metals (Nebest, 2022). The assessment table can be found in Figure 3.8. An example of a taken sample in the assessment is shown in Figure 3.9.

Subject of inspection	Assessment	Findings/observations
Type of conservation	~~organic~~ coating	Current white/grey paint layer
Toxic substances?	No	An inspection report by Nebest, 2022 shows no Chromium-6 or other heavy metals

Figure 3.8: Summary assessment of preservation

Material properties

The steel is older than the origin of the earliest code mentioned in the NTA 8713, which is 1955. At that time, the V.O.S.B 1936 was in place and contained regulations for the design, manufacture and erection of steel bridges code in place before 1955 ("VOSB 1936", 1933). The documentation shows that elements are either St. 37, which is converted to S235, or St. 52, which is equivalent to S355 (Movares, 2016a).

Destructive impact tests have been performed on the vertical and diagonal elements, and the fracture toughness has been calculated (H. Slot and J. Maljaars, 2016). A Charpy V-notch impact test has measured the energy absorption during impact to indicate toughness. This is expressed as fracture toughness using the British norm BSI 7910:2013. Figure B.1 in Appendix B shows the results of this calculation.

Fatigue calculation

As documented in H. Slot and J. Maljaars (2016), a fatigue assessment for the diagonal and vertical elements as well as the bottom and top cord is performed. The influence of the relative brittle material properties as found in the toughness calculation, is incorporated into the S-N curve, or rather the maximum allowable damage D, by means of a crack growth calculation based on fracture mechanics.

From the results of these calculations, it follows that the influence on the overall fatigue life is very limited as the fatigue initiation phase is dominant and is not affected by the fracture toughness of the material. The critical damage reduces from Dcrit = 1 for tough material to Dcrit = 0.94 to 0.99 for tensile-loaded riveted material in the Keizersveerbrug bridge. The fracture toughness does not affect pressure-loaded components. Therefore, the following remains true: Dcrit = 1.0.

Keizersveerbrug ► Noordwest bovenbouw ► Verfmonster 202092		VM
Bouwdeel:	Diagonaal (vakwerkligger)	
Algemene opmerkingen:		
Variant Grijs, 3 verflagen	Geen Cr6 aangetroffen in-situsneltest	Monster 202092

Figure 3.9: Screenshot assessment form of paint on Keizersveerbrug (Nebest, 2022).

Based on that, a calculation is done for the critical fatigue crack dimensions. Loading history and loading for a future scenario of the Keizersveerbrug staying at its current location up until 2053 is taken into account. Critical crack dimensions are conservative since the calculation is based on a temperature of -20 degrees and extreme values of the traffic loads. It is concluded that any fatigue cracks in tensile-loaded components may be critical before the cracks have grown out below the rivet head. Due to the fracture toughness of the material, a partial factor of $\gamma_m = 1.35$ is used in the calculation. It can be concluded that the calculated fatigue damages in 2053 are significantly lower than the critical values. Thus it is concluded that the calculated, safe residual life is greater than the target life (to 2053).

Examination and consequence class
Based on the documentation available and the results from the visual inspection and preservation assessment, it can be concluded that all consequence classes are possible for a design that includes reused elements from the Keizersveerbrug. However, if CC3 is desirable, it is impossible to use the longitudinal girders of the deck due to the loss of cross-section, and it should be verified in detail if the top cord deformation is within limits.

3.1.4. Other aspects

The bridge has an orange monumental status due to its long history and its being a well-preserved truss bridge from before the war. In line with a document of Rijkswaterstaat on monuments, Kader monument, any changes should be well-argued, and a permit must be granted (Rijkswaterstaat, 2014).

3.2. Site analysis for the new implementation (Ackerdijksebrug)

The Ackerdijksebrug, commissioned by the Municipality of Delft, should be designed to serve as a pedestrian and cycle bridge and a wildlife crossing over the A13 highway. Central to this project is reusing a part of the historic steel truss from the Keizersveerbrug, reinforcing Delft's commitment to sustainability and honouring the donor structure's rich history.

This project aims to establish a rapid cycling route between Delft and Rotterdam Alexander, which aligns with Delft's mobility policy, while also creating a vital ecological connection between Ackerdijkse Plassen and Midden-Delfland. By linking the east and west sides of the highway, the bridge not only promotes sustainable transportation but also enhances biodiversity through the wildlife crossing, reflecting the municipality's priority to conserve and connect landscapes (Gemeente Delft, 2020).

The Ackerdijksebrug, designed with a reused structure, reflects Delft's values: a city that is not only rooted in history but also embraces sustainability, inclusivity, and technological innovation. It can symbolise Delft's commitment to creating a connected and resilient city for the future.

3.2.1. Description of the area

The Ackerdijksebrug will be located in the municipality of Delft, within the province of South Holland, bridging the A13 highway. Delft is situated between Rotterdam and The Hague, with Leiden to the north, positioning it centrally within the Randstad. The A13 highway connects Rotterdam and The Hague, supporting over 150,000 vehicles daily (Waterstaat, n.d.).

The Ackerdijksebrug will address both human and ecological connectivity. It will link important cycling routes, including the path from Delft to Rotterdam Alexander in the South and Berkel in the East. Additionally, it will serve as a wildlife crossing, connecting the Ackerdijkse Plassen nature reserve to the east with Midden-Delfland to the west. The Ackerdijkse Plassen is a protected wetland, while Midden-Delfland is an agricultural and recreational area. An aerial view can be found in Figure 3.10. The species that the bridge should accommodate are small mammals like shrews, voles, bats and hedgehogs, as well as insects like the butterfly and the bumblebee.

Figure 3.10: View of the project area (Google Earth).

Figure 3.11 shows pictures from a site visit to this area, highlighting the most relevant aspects, like the car road, trees, bicycle path, water, grassland and the highway.

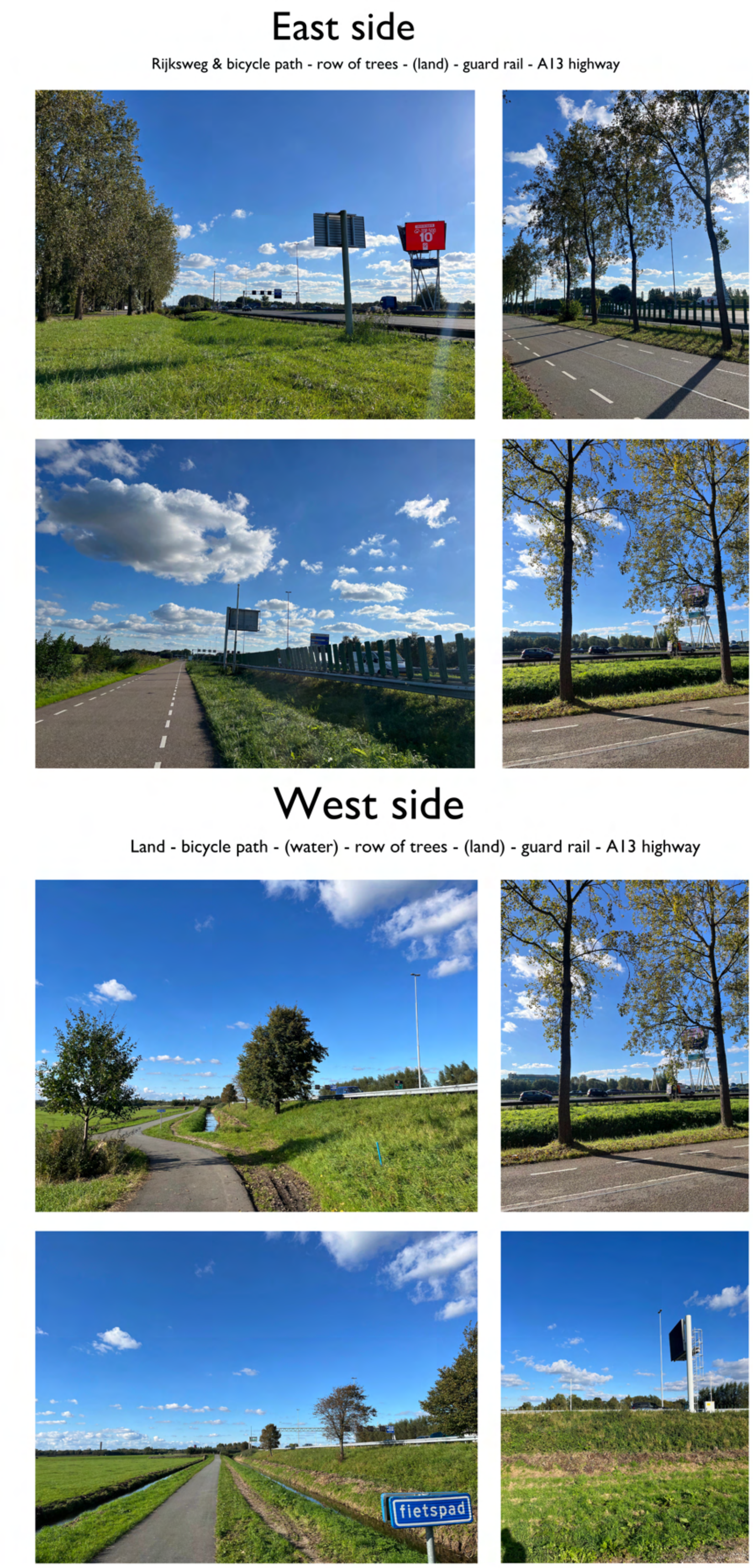

Figure 3.11: Pictures from a site visit of both sides of the A13 highway on the possible location of the Ackerdijkse brug.

3.2.2. General considerations for bridge alignment

The alignment of a bridge is an essential factor in ensuring functionality, safety, and integration within its surroundings. General important aspects and the possible impact of reuse are the following:

- **Connectivity**: The bridge should effectively connect existing routes, causing minimal disruption to current traffic flows of vehicles, pedestrians and cyclists.
- **Topography**: The terrain at the site, including flat or sloped areas, will influence the bridge's alignment. A smooth transition between the approaches and the main span of a bridge is required, which takes careful planning of the embankments and gradients. Furthermore, the topography influences the transportation possibilities of a donor structure's original and new locations. This is further specified in Section 3.3.
- **Mixed use and traffic flow**: For multi-use bridges, separating fast and slow-moving traffic like cyclists and pedestrians might be necessary for safety and efficiency. Mixed-use paths are also possible but should be wide enough to prevent user conflicts.
- **Slope design**: The slope at each end of the bridge impacts its accessibility. A steeper slope can be uncomfortable or unsafe for cyclists and pedestrians, but a less steep slope will take longer. A balance is required between slope steepness and the length of the approach. A donor structure has specific dimensions, such as the structural height of the deck, that can influence the slope design. Furthermore, the possibility of incorporating the reused objects in the slope could be considered.
- **Structural constraints**: The placement of supports is influenced by the structural properties of the bridge and any constraints in the surroundings. Support spacing should match the bridge's design while minimising the impact on the environment around and the infrastructure below the bridge. The possibilities for this depend on the dimensions of the donor structure and might be more or less flexible based on the typology of the structure.

3.2.3. Specific alignment for the Ackerdijkse Bridge

The Ackerdijkse Bridge will primarily serve as a connection for a west-east bicycle path. Key considerations for this site include:

- **Existing bicycle route**: A bicycle path runs from west to east. This can be seen in Figure 3.12 on the left. The new bridge must connect this route, though some deviation from the original path can accommodate the bridge's design. The connection should be logical and user-friendly to avoid confusion and ensure the bridge is valuable.
- **Topographical constraints**: Both ends of the path, Ackerdijkseweg, are occupied by houses and industrial buildings. This limits the availability of flat land and enough space for the bridge's approach. However, further north, there is more open space where the bridge can be better aligned. Furthermore, the height of the land ranges between -2.0 NAP to -1.30 NAP, as seen in Figure 3.13.
- **Mixed-use considerations**: A separate path for cyclists is desirable because the cyclists are expected to travel at higher speeds. This separation will reduce potential conflicts with pedestrians and ensure safety. The exact configuration of the paths will influence the slope design at both ends of the bridge, as steeper slopes can be used for an ecological passage but not for users on a bike.
- **Slope options**: Three primary options for the bridge slope are being considered:
  1. **Slope on embankment**: This option would involve creating an embankment for the slope. This requires significant amounts of soil, which can significantly impact the surrounding environment.
  2. **Slope on supports**: The alternative is to create the slope on bridge supports, reducing the need for extensive embankments but requiring the introduction of more building materials.
  3. **Slope from reused elements:** Another option would be to incorporate reused elements for the slope of the bridge if feasible.

- **Support placement**: The placement of the supports is constrained by the grit size of the donor bridge (Keizersveerbrug), which has a support spacing of 12.5 meters. The maximum length of the bridge is constrained by the availability of the donor structure, which is four elements of 100m and two of 87.5m. Furthermore, planning should account for a future tramline in the area, as shown in Figure 3.12 on the right. This reservation is located on the west side of the A13 highway. A preliminary design currently considered by the municipality consists of a bridge with a main span of 100 meters.

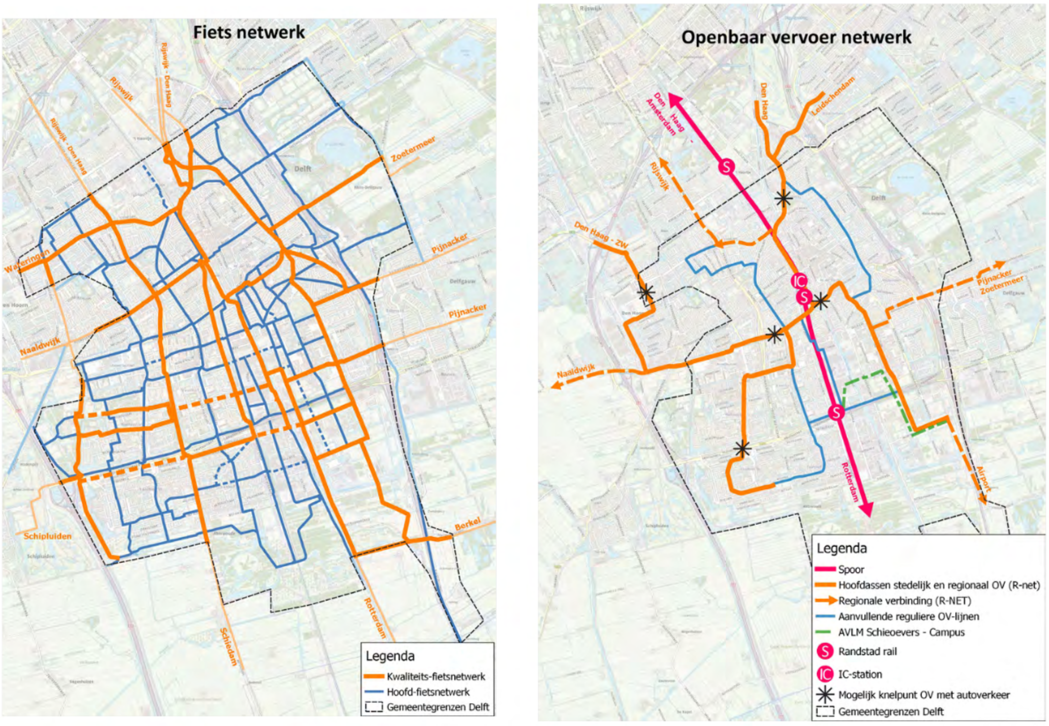

Figure 3.12: Cyclist network (left) and public transport network (right) of the municipality of Delft (Gemeente Delft, 2020).

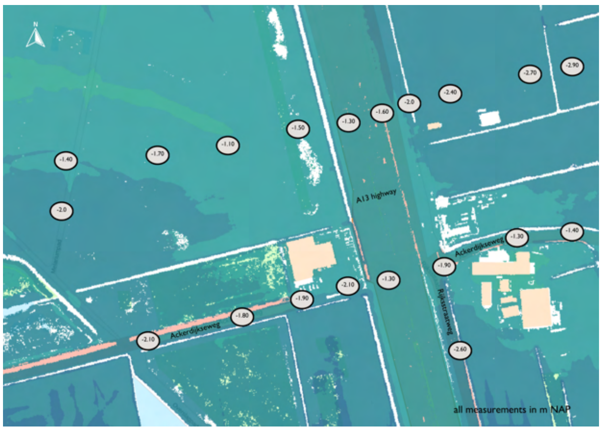

Figure 3.13: Height map of the area, with height in meters above NAP (adapted from “AHN5 - DTM | Viewer Actueel Hoogtebestand”, n.d.).

3.3. Logistics

3.3.1. Transport

An exploration of the possibility of transport of the 100m bridge elements from their location to a dock in Barendrecht has been conducted by Royal Haskoning (Royal Haskoning DHV, 2022). The dismantling can be done by lifting the bridge sections using a pontoon with steel support structures and removing them with water. The intended arrangement has two support structures on the 75x22m pontoon to dismantle the bridge, as shown in Figure 3.14. Based on calculations, it is concluded that the structure can resist the resulting forces due to this new support system without any steel reinforcement. Figure 3.15 shows the result of the model.

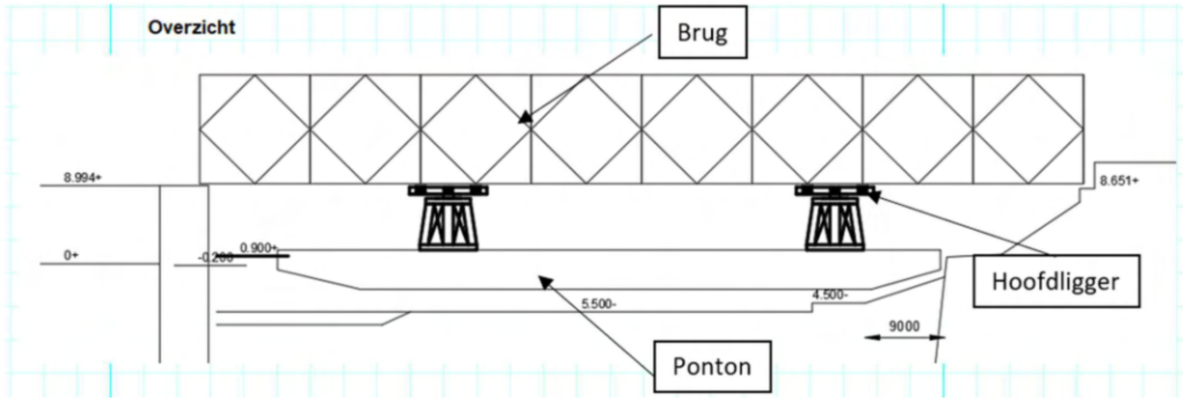

Figure 3.14: Schematic side view of jacking operation (Royal Haskoning DHV, 2022).

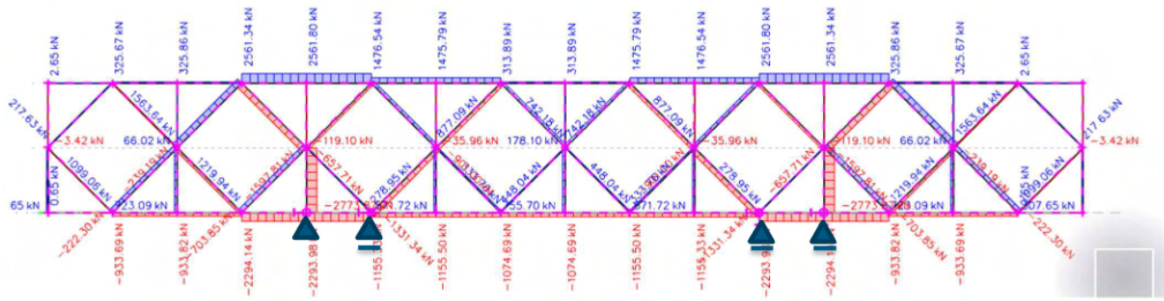

Figure 3.15: Result of calculation model during transport situation (Royal Haskoning DHV, 2022).

The suggested route from Keizersveer to the storage location can be seen in Figure 3.16. The waterways this route consists of are Bergsche Maas, Hollands Diep, Merwede and Oude Maas, and the route is about 65 kilometres long. The bridges that will be crossed are Spoorbrug Baanhoek Sliedrecht (1), Merwedebrug (2) and the rail and bascule bridge in Dordrecht(3). With their heights and widths, it is possible to cross them with the suggested pontoon structure. The structure's weight is estimated to be around 1800 tonnes, and the support structure (pontoon) around 116 tonnes, then summed up and rounded to 2000 tonnes.

The bridges were moved over water before they were relocated from Moerdijk to Keizersveer. This was also done with two supports on a pontoon, as can be seen in Figure 3.19. A possible way to transport the Keizersveerbrug to its new location at the Ackerdijkse Bridge site would also be by water. The following route outlines the key bridges and waterways, as well as their dimensions, which will affect the feasibility of the transport. The route can also be found in Figure 3.18.

Travel over the Oude Maas in the Northwest direction, cross (1) **Spijkenisserbrug**, with 40 meters of clearance width and (2) **Botlekbrug**, with 45 meters of clearance width. When crossing het Scheur, go in the East direction towards Nieuwe Maas. Continue eastward until the option to head towards the Schie is reached. Cross (3) **Grote Parksluis**, with a lock length of 125 meters and width of 13.55 meters.

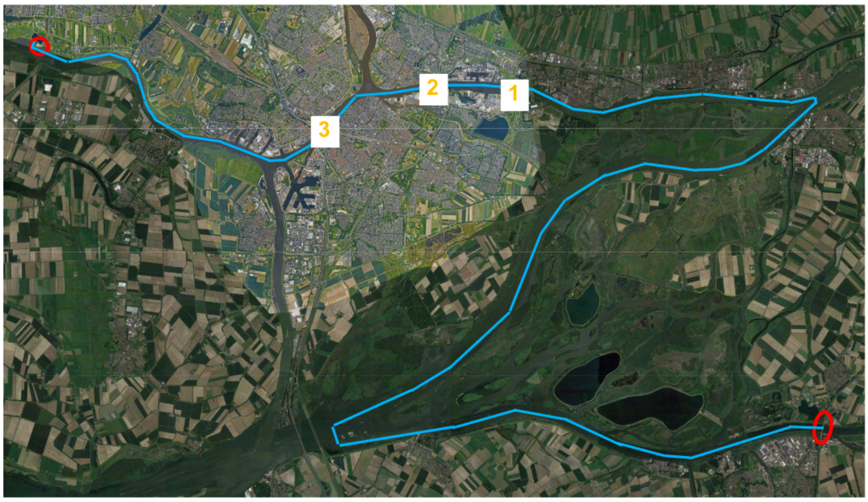

Figure 3.16: Suggested transportroute from Keizersveer to storage location (Royal Haskoning DHV, 2022).

Then, in the Coolhaven Section, pass the (4) **Coolhavenbrug**, which has a 14.5-meter clearance width and **(5) Pieter de Hoochbrug**, with a 13.6-meter clearance width.

Go onto the Delfshavensche Schie, heading Northwest. Pass the (6) **Lage Erfbrug**, which has a 13.6-meter width clearance and the (7) Mathenesserbrug, with an 8-meter width clearance; this is one of the narrowest points along the route and will need special attention during transport. Further along the Delfshavensche Schie, pass the (8) **Beukelsbrug** with 10.4 meters of clearance width and (9) the **Hoge Delfshavensche Schiespoorbrug**, which also has 10.4 meters of clearance width. Then the Delftse Schie is approached. The next bridges to pass are the (10) **Giessenbrug**, with 10.7 meters width clearance and (11) **Spaanse Brug**, which has 6 meters of clearance width and is thus the narrowest bridge on the route and the most constraining factor. Special measures may be required to pass through here.

Lastly, before arrival at the Delftse Schie, pass (12) **Hogebrug**, which has a clearance width of 7.94 meters. The two last bridges are the (13) **Doenbrug**, which has a 10.5-meter width clearance and (14) **Kandelaarbrug**, with a 10.5-meter width clearance. Then the transportboat arrives near Ackerdijkseweg, at the final site. From here, the bridge elements should be transferred to land and transported to the final site.

It can be concluded that the Spaanse Brug is the constraining element on this route. It becomes clear that the structure cannot be transported as a whole but should be demounted into smaller components. Since all the bridges on the route can be opened, it would be feasible to transport the truss elements up straight, so they would be 12.5m in height and, depending on the configuration of the pontoon, a couple of meters in width. Manoeuvring possibilities might constrain their possible length. Since the only lock on the route (Grote Parksluis) is 125m and the waterways are considerably straight, it is assumed that transporting a complete length of 100m of the bridge element is possible. A suggested way of decoupling the structure longitudinally is depicted in Figure 3.17.

3.3.2. Storage

Storage possibilities for a dock in Barendrecht have been researched by Royal Haskoning (Royal Haskoning DHV, 2022). Different aspects of this location have been examined: archaeology, explosive remnants of war, natural values, underground infrastructure, soil quality, unloading wharf and water levels. In addition to the shipping route, the landing operation, layout of the storage site and loads on the site were examined for bridge storage.

It can be concluded that sufficient information from previous conditioning studies is available to identify the implications, permitting procedures and risks of storing bridge components at the unloading dock area. However, the document does recommend that the physical suitability for reuse of the soil material

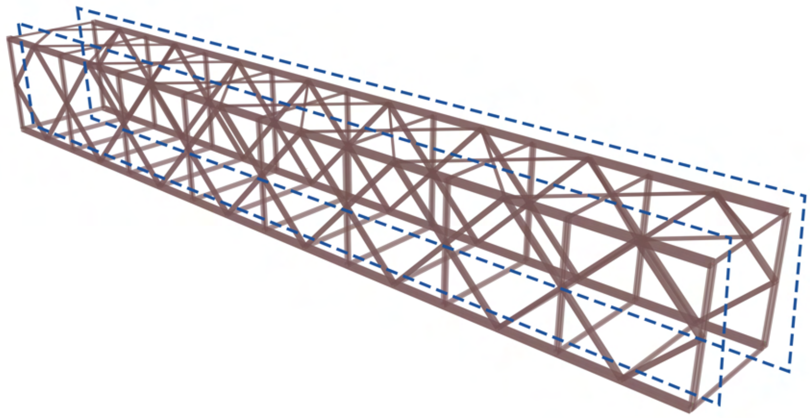

Figure 3.17: Suggested separation of the donor structure longitudinally into smaller parts for transport.

of the dock should be assessed in a subsequent phase in more detail (Royal Haskoning DHV, 2022).

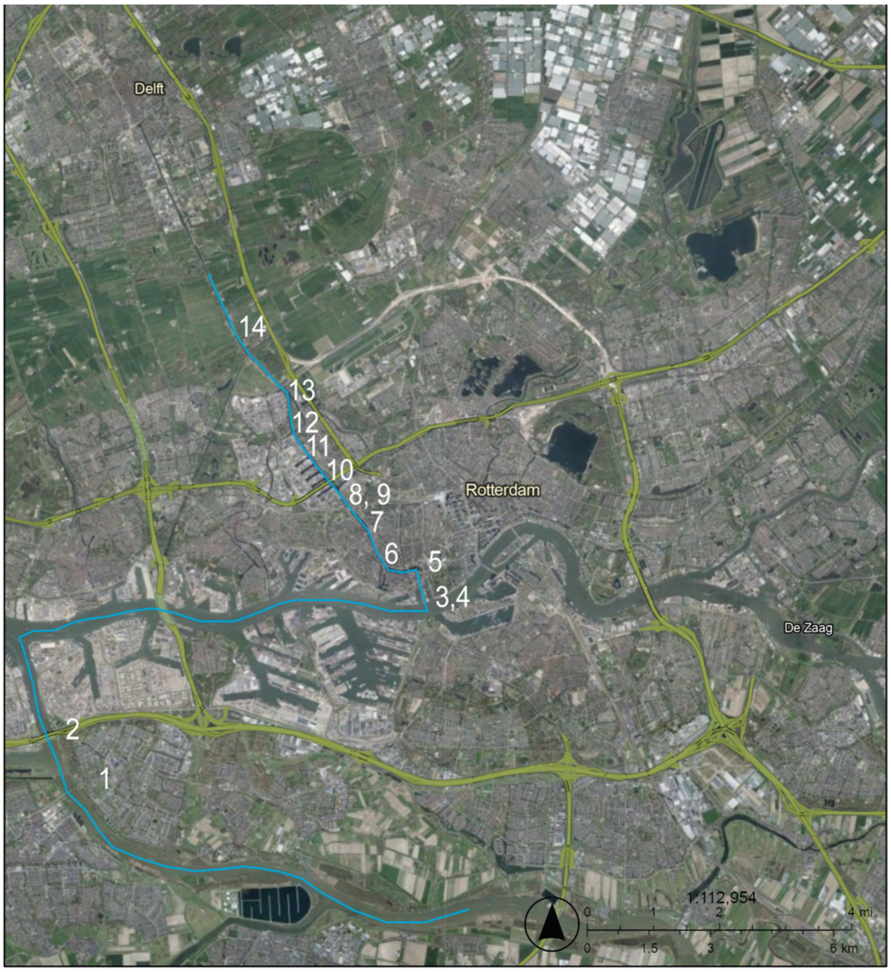

Figure 3.18: Suggested route from the storage location to the building site.

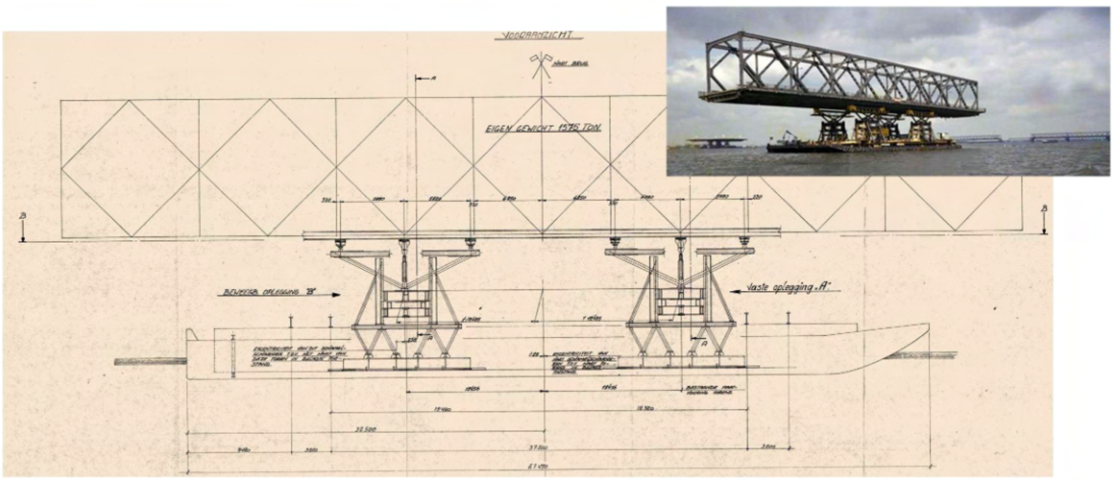

Figure 3.19: Transport structure and picture in 1978 (Royal Haskoning DHV, 2022).

4

Design Criteria, Synthesis and Design Possibilities

In this chapter, the design criteria for steel bridges, including reuse, are listed. First, the general design rules are stated, and second, design criteria specifically related to the case study.

4.1. Design Criteria

4.1.1. Lifespan and Consequence Class

An indicative Design life span for bridges is 50 years for bridges of consequence class CC1 and CC2. It is 100 years for bridges of consequence class CC3. ("National Annex to NEN-EN 1990 +A1:2006 +A1:2006/ C2:2019 Eurocode: Basis of structural design", 2019, Table NB.11). These determine the partial factors for the load combinations. The municipality has no specific requirements for the case study, so a CC3 is assumed. According to the National Annex of NEN-EN 1993-1-9 and ROK (ROK-0204), the partial factor for load-bearing (fatigue-prone) structural members of steel bridges is $\gamma_{Mf} = 1.35$ (Rijkswaterstaat, 2021). In the case study, there are no calculations concerning fatigue.

According to RBK, the partial factors for existing steel bridges are expressed in NEN-EN 1993-2, which are $\gamma_{M0} = 1.00$, $\gamma_{M1} = 1.10$, $\gamma_{M2} = 1.25$. These factors will be used in the structural analysis.

4.1.2. Loads cyclist and pedestrian bridge

Static models for vertical traffic loads - Characteristic values

The vertical live loads are uniformly distributed due to the presence of people (Load Model 4, crowd loading) and concentrated load by vehicles. The following values are considered, as by "NEN-EN 1991-2 Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges" (2015) and the National Annex.

- Uniformly distributed load on the floor
  - $q_{fk} = 5.0kN/m^2$ for bridges below 10-meter length
  - $q_{fk} = 2.0 + (120/L + 30)kN/m^2$ with a minimum of $q_{fk} = 2.5kN/m^2$ and with L = loaded length in [m].

  - So for the donor bridge with a length of 100m: $q_{fk} = 2.0 + (120/100 + 30) = 2.92kN/m^2$
- Concentrated Design Load on an area of 0.10x0.10[m] of $Q_{fwk} = 7kN$ *or* concentrated load due to a service vehicle of $Q_{serv} = 25kN$ per axle, with a wheelbase of 3 [m], a track width of 1.75 [m], and a contact area of 0.25x0.25 [m].

Static models for horizontal traffic loads - Characteristic values

People and vehicles crossing the bridge will result in horizontal loading along the bridge deck at the pavement level. For which the most significant value of the following two should be considered:

- Q_{flk} = 10% of the total distributed load of q_{fk};
- Q_{flk} = 30% of the total load of the service vehicle Q_{serv}.

The horizontal force is considered to act simultaneously with the corresponding vertical load and in no case with the concentrated load Q_{fwk}. It is considered in the longitudinal direction of the bridge.

Static models for traffic loads on railings - Characteristic values
The railing should be able to withstand a horizontal and vertical uniformly distributed line load of $q = 3.0kN/m$ on the top. This does not have to be combined with other variable loads on the bridge. However, a horizontal uniformly distributed line load of $q = 1.0kN/m$ on the top of the railing should be combined with other variable loads. In the case study, the railing will not be designed during the preliminary design, so this rule will not be applied.

Grouping of traffic loads - Characteristic values
According to NEN-EN 1991-2, the characteristic values of the traffic loads should be combined in a certain way. The combinations are shown in 4.1. It can be foreseen that the first combination group (gr1) is normative for the case study since, with a width of 6m, this will give a more significant bending moment in the main girders than with combination group 2.

Load type		**Vertical loads**		**Horizontal loads**
Loadsystem		Uniformly distributed load	Service vehicle	
Groups of loads	gr1	q_{fk}	0	Q_{flk}
	gr2	$0.8 \cdot q_{fk}$ [a]	Q_{serv}	Q_{flk}
[a] Not at the location of the service vehicle, including a space of 5 m in front and behind				

Figure 4.1: Load combinations of traffic loads (Table 5.1 of NEN-EN 1991-2)

Variable loads - Wind loads
The wind loads are calculated by NEN-EN 1991-1-4, as found in Appendix B.2. The values in three directions are:

- Transverse / x-direction: $Q_{wind-x} = 2.52kN/m$;
- Longitudinal / y-direction: $Q_{wind-y} = 0.572kN/m$;
- Vertical / z-direction: $Q_{wind-z} = 3.64kN/m$;

Transverse and vertical wind loads can be combined. When combining transverse and longitudinal wind loads, they both obtain the value of the longitudinal load.

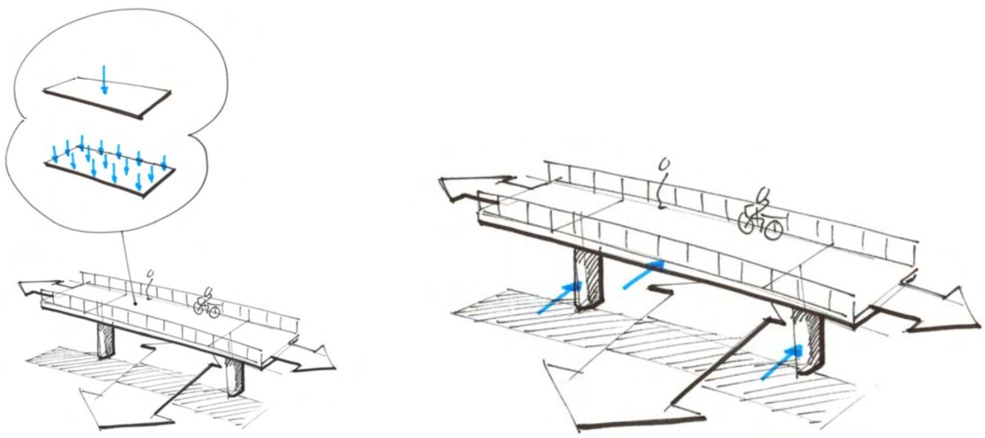

Figure 4.2: Basic traffic loads (left) and collision loads on bicycle bridge (ipv Delft, 2017).

Extraordinary loads - Collision loads
Accidental design situations considered are collision with road traffic under the bridge or the accidental presence of a heavy vehicle on the bridge.

- Collision force on piers in the case of a highway gives an impact of $1000kN$ in the direction of vehicle traffic or $500kN$ perpendicular to that direction.
- Collision force on decks in the case of a highway depends on the clearance height of the structure. For a clearance below 4.8[m], the force is $500kN$. Clearance above 7.0[m] gives a force of $0kN$ and all heights in between can be extrapolated.

If there are no obstacles to prevent unauthorised vehicles from entering the bridge, an additional load should be accounted for. Specifically, an axle load $40kN$ and $80kN$ a 3 [m] wheelbase, a 1.3 [m] track width and 0.2x0.2 [m] contact surface per wheel.

Permanent loads
Permanent loads will consist of the self-weight of the load-bearing structure and the finishes. For this, the volumetric weights of the materials can be used, as listed below. Furthermore, the greenery necessary to accommodate a green area/wildlife crossing can have a significant amount of self-weight, for which an estimation should be made. Figure 4.3 shows different possibilities for greenery on top of a structure, the amount of soil required, and the corresponding maximum weight.

- Reinforced concrete $\gamma_c = 25.0kN/m^3$;
- Steel $\gamma_s = 78.5kN/m^3$;
- Finishing deck layer
- Greenery + Soil (saturated) $\gamma_{green} = 0.75 - 10kN/m^2$

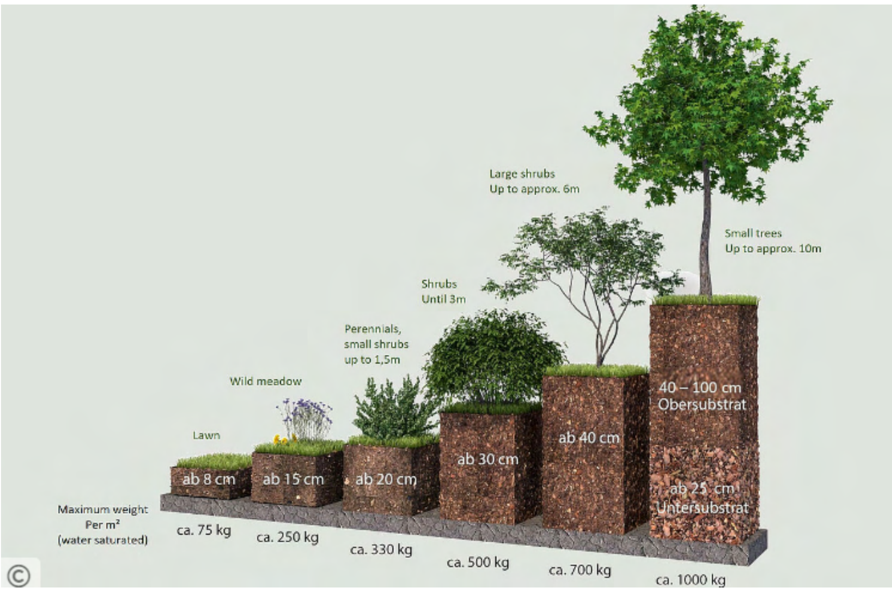

Figure 4.3: Options for green on bridges and their respective maximum weight (Stiftung Altes Neuland Frankfurt, n.d.).

Calculation of the self-weights of the main elements of the donor structure can be found in Appendix B.3.

4.1.3. Load combinations

UGT-B (ULS): Permanend design situation

The formula for the permanent design situation is:
$\gamma_G * G + \gamma_{Q,1} * Q + \sum \gamma q1 * \psi_{0,i} * Q_{k,i}$
It has been found that taking the traffic load as the primary variable load will lead to the governing load combination. This leads to the following equation:
$1.40 * G + 1.50 * Q + \sum 1.65 * 0.30 * Q_{k,wind}$

4.2. Case study-specific design criteria

4.2.1. Program of Requirements

The municipality of Delft has the following requirements for the Ackerdijksebrug:

- The bridge should be suitable for cyclists, pedestrians and wildlife. Wheelchair accessibility is preferable.
- The bicycle path must have a smooth path, without kinks. The average permitted inclination is 3%.
- The deck must have a railing with a minimum height of 1.3 m. A spherical body with a diameter of 0.5 m may not fit through the handrail. The handrail must withstand a horizontal force of 1kN.
- Lighting is an integrated part of the design and fits the context, does not blind users or passers-by and does not emit light pollution to the ecological zone and the sky.
- Noise reduction on the bridge is integral to the design and fits the context.
- Low maintenance: Easy cleaning, no slippery surfaces because of water or growth of mosses, vandalism proof, and high wear resistance of the deck.
- Sustainable material use: special consideration for water retainment/drainage.
- The design must be realistic within a reasonable budget.
- The clearance height for the highway is 4.8 m.
- The clearance gauge for cyclists on the deck (W x H): 4.0 m x 4.0 m.
- The pedestrian clearance gauge on top of the deck (W x H): 2.0 m x 2.5 m.

- The clearance gauge for wildlife on top of the deck (W x H): 4.0 m x 2.5 m.
- No changes to existing infrastructure owned by RWS (A13 highway).
- Take into account plans for the extension of the tramline.
- The design should be socially pleasant to use.

4.2.2. Animals on the fauna passage

The municipality of Delft expects certain animals to use the fauna passage. Figure 4.4 shows an overview of these animals. They are mainly small mammals. To design the fauna passage, it is vital to know the characteristics of these animals and what habitat they prefer. Specific information on the animals can be found in Appendix B.

From the analysis of the animals, it can be concluded that creating suitable conditions in the fauna passage for these species requires attention to the specific types of soil and vegetation that will support their survival. The soil must be loose and fertile enough to accommodate small mammals' burrowing and ground-dwelling needs. At the same time, vegetation should include dense ground cover, shrubs, and flowering plants that cater to mammal and insects dietary and shelter needs.

4.3. Synthesis and possible designs

As part of the synthesis, a brainstorming session is conducted to invent different possible designs for the Ackerdijkse brug. In a conventional design process, the decision on typology is one of the first considerations, but it is not when redesigning with a donor structure. In this case, the exploration starts with different possibilities for the cross-section layout. Simultaneously, the approach ramp possibilities are designed since the designs influence each other.

4.3.1. Alignment of the donor bridge

Based on the alignment requirements as stated in 3.2.3, an initial alignment of the 100-m donor structure over the A13 highway is designed. This alignment is visible in Figure 4.5. The approach ramp alignment design possibilities are explored in the following subsection.

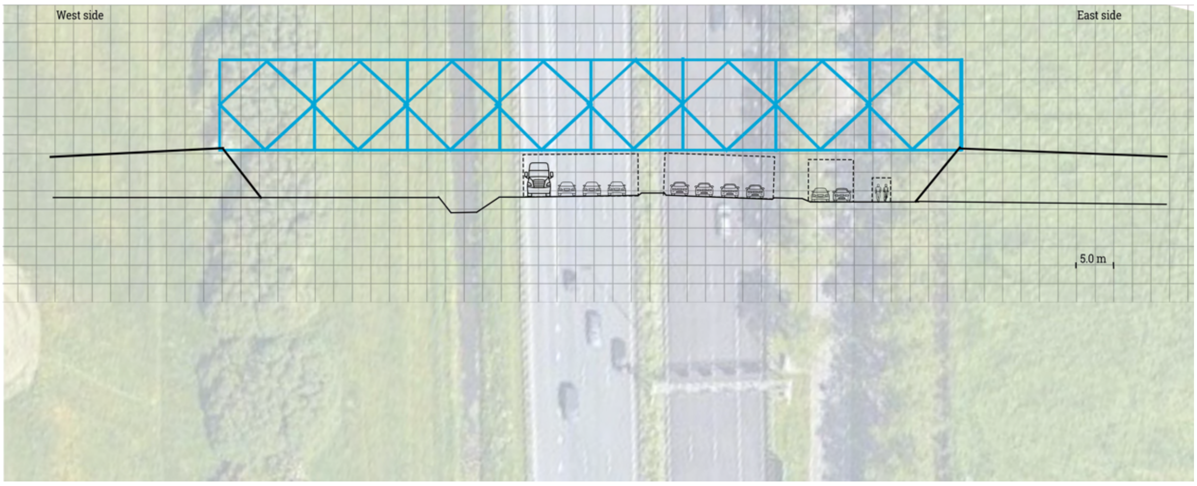

Figure 4.5: Alignment of the 100-m donor structure.

4.3.2. Design variants for layout and approach ramp

Nine different variants are explored. For each, sketches of the cross-section in two directions are given, alongside an explanation of the design. The type and dimensions of the approach ramp of each variant are summarised in the table in Figure 4.6. The sketches in a larger format can be found in Appendix B.

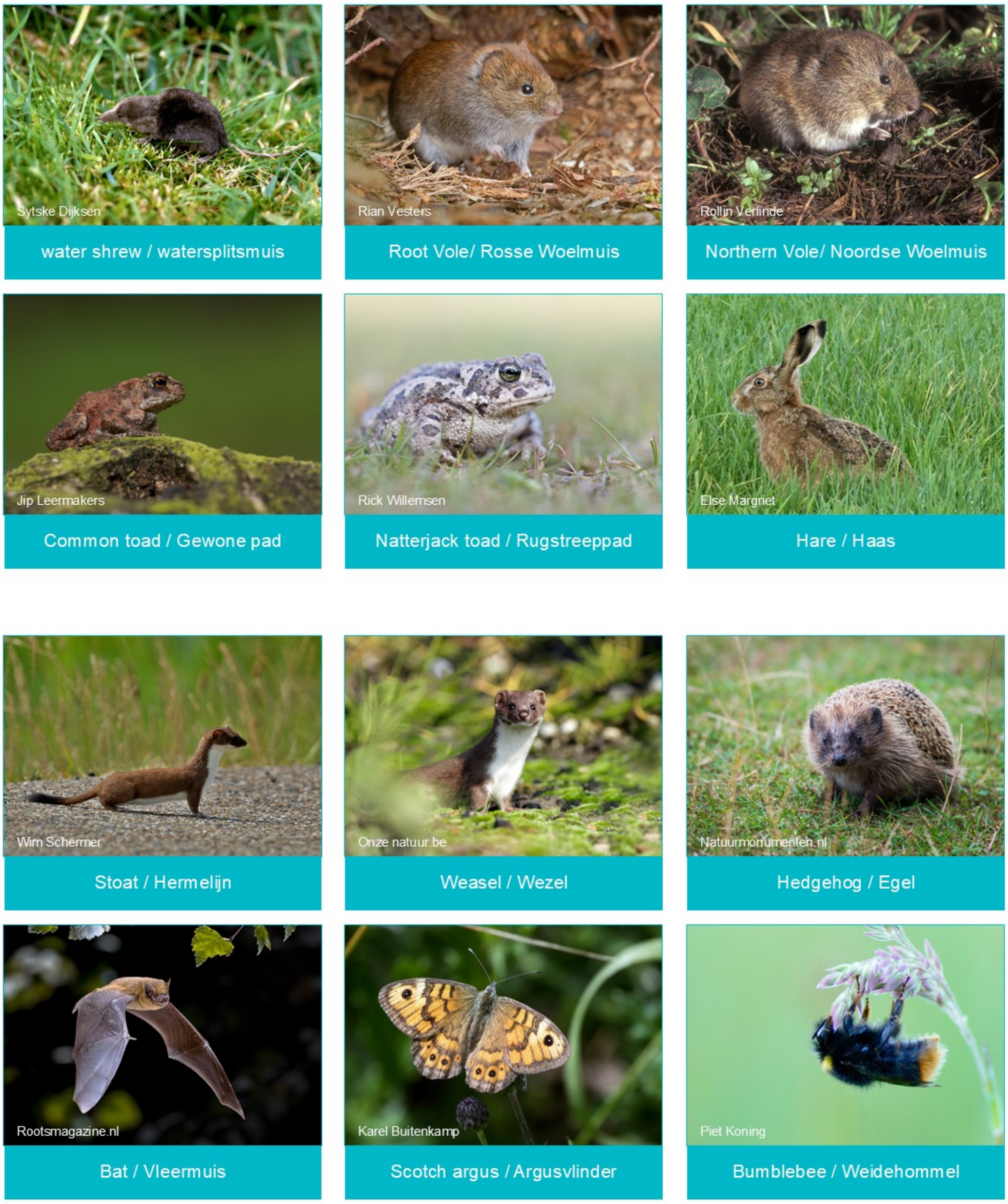

Figure 4.4: Target species of fauna passage

Variant number	height structure	Δh cyclists west [m]	length cyclist ramp west [m]	length eco ramp west [m]	Δh cyclists east [m]	length cyclist ramp east [m]	length eco ramp east [m]	Type of ramp humans	Type of ramp animals
Variant 1	2	7	233.33	70.00	7.5	250.00	75	8-m wide concrete	6-m wide soil
Variant 2b	2	7	233.33	70.00	7.5	250.00	75	two 4-m wide concrete that combines to one 6-m wide structure	6-m wide soil
Variant 3	2	7	233.33	70.00	7.5	250.00	75	4-m wide concrete and 2-m wide concrete	6-m wide soil
Variant 4	2	7	233.33	70.00	7.5	250.00	75	6-m wide concrete	6-m wide soil
Variant 5	2	7	233.33	70.00	7.5	250.00	75	6-m wide concrete	two 3-m wide concrete ramp
Variant 6a	0.6	5.6	186.67	56.00	6.1	203.33	61	6-m wide concrete	6-m wide soil
Variant 6b	0.6	5.6	186.67	56.00	6.1	203.33	61	donor structure and 6-m wide soil	donor structure and 6-m wide soil
Variant 7	0.6	5.6	186.67	56.00	6.1	203.33	61	6-m wide concrete	2-m wide concrete
Variant 8	0.6	5.6	186.67	56.00	6.1	203.33	61	6-m wide concrete	2-m wide concrete

Figure 4.6: A summary of the lengths and types of the approach ramp of different variants.

Variant 1

This design variant includes one external bike path, as in the original donor structure. The width within the truss is divided between a bicycle path in the other direction, a footpath and the fauna passage.

Figure 4.7: Design variant 1

Variant 2
In this variant, two external bike paths are reused from the donor structure. The second path is originally not there but could also be harvested and used from one of the other bridge elements of the Keizersveerbrug. These could be used by bikes, as shown in the figure, or could be switched with the pedestrian lane. In this variant, the fauna passage lies in the cross-section's centre.

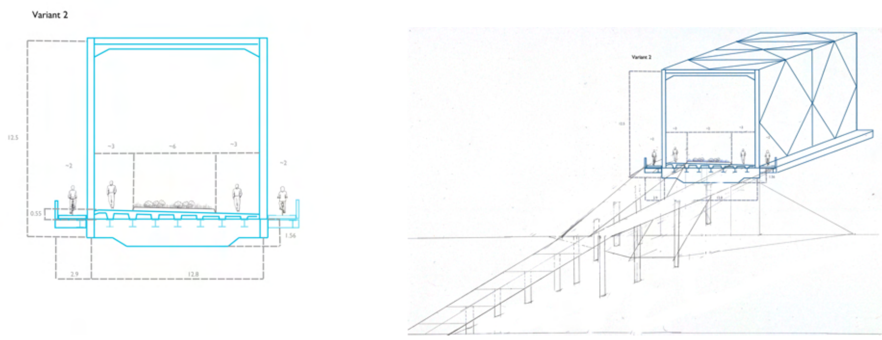

Figure 4.8: Design variant 2

Variant 3
Variant 3 is similar to variant 2 with two external bike paths. The difference is that the fauna passage is on one side of the truss structure in this variant.

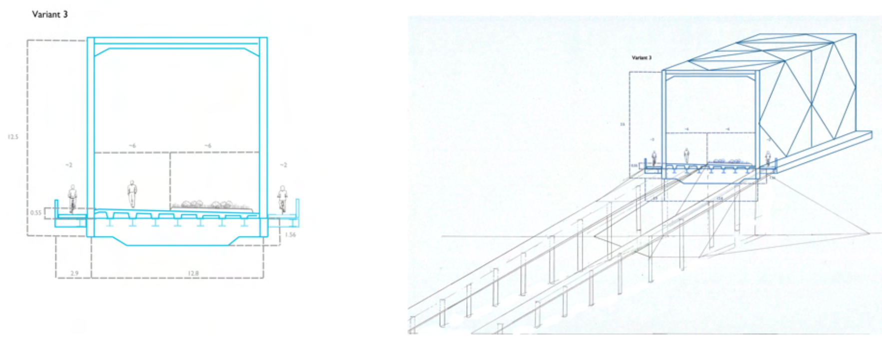

Figure 4.9: Design variant 3

Variant 4
In this design variant, all bridge users are within the truss structure. The footpath is located on one edge; the bicycle path is next to it. On the other end, the fauna passage is placed.

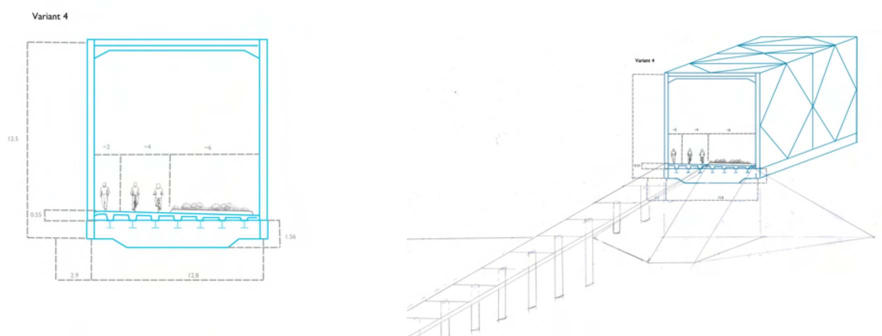

Figure 4.10: Design variant 4

The approach ramp of this design is similar to Variant 3.

Variant 5
This design variant also accommodates the different users between the trusses. However, the fauna passage is split and located on both sides. In the middle, the paths for cyclists and pedestrians are located.

Figure 4.11: Design variant 5

Variant 6a and 6b
Variant 6 has a similar layout to Variant 5. The difference, however, is the bridge deck, which is a new deck in this case. With this new deck, the structural height is reduced, resulting in a reduced length of the approach ramp.

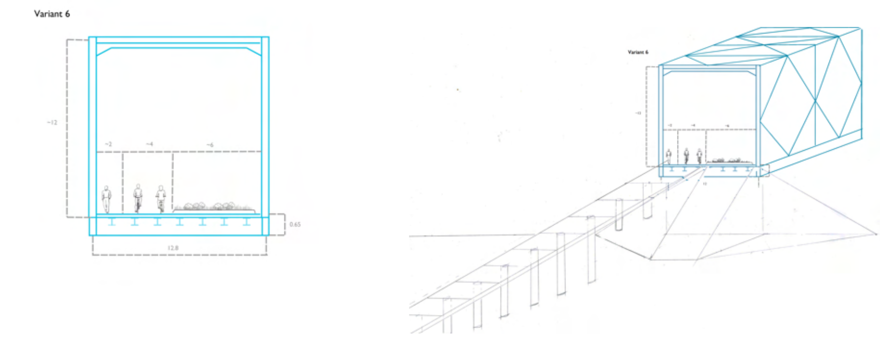

Figure 4.12: Design variant 6

The difference between Variant 6a and 6b is the approach ramp. The ramp of 6a is very similar to Variant 1, with a concrete structure for cyclists and pedestrians and a soil approach ramp for the fauna passage. For variant 6b, the possibility of incorporating another bridge element of the donor structure is explored. A 100-m structure with an inclination of 3% covers a 3-m height difference on each side, about half the required height.

Variant 7
The layout for Variant 7 is more out of the box; the fauna passage is on top of the bridge. As a result, the cross-section on floor level is only shared between pedestrians and cyclists. This design could also include a new bridge deck with reduced height.

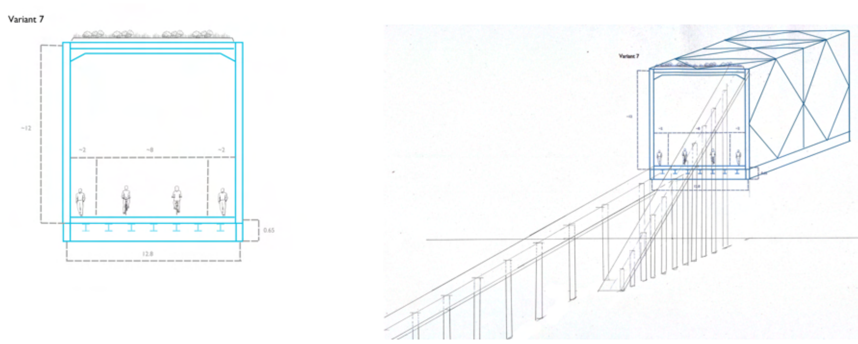

Figure 4.13: Design variant 7

Variant 8
This design variant also houses the fauna passage on its roof. A difference from all the other variants is that the structure's width is reduced to about 7 meters.

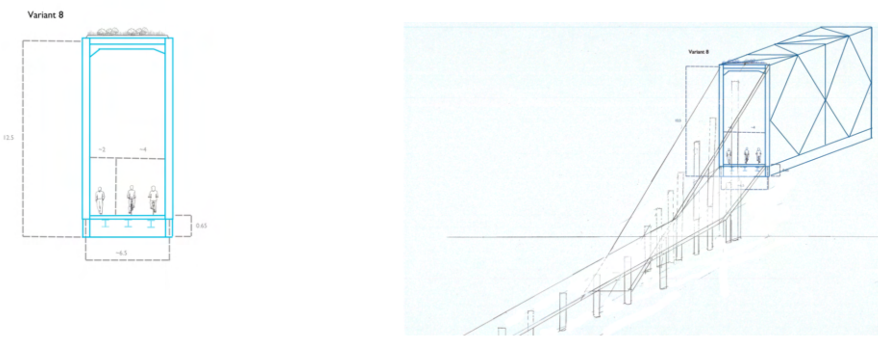

Figure 4.14: Design variant 8

4.3.3. Design of other structures

Design of a simple concrete approach ramp
The design of a simple concrete approach ramp follows common practice for cyclist bridges in the Netherlands, such as the cyclist bridge in Nigtevecht, called Liniebrug. It includes a reinforced concrete deck supported by concrete columns and a foundation of prefabricated concrete piles. The deck is estimated to have a height of 0.45 meters, and its width is variable. The columns, circular in cross-section, also have a variable diameter, but the diameter is set at 0.8 meters for this design. The columns are spaced at regular intervals of 12 meters (ipv Delft creatieve ingenieurs, 2018). An impression of such a structure can be found in Figure 4.15.

Using a Python script, which can be found in Appendix C.1, the total number of columns is calculated based on the ramp's length, with a default slope of 3%, though this can be adjusted depending on site conditions. The steel reinforcement is estimated at 130 kg per cubic meter of concrete for the deck and 100 kg per cubic meter for the columns (D. Janicki, n.d.). These estimates and the total volume of concrete are used as input for the environmental impact analysis conducted using DuboCalc. The structure's weight per 12-meter section is also calculated to determine the required number of foundation piles, which is then included as an input for DuboCalc to assess the overall sustainability of the design.

Design of a simple soil approach ramp
The design of the simple soil ramp has a trapezoidal cross-section, with the sides sloping at 1:2 in the

Figure 4.15: Bicycle ramp Liniebrug from two perspectives (ipv Delft creatieve ingenieurs, 2018, MVM betonstaal bv, n.d.)

width direction. The slope in the length direction is variable, typically set at 3% for the bicycle path but can be as steep as 10% for the ecological passage. Due to the geometric complexity of the ramp, a Python script is used to calculate the volume of material needed. This script can be found in Apendix C.1.

The ramp has two material layers: 20% of the volume is sand for the bottom layer, while 80% is soil. Additionally, the script calculates the total ground area, which is critical for determining the amount of geotextile required. The volume of sand, soil, and the area of geotextile are used as input parameters for the environmental impact analysis in DuboCalc, ensuring the sustainability of the design. The width of the ramp is variable, allowing for flexibility in adapting to different site conditions.

Design of foundation piles

The Koppejan method calculates the base and shaft capacity of the pre-cast concrete foundation piles. A Cone Penetration Test (CPT) on the site shows the build-up of the soil layers. A calculation of the capacity of a foundation pile with dimensions of 0.25mx0.25m and 0.40x0.40m and a length of 17.5m is performed, resulting in a design loadbearing capacity of 319 kN and 1111.11 kN, respectively. An elaborate calculation of these capacities can be found in Appendix B.4 and the CPT specifically in figure B.2 . For piles of dimensions of 0.4x0.4m, a pile cap with dimensions of 2.20x2.20m and a height of 0.60m is assumed to be sufficient. This way, there is a spacing of 1.2m centre-to-centre between the foundation piles and an overhang of 0.3m to the sides.

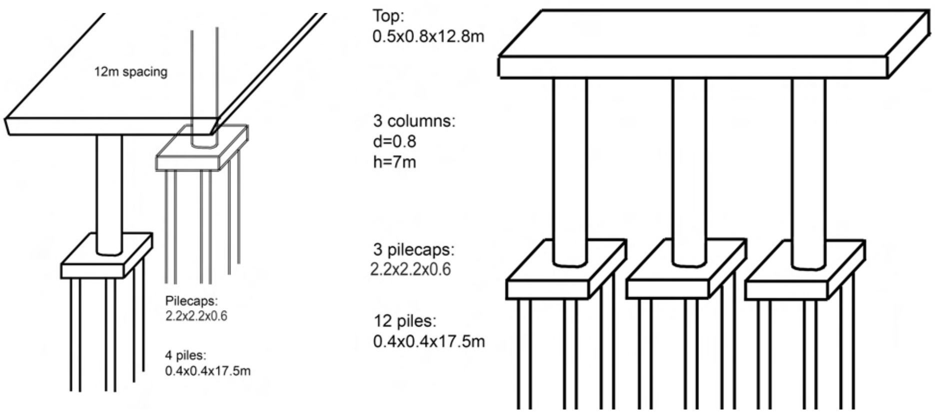

Figure 4.16: The simple design of concrete foundations for a concrete approach ramp (left) and the donor structure (right).

Reuse of deck structure

The connection between the longitudinal beams and the donor structure's concrete deck is realised with dowels and in-situ concrete. Part of the deck is also precast concrete. If it is decided to reuse the load-bearing steel deck structure, this concrete deck should be partially removed to replace it with the proposed new timber deck for cyclists and pedestrians. Half of the existing concrete deck on the side of the fauna passage can be reused.

An example of such a removal procedure can be found in Figure 4.17.

Figure 4.17: Removal of concrete deck from steel girders (*Bridge Removal Manual*, 2023).

Design of a new deck structure
A new steel bridge structure could be introduced to reduce the structural height of the current bridge. Figure 4.18 shows that the cross beams are higher than the main load-bearing longitudinal truss beams. Thus, a reduction of up to 1.0 m is feasible by replacement. Based on the expected forces on the deck, performing a simple hand calculation, it could be concluded that the deck could, for example, consist of IPE 600(V) crossbeams and IPE 400 (A) longitudinal girders.

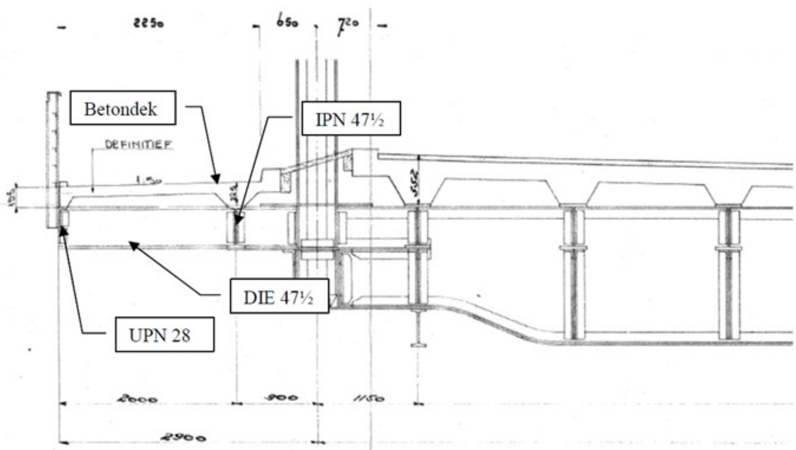

Figure 4.18: Detailed cross-section at the location of the bike path (Movares, 2016b).

5

Simulation, evaluation and final design

5.1. Simulation

In the simulation step, a structural analysis of the donor structure is carried out. A model is created using Rhino, with the Grasshopper extension, a visual programming language for parametric modelling. This model represents the main elements—cross beams, main horizontal beams (top and bottom cords), main vertical beams, diagonal beams, and wind braces—as lines. The dimensions are parametric; the span and width can be changed. This can be seen in Figure 5.1 and Figure 5.2. The figures also show the definition of the axis, which are: y-axis along the width of the bridge, x-axis along the length of the bridge and z-direction along the height of the bridge.

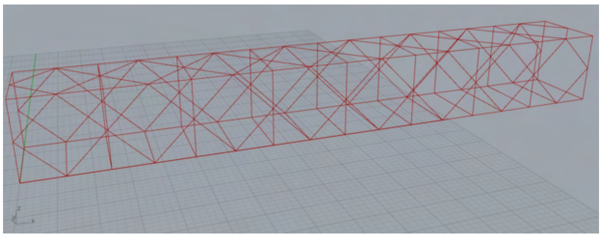

Figure 5.1: One element of the donor Keizersveerburg is a line model in Rhino.

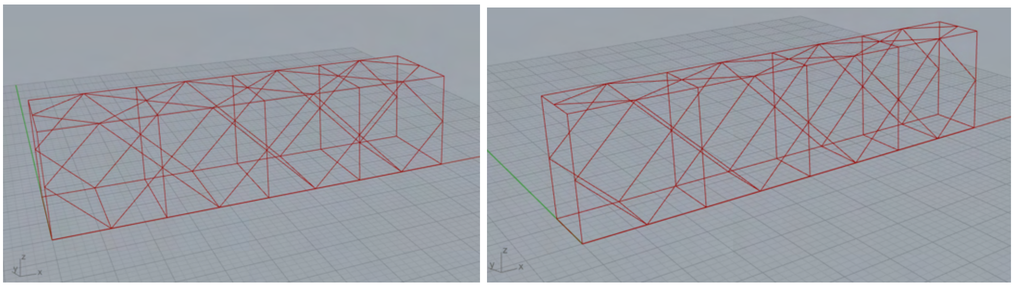

Figure 5.2: Demonstration of change of dimensions of the line model.

Using the Karamba3D extension, the forces calculated in Chapter 5 are applied to the model. The supports and connections are defined. The following modelling decisions are made, as also can be found in Figure 5.3.

- The dimensions of the cross-sections are not modelled identically to the actual situation because those cross-sections are not standard. There are open cross-sections that are connected by plates in several locations. This is replaced by closed cross-sections with similar properties. This does not influence the structural analysis since the model confirms the forces and moments in the elements. Verification of the strength of the cross-section is done separately by hand calculations and based on the actual properties of the sections.
- There are four supports, and those are modelled to be fixed for all directions and free in the x and y direction on one side. On the other side, movement in the x-direction is allowed, as well as movement in the x and y-directions. This allows movement of the bridge due to thermal expansion. Due to the replacement of the deck, it can be assumed that it is possible to realise such supports.
- Connections between the cross-beams and the bottom cord are hinged, thus the cross-beams act as simply supported beams. The longitudinal deck-beams are not modelled, their forces are spread as distributed forces on the cross-beams. This is an assumption that deviates from reality but is assumed to be accurate enough for structural calculations of a preliminary design.
- Connections between the vertical elements and the top and bottom cord are modelled to be hinged in y-direction. Thus, there is no transfer of moment between the elements. The connections between the diagonal truss elements and the vertical elements do transfer moments. This is a modelling choice which results in normal forces to be the most significant forces in the vertical elements. This corresponds to the theory of forces within a truss. However, due to the lack of information from construction drawings and inspection of the existing structure, it cannot be confirmed if this is an appropriate modelling choice. For a detailed design, this should be analysed further.
- As a result of the modelling choices of the connections, the top and bottom cords act as a continuous beam on multiple supports. Occurrence

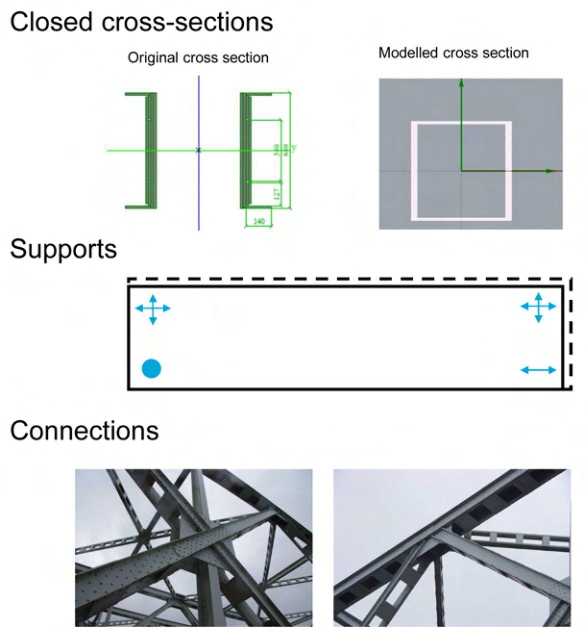

Figure 5.3: Modelling choices made for a model of the Keizersveerbrug.

The model is verified by sanity checks and comparison with the model built by Movares (Movares, 2016b), with SCIA Engineer.

- The maximum moments within the cross-beams from the model are checked by hand, using $M_{middle} = 1/8 * q * l^2$.

- The moments in top and bottom cords are compared with a model of a continuous beam on multiple supports in MatrixFrame.
- Occurance of jumps in moment lines and normal forces are checked.

The complete Grasshopper script can be found in Appendix C, Section C.5.

5.2. Evaluation

The evaluation is done based on different parameters, as can be seen in Figure 5.4. A decision matrix is made based on ranking the variants from 1 to 9. If variants have the same spot in the ranking, an average score will be given. For example, three variants score the best (first, second, and third place); they all receive a score of 2. A score is given for the three categories, and the final score is based on the average grade. It could be considered to assign a category a bigger weight, but that is not done in this case because the categories are found to be equally important.

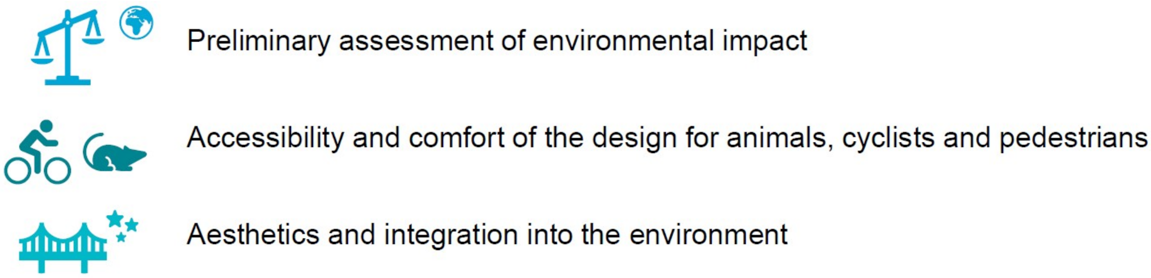

Figure 5.4: Three evaluation parameters.

5.2.1. Environmental impact

An exploratory analysis of the environmental impact of each variant is done. As previously explained in 4.3, an estimation of the quantities of the primary materials is done. An important variable that affects these quantities is the height that the approach ramp has to overcome, which depends on the height of the land and the height of the main bridge structure. Furthermore, the dimensions and type of structure chosen as the approach ramp influence the environmental impact.

These variables are summarised in Figure 4.6 and the quantities of each material are calculated. Using the 'Dubocalc' programme, an environmental impact analysis is performed. This program is a tool developed by Rijkswaterstaat to calculate and compare the impact of tenders. Clients and potential contractors use it to investigate different variants of civil engineering tenders and assess them based on their impact. The calculation is done based on the "NEN-EN 15804:2012+A2:2019 en", 2019 A1 indicators. A resulting bar graph of the environmental costs per design variant is shown in Figure 5.5. These values are compared to evaluate the different design scenarios.

1. **External path or not?** If an external bicycle path is included, the width of the approach ramp increases. For example, in Variant 1, the concrete ramp for pedestrians and cyclists is 8 meters wide, resulting in a 19% higher environmental impact than the 6-meter-wide ramp in Variant 4. Comparing Variant 2 with two external pedestrian paths and thus two concrete approach ramps, results in a 13.9% higher impact than Variant 4. It can be concluded that no external path should be used to decrease the environmental footprint.
2. **New Deck or Not?** Replacing the donor structure's old bridge deck (load-bearing beams and girders) allows for a height reduction, shortening the approach ramp. However, this introduces some additional materials and thus environmental impact. By comparing Variant 4 and Variant 6a, which share the same layout for users, a reduction of 19.4K is achieved by shortening the ramp length, offset by an additional 12.6K impact from the new deck materials, resulting in a net decrease of 6.8K. Overall, constructing a new deck is estimated to reduce environmental impact by 10.3%.
3. **Concrete or Soil Approach Ramp for Fauna?** Whether a soil ramp or a concrete structure has a lower environmental impact depends on their dimensions. The soil ramp has a higher impact

for narrower ramps with greater height. This is mainly due to the dimension requirements of soil, resulting in high volumes of soil necessary. The environmental impact becomes high mainly due to the impact of transport per truck. Conversely, the concrete structure's impact is higher for wider ramps with lower height.

4. **Fauna passage on the roof?** An approach ramp should overcome an additional 12.8m to realise a fauna passage on the roof. Comparing Variant 6 with a wide and low soil approach ramp to Variant 7 with a high, small concrete approach ramp, the difference in environmental impact is 8.6%, indicating that a fauna passage on the roof would increase the design's environmental impact.
5. **Soil or partly foam ramp?** The environmental impact of the soil ramp is primarily influenced by the transport required for the substantial volume and weight of soil. A lighter material like Expanded Polystyrene (EPS) could reduce this transport impact. However, according to environmental impact data from the Dutch supplier Joosten Groep, EPS has a higher impact per cubic meter than soil. Nevertheless, EPS's lower weight could lead to reduced ground settlements, potentially decreasing the required overall volume, which may mitigate the environmental impact.
6. **Donor structure as ramp?** Another design variant would be implementing another 100-m bridge element from the Keizersveerbrug as part of the ramp. With an inclination of 3%, it will cover 3 meters of height difference. This will introduce some material for the foundations and deck, as well as extra processes, such as shipping this structure. A concrete or soil ramp overcomes the remaining height. Comparing variants 6a and 6b, with the only difference of the usage of the donor structure for 6b, results in a decrease of the ECI of 45.0%.

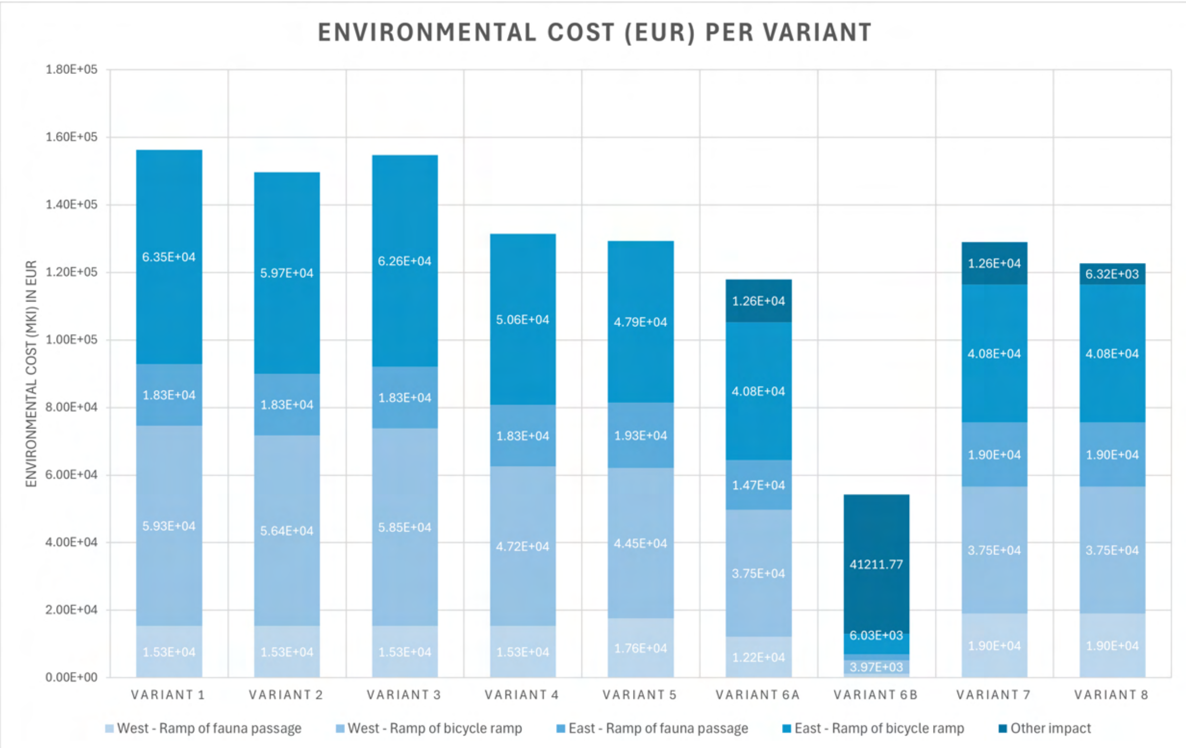

Figure 5.5: Environmental impact (EUR) per variant.

5.2.2. User comfort

When evaluating bridge designs for user comfort, both for animals and pedestrians and cyclists, factors that influence the structure's ease of use and safety must be considered.

Animal Use and Comfort

The layout and dimensions of the bridge play a significant role in encouraging animals to use the passage. In particular, for eco-bridges shared by multiple user types, it is ideal to position the shared-use zone as far as possible to one side of the bridge. This setup minimises disturbances for the target species and maximises the width available for safe animal passage (C. Rosell et al., n.d.). Variants 2 and 5, which allocate less width for animals, may be less effective due to restricted space, reducing comfort and usage among the animal species. The width is critical, as larger crossings generally feel safer and more accommodating for animals, thus enhancing passage success.

Additionally, a smooth and direct approach is crucial for animals. Long, elevated ramps tend to discourage use, as they require more energy to traverse and increase exposure to potential threats (C. Rosell et al., n.d.). For this reason, variants 7 and 8, which require animals to travel to the roof level of the bridge, may be unsuitable as they involve longer, more challenging access routes.

Lastly, incorporating strips of natural soil along the bridge, ideally 1 to 2 meters wide, could promote spontaneous vegetation growth. These strips support natural movement for some target species, particularly smaller animals like invertebrates and small vertebrates, by providing familiar and sheltered pathways within the bridge.

Pedestrian and Cyclist Use and Comfort

For pedestrians, placing walkways along the outer edges of the bridge allows them to enjoy scenic views. It gives space for stair access points, which can enhance comfort and accessibility (Wahls, 1990). Cyclists, on the other hand, tend to prefer shorter approaches that minimise elevation gain. Designs with a lower deck, such as variant 6, are likely more appealing for cyclists as they offer a more efficient, direct route onto the bridge.

5.2.3. Aesthetics and integration into the environment

Integration of the Ackerdijkse Bridge into the surrounding landscape and its aesthetic impact are central considerations in the design evaluation. The distinct dimensions of the donor bridge—12.5 by 12.5 meters in length and height—are highly valued, as they create a balanced, proportionate structure. Altering these dimensions, as seen in variant 8, where the bridge width is reduced, risks disrupting this visual harmony and could make the bridge look out of proportion within its environment.

The Keizersveerbrug, renowned for its significant length, will stand out in the flat Dutch landscape, especially given its prominence from surrounding views. A single, 100-meter bridge segment could appear more obtrusive in this setting. Extending the approach ramp using additional donor elements, as proposed in variant 6b, creates a unified 100-meter structure that blends more naturally with its surroundings. This approach, supported by feedback from a discussion with the municipality of Delft, enhances visual integration and minimises the bridge's impact on the landscape.

Furthermore, including external bike paths and railings has a substantial visual impact, especially for drivers approaching from the A13 highway. Keeping all pathways within the bridge's trusses helps reduce this visual disruption and maintains a cohesive, less intrusive appearance. Using transparent or minimalist railing designs within the bridge trusses can preserve the open, see-through quality of the structure, which, despite its considerable size, minimises its visual footprint. Variants 1, 2, and 3, which propose external bike paths, would intensify the bridge's visibility and disrupt its visual integration, making these options less favourable. Figure 5.6 shows a visualisation of this.

Figure 5.6: Pictures of the Keizersveerbrug show the design's transparency and the railings' effect on this.

5.3. Results

5.3.1. Ranking of variants

The resulting scores and ranking can be found in Figure 5.7. The last column shows the final score, which can be interpreted as a ranking. Thus, variant 6b scores first place, variant 6a scores second place, variant four scores third place, and so on.

Variant	Environmental impact	Users comfort	Aesthetics and integration	Average score	Final score
Variant 1	9	4	6	6.3	7
Variant 2	7	7	6	6.7	8
Variant 3	8	4	6	6.0	6
Variant 4	6	4	3	4.3	3
Variant 5	5	7	3	5.0	4
Variant 6	2	1.5	3	2.2	2
Variant 6b	1	1.5	1	1.2	1
Variant 7	4	9	4	5.7	5
Variant 8	3	8	9	6.7	8

Figure 5.7: Results of decision matrix based on three categories.

Considering environmental considerations, user comfort, animal needs, and aesthetical integration, variant 6b is the optimal design choice. By incorporating the donor structure as part of the approach ramp, this variant minimises environmental impact by reducing the amount of soil necessary. For user comfort, cyclists benefit from a lower and thus shorter approach ramp. Pedestrians are positioned at the side of the bridge's section for optimal views and easy stair access, enhancing accessibility.

Variant 6b provides a separate, undisturbed path for wildlife, ensuring minimal disruption for the target species. From an aesthetic standpoint, this variant preserves the original Keizersveerbrug's 12.5-meter modular grid, avoiding visually intrusive external paths or railings. The cohesive 300-meter-long structure created using three donor objects harmonises with the flat landscape, a design approach supported by the municipality of Delft. Additionally, a transparent railing design and internalised paths reduce the visual impact of the bridge's large dimensions. Overall, variant 6b effectively balances environmental, functional, and aesthetic priorities, making it the ideal choice for the Ackerdijkseburg project.

5.3.2. Environmental costs of final variant

The environmental costs of the complete bridge project, calculated with the same method as in the previous sections, are shown in Figure 5.8. The following elements are considered:

- Three 100-m Keizersveerbrug donor objects, 511.6 tonnes of steel per object.
- New steel bridge deck from recycled steel, for all three donor objects. 85.4 tonnes per deck.
- Timber deck for pedestrians and cyclists, with a 6.5m width and 100m length, thus a total area of 1950 m^2 for all three bridge objects combined.
- Concrete deck for the fauna passage with a height of 10 cm and area of 1950 m^2.
- East fauna passage, which is a soil ramp that is 6m wide, has a 10% inclination and covers a height of 5.6m.
- West fauna passage, which is a soil ramp that is 6m wide, has a 10% inclination and covers a height of 6.1m.
- East pedestrian/cyclist passage, which is a soil ramp that is 6m wide, has a 3% inclination and covers a height of 2.6m.
- West pedestrian/cyclist passage, which is a soil ramp that is 6m wide, has a 3% inclination and covers a height of 3.1m.
- Transportation of 100 km (60 km to the storage location and 40 km to project location) and a weight of 1803 tonnes, resulting in 180300 tkms per donor bridge object.
- Removal of the old paint layer of the three donor bridge objects, assuming a treatment area of 7 m^2 per m^2 bridge, so 8960 m^2 per bridge.
- Application of a new conservation layer over the same area as removing the old layer.
- Foundations for all three donor structure objects, realised in concrete, as described in Chapter 4.3.3.
- Wear layer that covers the same area as the timber deck.

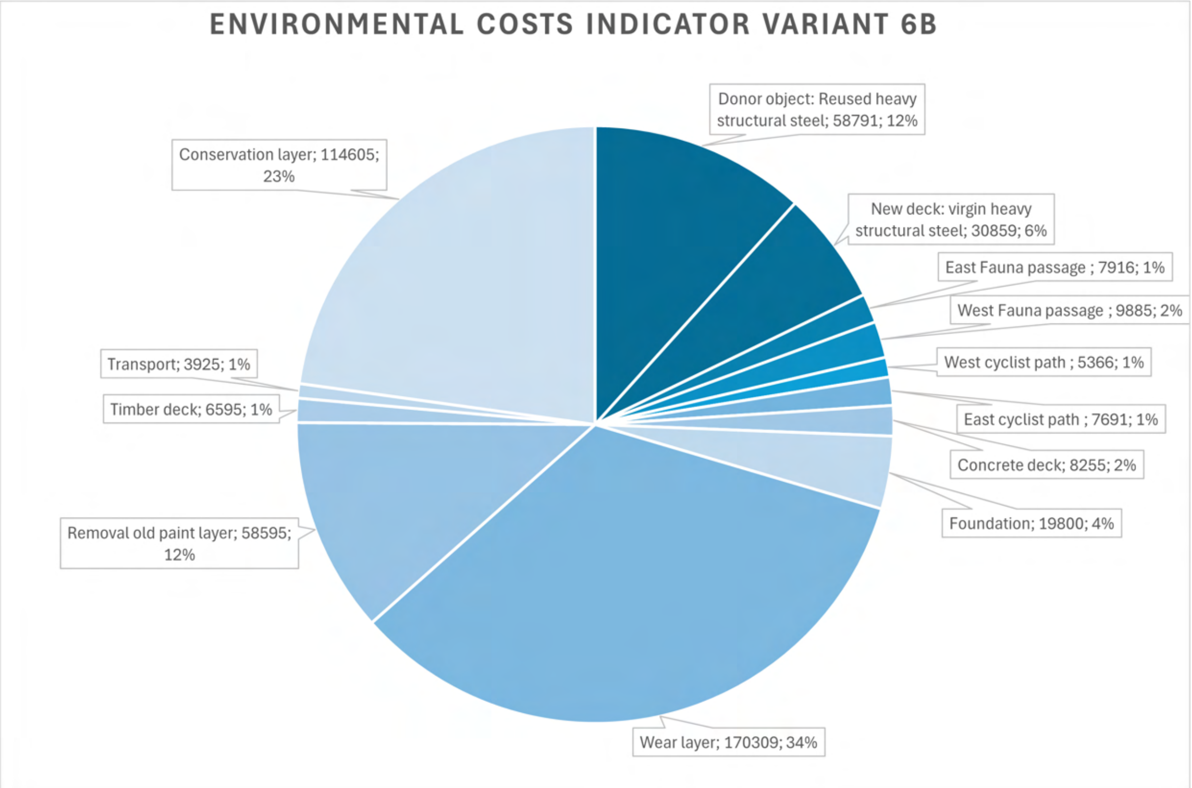

Figure 5.8: Preliminary environmental costs (in euros and in percent of the total amount) of the complete design, calculated with Dubocalc A1-indicators.

5.3.3. Impact paint and wear layers

The environmental impact of the paint layer and the wear layer is discussed in this section. The environmental costs per lifecycle stage of the paint layer and the wear layer is shown in Figure 5.9.

Environmental cost of steel paint layer

As can be found in Figure 5.8, the environmental impact of a conservation layer has a significant share in the total environmental costs. As explained in Chapter 2.2.2, a conservation layer is necessary to protect steel structures from corroding, mainly atmospheric corrosion. However, not many studies on the life cycle assessment of bridges consider the contribution of the coating system (Adsetts et al., 2023). In the case of this analysis, the source of the data on the environmental impact of the paint layer is Stichting Nationale Milieudatabase (Branco Schipper et al., 2021), product called 'Natlaksysteem'.

This is a three-layer paint system, consisting of an epoxy primer, a mixed middle layer and a polyurethane top layer. All thinned before application. Regarding the lifespan, it is assumed that after 15 years of use, some spots should be coated again. After 35 more years, the complete conservation system needs to be removed and repainted. Removal is done using hot-melt slag grit blasting, which is generally made from slag from the metal industry and coal-fired power plants. A significant share of the total environmental impact of the paint layer is a result of this replacement, as is part of use phase B1 and waste disposal phase C4, as is shown in Figure 5.9.

The impact of the paint layer on the LCA is relevant for every steel bridge design, from exposed steel. When introducing reuse, the effect of this paint layer becomes even more significant when considering that the old layer should be removed. If this is necessary, it depends on the status of the layer and the situation. If a bridge object has been repainted recently before reuse, it might not be required. This analysis includes paint removal by adding the impact of phases C1-C4 from the original 'natlaksysteem' as a separate element into the LCA assessment. For both the removal and new painting system, the unfavourable amount of 7 m^2 per m^2 bridge paint area is used, which could be in a range between 4-7 m^2 per m^2 bridge (Ir. C.J.F. Hulsebosch et al., 2023).

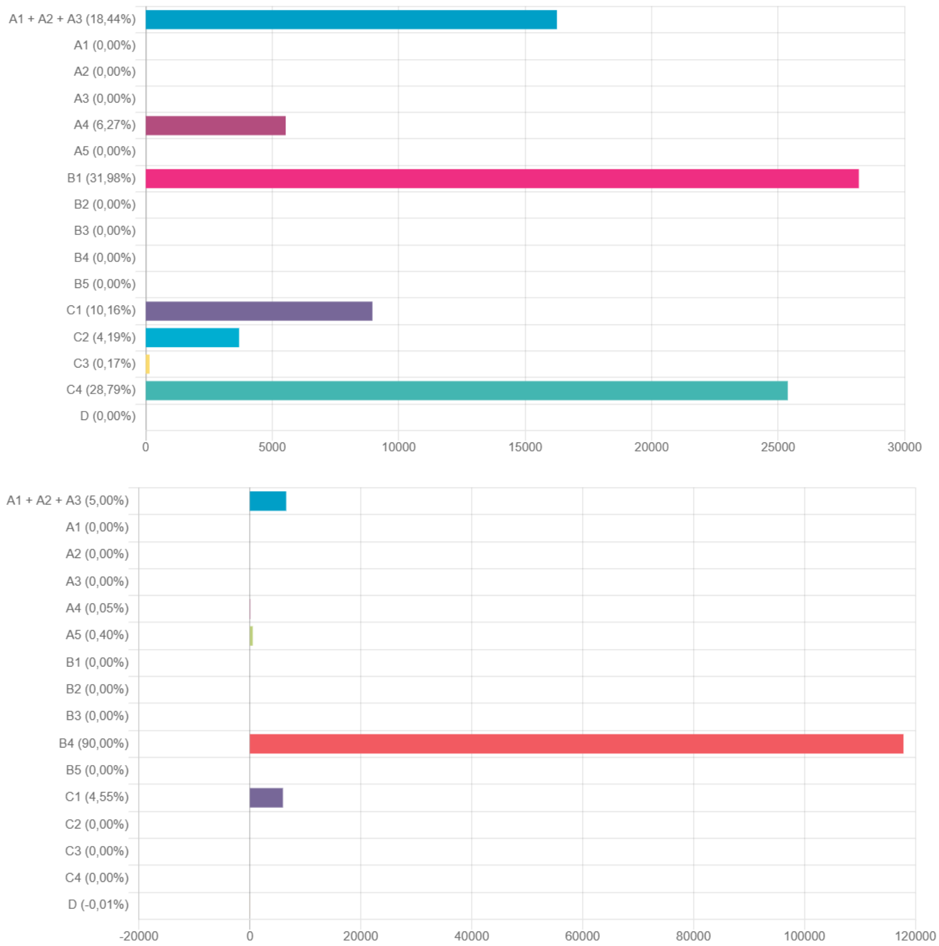

Figure 5.9: Environmental cost in euros per life cycle phase of 8960 m^2 paint system (top) and 1950 m^2 wear layer (bottom).

Environmental costs of wear layer

A wear layer is necessary on top of a deck to avoid slipping of the bridge's users. The environmental impact of the wear layer is significant, one third in the case of design variant 6b, as shown in Figure 5.8. A wear layer is necessary for a steel, timber, and concrete bridge deck. It consists of a primer, a slurry and filler material (HIM Products B.V., 2024).

Figure 5.10: Wear layer on timber deck (DeckX Products, n.d.), concrete deck (Gacon, n.d.) and steel deck (Krafton, n.d.).

The environmental costs in euros per lifecycle of the wear layer is shown in Figure 5.9 based on a wear layer from the Stichting Nationale Milieudatabase (Branco Schipper et al., 2021). There is not much detailed information except that this is a wear layer for application on steel, such as bridges. The layer is 5 mm thick and is composed of epoxy and grit. The wear coatings can also be applied to wood, plastic and concrete, however, a primer must be used, which is not part of this product card. The wearing course has a service life of 10 years and is thus replaced 9 times for a service life of 100 years, which is included in this analysis. This replacement introduces high environmental costs under life cycle phase B4, accounting for 90% of the total environmental costs of the wear layer.

In terms of reuse, replacing the existing wear layer of a donor structure might be necessary, raising the environmental costs of such a design. Considering replacement times of 10 years, this additional replacement procedure will have a small share of the total environmental costs. Thus, it can be concluded that a wear layer's environmental costs are generally high, but not necessarily different for a reuse variant.

5.4. Final preliminary design

A structural analysis of the final design is performed in the model described in 5. The structural verification is included in Appendix C. Figure 5.11 shows a longitudinal cross-section of the bridge design placed.

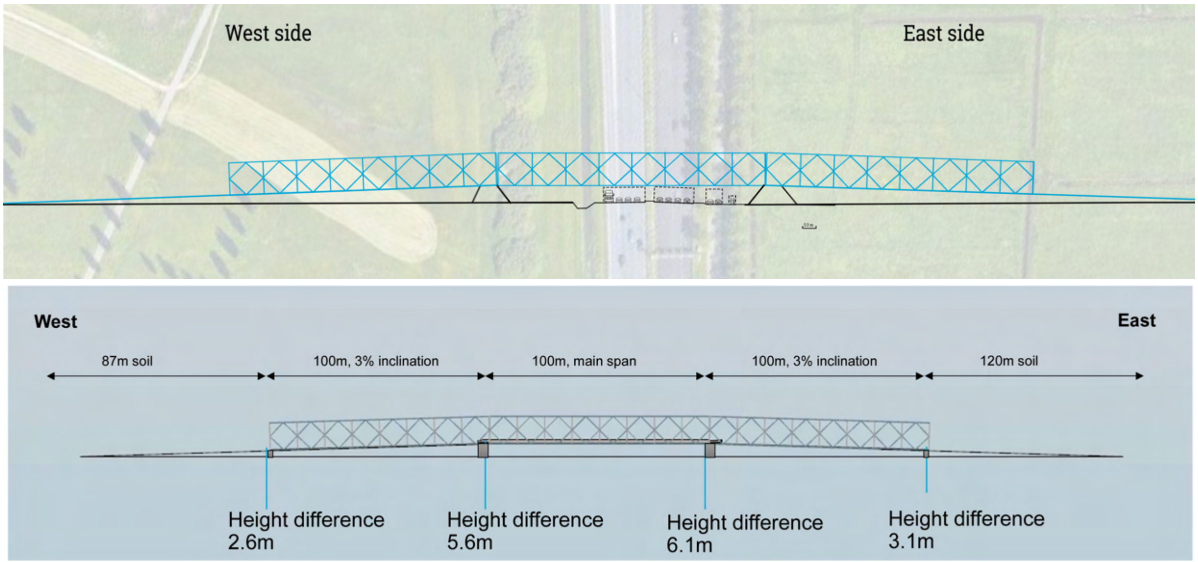

Figure 5.11: Longitudinal cross-section of the bridge design variant including three 100m bridge elements.

On each side of the bridge's main span, the 100m donor bridge objects are placed. They are placed with a 3% slope, resulting in a situation where they cover a 3-meter height difference. A soil slope perpendicular to the bridge is realised at the intersection between these elements, connecting the fauna passage to the surrounding land. This enables a shorter route for the animals to cross the A13 highway. The remaining height difference for pedestrians and cyclists is also realised with a soil approach ramp.

A 3D render from bird-perspective of the bridge can be found in Figure 5.12. It shows the path for pedestrians and cyclists on both ends of the structure and the fauna passage. Figure 5.13 shows a perspective onto the bridge from the highway, and Figure 5.14 and Figure 5.15 are two renders from the perspective on top of the bridge.

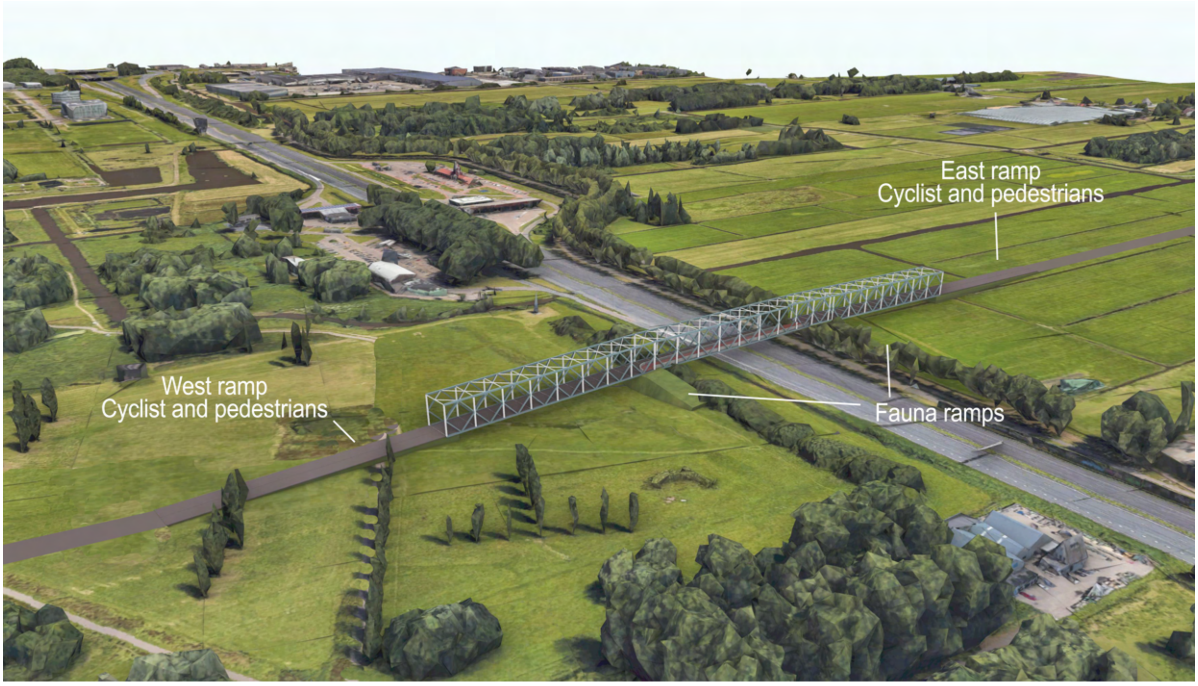

Figure 5.12: 3D model render of the preliminary design of the Ackerdijksebrug from bird-perspective.

Figure 5.13: 3D model render of the preliminary design of the Ackerdijksebrug from the perspective of the highway.

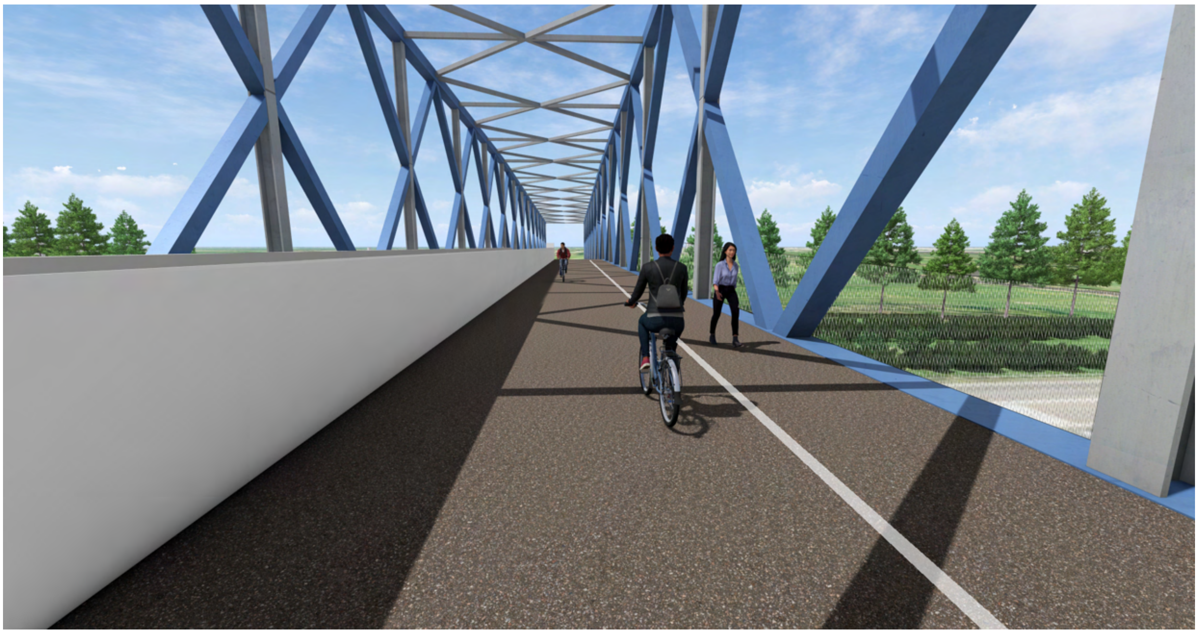

Figure 5.14: 3D model render of the preliminary design of the Ackerdijksebrug from the perspective of the cyclists.

Design is an iterative process. Some design possibilities for the main load-bearing structure were considered. These can be found in Figure 5.16 and are the following:

- **Animal path:** There are multiple options where the animals could enter and exit the bridge. With most approach ramp variants, the slope of the approach ramp was steeper. For the chosen variant, however, the slope is realised using another donor structure element, which was shared between humans and animals. This would, however, mean that the path for animals would become long, which is unwanted. So, a solution was found where the animal path starts and stops between the interface of the main span and the approach ramps.
- **Width of the approach ramp:** Since the approach ramp is not shared between the users, the width of 12.5m is large for only humans. Gradually making the approach ramp smaller was considered to save material costs for the new deck. However, after researching the connection, it has become clear that this is not feasible. The connections between the main load-bearing structure and the deck and the connections with the wind braces on top would have a changed angle, which is not practical to realise.
- **Color of the structure:** Since the structure should be repainted, it can be considered to change from its original white paint to another colour, giving some architectural freedom. For the final design, two colours are chosen that provide a modern look for the reused bridge and focus on the structure's diagonals, allowing the verticals to merge with the colour of the sky.

Figure 5.15: 3D model render of the preliminary design of the Ackerdijksebrug including the fauna passage.

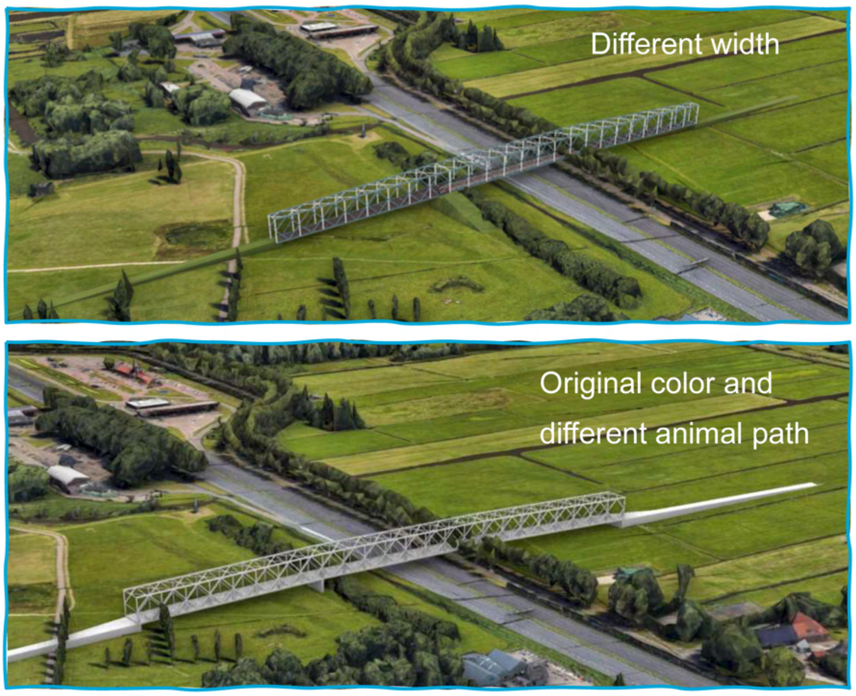

Figure 5.16: Different design possibilities were iterated to the final design.

5.4.1. Structural analysis

The values of the normative unity checks per load-bearing element are summarised in Figure 5.17. These are the values calculated with $\gamma_M = 1.25$. A value for the maximum gamma is also calculated, giving insight into the current design's safety margin. It can be seen that the lowest gamma max has a value of 1.65 for the top main beams. It could be concluded that the material factor can be increased, and the structure would still comply with the unity checks.

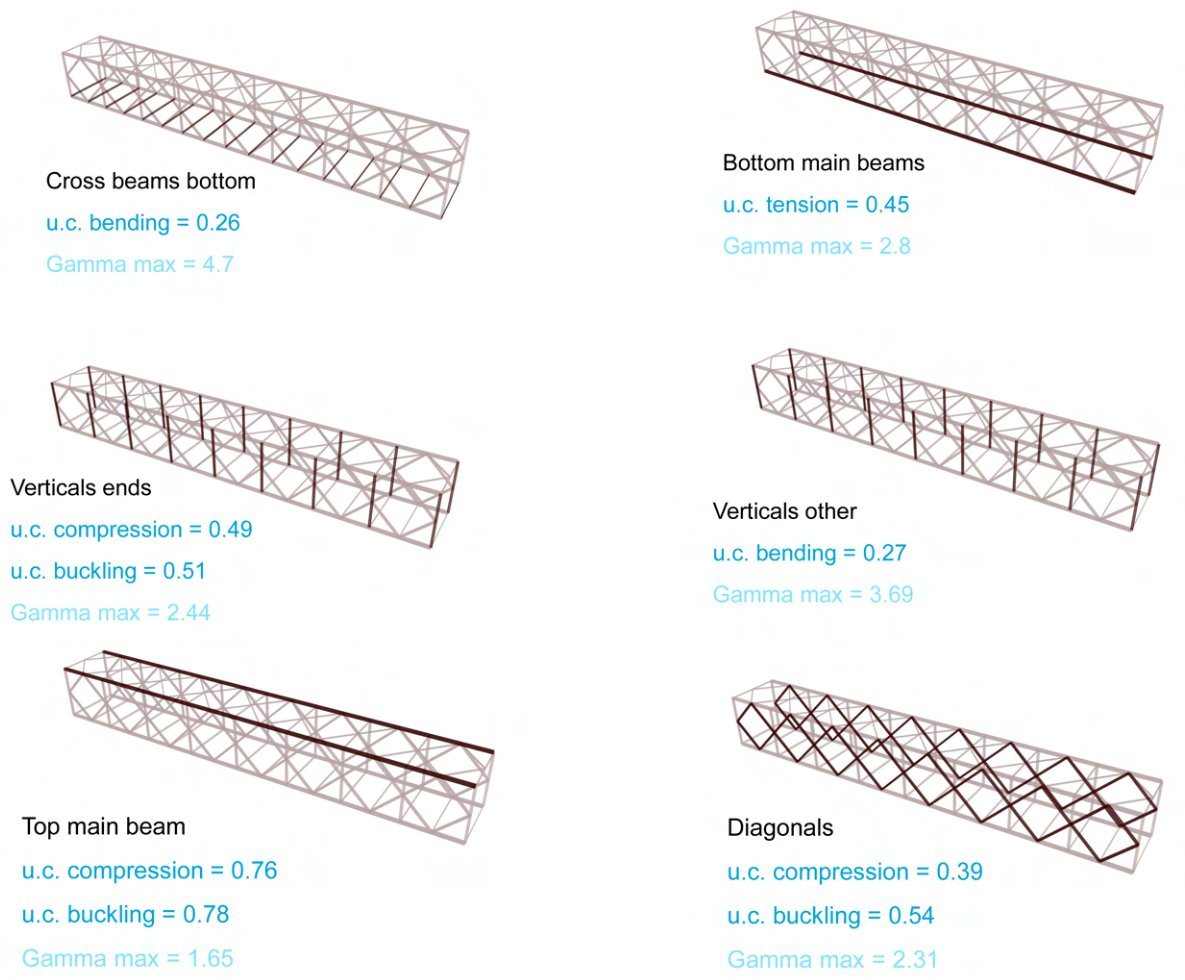

Figure 5.17: Overview of load-bearing elements and their normative unity checks.

5.4.2. New connections

From research into the logistical operation of moving the donor structure from its original location to the storage location and later to the new location, it could be concluded that the structure should be split up into parts. The connection between the main load-bearing longitudinal beam and the crossbeams should be disconnected—as well as the main top beam and the crossbeams at the top.

There are multiple possibilities when it comes to disconnecting and reconnecting these elements. The original connections are realised by rivets, which could be removed and later replaced by bolted connections. Another possibility would be disconnecting the elements at a location without a connection, for example, by thermal or mechanical cutting of the cross beams. After transport, a new connection could be realised with bolts.

Replacing rivets with bolts

Figure 5.18 shows the possible procedure for removing rivets. It is done with special equipment and by the following steps: drilling of the rivet head, drilling through the head and drilling through the core, removing the head, drilling till about 80% of the depth of the rivet, punching out the rivet body with a hammer and lastly removing any remains or resizing the hole using a reamer.

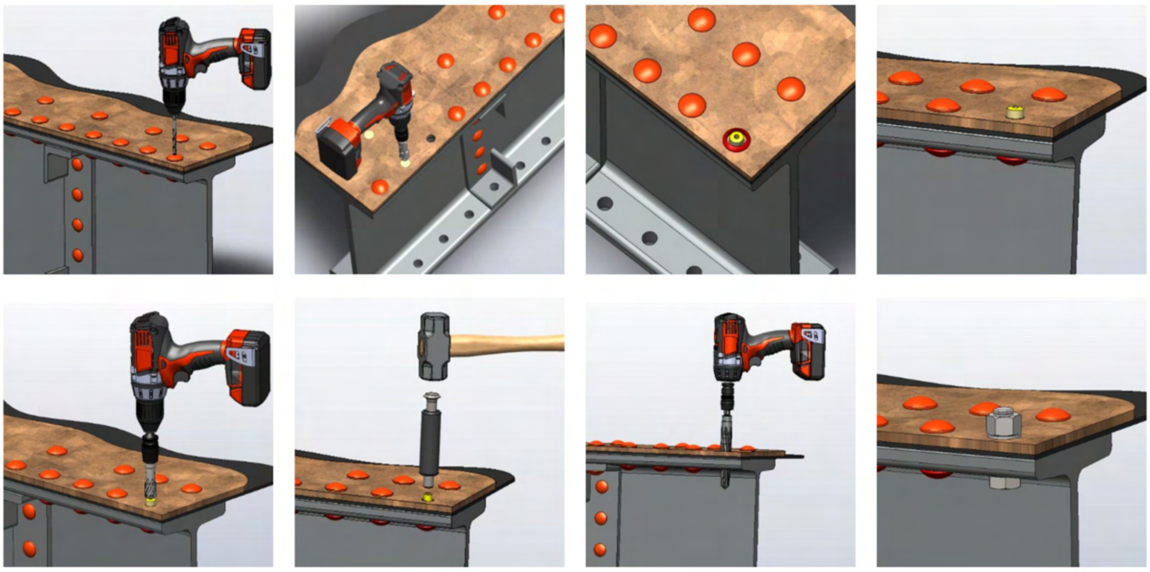

Figure 5.18: Overview of the steps for the removal of rivets ("HMT Rivet Drilling Process - Planning", n.d.)

To reuse this connection and replace rivets with prestressed bolts, the dimensions should follow the rules from NEN-EN 1993-1-8: Design of steel structures. This prescribes minimal and maximum spacing, edge, and end distances, depending on the hole diameter or the plate thickness.

A first estimation is that the dimensions of these riveted connections allow for replacement by bolts. When the donor structure was realised in 1936, the current rule in use was the VOSB 1936, which also has specific distance requirements. The requirements for minimal distances are slightly larger than the current rules. This can also be seen in Figure 5.19.

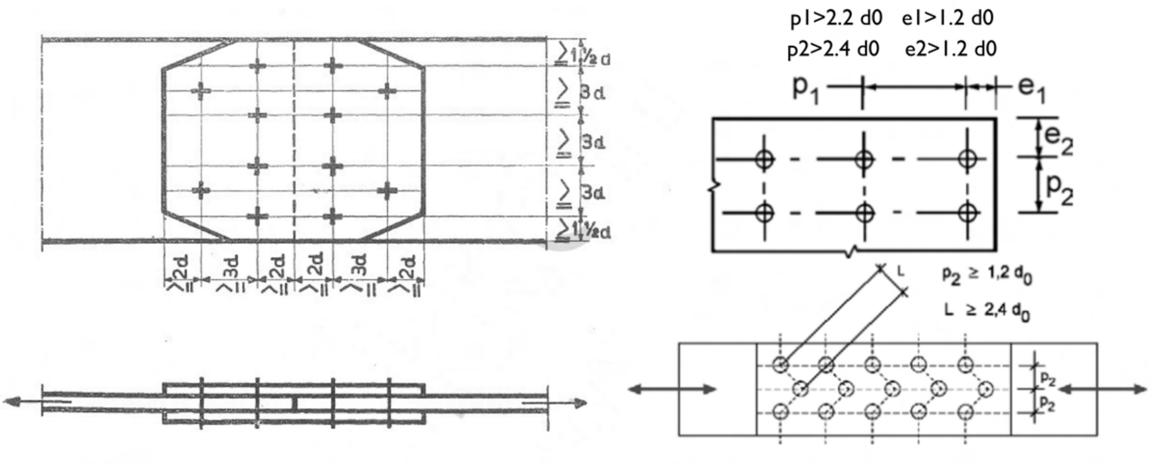

Figure 5.19: Left: Minimal distances for rivets connections old code (VOSB 1936) compared to right: new connections (NEN-EN 1993-1-8).

This assumption is checked by reviewing the connection between the primary and cross beams. The construction detail drawing available is of low quality, resulting in some uncertainty regarding the exact dimensions. In practice, the connection detail can be visually inspected to confirm these uncertainties.

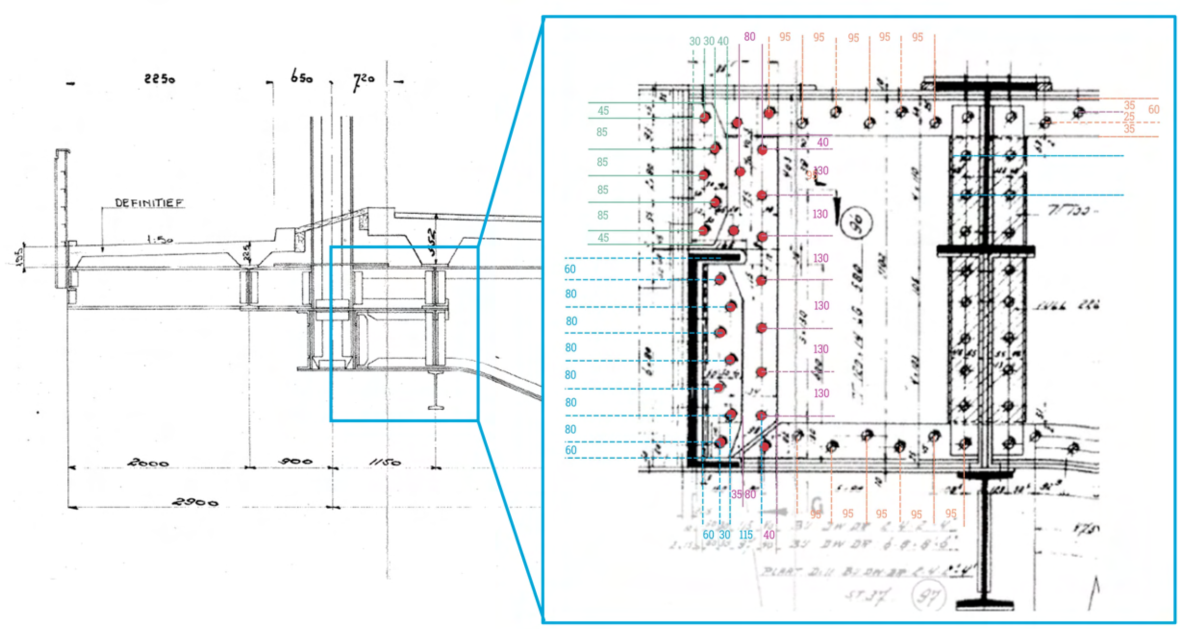

Figure 5.20: Connection detail of the main beam and cross beam with dimensions of rivets.

Most dimensions satisfy the requirements for minimal distances according to NEN-EN 1993-1-8, as shown in Figure 5.20. For this comparison, it is assumed that the diameter of the holes is the same as that of a rivet, which is 23 millimetres according to Royal Haskoning DHV, 2022. Only the spacing between the staggered row of fasteners is suspected to be 25mm, while the minimum requirement should be 27.6mm. The maximum distance, which is the smallest of 14t (t = plate thickness) or 200 millimetres, is satisfied for each rivet. Based on the assumption that the minimum plate thickness of connection plates is 10 millimetres.

In conclusion, it is possible to demount the structure by removing the rivets and reconnecting using pre-tensioned bolts and the old rivet holes. However, the removal process of rivets is labour-intensive. An estimation can be made that each connection contains 24 rivets to be replaced, as marked red in Figure 5.20. Doing this on each side and for 17 cross-beams adds up to over 800 rivets. Furthermore, according to studies by Chen et al., 2022, the load is distributed over the other rivets while removing rivets, which could cause an excessive force increase. Thus, this must be done under careful consideration.

Cutting and realising a new connection
Steel can be cut thermally by plasma, oxy-fuel, or laser cutting. It could also be cut mechanically using saws or shears. There is more freedom in choosing which location to cut the connection between the deck and the truss structure. A new connection could be realised between the same donor elements or between a new steel cross-beam.

Welding a new connection is not advised, based on available material test reports from H. Slot and J. Maljaars, 2016. When tested, the fracture toughness of the plate materials from the Keizersveerbrug is low. Thus, the steel is more prone to brittle failure, creating potential welding risks. This is avoided when using bolts to make a connection. High-strength bolts and connection plates could be used to realise a new connection between the longitudinal and cross beams. The holes that should be made for this connection in the old steel can be realised with cold drilling, minimising the risk of local stress concentrations. Figure 5.21 shows this possible new connection.

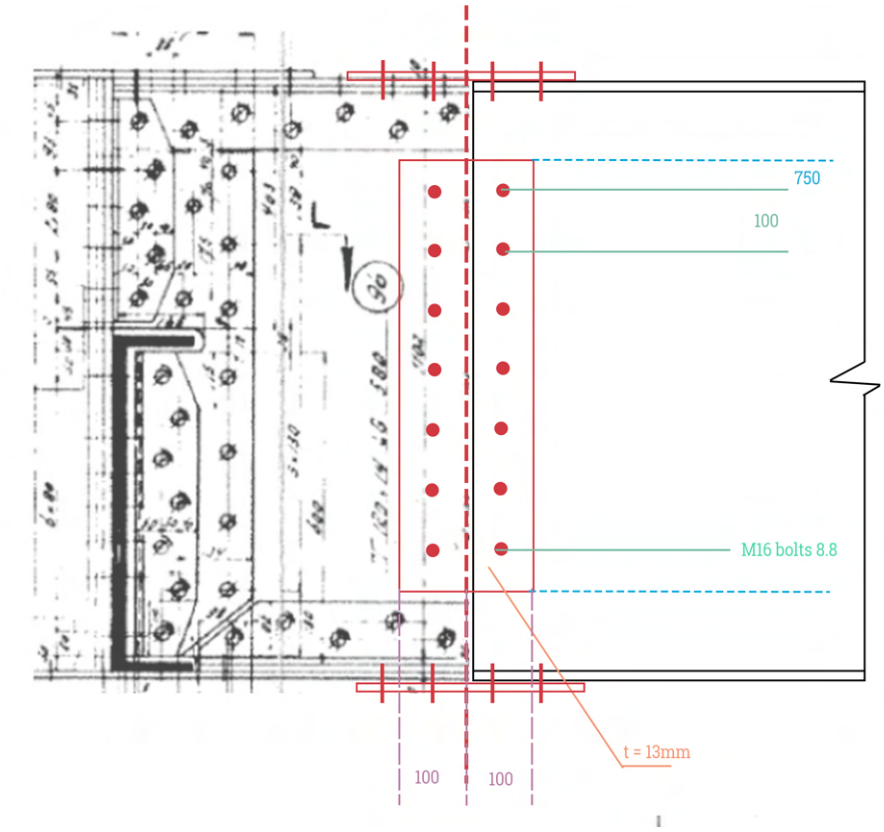

Figure 5.21: Possible new connection between the main load-bearing longitudinal beam and the remnant of the cross-beam to a new cross-beam.

Connections new deck

A new connection should be made between the hardwood timber floorboards and the longitudinal girders after removing the concrete deck. The distance between the longitudinal beams is 1.75m. The floorboards from the reference project are 1m in length, 210mm in width, and 100mm thick. Bolts form the connection between the boards and the top flange of the longitudinal girders.

Deck system fauna passage

To accommodate a soil layer necessary for a fauna passage, a concrete deck should be constructed. This requires a reinforced concrete slab with a drainage system that can be connected to the new steel deck. Concrete walls on either side act as a barrier between the zones of humans and animals and a sound barrier on the side of the highway. For large animals, this barrier should have a height of 2 meters (M. Terink, 2010). However, since this passage is designed for smaller animals, a height of 1m above the soil is assumed to be sufficient. This way, the view of people on their bikes is not entirely blocked on one side, but there is still a sound barrier for the animals. A sketch of this design is shown in Figure 5.22.

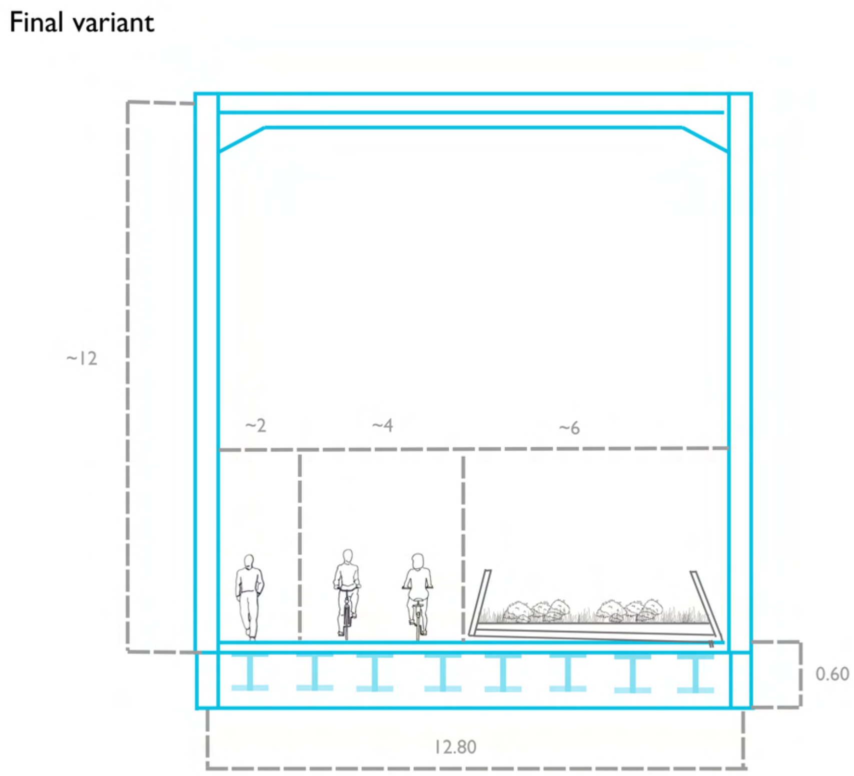

Figure 5.22: Sketch cross-section of final design.

5.4.3. Design recommendations

Based on the simulation and evaluation of the designs found in the steps of the synthesis and design possibilities, some suggestions for engineers for designing with reused objects are listed below.

- Include an environmental cost analysis in the evaluation step to gather insight into the impact of design decisions, since those could be counter-intuitive. An example of such an evaluation is whether or not to construct a new deck structure that introduces new material to the system but results in a lower bridge height and thus shorter approach ramps.
- Dubocalc is a useful tool for this initial environmental impact assessment, since it includes enough basic information on common construction materials. An overview of the products/materials used in this analysis is given in Appendix C, Section C.3.
- When reusing an existing structure, there are many possibilities to create a new structure. However, the engineer should evaluate the practical implications of some design changes, since some might not be feasible. An example of this case study is the idea to gradually change the width of the bridge. However, this would require changing and reconstructing the existing connections, which is very labour-intensive.

6 Environmental implications and costs

The environmental implications of the preliminary design as described in Chapter 5 are found. To assess a difference in environmental impact, it is compared with other design scenarios. The used Environmental Product Declarations are explained first. These show the effects per lifecycle stage according to NEN-EN 15804:2012+A2:2019 for a certain quantity of material. These are translated into environmental costs by multiplying the environmental indicators by their shadow costs, resulting in environmental costs per quantity of material. Multiplying by the amount of material used, results in environmental costs per bridge design scenario.

6.1. Environmental Product Declarations

Information provided by ”Samenwerkende Nederlandse Staalbouw” and ”Bouwen met Staal” is used for the environmental impact analysis of steel structures. ”Samenwerkende Nederlandse Staalbouw” is a Dutch association for steel construction companies, and ”Bouwen met Staal” is an organisation devoted to knowledge transfer in steel engineering. The following three Environmental Product Declarations for steel are considered:

- Heavy structural steel, 16% reuse end of life (SNS and Bouwen met Staal, 2022a);
- Heavy structural steel from 90% reuse, 16% reuse end of life (SNS and Bouwen met Staal, 2022b);
- Heavy structural steel, designed for reuse, spans up to 25m, 80% reuse (SNS and Bouwen met Staal, 2022c).

The choice to use these EPDs is due to their consistency and comparability; All three originate from the same source, making a fair comparison possible. They include the same life cycle phases and are calculated using the same methodology, resulting in a uniform basis for analysis. The environmental profiles are based on a weighted average of the market share (in tonnage) of SNS member suppliers, who collectively cover 70% of the Dutch heavy structural steel market. This makes the inventory representative of heavy structural steel in the Netherlands.

For other materials, the following EPDs are used:

- Structural hollow sections from virgin steel (Tatasteel, 2022);
- Precast concrete elements for walls, pillars and beams (Holcon GmbH, 2021);
- Structural Steel: Heavy Plates (Bauforumstahl, 2023).

These three EPDs are selected based on their comprehensiveness and the level of detail provided. They are among the few available, including information on the assumptions and processes considered for the various life cycle stages and that are found to be representative of the products to be used in reality.

The EPD for structural hollow sections is relevant due to its traditional production method: virgin steel is produced by a blast furnace from the raw materials iron ore, limestone and coke, with the addition of some steel scrap. The data is sourced directly from Tata Steel's production processes, ensuring it reflects practical and real-world conditions

The concrete EPD is based on data from Holcon, a Dutch company specialising in prefabricated concrete with production facilities located in Germany. While the geographical reference area is Germany, the information is assumed to be representative and applicable to Dutch projects, as it is stated in the EPD to be representative of Western Europe.

Lastly, the plate steel EPD is based on data provided by Bauforumstahl, a German association representing the structural steel industry. The data includes contributions from Dillinger, with production sites in Dillingen (Germany) and Dunkirk (France), representing over 95% of the annual production of heavy plates by Bauforumstahl e.V. member companies. While the geographical reference area is Germany and France, the data is considered representative and applicable for projects in the Netherlands due to the close integration of European steel markets.

All of the EPDs mentioned above are publically accessible through the following links:

- Heavy structural steel from 90% reuse, 16% reuse end of life
- Heavy structural steel, 16% reuse end of life
- Heavy structural steel, designed for reuse, spans up to 25m, 80% reuse
- Structural hollow sections from virgin steel
- Precast concrete elements for walls, pillars and beams
- Structural Steel: Heavy Plates

The most important information is summarised in Tables 6.1 and 6.2, The second row in the table shows an acronym for the EPD names. which will be used in the analysis.

Table 6.1: Summary of the EPDs of recycled steel, reused steel and to-be-reused steel.

	Heavy structural steel, 16% reuse end of life	Heavy structural steel, 90% reuse, 16% reuse end of life	Heavy structural steel, design for reuse, span up to 25m, 80% reuse
	Recycled steel	*Reused steel*	*To be reused steel*
Functional unit	1 kg heavy structural steel	1 kg heavy structural steel from reuse	1 kg 'design for reuse' heavy structural steel with a span of up to 25 metres
Product details	Structural steel profiles (94.9% secondary)	90% reused and 10% structural steel profiles (94.9% secondary)	Structural steel profiles (94.9% secondary)
A1-A3 Production phase	Manufacturing, delivery, processing (connections), hot-dip galvanising and applying of organic coating	Only 10% manufacturing, 100% delivery, processing (connections), hot-dip galvanising and applying of organic coating	Manufacturing, delivery, processing (connections), hot-dip galvanising and applying of organic coating
A4 Transport to site	150 km per truck	150 km per truck	150 km per truck
A5 Installation	Assembly per crane, 1.5-tonne steel per hour, 50% diesel and 50% electric	Assembly per crane, 1.5-tonne steel per hour, 50% diesel and 50% electric	Assembly per crane, 1.5-tonne steel per hour, 50% diesel and 50% electric
B1-7 Usage	Not considered	Not considered	Not considered
C1 Demolition	Same as installation	Same as installation	Same as installation
C2 Transport	50 km per truck for reuse and recycling	50 km per truck for reuse and recycling	50 km per truck for reuse and recycling
C3 Waste treatment	Sorting and compacting the steel scrap at a recycling plant	Sorting and compacting the steel scrap at a recycling plant	Sorting and compacting the steel scrap at a recycling plant
C4 Final waste treatment	1% landfill	1% landfill	1% landfill
D Environ-mental costs and benefits outside the system boundary	16% reuse with K=90%, rest is recycled for 99% and 1% becomes landfill.	16% reuse with K=90%, the rest is recycled for 99%, and 1% becomes landfill.	80% reuse with K=90%, the rest is recycled for 99%, and 1% becomes landfill.

Table 6.2: Summary of the EPDs of virgin steel, concrete and plate steel.

	Structural hollow sections from virgin steel	Precast concrete elements for walls, pillars and beams	Structural Steel: Heavy Plates
	Virgin steel	*Concrete*	*Plate steel*
Functional unit	1 kg steel structural hollow section (orginally 1 metric ton but converted)	1 m³ of precast concrete	1 kg structural steel heavyplates (orginally 1 metric ton but converted)
Product details	Structural hollow steel sections manufactured by Tata Steel UK and NL	Concrete C50/67 including 6m% reinforcing and prestressed steel	Hot rolled product produced by blast furnace with 35% scrap steel
A1-A3 Production phase	Raw material extraction and processing, preparation of recycled scrap, steelmaking and production of hot rolled coil, transport, forming of sections	Manufacturing, including delivery of raw materials, preparation of the moulds, concrete mixing, filling and curing, removal of the formwork, finishing and storing	Manufacturing, delivery and integrated steel production
A4 Transport to site	Initially not considered, replaced by 150 km per truck	Initially not considered, replaced by 150 km per truck	Initially not considered, replaced by 1950 km per truck
A5 Installation	Initially not considered, replaced by 1.5-tonne concrete per hour, 50% diesel and 50% electric	Initially not considered, replaced by 1.5-tonne concrete per hour, 50% diesel and 50% electric	Initially not considered, replaced by 1.5-tonne steel per hour, 50% diesel and 50% electric
B1-7 Usage	Not considered	Not considered	Not considered
C1 Demolition	Included, based on German data	Press cutting demolition by longfront excavators with demolition clamps. 30 minutes per m2 concrete	Included but specifics unknown
C2 Transport	150 km for recycling and reuse and 100 km for landfill	No specific distance known	Included but specifics unknown
C3 Waste treatment	Energy associated to cutting tubes for recycling	Sorting and crushing concrete for recycling	Waste processing for reuse, recovery or recycling
C4 Final waste treatment	1% landfill	Included but specifics unknown	Included but specifics unknown
D Environ-mental costs and benefits outside the system boundary	92% is recycled and 7% is reused	99% of concrete is recycled and reused as aggregate. 95% of reinforced steel becomes scrap metal	88% is recycled, 11% is reused, and1% is lost (EU average)

The EPDs mentioned in 6.2 initially do not include phases A4 (transport to site) and A5 (installation). Values from steel EPDs by SNS are used, considering 150 km transport and installation by telecare.

Furthermore, the phases for usage of the elements, B1-B7, are not considered. This is common for EPD, since they are generalised materials and not specified for a certain situation. For a complete LCA, impact for this stage could be added separately.

6.2. Environmental Cost Indicator

The shadow costs for all environmental impact indicators according to NEN-EN 15804:2012+A2:2019 are shown in Figure 6.1. Only the core indicators, which are the first 13, are used in the analysis. Since the additional indicators (last 5) are optional and currently often not included in all the EPDs.

The EPDs presented in the previous section, and their impact per indicator and lifecycle module can be translated to costs using these shadow costs. This is summarised in the top table in figure 6.2. The second table in the figure is the same but multiplied all values by 1000 to change the unit from kg to tonne and make the table better readable. The complete overview can be found in Appendix D.

Environmental impact category	Unit	Weighting factor (€/unit indicator)
Climate change - total	kg CO2-eq	0.116
Climate change - fossil	kg CO2-eq	0.116
Climate change - biogenic	kg CO2-eq	0.116
Climate change - land use and land use change	kg CO2-eq	0.116
Ozone layer depletion	kg CFC11-eq	32
Acidification	Mol H+-eq.	0.39
Freshwater eutrophication	kg PO4-eq	1.96
Saltwater eutrophication	kg N-eq	3.28
Land degradation	Mol N-eq.	0.36
Smog formation	kg NMVOC-eq.	1.22
Depletion of abiotic raw materials minerals and metals	kg Sb-eq	0.3
Depletion of abiotic resources fossil fuels	MJ, net cal. val.	0.00033
Water use	m3 water, world eq. deprived	0.00506
Fine dust emissions	kg disease incidence	575838
Ionising radiation	kg kBq U235-eq	0.049
Ecotoxicity (freshwater)	CTUe	0.00013
Human toxicity, carcinogenic	CTUh	1096368
Human toxicity, non-carcinogenic	CTUh	147588
Land use-related impact / soil quality	Pt/m2.year	0.000178

Figure 6.1: Schadowcosts per environmental impact category (Rijkswaterstaat, 2024).

Environmental costs per EPD (€/declared unit)														
EPD name	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D	Total costs
Recycled steel [kg]	1.55E-01	2.96E-03	7.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.55E-03	9.77E-04	3.93E-03	7.74E-06	-2.99E-02	0.147862219
Reused steel [kg]	3.51E-02	2.96E-03	7.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.55E-03	9.77E-04	3.93E-03	7.74E-06	-2.47E-03	0.05564929
Virgin steel [kg]	3.34E-01	2.96E-03	7.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.05E-04	2.45E-03	1.29E-04	2.09E-05	-2.21E-01	0.127143
To be reused steel [kg]	1.55E-01	2.96E-03	7.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.55E-03	9.71E-04	3.96E-03	1.84E-06	-1.05E-01	0.072455621
Plate steel [kg]	3.21E-01	2.96E-03	7.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.66E-04	3.13E-04	0.00E+00	2.09E-05	-1.84E-01	0.147842845
Precast reinforced concrete [m3]	1.47E+02	7.22E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.18E+00	4.65E+00	1.16E+00	5.23E-02	-1.40E+01	155.6661345

Environmental costs per EPD (€/declared unit*1000)														
EPD name	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D	Total costs
Recycled steel [tonne]	154.77	2.96	7.55	0.00	0.00	0.00	0.00	0.00	7.55	0.98	3.93	0.01	-29.88	147.86
Reused steel [tonne]	35.14	2.96	7.55	0.00	0.00	0.00	0.00	0.00	7.55	0.98	3.93	0.01	-2.47	55.65
Virgin steel [kg]	334.28	2.96	7.55	0.00	0.00	0.00	0.00	0.00	0.70	2.45	0.13	0.02	-220.95	127.14
To be reused steel [tonne]	154.77	2.96	7.55	0.00	0.00	0.00	0.00	0.00	7.55	0.97	3.96	0.00	-105.31	72.46
Plate steel [kg]	320.60	2.96	7.55	0.00	0.00	0.00	0.00	0.00	0.37	0.31	0.00	0.02	-183.97	147.84
Precast reinforced concrete [1000 m3]	147403.17	7215.77	0.00	0.00	0.00	0.00	0.00	0.00	9176.23	4653.63	1164.66	52.32	-13999.64	155666.13

Figure 6.2: Table with summary Environmental costs per EPD.

6.2.1. Results

Now that all the environmental impact categories are expressed in terms of the same unit, it is more practical to compare the different EPDs and the impact of different life cycle stages on the total environmental costs. The graph shown in Figure 6.3 shows the environmental costs per life cycle stage for the steel EPDs. Concrete is shown separately in Figure 6.4 , since the unit is different.

Relevant observations are listed below.

- Lifecycle stages A1-3 and D have the most significant impact; there are also the biggest differences between the EPDs noticeable.

- The difference in production methods is directly visible and depends mainly on how much virgin or recycled steel is used. The found values are similar to values found in literature, like an article from Bouwen met Staal (J-P. den Hollander, 2024). Production with a blast furnace results in a Global Warming Potential of $2kg[CO_2 - eq.]/kg$ steel. For the production method of the Electric arc furnace, a Global Warming Potential of $0.5kg[CO_2 - eq.]/kg$ steel is expected.
- All the other life cycle stages are very similar and have a smaller impact; thus, differences in those stages barely contribute to the total environmental implications.
- There is a significant difference in Module D values, which is expected given how these calculations are performed. Plate steel, produced with 65% virgin material and later recycled, results in substantial savings because it offsets the production of new virgin steel—a highly impactful process. Reused steel achieves the second-highest negative value in Module D because it offsets the production of recycled steel. However, since recycled steel has a lower environmental impact in Modules A1-A3, the savings from recycling it again are comparatively smaller. Reused steel has the lowest impact in Module D because it is directly reused, meaning its A1-A3 impacts are already lower, avoiding additional processing.

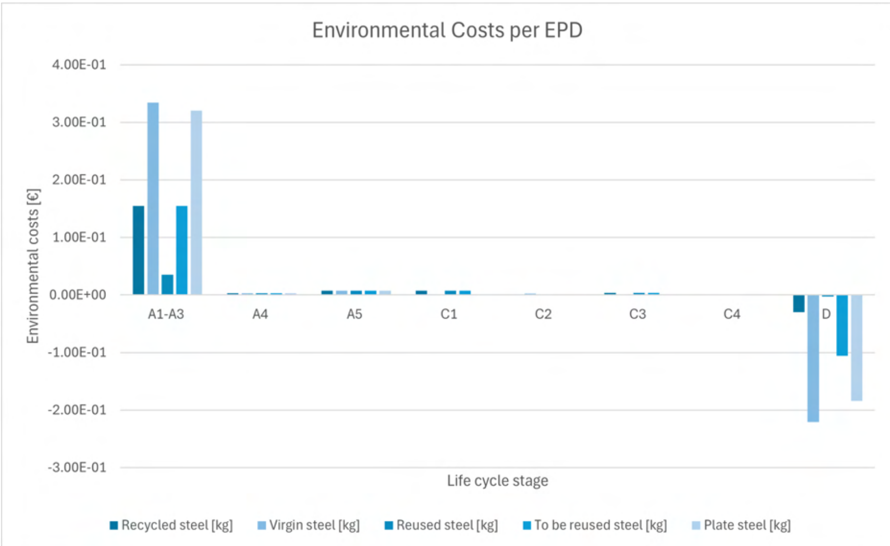

Figure 6.3: Graph showing the environmental costs per steel EPD for each considered life cycle stage.

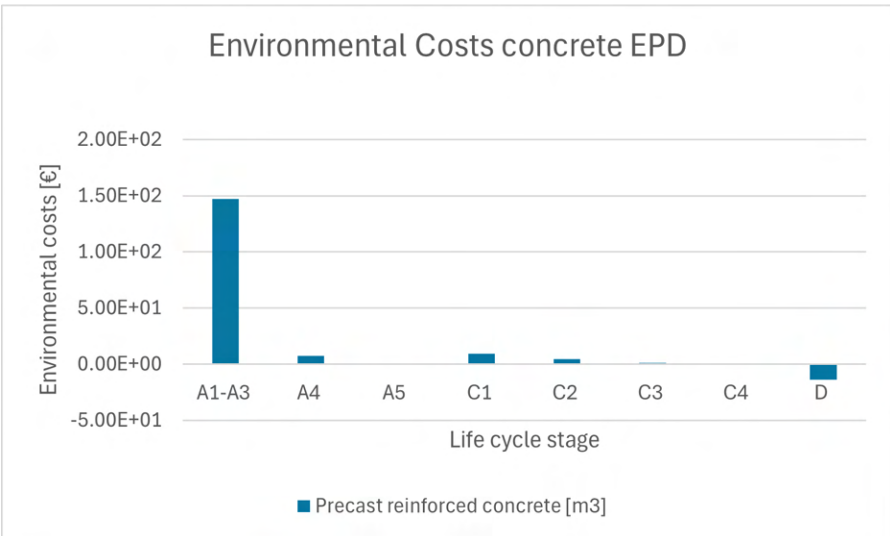

Figure 6.4: Graph showing the environmental costs for concrete EPD for each considered life cycle stage.

6.3. Environmental impact of different design scenarios

To put the environmental impact of a reuse scenario into perspective, it is compared to other design scenarios. An overview of those scenarios is shown in Figure 6.5 and are the following:

1. Ackerdijkse bridge, including reused elements from Keizersveerbrug.
2. Newly produced steel truss bridge from recycled steel.
3. Newly produced steel truss bridge from virgin steel.
4. Newly produced steel truss bridge designed for reuse, made from recycled steel
5. Concrete preliminary design of Ackerdijkse brug from municipality Delft.
6. Newly designed steel plate bridge.

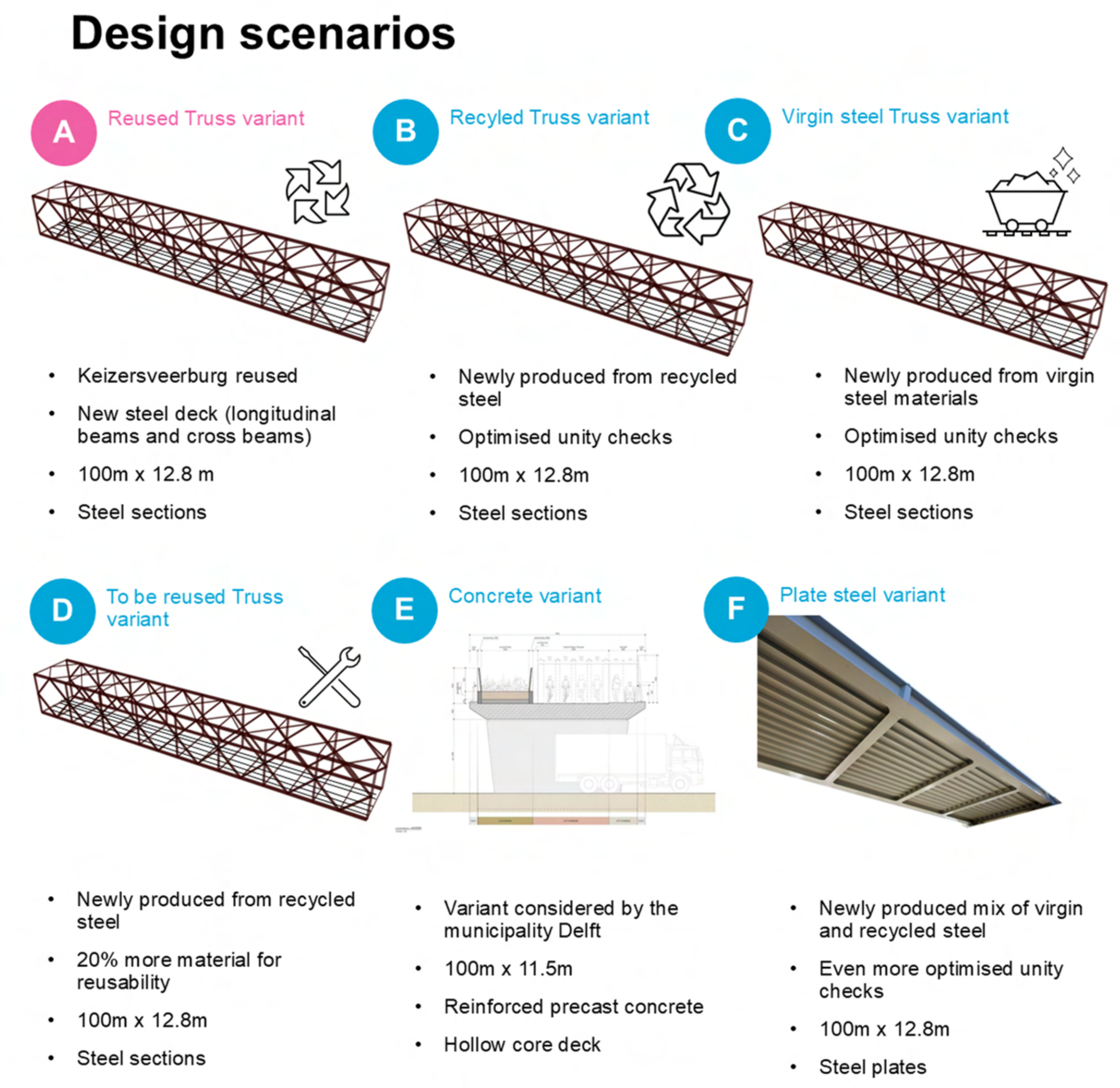

Figure 6.5: Summary of the six different design scenarios considered in the analysis.

To make a correct and fair comparison, the conditions of all design scenarios are as similar as possible. In this analysis, only the load-bearing superstructure with a main span of 100m is considered and compared. To take into account the difference in width between the steel variants and the concrete bridge design, the total environmental costs are divided by the area of the bridge to arrive at an impact per squared meter.

The aspects not considered in this analysis are the foundations, approach ramp, railing, corrosion paint and details regarding the deck, e.g., the wear layer. These are either the same/very similar for the design situations or are expected not to be of a big influence on the final conclusions. As discussed in Section X, the paint layer to protect steel against corrosion and the wear layer on top of the decks against slipping significantly impact the environmental costs of a bridge design. However, the impact difference between a reuse variant and a new bridge structure is more minor, which is why the aspects are not considered in this analysis. The effect of this assumption on the results is elaborately discussed in chapter 7.

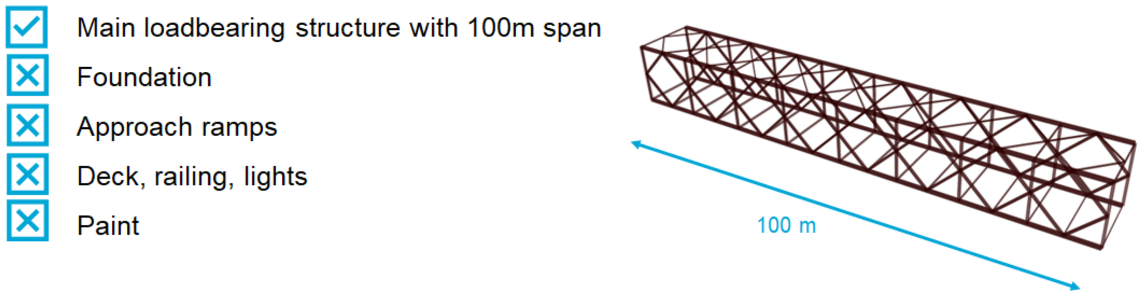

Figure 6.6: The unit considered in the analysis.

6.3.1. Design scenario A - Reused steel elements

Description of the design
This design's main load-bearing structure is the reused steel truss structure of the Keizersveerbrug of 100m length, 12.8m width and height. The deck (longitudinal and cross beams) is replaced by a new steel deck made from virgin steel.

Environmental costs
The materials considered in the calculation are:

- 511.6 tonnes of reused steel;
- 85.4 tonnes of virgin steel.

This results in a total environmental impact of €39327.95 divided over an area of 1280 square meters, resulting in a value of €30.72 per square meter.

6.3.2. Design scenario B - Recycled steel elements

Description of the design
This design considers a newly constructed steel truss bridge of 100m in length and 12.8m in width and height. An assumption is made that the structure is more optimised than design scenario A, since it became clear from the structural analysis in Chapter 5, that the reused truss is over-dimensioned. This results in a reduction of steel input of around 25%.

Environmental costs
The materials considered in the calculation are:

- 453.3 tonnes of recycled steel.

This results in a total environmental impact of €67024.25 divided over an area of 1280 square meters, resulting in a value of €52.36 per square meter.

6.3.3. Design scenario C - Virgin steel elements

Description of the design
Similarly to design variant B, this design is an optimised steel truss bridge of 100m length and 12.8m

width and height. It is, however, made using virgin steel products.

Environmental costs
The materials considered in the calculation are:

- 453.3 tonnes of virgin steel.

This results in a total environmental impact of €57632.32 divided over an area of 1280 square meters, resulting in a value of €45.03 per square meter.

6.3.4. Design scenario D - To be reused steel

Description of the design
This design is also a newly built truss bridge. However, the design is made for reuse after its service life in this location. The EPD of 'design for reuse' can be used to calculate the environmental impact. The design is assumed to use 20% more material compared to the optimised structures from scenarios B and C. This is a result of a design with more similar elements, which are thus not optimised, as well as more robust demountable connections.

Environmental costs
The materials considered in the calculation are:

- 543.9 tonnes of to be reused steel.

This results in a total environmental impact of €39411.96 divided over an area of 1280 square meters, resulting in a value of €30.79 per square meter.

6.3.5. Design scenario E - Concrete bridge municipality

Description of the design
The municipality of Delft has a preliminary design of a concrete Ackerdijksebrug. Available figures from this design can be found in Appendix D.2. It has a width of 11.125m and a length of 100m. No detailed information is available on this design, so the quantity of the materials is estimated. In the longitudinal direction, this design is supported on both ends, as well as on three columns. According to "HMP-ligger", n.d., for a maximum span of 30m, a HKP-900 box-girder is appropriate. With a centre-to-centre distance of 1.5m, this results in a design with 7 box girders next to each other, with a total width of 10.5m.

Environmental costs
The materials considered in the calculation are:

- 613.2 m^2 of precast reinforces concrete.

This results in a total environmental impact of €95454.47, divided over an area of 1050 square meters, resulting in a value of €90.91 per square meter.

6.3.6. Design scenario F - Plate steel bridge

Description of the design
A common typology for steel cyclist and pedestrian bridges nowadays is a plate girder bridge from plate steel. It can make very efficient and slender bridge designs by efficient material placement. For this design scenario, inspiration is taken from the Watersportbaan (Annie van der Wiele brug) by NEY&Partners. This is not the exact design, as the dimensions differ, and this version does not include a fauna passage. Materials use is estimated by assuming a 10% reduction of steel compared to the efficient truss designs of variants B and C.

Environmental costs
The materials considered in the calculation are:

- 408.0 tonne plate steel

This results in a total environmental impact of €60313.92 divided over an area of 1280 square meters, resulting in a value of €47.12 per square meter.

6.3.7. Results

The table in Figure 6.7 shows the environmental costs of the six scenarios per lifecycle, as well as the total effect on euros and total impact per squared meters. The last column in the table shows the total costs at the end of the lifecycle per square meter. Only considering the final total impact, as done with the 50:50 approach, the best-scoring variant is the variant with the lowest impact. The ranging is the following:

1. Design with reused elements from Keizersveerbrug - costs €30.72 per square meter.
2. Newly produced steel truss bridge designed for reuse made from recycled steel - costs €30.79 per square meter.
3. Newly produced steel truss bridge from virgin steel. - costs €45.03 per square meter.
4. Newly designed steel plate bridge - costs €47.12 per square meter.
5. Newly produced steel truss bridge from recycled steel - costs €52.36 per square meter.
6. Reinforced concrete variant - costs €90.91 per square meter.

Plotting the environmental costs of the six variants per lifecycle gives insight into the progression of these environmental costs over the life stages of the design scenarios. This is shown in Figure 6.8.

Environmental costs per design scenario										
Scenario	A1-A3	A4	A5	C1	C2	C3	C4	D	Total costs [€]	Costs [€] per 1 m2
Scenario 1 reused steel elements	46527.89	1764.81	4508.16	3923.39	709.39	2023.72	5.75	-20135.14	39327.95	30.72
Scenario 2 recycled steel elements	70155.06	1340.01	3423.02	3423.02	442.81	1783.33	3.51	-13546.52	67024.25	52.36
Scenario 3 virgin steel elements	151524.98	1340.01	3423.02	319.42	1112.57	58.69	9.48	-100155.86	57632.32	45.03
Scenario 4 to be reused steel elements	84186.07	1608.01	4107.62	4107.62	528.11	2155.61	1.00	-57282.09	39411.96	30.79
Scenario 5 concrete	90387.62	4424.71	0.00	5626.86	2853.61	714.17	32.08	-8584.58	95454.47	90.91
Scenario 6 plate steel	130793.11	1206.01	3080.72	149.51	127.56	0.00	8.54	-75051.51	60313.92	47.12

Figure 6.7: Table of environmental impact per design scenario per lifecycle stage.

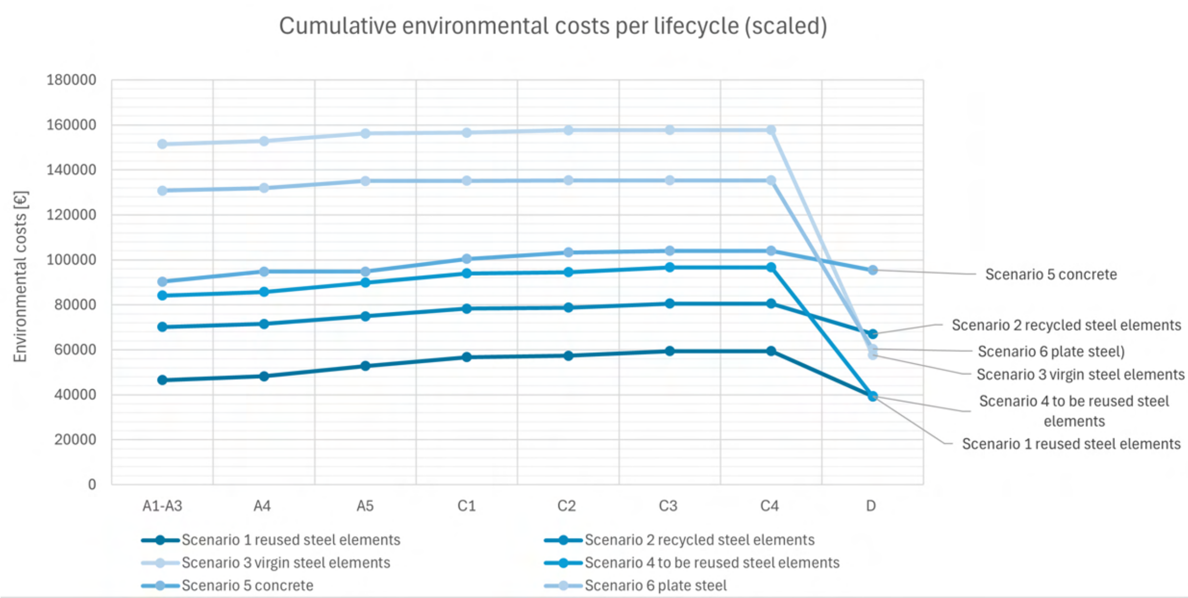

Figure 6.8: Cumulative graph of the environmental costs per life cycle stage.

From the cumulative graph, it can be concluded that there is a difference in the ranking of the design scenarios, depending on which stage in the life of the structure is considered. For most life cycle stages, A1 up until C4, the ranking is the same. The results when taking on the Cut-off approach (not considering module D) are as follows:

1. Design with reused elements from Keizersveerbrug - costs €46.46 per square meter.

2. Newly produced steel truss bridge from recycled steel - costs €62.95 per square meter.
3. Newly produced steel truss bridge designed for reuse made from recycled steel - costs €75.54 per square meter.
4. Reinforced concrete variant - costs €81.28 per square meter.
5. Newly designed steel plate bridge - costs €105.75 per square meter.
6. Newly produced steel truss bridge from virgin steel. - costs €123.27 per square meter.

Differences occur due to phase D, where environmental gains differ per scenario. Especially for the scenarios of to-be-reused steel elements, virgin steel elements and plate steel elements, the D-phase results in a big decrease in environmental costs.

6.3.8. Comparison with bridges from the field

To put the analysis of the environmental impact into a more practical context, a comparison is done with existing bridges and their environmental impact. This requires the calculation of the environmental impact in terms of carbon dioxide emissions for the used materials only. Again, only the material for the main loadbearing superstructure is considered. This methodology is chosen in order to compare with bridges from the database of NEY&Partners, an engineering firm specialised in bridge design. This is done for variant A, B, E and F.

For this, values from the same EPD for reuse are applied, but the EN 15804-A1 indicators instead. This is to make a comparison possible with the database from the company. For the other materials, the values that are used in the database are the following:

- Reused steel: $507kg\ CO_2 - eq./tonne$ steel;
- Plate steel: $2400kg\ CO_2 - eq./tonne$ steel;
- Recycled steel: $1400kg\ CO_2 - eq./tonne$ steel;
- Concrete: $413kg\ CO_2 - eq./m^3$ concrete;
- Reinforcement steel: $1400kg\ CO_2 - eq./tonne$ steel;

Design scenario A - reused truss variant
The materials considered in the calculation are:

- 511.6 tonnes of reused steel;
- 85.4 tonnes of recycled steel.

This results in a total environmental impact of 362371.16 $kg\ CO_2 - eq.$, divided over an area of 1280 square meters, resulting in a value of 283.10 $kg\ CO_2 - eq.$ per square meter. The design has an average span of 100m.

Design scenario B - recycled truss variant
The material considered in the calculation is:

- 453.3 tonnes of recycled steel.

This results in a total environmental impact of 634620 $kg\ CO_2 - eq.$, divided over an area of 1280 square meters, resulting in a value of 495.80 $kg\ CO_2 - eq.$ per square meter. The design has an average span of 100m.

Design scenario E - concrete variant
The materials considered in the calculation are:

- 613.2 m^2 of concrete;
- 141.0 tonnes of reinforcement steel.

This results in a total environmental impact of 450702 $kg\ CO_2 - eq.$, divided over an area of 1050 square meters, resulting in a value of 429.24 $kg\ CO_2 - eq.$ per square meter. The design has an average span of 100m.

Design scenario F - plate steel variant
The material considered in the calculation is:

- 408.0 tonnes of recycled steel.

This results in a total environmental impact of 979200 $kg\ CO_2 - eq.$, divided over an area of 1280 square meters, resulting in a value of 765.00 $kg\ CO_2 - eq.$ per square meter. The design has an average span of 30m, since it has multiple columns over the total span, as can be seen in the cross section in Appendix D.2.

Results
Figure 6.9 is a graph from NEY&Partners that shows the environmental impact in kg $CO_2 - eq.$ per area of the superstructure of different pedestrian and cycle bridges from different materials. This is plotted against their average span. The above discussed variants are added to this graph. The following results can be highlighted:

- All three design variants from steel with a 100-m span have a lower environmental impact than bridges from the database. Although steel is a commonly used material for bridges of these dimensions, typologies differ. Nowadays, truss traffic bridges are not commonly constructed due to the high labour costs. From the results it can be concluded that in terms of carbon-dioxide emissions, a truss variant is a very efficient design.
- Comparing the plate steel variant of 408 tonnes steel with plate steel bridge designs from the database, it can be concluded that the assumptions done for the design could be too optimistic. Comparing specifically with the bridge 'Watersportbaan', which is a very slender and optimally designed bridge with a length of 90 meters, average span of 68 meters and a width of 7 meters, but a higher amount of steel of 550 tonnes.
- The design variant of concrete has a similar environmental impact compared to other concrete bridges with an average span between 20-40 meters. The CO_2 emissions of these concrete bridges is lower than steel bridges with a similar span.
- When comparing the four design variants only on $CO_2 - eq./m^2$, the design including reuse scores best, after which the concrete design, the steel truss bridge and lastly the plate steel bridge. Remarkable is the high position of the concrete variant compared to the previous analysis based on environmental costs.

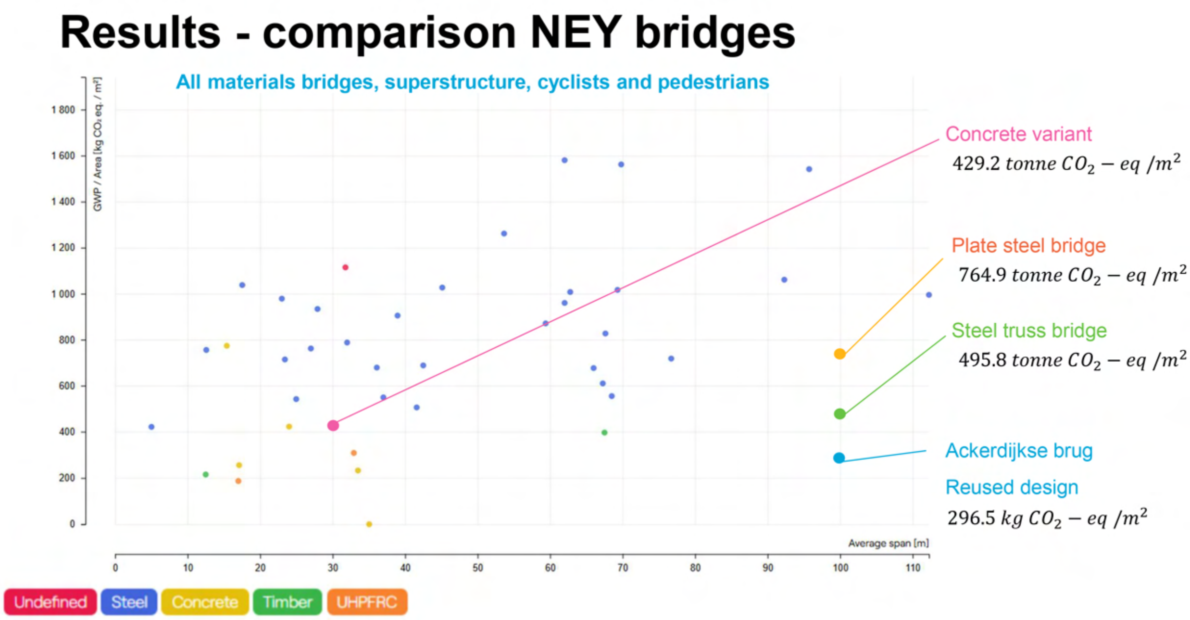

Figure 6.9: Graph of environmental impact in kg/CO2-equivalent of the superstructure of pedestrian and cyclist bridges from NEY&Partners, of different materials.

7 Discussion: design cycle steps, including reuse

This chapter integrates the concept of reuse into the traditional design cycle, addressing one of the key objectives of this thesis. Additionally, it serves as the discussion chapter of the research. The original design cycle, introduced in the methodology section of the introduction, is shown in Figure 1.3.

In Figure 7.1, the design cycle is extended to incorporate the reuse considerations. The subsequent sections provide a detailed explanation and discussion of each element of the extended cycle. Additionally to this general discussion, insights are shared from the case study of reusing the Keizersveerbrug as a donor structure for the Ackerdijksebrug, a cyclist bridge and fauna passage in Delft.

Lastly, the limitations of the research are discussed.

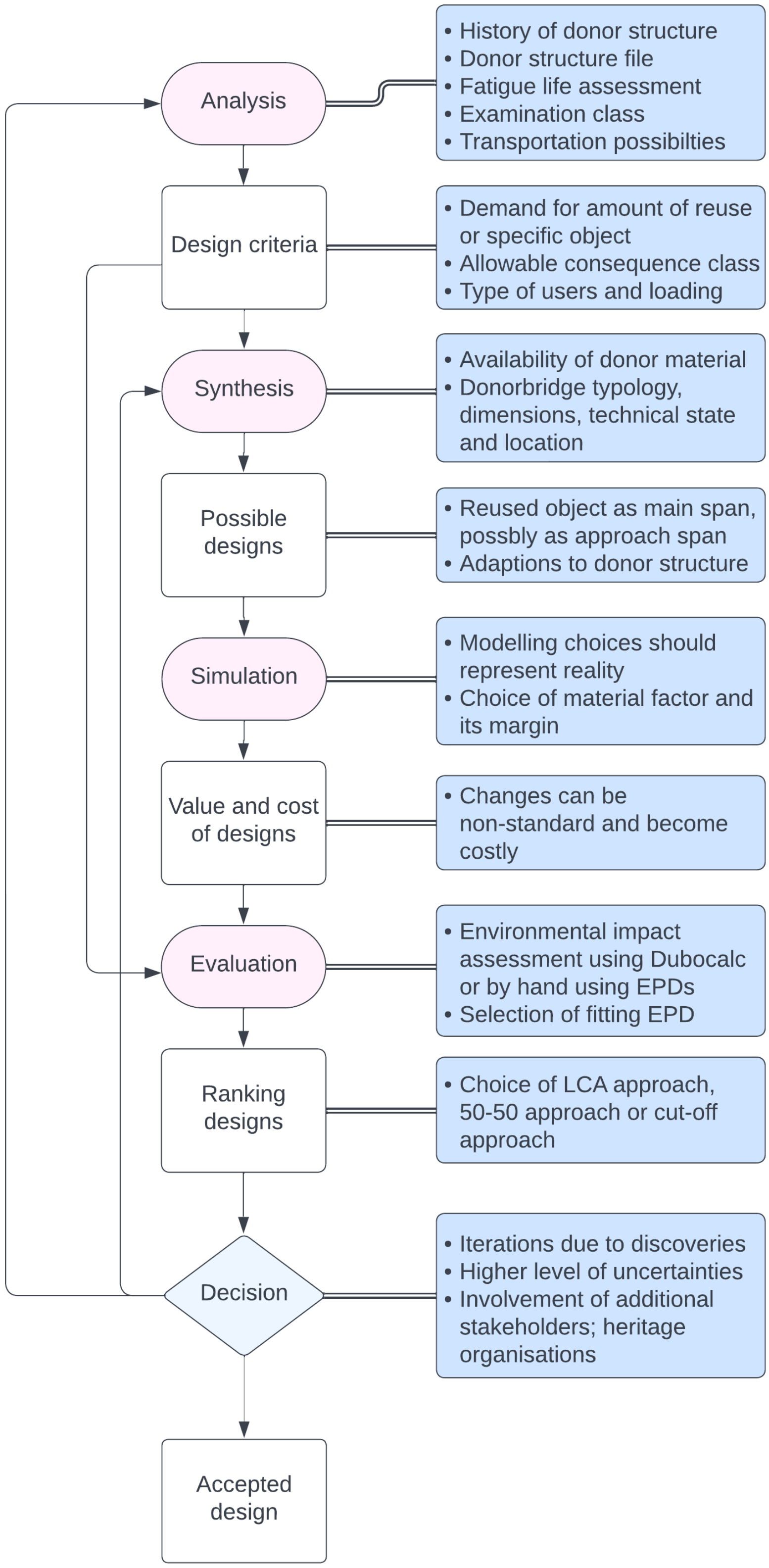

Figure 7.1: Design cycle, including considerations for design with reused objects.

7.1. Analysis

General

Traditionally, the goal of the analysis is to understand the design assignment and gather the relevant data on the project. In the context of reuse, this step is expanded to include a detailed evaluation of the donor structure. Key tasks involve creating a donor structure file, which consists of an overview of the object's history, technical details, inspection reports, assessing preservation, corrosion and material properties. The current fatigue state of traffic bridges that are cyclically loaded should also be assessed. The analysis determines the examination class and, thus, the possible consequence class for the new design application. Additionally, transportation routes between the location of the reused object and the new project site should be evaluated. In conclusion, this comprehensive analysis ensures that reuse challenges, such as hidden defects of structural elements or logistical constraints, are identified early. These can influence later stages of the design cycle.

Case study

The case study focuses on reusing the Keizerveerbug as a donor structure for the Ackerdijkse brug. The bridge has a fascinating history since it was initially constructed in 1936 as the Moerdijkbridge. It consisted of six 100-meter truss bridge structures and was partly destroyed in 1944 in the war. Then, it was repaired, and six bridge objects were relocated to Keizersveer in 1978. The bridge is planned to be replaced due to an increasing traffic demand.

A donor structure file is compiled, revealing minimal damage and corrosion, no presence of chromium-6, and elements materials of S235 (St. 37) and S355 (St. 52) steel grades. Furthermore, the old application has been susceptible to fatigue, resulting in the necessity for an assessment of the remaining fatigue life. Reports show that the structure can be implemented safely for over 30 years at its current location under these high traffic loadings. Transportation between the sites is possible by water, adding to the practicality of reuse. Additionally, the truss has a monumental status, which requires changes to the design to be well-justified.

However, acquiring the necessary data to complete the donor structure file is found to be a challenging process. Reports for Rijkswaterstaat were made by various organisations and are thus inconsistently formatted and not always accessible. This highlights the need for centralised, well-archived documentation to streamline the reuse process for future projects.

7.2. Design criteria

General

This step includes defining specific and measurable criteria for the design, like the technical, functional, and ecological requirements. An important influence of reuse on the design criteria is the allowable consequence class, which depends on the examination class found in the analysis step. Besides that, reuse can introduce unique considerations. For instance, a client might include reuse as a project requirement, specifying a minimum reuse percentage or demanding incorporation of a specific donor object. Requirements concerning the users of the new bridge influence the type of loading that should be taken into account. By aiming for reuse scenarios where there is no car traffic in the new application, an elaborate and thus complex assessment of fatigue is not necessary.

Case study

In this case study assignment, the incorporation of the reuse of bridge objects of the Keizersveerbrug is a key design criterion. Findings from the analysis step support the conclusion that the bridge could meet consequence class CC3 requirements for the new design. In this case, there is no requirement for an exact amount of reuse. The new application, the Ackerdijksebrug, is intended for pedestrians, cyclists and certain animals, such as small mammals and insects. These users have specific functional and ecological requirements. For example, for the animals, an undisturbed, separate and short path is preferred. Furthermore, due to these new users, there is no cyclic loading, avoiding the need for an extensive fatigue analysis.

7.3. Synthesis

General

During the synthesis step, insights from the analysis and the criteria are combined to outline potential solutions. In the context of reuse, this process is influenced by constraints such as the donor structure's availability, typology, dimensions, and technical state. As well as logistical considerations like transportation routes. The new application for the donor structure and the new bridge users also influence design possibilities.

Case study

In this design example, the restraints were relatively limited. The availability of the donor structure - four 100-meter elements and two 87.5-meter elements - provides flexibility. One 100-meter element is fitting to cross the highway. The modular nature of the truss typology, with its 12.5-meter grid size, would even allow for adjustments if necessary. Furthermore, the current width of 12.5 meters is large enough to fit all of the bridge's user requirements, and thus does not pose a constraint. However, the transport constraints dictate that the connection between the truss and deck and between the truss and wind braces should be separated to enable shipping by water.

7.4. Possible designs

General

Feasible designs are generated in this step, exploring multiple variants that meet the design criteria. While reuse may initially seem limiting, it encourages innovative thinking and creative problem-solving. For example, approach ramps of the bridge are traditionally constructed with soil or concrete structures but could also be realised using a donor structure. Furthermore, modifying the dimensions or removing and replacing certain elements of the donor object can open up new possibilities for design. By considering these options, reuse transforms from a constraint into an opportunity for unique solutions.

Case study

In this case study, the original truss is the basis for generating nine design variants. Allocating the bridge's different users within the cross-section and combining them with the three options for an approach ramp (soil, concrete or donor structure), results in various designs. The transport limitations, the need to disassemble the truss for shipping, influence the design process. The possibilities of reusing or replacing the bridge deck are explored. From the analysis step, it is concluded that some cross beams are corroded, thus replacement or repair is necessary.

7.5. Simulation

General

The designs are tested structurally using a structural model, and by performing structural calculations. In a conventional method, modelling choices and the structure's design influence each other, particularly regarding supports and connections. When designing with reused structures, the simulation process becomes different, as the model must accurately represent the reality of the donor structure, including its current state and any existing constraints. Engineers must make assumptions based on the available information and their professional judgment for preliminary designs. Besides that, it is found beneficial to create a parametric model as it allows for different design configurations and adapts to the iterative nature of the design process. Additionally, uncertainty in material properties and the state of the elements may necessitate adjustments to the material factor used in the calculations. Existing literature does not fully address material factors for reused steel objects, which poses an uncertainty for structural calculations.

Case study

In this case study, a parametric line model of the Keizersveerbrug is created in Rhino and Grasshopper. Its structural performance is analysed using Karamba 3D. The elements are validated through hand calculations based on the stresses acquired from the model. Assumptions are made to represent the behaviour of the existing structure, particularly regarding connections and supports.

A material factor of 1.25 was initially assumed, which aligns with the literature. Calculations were made to determine the maximum allowable material factor that would maintain a unity check of one. This maximum factor indicates the structure's capacity for changes in the requirements. A lower factor (e.g., 1.5) offers less flexibility, increasing the risk of the structure being unsafe if future research shows a higher material factor is needed. A higher factor (e.g., 2.5) provides more margin, reducing the chance of the necessity for recalculation in the future. This approach demonstrates how simulations can manage uncertainties and assess the feasibility of reusing steel structures. For the Keizersveerbrug, the material factor possible ranges between 1.65 and 4.7 for different bridge elements.

7.6. Value and costs of designs

General

For this research, only the environmental impact and cost calculation were within the scope; thus, the actual construction costs were not calculated. However, during a preliminary design that includes reuse, it is helpful to consider whether certain design choices are practical and cost-effective. Some changes to the structure require a different approach than the standard practice for producing new steel structures. Furthermore, acquiring a reusable bridge object from Bruggenbank and Platform Bruggen saves potential costs since the buyer pays for the service (for the platform and, for example, the transport) but not for the actual bridge material.

Case study

Reconnecting the existing deck with the main loadbearing structure is considered. Due to the brittle material properties of the donor steel, it is necessary to remove the rivets and replace them with bolts. Since this is not common practice and there are many rivets to replace, it would be a very costly process. An alternative is proposed, to realise a connection to a new deck. However, this does negatively impact the environmental footprint of the design, and demonstrates that complete reuse is not always feasible.

7.7. Evaluation

General

During the evaluation, the designs are assessed based on different criteria. Environmental impact is sometimes implemented as an evaluation criterion in a traditional design cycle for a bridge. From the literature, different sustainability models show and rank approaches, like the R-ladder: reduce, reuse, recycle. Stakeholders have implemented those by personal goals, for example, Rijkswaterstaat, who strives for: 'high-quality reuse, unless...'. If reuse is included, the evaluation of environmental impact or costs becomes even more relevant.

Tools like Dubocalc have proven helpful for an initial estimation and comparison of the environmental impact of different design variants. However, it requires the engineer to be critical when applying it to reuse. For new materials, it often already includes all the processes involved. For reused material, steel, in this case, a process like repainting and transport is not automatically included and should be added manually. Besides that, this tool is currently still based on the NEN-EN 15804-A1 indicators. However, a transition to A2 indicators has started.

A more elaborate evaluation of environmental impact can be done by using Environmental Product Declarations. Although the method is straightforward, it has been found challenging to find relevant and complete EPDs that can be used to ensure a fair comparison. Especially with the transition to the A2 set of indicators, which progresses slowly at different paces per platform, company or country. There is currently an EPD available from 'Bouwen met Staal' for reused structural steel elements that is complete, includes both A1 and all A2 indicators and is representative of the Dutch market; thus, it is recommended to be used in this analysis.

Case study

In the case study, DuboCalc is used to compare different approach ramp and cross-section layouts. The environmental impact of various design choices is calculated and evaluated, which are: external bike path, new deck, concrete or soil approach ramp, fauna passage on the roof, soil or foam ramp and donor structure as a ramp or not. Interesting conclusions are found, some of which are counter-intuitive. Based on the R-Ladder, it is expected that reusing the deck would be a more sustainable choice than replacement. It becomes clear that it is important to view the broader picture. By replacing the deck and reducing its structural height, there is a lower height difference with the ground. This results in a reduction in materials necessary to construct the approach ramps, resulting in a total lower environmental impact. When assessing whether a concrete or soil approach ramp has lower environmental costs, it is concluded that this depends on the dimensions of the ramp. Surprisingly, a soil ramp can have higher environmental costs, due to the transportation of big volumes of material per truck. However, for low height ramps, it does have a lower environmental impact than a concrete ramp. A consideration that has a very clear result is whether or not to implement a donor structure as an approach ramp, which, as expected, clearly results in a large environmental gain.

In a later phase, a more elaborate environmental impact assessment is carried out. A design that includes the 100-m donor bridge structures with a replaced deck is compared with other design variants. The different design variants are: a newly produced steel bridge from recycled steel, a newly produced steel bridge from virgin steel, a newly produced steel bridge from recycled steel but designed to be reused, a concrete girder bridge and a newly designed steel plate bridge. Only the main loadbearing structure is compared, so the approach ramp, foundations, deck, railing, and lights are not considered. The system boundaries of the analysis are from cradle to grave, so it includes all life stages of the structure. Only the core environmental indicators of the A2-set are used.

7.8. Ranking the designs

General

Besides the environmental impact, evaluation criteria could be the users' comfort, aesthetics, and integration into the environment. When the ranking is based on environmental impact, a choice should be made for the LCA approach used. The literature shows that different boundary systems are relevant to various applications. This research's results support this since it shows significant differences in the ranking of the designs depending on the boundary system used.

Case study

The resulting environmental impact and costs per life stage by design variant are calculated. The ranking of the design scenarios based on the 50:50 approach, so including lifecycle stage D, is as follows:

1. Ackerdijkse bridge, including reused elements from Keizersveerbrug - costs €30.72 per square meter.
2. Newly produced steel truss bridge designed for reuse made from recycled steel - costs €30.79 per square meter.
3. Newly produced steel truss bridge from virgin steel. - costs €45.03 per square meter.
4. Newly designed steel plate bridge - costs €47.12 per square meter.
5. Newly produced steel truss bridge from recycled steel - costs €52.36 per square meter.
6. Concrete preliminary design of Ackerdijkse brug from municipality Delft - costs €90.91 per square meter.

Interestingly, it can be concluded that the environmental costs of the design of a truss bridge from reused objects score almost the same as a newly produced truss bridge from recycled steel that is designed to be reused. Only considering the EPDs, the impact for life cycle stage A1-A3 for reused steel is lower (€35.14 per tonne steel) than to-be-reused steel (€154.77 per tonne steel). The difference is not that big due to the use of recycled steel; compared to virgin steel (€334.28 per tonne steel). This difference is compensated by including life stage D, where a to-be-reused design has larger environmental gains (-€105.31 per tonne steel) than a design that includes reuse (-€2.47). Considering the complete designs, the reuse design does include some new virgin steel for the bridge deck and the to-be-reused scenario is considered to have a more efficient design and thus includes less steel in total. It is debatable how realistic the scenario of a design of a bridge for reuse is, as well as it being constructed from recycled steel only. In conclusion, the comparison is made to be as conservative as possible, but still shows environmental gains for designs that include reuse.

When life stage D is not considered, the ranking shifts, marking the importance of the choice of approach for the environmental impact assessment. With the Cut-off approach, the ranking is as follows:

1. Ackerdijkse bridge, including reused elements from Keizersveerbrug - costs €46.46 per square meter.

2. Newly produced steel truss bridge from recycled steel - costs €62.95 per square meter.
3. Newly produced steel truss bridge designed for reuse made from recycled steel - costs €75.54 per square meter.
4. Concrete preliminary design of Ackerdijkse brug from municipality Delft - costs €81.28 per square meter.
5. Newly designed steel plate bridge - costs €105.75 per square meter.
6. Newly produced steel truss bridge from virgin steel. - costs €123.27 per square meter.

The design that comes close to good performance in terms of the environmental impact of the reuse variant is the steel truss bridge made from recycled steel. The reasons for this are similar to previous comparisons with the to-be-reused design. The truss bridge made from recycled steel is assumed to be even more material efficient. Therefore, the results are expected. However, it can be argued whether the design scenario of recycled steel is a realistic scenario. The availability of recycled structural steel in the Netherlands is, in practice, not common. The use of plate steel, virgin steel or concrete is standard practice. This is also supported by the comparison to bridges from the company database (Section 6.3.8). In this case, the concrete design thus comes closest to being a realistic competitor to the reuse scenario. With a reduction of environmental costs of about 40% compared to a concrete alternative, the design, including reuse, shows great potential.

Although carefully considered, the assumption to only account for the main loadbearing structure in this analysis does result in some uncertainties. The used EPDs are selected to be representative, transparent, and complete, but there could still be unexpected processes that have a particular impact. However, when comparing the impact per life cycle, it is clear that stage A1 of production and stage D of end-of-life have the biggest impact. The used EPDs have values for these stages that are found to be representative compared to other sources. Missing processes are thus expected to fall into another lifecycle stage and have a relatively small impact. Aspects that are found to have a big impact are the wear layer and the paint layer. The wear layer is however necessary for every design variant. The paint layer does introduce environmental costs during the use phase of the steel bridges, and not in the case of concrete. However, if the analysis would include the approach ramps, the gap between the impact of the reused variants and the other variants would become bigger. The reused variant would score more positively since it also includes reused bridge objects for the approach ramp. This contributes to the conclusion that a design that includes reuse has a lower environmental impact than designs that do not, even if some processes might have been overlooked.

7.9. Decision and Accepted design

General

In the design cycle's final steps, a design decision is made. Designing is an iterative process, as indicated by the arrows from the decision step back to the analysis and synthesis steps. This iterative process can play a more significant role in a design cycle, including reuse, compared to a traditional cycle. New information about the current state of the donor structure, such as hidden defects, may necessitate changes to the design. Higher uncertainty inherent in reuse must be accounted for, which can be addressed through contingency planning, such as incorporating modular or adaptable design elements. Another difference in reuse-focused designs is the involvement of additional stakeholders, such as heritage organisations, who may influence the decision. Their input can require design changes to be in line with preservation goals.

Case study

The case study in this research proposes a preliminary design for the Ackerdijksebrug that includes the reuse of three 100-m bridge objects from the Keizersveerbrug. Based on the analysis, the technical feasibility of reuse is promising. There are, in total, six donor objects available. In case of unexpected damage being discovered upon retrieval, there are more objects available than are necessary, thus reducing the risks. Furthermore, the sustainability goals of Rijkswaterstaat and the Municipality of Delft's openness to innovation suggest strong stakeholder support for a design that includes reuse. The monumental state of the Keizersveerbrug adds a layer of complexity, as any proposed changes must be well-justified to align with preservation objectives. Reusing the bridge elements aligns with these goals and offers an alternative to remelting the steel, and thus is expected to gain stakeholder approval.

7.10. Limitations of the research

Focus on truss bridge typology
A significant limitation of this research is the focus on a truss bridge as the case study example. As discussed in the introduction, other steel bridge types are scheduled for replacement by Rijkswaterstaat. These are plate girder and arch bridges, which exhibit different characteristics, particularly in terms of design flexibility. For example, splitting the truss bridge into smaller components for reuse is more feasible than plate girder or arch bridges. This focus makes the findings less general to some extent. However, the research still provides valuable insights into the general reuse process, such as structural analysis, design modifications, and environmental impact assessment. Truss bridges also represent a 'best-case scenario,' offering a benchmark for reuse potential that can inform future studies on other typologies.

Limited investigation into fatigue
As the new implementation of the case study bridge is not susceptible to fatigue, the research gained limited insights into this complex topic. The literature study highlights the challenges of fatigue assessment, and references such as "Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life" provide valuable guidance. However, it can be argued that this limitation rather is a recommendation to aim for reuse scenarios where there is no cyclic load from the bridge's users. This way, the necessity for a complex analysis is avoided and uncertainties are reduced, while high-quality re-use is still feasible.

Uncertainty surrounding the reuse of older steel
Current standards for reuse apply to structural steel produced after 1955, while the steel from the case study dates back to 1936. As no technical regulations currently allow for the reuse of such older materials, this research assumes that older steel could be reused without significant issues. This introduces uncertainty regarding the practical feasibility of the research findings. However, exploring the reuse of older steel remains meaningful as it highlights potential future applications, particularly in light of sustainability goals. The findings demonstrate the feasibility of structural reuse and emphasise areas where standards might evolve to support circular construction.

8
Conclusion

This thesis investigated the feasibility and environmental implications of reusing steel bridge objects, focusing on a case study of the Keizersveerbrug, a historic steel truss bridge. The research has provided a detailed assessment of reuse's environmental costs and benefits, developed an inspiring design example, and documented a step-by-step process for incorporating reuse into the design cycle. The following conclusions address the research questions and reflect on these objectives.

8.1. Sub research questions

How can the reuse potential of a steel bridge be assessed?
The reuse potential of a steel bridge can be assessed by evaluating its current structural condition, material properties, adaptability to new applications, and susceptibility to fatigue. This process involves examining existing documentation, conducting inspections, and possibly performing material tests. For the Keizersveerbrug, an explorative structural analysis has shown that its structural performance is sufficient for the new application. The modular nature of the truss typology facilitates adaptation to the new location, although its large dimensions necessitate splitting the structure for water transport. This research has focused on the preliminary design phase, and further detailed design would require additional information and steps, such as more extensive testing and refined analysis. Furthermore, uncertainties remain regarding material properties, modelling choices, and fatigue performance, depending on the original and new design requirements. Notably, current reuse standards do not include specific requirements for fatigue assessment. Updated standards that account for older steel and address connection considerations are needed to improve the accuracy and reliability of the evaluation of the reuse potential of steel bridges.

How can reuse be implemented in the design cycle/steps of preliminary design?
Reuse can be implemented in the design cycle of a preliminary design by integrating additional steps and adapting existing ones to address the specific challenges and opportunities of working with reused structures. For example, during the analysis step, creating a donor structure file. In the synthesis step, considerations are made for adapting the structure to the new site and design requirements, while the evaluation step is expanded to include assessment of the environmental impact of reuse, enabling a comparison with alternative solutions. The expanded design life cycle is shown in Figure 7.1 in Chapter 7.

In the case study of the reuse of the Keizersveerbrug, the design cycle has been adapted to align the structure with the new site and users. This has included steps such as disconnecting components for transport, replacing the deck, and modifying the truss design to meet site-specific requirements. The case study demonstrates that, while reuse introduces certain constraints, it also offers unique design opportunities by adapting existing elements to new needs. This demonstrates that it is possible to fit reuse into the traditional design cycle workflow, provided that flexibility and creativity are embraced.

What are the environmental implications of the design from reuse compared to similar existing bridges built with new materials?
Reusing the Keizersveerbrug has shown significant potential for reducing environmental impact compared to constructing similar bridges with new materials. The case study revealed that, when evaluating the complete life cycle using the 50:50 approach, the environmental costs are reduced by 0-66% by reuse. When applying the cut-off approach, so excluding end-of-life benefits from the assessment, the reused design demonstrates a potential reduction in the environmental cost between 25-60%. Exact values of the impact are shown in Figure 8.1. The results for the 50:50 approach are displayed in blue, while those for the cut-off approach are shown in orange.

This analysis is based on the main load bearing superstructure of the designs. While there is some uncertainty regarding the influence of unforeseen processes required for reuse, their impact is expected to be minimal. These findings highlight the environmental advantages of reuse and its potential to contribute meaningfully to sustainability goals by reducing the environmental costs of infrastructure projects.

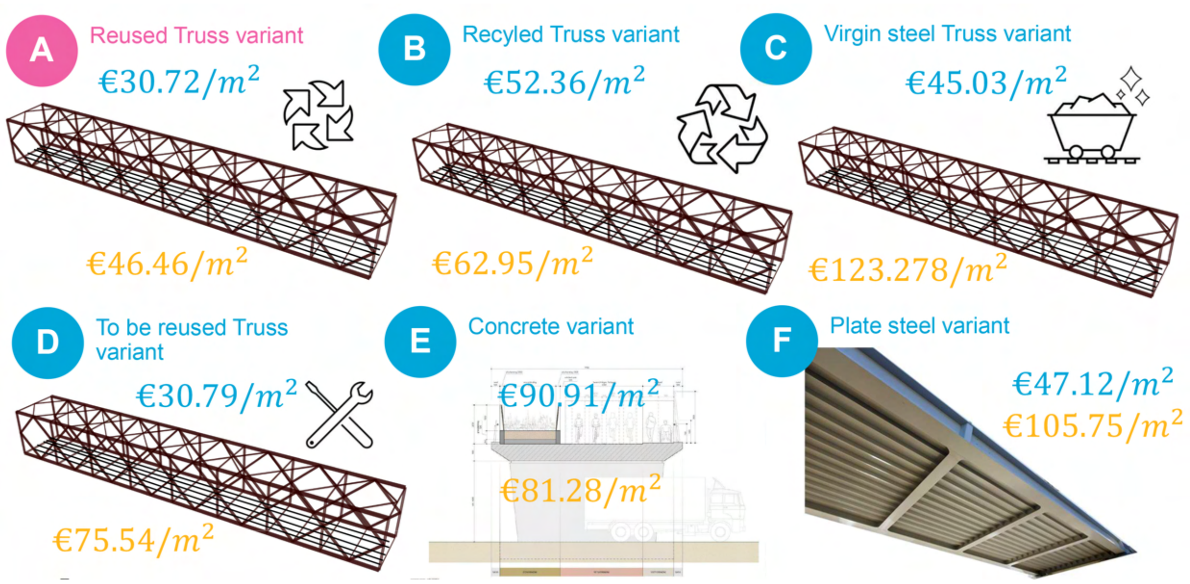

Figure 8.1: Environmental costs per area of the bridge, for six design variants.

8.2. Main research question

What are the feasibility and environmental implications of reusing the Keizersveerbrug, a steel truss bridge, on an object-level basis, as assessed through a comprehensive case study design process?
Based on the exploration at the preliminary design level, it can be concluded that reusing the Keizersveerbrug is both feasible and environmentally advantageous. The case study showed that it is possible to design the Ackerdijksebrug by incorporating three 100-meter donorbridge objects of the Keizersveerbrug, resulting in significant environmental cost savings compared to alternative designs. Environmentally, reuse offers substantial benefits, as the savings in production outweigh the additional impacts from processes such as special transport and material conservation. The feasibility for reuse depends on factors such as the current structural condition, material properties, adaptability to new applications, and susceptibility to fatigue. The traditional design cycle steps have been adapted to include reuse, with modifications made to ensure they are as general as possible, allowing them to apply other steel bridge typologies. The documented new steps of the design cycle can serve as a useful guide for engineers, helping them address the challenges of the reuse of steel objects.

Figure 8.2: 3D render design for Ackerdijksebrug based on three 100-m bridge objects from donor Keizersveerbrug.

8.3. Recommendations

8.3.1. Recommendations for further research

Based on the research conducted in this thesis, the following recommendations are made for further research:

- **Consideration of Actual Construction Costs:** This research did not include actual construction costs for reuse. Some studies, such as Yeung et al. (2017), suggest that reuse costs may be higher compared to recycling. This aspect could influence stakeholders' willingness to embrace reuse, and further research into cost comparisons would provide valuable insights for decision-making.
- **Modelling of Object Realities:** Modelling the donor object, particularly its connections, has proven challenging in this research. Developing a practical guideline for steel structures, especially those involving rivets, would be valuable for engineers working on similar reuse projects.
- **Incorporating Reuse in NTA 8713:** It could be beneficial to explore how the NTA 8713 standards could incorporate the reuse of entire steel objects, rather than just individual steel elements. Additionally, expanding the standards to include older steel, particularly pre-1955 steel, would enhance their applicability to a wider range of reuse projects.
- **Practical Case Studies:** This research was based on theoretical exploration at the preliminary design stage. As noted in the introduction, it would be valuable to initiate an actual reuse case study that could provide deeper insights into the challenges and opportunities of reuse in real-world applications.

These recommendations can help guide future research and contribute to the development of practical frameworks and standards for the reuse of steel structures.

8.3.2. Recommendations for stakeholders

The following recommendations are done for the different stakeholders relevant to a reuse project:

- **Rijkswaterstaat:** While significant efforts are being made to achieve circularity by 2030, it is recommended that Rijkswaterstaat take an even more active role in projects involving the reuse of steel bridges. Beyond offering bridges on platforms such as Bruggenbank, providing technical and financial support could be crucial in facilitating these projects. The analysis in this research highlighted the importance of accessible and well-documented information. To streamline the reuse process for future projects, Rijkswaterstaat could enhance its role by establishing a centralized and well-archived documentation system.

- **Municipality of Delft:** A key recommendation for the Municipality of Delft is to reconsider the necessity of constructing a new bridge at the proposed Ackerdijk location, as the most sustainable approach is 'to Refuse' building new structures that are not essential. However, if a bridge is deemed necessary, it is advised to explore the reuse of an existing bridge, as proposed in this research. Implementing such an unconventional approach requires a motivated stakeholder, and given the municipality's claim of being technically progressive, this would be a fitting and forward-thinking solution.
- **Engineering Firms:** This research demonstrates the significant impact of methodological choices in environmental impact assessments. It is recommended that engineering firms adopt a critical approach when performing Life Cycle Assessments and carefully consider the environmental impact of design choices. For reuse projects, firms should follow the design cycle steps, incorporating the reuse framework developed in this research, to ensure a structured and sustainability-driven approach.

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A Literature study

This appendix contains figures of relevance to the literature study that can be found in Chapter 2.

The figure below shows Figure 1.1 from EN-NEN 1993-1-1, which should be used to specify the dimensions of a cross-section.

The figure below shows the assessment method by Kühn et al. (2008) on assessing the remaining fatigue life of steel structures. The graph below shows the R-strategies and their order. This is a strategy to transfer from the linear economy to a circular economy.

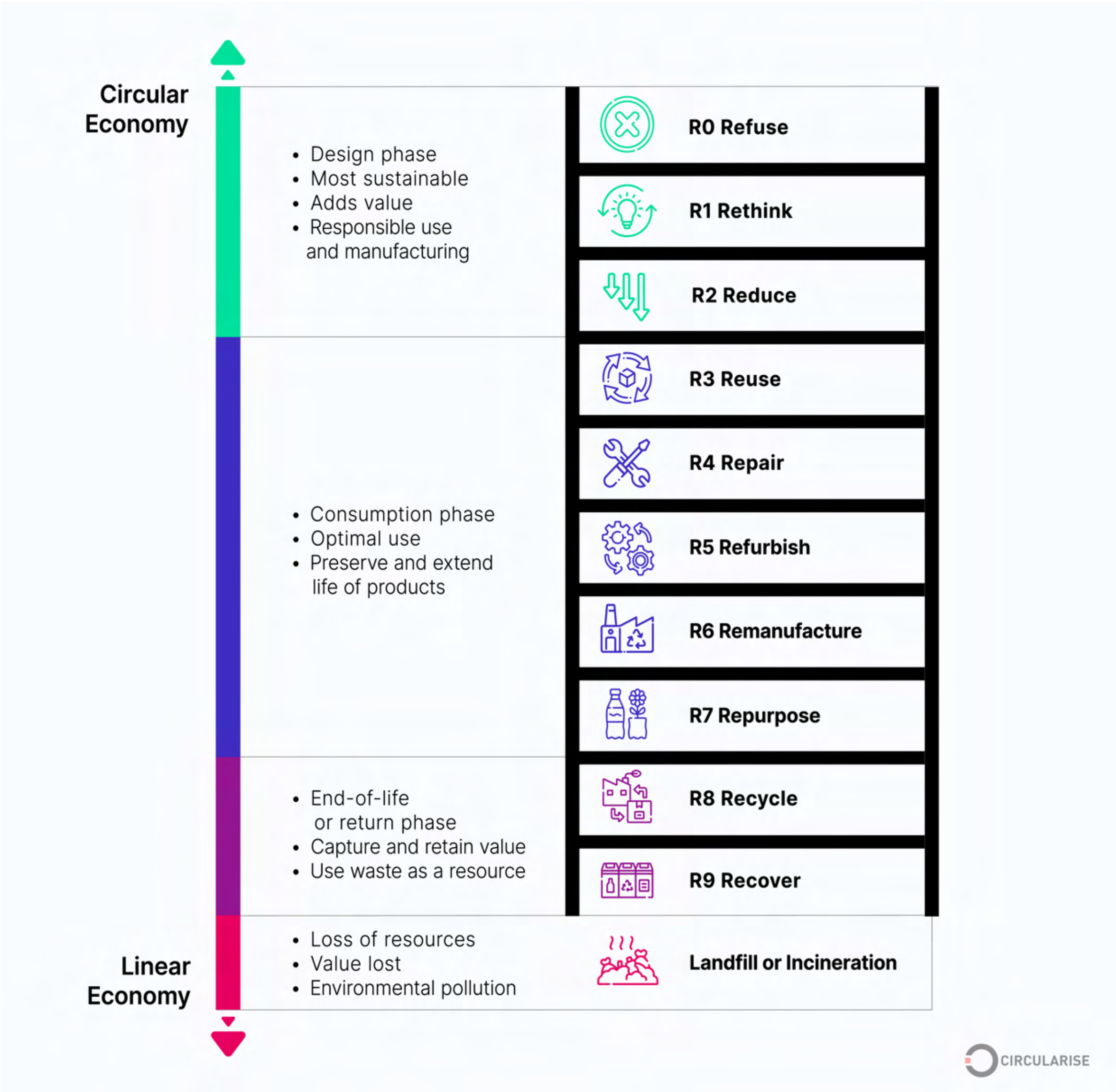


Figure A.3: Graph showing the R-Strategies (Larae Malooly and Tian Daphne, 2023).

The graph below shows the production processes of a traditional steel production compared with the processes when reuse is implemented.

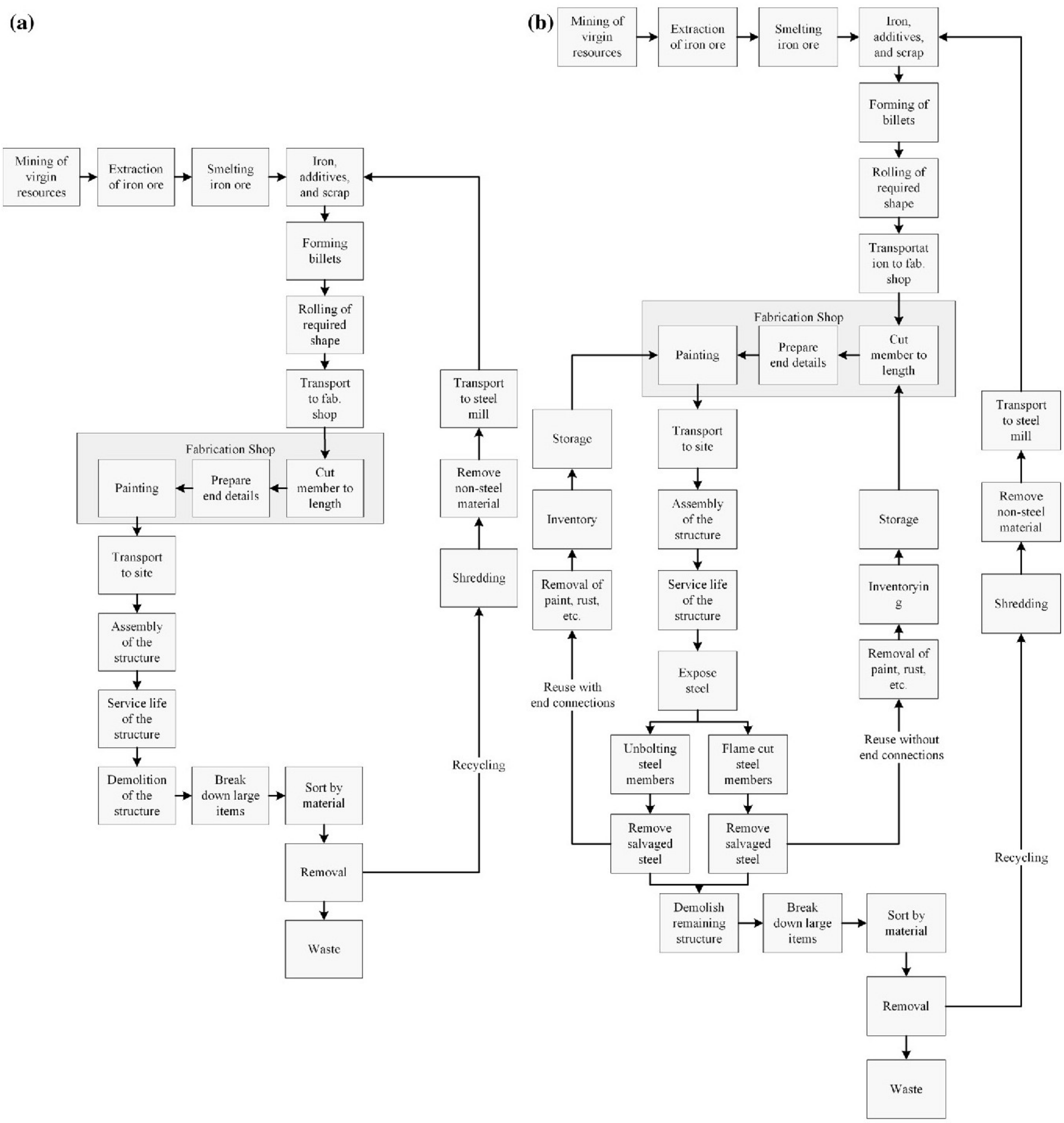
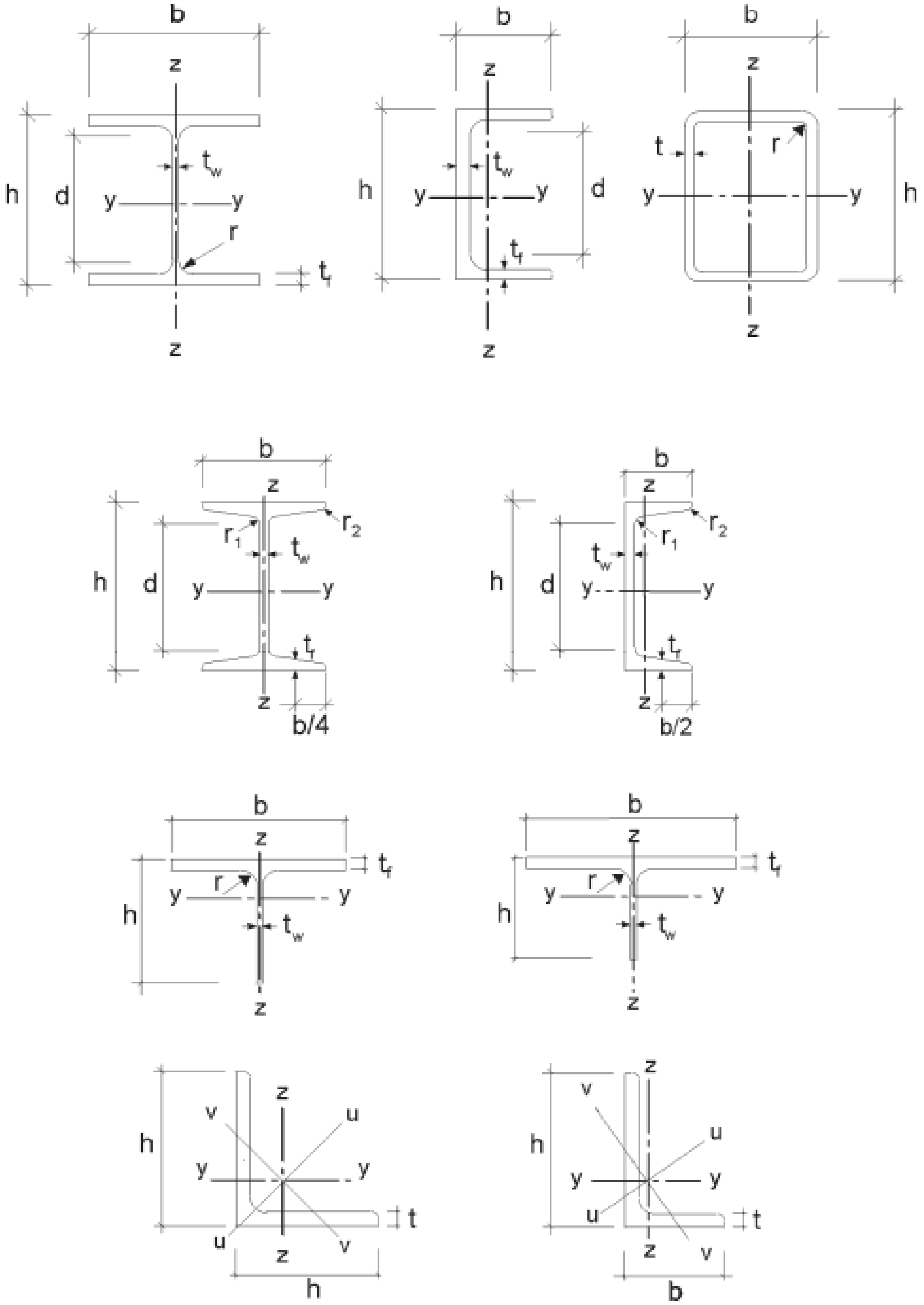


Figure A.4: Overview of steel production process with (a) recycling and (b) reuse (Yeung et al., 2017).



Figuur 1.1 — Afmetingen en assen van doorsneden

Figure A.1: Dimensions and axes of sections (Nen-En, n.d.)

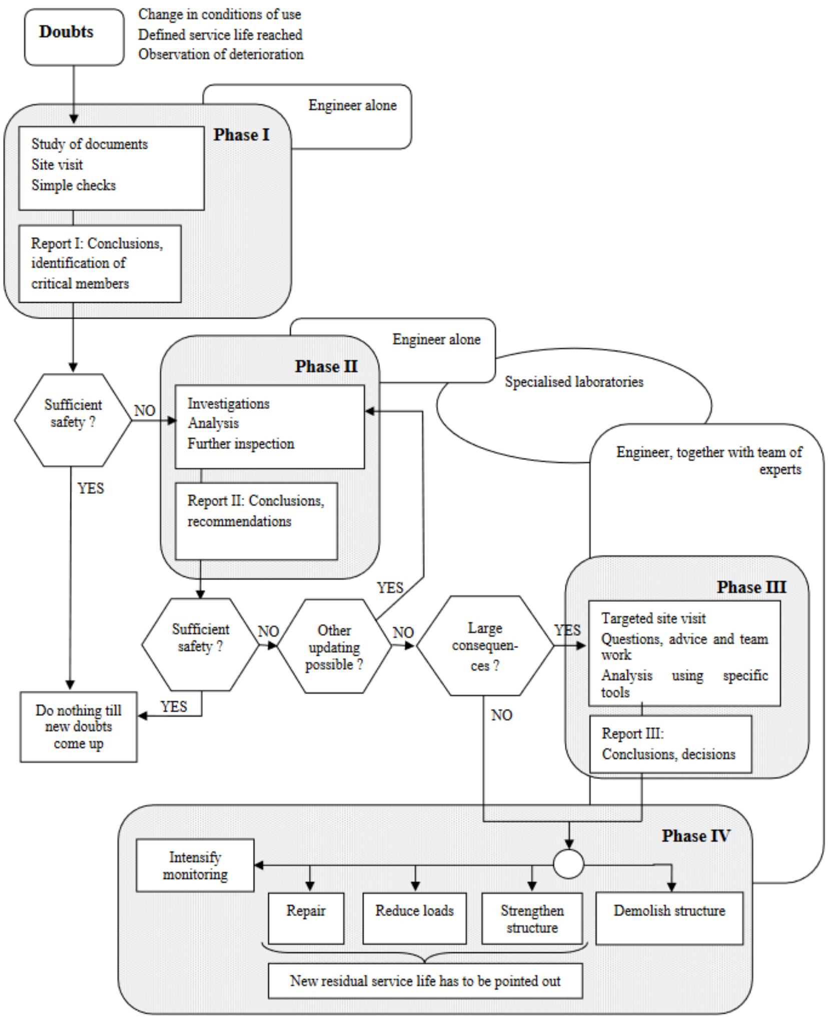


Figure A.2: Assessment method remaining fatigue life steel structures Kühn et al., 2008

B

Analysis

In this appendix, relevant information for the analysis step of the design is included.

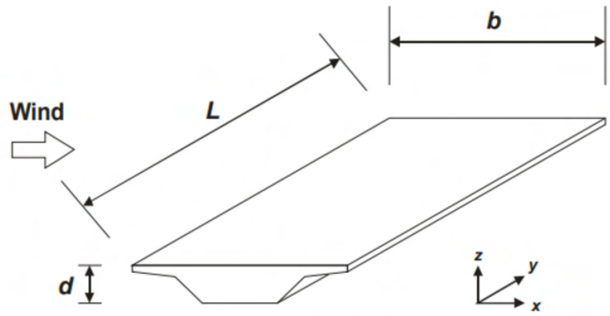
B.1. Material properties

Results of the conversion of Charpy-V impact tests of the verticals and diagonals of the Keizersveerbrug to fracture toughness are shown in Figure B.1. This conversion is done in accordance with BS7910, Annex J, [3].

The used equations for this conversion is as follows: Fracture toughness should not exceed the value given by the following equation:

B.2. Calculations of wind loads

This section gives the calculation of the windloads.



x-direction: is the direction in width direction of the bridge deck perpendicular to the span.

y-direction: is the direction in span direction.

z-direction: is the direction perpendicular to the deck

Found according to EN 1991-1-4.

The following parameters are considered:

Windarea

Windarea II, province of Zuid-Holland→ $v_{b,0} = 27.0 \text{ m/s}$ **[NEN-EN1991-1-4 4.2 (1)]**.

Constructie element	Constructie materiaal	Locatie code	Kerfslagproeven		Breuktaaiheid		
			T (°C)	Minimum Cv waarde (J)	K_{mat} (min Cv) J.1[1)] (MPa√m)	J.5[1)]	Min[2)]
Verticalen	Plaat Dikte 12 mm	AVO	5	42	89.4	77.7	**77.7**
		AVB	-20	7	34.1	58.8	**34.1**
		BVO	5	15	51.8	63.1	**51.8**
		BVB	-20	8	36.7	59.3	**36.7**
		CVO	5	16	53.6	63.6	**53.6**
		CVB	-20	5	28.2	57.7	**28.2**
Diagonalen	Profiel Dikte 14 mm	ADO	5	27	69.0	69.6	**69.0**
		ADB	-20	12	44.9	61.5	**44.9**
		BDO	5	29	71.6	70.7	**70.7**
		BDB	-20	12	44.9	61.5	**44.9**
		CDO	5	50	95.0	82.0	**82.0**
		CDB	-20	19	57.3	65.3	**57.3**

Figure B.1: Results conversion of impact tests Vertical and Diagonal Bridge Keizersveer to fracture toughness (H. Slot and J. Maljaars, 2016)

J.1

$$K_{mat} = \left[\left(12\sqrt{C_V} - 20\right)\left(\frac{25}{B}\right)^{0.25}\right] + 20$$

where:
K_{mat} = estimate of the fracture toughness (MPa√m);
B = thickness of the material for which an estimate of K_{mat} is required (mm);
C_V = lower bound Charpy V-notch impact energy at the service temperature (J).

$$K_{mat} = 0.54\, C_V + 55$$

Basis windspeed

The standard annual exceedance probability in NEN-EN1991-1-4 is 50 years. c_{prob} is applied to convert this to the design life of 100 years. **[NEN-EN1991-1-4 4.2 (2)]**

$$c_{prob} = \left(\frac{1 - K * \ln(-\ln(1-p))}{1 - K * \ln(-\ln(0.98))}\right)^{n}$$

With thereby applicable, according **to [NEN-EN1991-1-4 4.2 (2)]**

Tabel NB.2 — De factoren *K* en *n* voor toepassing in Nederland

Windgebied	**I**	**II**	**III**
K	0,2	0,234	0,281
n	0,5	0,5	0,5

For windarea II :

$$c_{prob} = \left(\frac{1 - 0.234 * \ln(-\ln(1-0.01))}{1 - 0.234 * \ln(-\ln(0.98))}\right)^{0,5}$$

$$c_{prob} = 1.042$$

Furthermore, according to the national annex:

$c_{dir} = 1$ (wind direction factor)

$c_{season} = 1$ (seasonal factor)

$v_{b,0} = 27.0$ needs to be increased for the design life and multiplied by the wind direction factor and seasonal factor to obtain the base wind speed.

$$v_b = c_{prob} * c_{dir} * c_{season} * 27.0$$

$$v_b = 1.042 * 1 * 1 * 27.0 = 28.13$$

Terrain category

The bridge lies in an undeveloped area → Terreincategorie II **[NEN-EN1991-1-4 NB tabel NB.3 – 4.1].**

Tabel NB.3 – 4.1 — Terreincategorieën en terreinparameters

Terreincategorie		**z_0** m	**z_{min}** m
0	Zee of kustgebied aan zee	0,005	1
II	Onbebouwd gebied	0,2	4
III	Bebouwd gebied	0,5	7

Height (distance between road and centre of bridge deck) : z = 4.8m

Terrain roughness

In accordance with the National Appendix, the site factor is determined as follows:

$$k_r = 0.19 * \left(\frac{z_0}{0.05}\right)^{0.07}$$

$$k_r = 0.19 * \left(\frac{0.2}{0.05}\right)^{0.07} = 0.21$$

Now the roughness factor can be determined:

$$c_r(z) = k_r * \ln\left(\frac{z}{z_0}\right)$$

$$c_r(4.8) = 0.21 * \ln\left(\frac{4.8}{0.2}\right) = 0.67$$

Average windspeed:

The average wind speed is now determined using formula **[NEN-EN1991-1-4 (4.3)]**:

$$v_m(z) = c_r(z) * c_o(z) * v_b$$

$$v_m(7) = 0.67 * 1 * 28.13 = 18.85 \frac{m}{s}$$

Wind turbulence

The turbulence intensity is calculated using the following formulas **[NEN-EN1991-1-4 (4.7)]:**

$$l_v(z) = \frac{k_I}{c_o(z) * \ln\left(\frac{z}{z_0}\right)}$$

Orography factor: $c_o(z) = 1.0$

Turbulence factor: $k_I = 1.0$

Roughness length: $z_0 = 0.2$

In closed position:

$$l_v(z) = \frac{1}{1 * \ln\left(\frac{4.8}{0.2}\right)} = 0.31$$

Extreme pressure

$$q_p(z) = \left(1 + 7 * l_v(z)\right) * \frac{1}{2} * \rho * v_m^2(z)$$

$\rho = 1.25\ kg/m^3$ (the density of air during storm conditions)

$$q_p(4.8) = (1 + 7 * 0.31) * \frac{1}{2} * 1.25 * 18.09^2 = 648\ N/m^2$$

Wind in cross direction (x-direction)

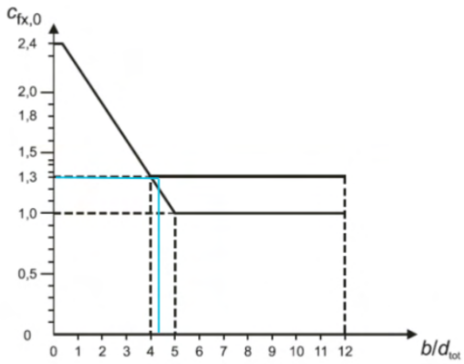
Force coefficient

$c_{f,x,o}$ is determined using NEN-EN 1991-1-4 Figure 8.3 based on the ratio b/d_{tot}

To determine the force coefficient without end effects, $c_{fx,0}$, we first determine the dimensions to be used:

- b = 13m
- d_{tot} = 3m
- b/d_{tot} = 1.0

→ $c_{fx,0}$ = 1.3



Reference pressure : $q_b = \frac{1}{2}\rho v_b^2 = \frac{1}{2} * 1.25 * 28.13^2 = 494.56 N/m$

The wind load factor C for bridges is taken from NEN-EN 1991-1-4+A1+C2 **[NEN-EN 1991-1-4 (4.9)]**:

$$c_e(z) = \frac{q_{p(z)}}{q_b} = \frac{648}{494.56} = 1.31$$

The reference plane can be determined as the area projected to the wind of fixed obstacles or noise barriers.

The wind force in the transverse direction was determined using the following formula **[NEN-EN1991-1-4 8.3.2]**:

$$F_w = \frac{1}{2} \cdot \rho \cdot v_b^2 \cdot C \cdot A_{ref,x} \text{ met } C = c_e . c_{f,x} = c_e . c_{fx,0}$$

$$C = 1.31 \cdot 1.3 = 1.70$$

$$F_w = \frac{1}{2} \cdot 1.25 \cdot 28.13^2 \cdot 1.70 \cdot A_{ref,x}$$

This gives a wind load on the transverse side of:

$$q_{w,x} = \frac{F_{w,x}}{A_{ref,x}} = \frac{1}{2}\rho v_b^2 C = q_b C = q_b c_e(z) c_{fx,0} = q_b(z) c_{fx,0}$$

Windload in transverse direction:			
$F_{w,x,surf}$ =	840.8	N/m^2	
$F_{w,x,lin}$ =	**2.52**	**kN/m**	840.5 N/m^2 x 3.0m (d_{tot})
h =	**1.5**	**m**	d_{tot}/2

Wind in longitudinal direction

A wind load in the longitudinal direction of the bridge is taken into account, which occurs simultaneously with an equally large wind load in the transverse direction of the bridge. In accordance with NEN-EN 1991-1-4+A1+C2 Note 8.3.4, the longitudinal wind load is 40% of the total wind load perpendicular to the bridge.

Windbelasting in longitudinal direction :			
$F_{w,y,surf}$ =	**336.3**	**N/m^2**	840.8 N/m^2 x 0,4
h =	**1.70**	**m**	Height of the structure
$F_{w,x,lin}$ =	**0.572**	**kN/m**	

The wind force in the y-direction occurs simultaneously with an equally large wind force in the x-direction **[NEN-EN1991-1-4 NB 8.3.4]**.

Wind in vertical direction

The national annex NEN-EN 1991-1-4+A1+C2/NB does not give values for $c_{f,z}$. In the absence of wind tunnel tests, the recommended value may be set equal to ± 0,9.

The forces due to wind in the vertical direction are calculated using the following formula **[NEN EN 1991-1-4]** :

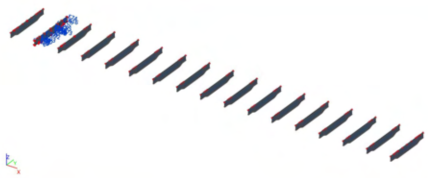
$$F_w = \frac{1}{2}\rho v_b^2 . C . A_{ref,z} \text{ met } C = c_e . c_{f,z} = c_e \times 0.9 = 1.31 \cdot 0.9$$

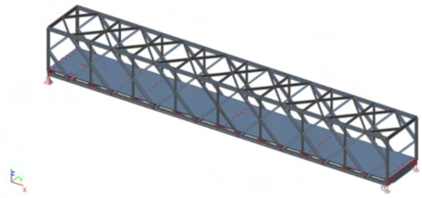
Windforce in z-direction:			
$F_{w,z,surf}$ =	583	N/m^2	
$F_{w,z,lin}$ =	3.64	kN/m	583 N/m^2 x 6.25 m (on vertical beams)
e=	3.25	m	13m/4

B.3. Calculations forces including self-weight

This section gives an overview of the loads on the crossbeams and the self-weights of the other elements. This is an input for the loads in the grasshopper model.

Crossbeams / Dwarsdragers

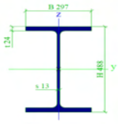


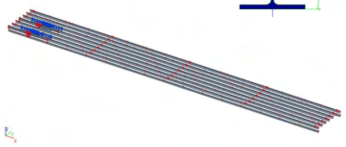


Loads on crossbeams

selfweight longitudinal beams / langsliggers

A [m^2]	0.02048
material weight [Kn/m^3]	78.5
selfweight [kN/m]	1.60768
pointload on crossbeam per beam [kN]	10.048
total pointload [kN]	80.384
recalculated as distributed load [kN/m]	6.28



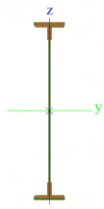


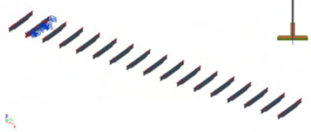
Langsligger		
Type	I	
Uitgebreid	488; 297; 24; 13; 24	
Vormnorm	1 - I doorsneden	
Vorm type	Dunwandig	
Onderdeelmateriaal	S 235	
Bouwwijze	gewalst	
Knik y-y, Knik z-z	a	b
A [m²]	2,0480e-02	
A_y [m²], A_z [m²]	1,3599e-02	6,4732e-03
A_L [m²/m], A_D [m²/m]	2,0966e+00	2,0966e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	148	244
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	8,8348e-04	1,0496e-04
i_y [mm], i_z [mm]	208	72
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	3,6208e-03	7,0677e-04
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	4,0447e-03	1,0831e-03
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	9,50e+05	9,50e+05
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	2,55e+05	2,55e+05
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	3,4132e-06	5,6403e-06
β_y [mm], β_z [mm]	0	0

selfweight crossbeam (dwarsdrager hoog 3pl)

A [m^2]	0.044276
material weight [Kn/m^3]	78.5
factor to include connection plates*	1.05
selfweight [kN/m]	3.649449

*(connection plates are accounted for by multiplying with this factor)





Dwarsdrager hoog 3pl		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	S 235	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	4,4276e-02	
A_y [m²], A_z [m²]	2,3273e-02	1,9559e-02
A_L [m²/m], A_D [m²/m]	4,1760e+00	4,1760e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	1,8035e-02	1,2865e-04
i_y [mm], i_z [mm]	638	54
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	2,3122e-02	9,5296e-04
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	2,6357e-02	1,5511e-03
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	6,19e+06	6,19e+06
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	3,65e+05	3,65e+05
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	1,5179e-05	7,3694e-05
β_y [mm], β_z [mm]	0	0

finishing bicyclepath: Azobe timber		
thickness deck [m]	0.1	(Thickness is assumed)
material weight [Kn/m^3]	10.79	
width [m]	6.25	
selfweight [kN/m]	6.74375	(only applicable on area of fauna passage)

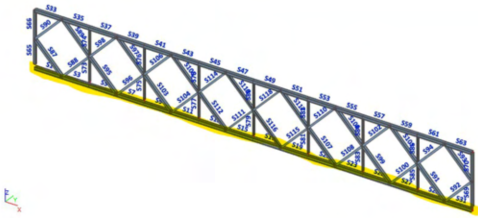
finishing fauna passage: concrete deck layer		
thickness deck [m]	0.1	(Thickness is assumed)
material weight [Kn/m^3]	25	
width [m]	6.25	
selfweight [kN/m]	15.625	(only applicable on area of fauna passage)

permanent load soil layer		(only applicable on area of fauna passage)
weight 50 cm soil [kN/m2]	5	
width [m]	6.25	
selfweight [kN/m]	31.25	

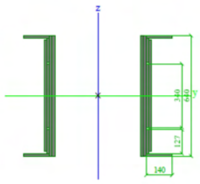
Live load		(Only applicable to pedestrian/bikepath)
load [kN/m2]	2.92	
width [m]	6.25	
selfweight [kN/m]	18.25	

Total	pedestrian/bike path	fauna passage
	34.9232 kN/m	56.80445 kN/m

Main beams bottom/ hoofdligger onder



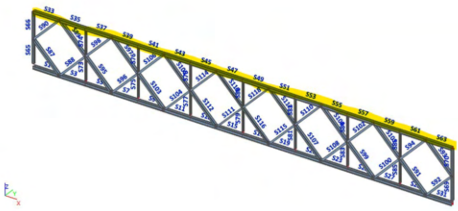
Selfweight	
A [m2] *	0.078824
material weight	
[Kn/m^3]	78.5
factor to include	
connection plates	1.25
selfweight [kN/m]	7.734605



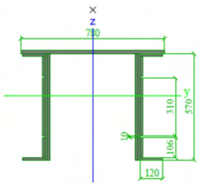
Hoofdligger RO4		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 vakwerk (zwaar)x1.25	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m^2]	7,8824e-02	
A_y [m^2], A_z [m^2]	1,6101e+00	6,4653e-02
A_L [m^2/m], A_D [m^2/m]	3,8080e+00	3,9920e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	320
α [deg]	0,00	
I_y [m^4], I_z [m^4]	3,0254e-03	5,6026e-03
i_y [mm], i_z [mm]	196	267
$W_{el.y}$ [m^3], $W_{el.z}$ [m^3]	9,4543e-03	1,4006e-02
$W_{pl.y}$ [m^3], $W_{pl.z}$ [m^3]	1,3397e-02	2,0891e-02
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	3,15e+06	3,15e+06
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	4,91e+06	4,91e+06
d_y [mm], d_z [mm]	0	0
I_t [m^4], I_w [m^6]	1,5157e-04	0,0000e+00
β_y [mm], β_z [mm]	0	0

main beam has different cross sections. For own weight, the heaviest cross section is assumed

Main beams top/ hoofdligger boven



Selfweight	
A [m2] *	0.070356
material weight	
[Kn/m^3]	78.5
factor to include	
connection plates	1.25
selfweight [kN/m]	6.903683



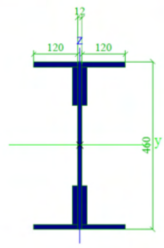
Hoofdligger RB3		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 vakwerk (zwaar)x1.25	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m^2]	7,0356e-02	
A_y [m^2], A_z [m^2]	1,2450e-02	4,7177e-02
A_L [m^2/m], A_D [m^2/m]	4,4140e+00	4,4140e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	347
α [deg]	0,00	
I_y [m^4], I_z [m^4]	2,8176e-03	4,5452e-03
i_y [mm], i_z [mm]	200	254
$W_{el.y}$ [m^3], $W_{el.z}$ [m^3]	8,1192e-03	1,1654e-02
$W_{pl.y}$ [m^3], $W_{pl.z}$ [m^3]	1,2449e-02	1,7322e-02
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	2,93e+06	2,93e+06
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	4,07e+06	4,07e+06
d_y [mm], d_z [mm]	0	458
I_t [m^4], I_w [m^6]	3,5036e-05	1,6146e-04
β_y [mm], β_z [mm]	-995	0

* main beam has different cross sections. For own weight, the heaviest cross section is assumed

Vertical beams

two on the ends are wv1, others are wv2, so wv2 is taken

Selfweight	
A [m2]	0.018176
material weight	
[Kn/m^3]	78.5
factor to include	
connection plates	1.05
selfweight [kN/m]	1.498157

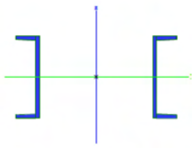


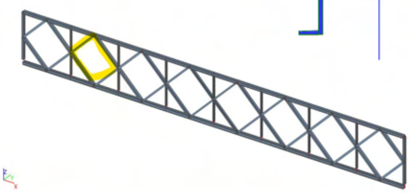
Hoofdligger WV2		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 overigx1.05	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m^2]	1,8176e-02	
A_y [m^2], A_z [m^2]	8,8213e-03	7,2226e-03
A_L [m^2/m], A_D [m^2/m]	1,9040e+00	1,9040e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m^4], I_z [m^4]	5,9490e-04	3,8503e-05
i_y [mm], i_z [mm]	181	46
$W_{el.y}$ [m^3], $W_{el.z}$ [m^3]	2,5865e-03	3,0558e-04
$W_{pl.y}$ [m^3], $W_{pl.z}$ [m^3]	3,1009e-03	5,3725e-04
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	7,29e+05	7,29e+05
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	1,26e+05	1,26e+05
d_y [mm], d_z [mm]	0	0
I_t [m^4], I_w [m^6]	5,1265e-06	1,8569e-06
β_y [mm], β_z [mm]	0	0

Diagnoals

assumed all are WD3

Selfweight	
A [m2]	0.01609
material weight [Kn/m^3]	78.5
factor to include connection plates	1.05
selfweight [kN/m]	1.326218



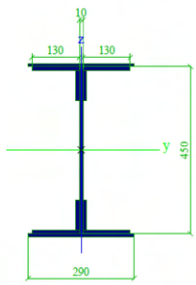


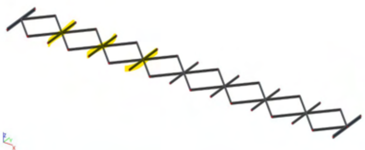
Hoofdligger WD3		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	S 235	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	1,6090e-02	
A_y [m²], A_z [m²]	9,3467e-01	1,0046e-02
A_L [m²/m], A_D [m²/m]	2,1343e+00	2,1343e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	2,6292e-04	1,1811e-03
i_y [mm], i_z [mm]	128	271
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	1,5024e-03	3,4135e-03
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	1,8514e-03	4,3364e-03
$M_{pl.y+}$ [Nm], $M_{pl.y-}$ [Nm]	4,35e+05	4,35e+05
$M_{pl.z+}$ [Nm], $M_{pl.z-}$ [Nm]	1,02e+06	1,02e+06
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	1,3848e-06	0,0000e+00
$β_y$ [mm], $β_z$ [mm]	0	0

Verticals top / bovenwindverband

assumed all are WD3

Selfweight	
A [m2]	0.01754
material weight [Kn/m^3]	78.5
factor to include connection plates	1.05
selfweight [kN/m]	1.445735



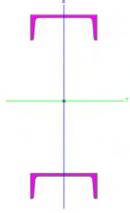


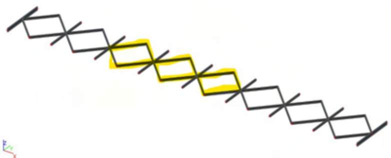
Bovenwindverband V1		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 overigx1.05	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	1,7540e-02	
A_y [m²], A_z [m²]	1,0435e-02	5,7900e-03
A_L [m²/m], A_D [m²/m]	2,0720e+00	2,0720e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	6,7072e-04	6,5706e-05
i_y [mm], i_z [mm]	196	61
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	2,8786e-03	4,5315e-04
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	3,2728e-03	7,4365e-04
$M_{pl.y+}$ [Nm], $M_{pl.y-}$ [Nm]	7,69e+05	7,69e+05
$M_{pl.z+}$ [Nm], $M_{pl.z-}$ [Nm]	1,75e+05	1,75e+05
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	2,5605e-06	3,2804e-06
$β_y$ [mm], $β_z$ [mm]	0	0

diagonals top / bovenwindverband

assumed all are WD3

Selfweight	
A [m2]	0.00338
material weight [Kn/m^3]	78.5
factor to include connection plates	1.05
selfweight [kN/m]	0.278588





Bovenwindverband D1		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 overigx1.05	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	6,4386e-03	
A_y [m²], A_z [m²]	3,3799e-03	6,4561e-02
A_L [m²/m], A_D [m²/m]	1,3205e+00	1,3205e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	234
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	3,5551e-04	3,8228e-05
i_y [mm], i_z [mm]	235	77
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	1,2307e-03	3,8228e-04
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	1,5066e-03	4,5564e-04
$M_{pl.y+}$ [Nm], $M_{pl.y-}$ [Nm]	3,54e+05	3,54e+05
$M_{pl.z+}$ [Nm], $M_{pl.z-}$ [Nm]	1,07e+05	1,07e+05
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	1,2016e-07	0,0000e+00
$β_y$ [mm], $β_z$ [mm]	-1	0

B.4. Calculations of foundation piles

This subchapter shows a calculation of the design load-bearing capacity of concrete prefabricated foundation piles with a rectangle cross-section of 0.25x0.25m and 0.4x0.4m. The calculation is done using the Koppejan method, per NEN 9997-1, chapter 7.

B.4.1. Foundation piles 0.25x0.25m

Load-bearing capacity of the tip

$$R_{b;cal;max} = q_{b;max} \cdot A_b$$

$$q_{b;max} = \alpha_p \cdot \beta \cdot s \cdot 0.5 \cdot (0.5 \cdot (q_{cI;av} + q_{cII;av}) + q_{cIII;av})$$

- Pile class factor $\alpha_p = 1.0$ (soil displacing pile)
- Factor pile base shape $\beta = 1.0$ (no weighted base)
- Form factor cross-section pile base $s = 1.0$ (rectangular piles)
- Area of the pile tip = $A_b = 0.25^2 m^2$

For the values of $q_{cI}, q_{cII}, q_{cIII}$, the CPT as displayed in Figure B.2 is used. The equivalent diameter of the piles is calculated to be:

$$D_{eq} = \sqrt{4/\pi} \cdot a = 1.13 \cdot 0.25 = 0.2825$$

This results in the following values:

- $q_{cI;av} = 15MPa$ (The average value of the cone resistance of section I, running from pile tip level to a level between 0.7 - 4 D_{eq} lower).
- $q_{cII;av} = 12.5MPa$ (The average value of the cone resistance of section II, running from the level zone I ended back to the pile tip level, where the value to be charged should never exceed the value below it.)
- $q_{cIII;av} = 2MPa$ (The average value of the cone resistance of section III, running from pile tip level to a level of 8 D_{eq} higher, where the value to be charged should never exceed the value below it.)

so, $q_{b;max} = 1.0 \cdot 1.0 \cdot 1.0 \cdot 0.5 \cdot (\ 0.5(15 + 12.5) + 2) = 7.875 \leq 15MPa)$ and thus

$$R_{b;cal} = 7.875 \cdot 0.25^2 = 0.49MN = 492.18kN$$

Load-bearing capacity of the shaft

The load-bearing capacity of the shaft can be calculated using the following formula:

$$R_{s;cal} = O_s \cdot \Delta L \cdot q_{c;gem} \cdot \alpha_s$$

- Circumference of pile shaft $O_s = 4 \cdot d = 4 \cdot 0.25m$
- Shaft friction length $\Delta L = 1[m]$ because there are no peaks above 12 MPa.
- $q_{c;gem} = 4MPa$
- $\alpha_s = 0.01$ (Prefabricated and constant transverse dimensions)

This results in the load-bearing capacity of the shaft becoming:

$$R_{s;cal} = 4 \cdot 0.25 \cdot 1 \cdot 4 \cdot 0.01 = 0.04MN = 40kN$$

Total load-bearing capacity

The total load-bearing capacity becomes:

$$R_{c;cal} = R_{b;cal} + R_{s;cal} = 492.18 + 40 = 532.18kN$$

The correlation factor ζ is used to get the characteristic value of the load-bearing capacity. It depends on if redistribution is possible and the kind of probing information that is available. Since the foundation is not stiff and there is 1 CPT, the value of $\zeta_3 = \zeta_4 = 1.39$. This results in:

$$R_{c,k} = R_{c;cal}/\zeta = 532.18/1.39 = 382.86kN$$

The design load-bearing value can then be calculated:

$$R_{c,d} = R_{c;k}/\zeta_t = 382.86/1.2 = 319kN$$

B.4.2. Foundation piles 0.4x0.4m

The same calculation can be done for foundation piles with dimensions of 0.4x0.4m. **Load-bearing capacity of the tip**

$$R_{b;cal;max} = q_{b;max} \cdot A_b$$

$$q_{b;max} = \alpha_p \cdot \beta \cdot s \cdot 0.5 \cdot (0.5 \cdot (q_{cI;av} + q_{cII;av}) + q_{cIII;av})$$

- Pile class factor $\alpha_p = 1.0$ (soil displacing pile)
- Factor pile base shape $\beta = 1.0$ (no weighted base)
- Form factor cross-section pile base $s = 1.0$ (rectangular piles)
- Area of the pile tip = $A_b = 0.4^2 m^2$

For the values of $q_{cI}, q_{cII}, q_{cIII}$, the CPT as displayed in Figure XX is used. The equivalent diameter of the piles is calculated to be:

$$D_{eq} = \sqrt{4/\pi} \cdot a = 1.13 \cdot 0.4 = 0.452$$

This results in the following values:

- $q_{cI;av} = 14MPa$ (The average value of the cone resistance of section I, running from pile tip level to a level between 0.7 - 4 D_{eq} lower).
- $q_{cII;av} = 12MPa$ (The average value of the cone resistance of section II, running from the level zone I ended back to the pile tip level, where the value to be charged should never exceed the value below it.)
- $q_{cIII;av} = 2MPa$ (The average value of the cone resistance of section III, running from pile tip level to a level of 8 D_{eq} higher, where the value to be charged should never exceed the value below it.)

so, $q_{b;max} = 1.0 \cdot 1.0 \cdot 1.0 \cdot 0.5 \cdot (\ 0.5(14 + 12) + 2) = 7.5 \leq 15MPa)$ and thus

$$R_{b;cal} = 7.875 \cdot 0.4^2 = 1.2MN = 1200kN$$

Load-bearing capacity of the shaft
The load-bearing capacity of the shaft can be calculated using the following formula:

$$R_{s;cal} = O_s \cdot \Delta L \cdot q_{c;gem} \cdot \alpha_s$$

- Circumference of pile shaft $O_s = 4 \cdot d = 4 \cdot 0.4m$
- Shaft friction length $\Delta L = 1[m]$ because there are no peaks above 12 MPa.
- $q_{c;gem} = 4MPa$
- $\alpha_s = 0.01$ (Prefabricated and constant transverse dimensions)

This results in the load-bearing capacity of the shaft becoming:

$$R_{s;cal} = 4 \cdot 0.4 \cdot 1 \cdot 4 \cdot 0.01 = 0.064MN = 64kN$$

Total load-bearing capacity
The total load-bearing capacity becomes:

$$R_{c;cal} = R_{b;cal} + R_{s;cal} = 1200 + 64 = 1264kN$$

The correlation factor ζ is used to get the characteristic value of the load-bearing capacity. It depends on if redistribution is possible and the kind of probing information that is available. Since the foundation is not stiff and there is 1 Cone Penetration Test, the value of $\zeta_3 = \zeta_4 = 1.39$. This results in:

$$R_{c,k} = R_{c;cal}/\zeta = 1264/1.39 = 909.35kN$$

The design load-bearing value can then be calculated:

$$R_{c,d} = R_{c;k}/\zeta_t = 909.35/1.2 = 757.8kN$$

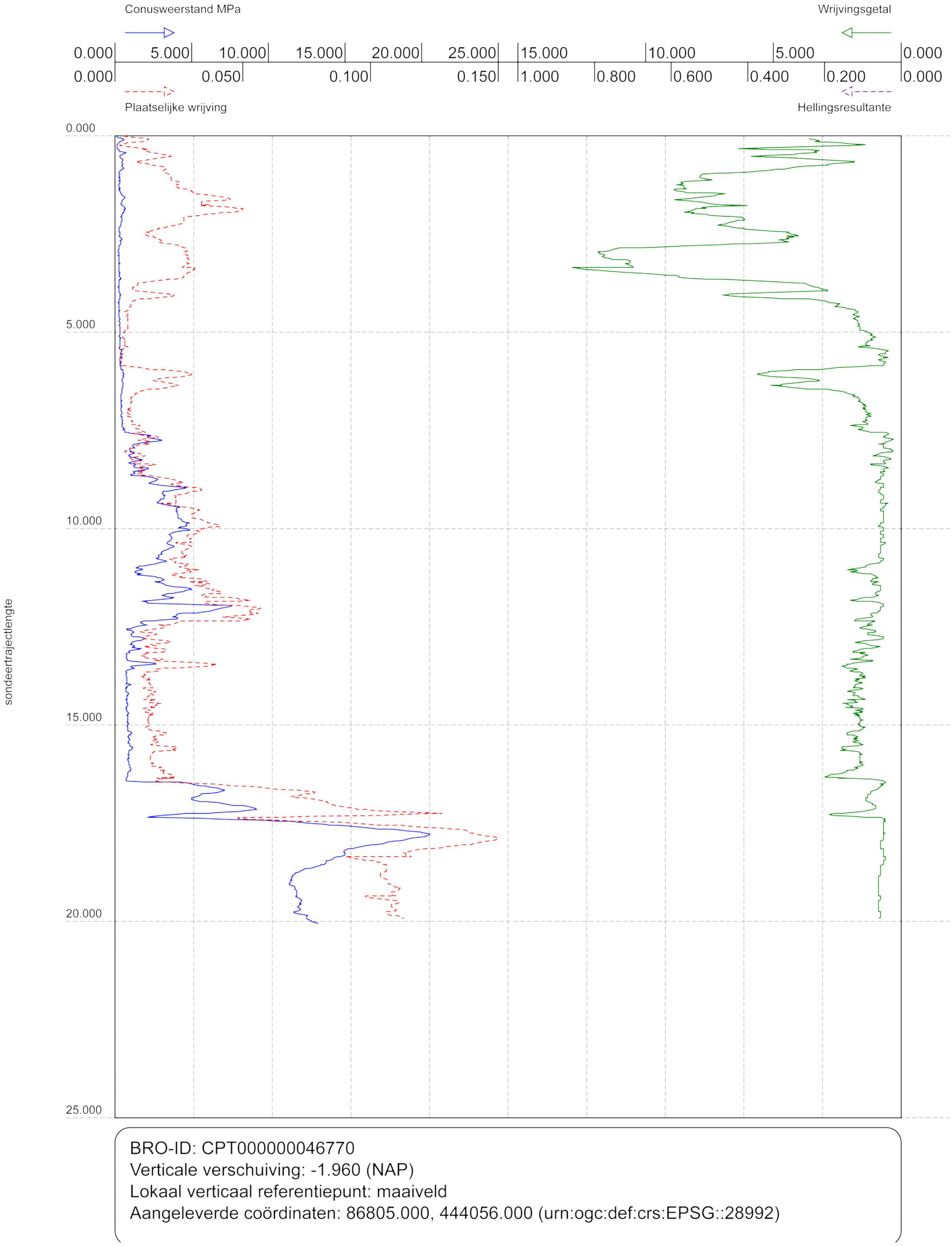


Figure B.2: CPT Delft south (DINO Loket)

B.5. Animals

Among the small mammals expected to use the passage are shrews, voles, bats, and hedgehogs. **Shrews** are tiny creatures, typically only 5–8 centimeters long and weighing 5–15 grams. They favour moist areas rich in vegetation, often with loose, organic-rich soil that supports a diverse insect population. Dense ground cover, such as grasses, shrubs, and leaf litter, is essential for shrews as it provides them with both food and shelter ("Waterspitsmuis | De Zoogdiervereniging", n.d.). **Voles**, which are slightly larger at 9–12 centimeters, also thrive in environments with loose, fertile soil, such as grasslands, meadows, and fields. They depend on low vegetation like grasses and sedges, which offer protection from predators and serve as a food source ("Rosse woelmuis | De Zoogdiervereniging", n.d.). **Hares**, much larger than other animals here, typically weigh 3–5 kilograms and require open areas with scattered low vegetation for both foraging and hiding. They are drawn to areas with varied soil types, including sandy or loamy soils, which are easy for burrowing and nesting.

The **weasel**, a small predator, measures around 20 centimeters in length and inhabits areas with a mix of low and dense vegetation that provides cover during hunting. Weasels are highly adaptable but prefer habitats with abundant prey, such as open fields, forest edges, and hedgerows ("Wezel | De Zoogdiervereniging", n.d.). **Hedgehogs,** also around 20–30 centimeters long, require mixed environments like gardens, woodlands, and meadows. They depend on dense shrubs, hedgerows, and leaf litter for food and nesting sites, as this provides both cover and access to invertebrates, which are their main diet ("egel | De Zoogdiervereniging", n.d.).

Bats, with wingspans between 20–30 centimeters, use the bridge corridor as a connecting route between feeding grounds, as they are drawn to insect-rich areas. They roost in nearby trees or structures, and their preferred environments include trees and nearby fields or water sources that support insect populations ("vleermuizen | De Zoogdiervereniging", n.d.). Insects such as butterflies and bumblebees are also anticipated to benefit from the fauna passage. **Butterflies**, which range in wingspan from 3 to 10 centimeters, prefer open, sunlit areas with flowering plants. A diversity of native wildflowers is essential to sustain them, as these plants provide both nectar and shelter. **Bumblebees**, which measure 1–2.5 centimeters in body length, favor meadows and woodland edges with flowering plants, particularly those like clover and dandelions that offer accessible pollen.

Amphibians such as **toads** are likely to use the passage as well, benefiting from moist, sheltered environments. Toads, which range from 5–15 centimeters in length, need areas with damp soil or proximity to water. They prefer shaded ground cover that helps them regulate moisture and offers protection from predators. Vegetation, including leaf litter and damp soil layers, provides an ideal habitat for these amphibians, as well as abundant food in the form of insects and other small invertebrates ("Gewone pad", 2024).

C

Synthesis

C.1. Python script volumes

The script made in Python to calculate volumes of the materials used in the different design variants, is shown below.

In [2]:

```
import numpy as np
from scipy.integrate import quad

# Define constants
h_max = 3.6   # maximum height in meters
slope_length = 0.1  # slope (3% in the length direction)
S = 3  # side slope ratio (1:3 for side slopes)
W = 6  # top width (bike path width) in meters
L_r = h_max / slope_length  # total length of the embankment based on slope in
# length direction

# Define the cross-sectional area function A(x) as a function of x
def A_with_slope(x):
    h_x = h_max * (1 - x / L_r) # height at point x(varies along the embankment)
    B_w_x = 2 * S * h_x + W  # base width at point x including side slopes
    return 0.5 * (B_w_x + W) * h_x  # trapezoidal cross-sectional area

# Calculate the volume by integrating A_with_slope(x) from 0 to L_r
volume_with_slope, _ = quad(A_with_slope, 0, L_r)

# Define the bottom width function B_b(x)
def bottom_width(x):
    h_x = h_max * (1 - x / L_r)  # height at point x
    return 2 * S * h_x + W  # bottom width at point x

# Calculate the bottom surface area by integrating B_b(x) from 0 to L_r
A_bottom, _ = quad(bottom_width, 0, L_r)

# calculate how much material
volume_sand = 0.2 * volume_with_slope
volume_soil = 0.8 * volume_with_slope

# Output the result
print('results for a ramp with height of', h_max, 'm, slope of',
      (slope_length*100), 'percent and length of', L_r, 'm, and width of', W, 'm.')
print('length slope:', L_r, 'm,', 'length railing:', (L_r*2), 'm')
print('Volume slope:', volume_with_slope, 'm3, which is sand:',
      volume_sand, 'm3, and which is soil', volume_soil, 'm3')
print('Area of bottom of slope:', A_bottom, 'm2')
```

```
results for a ramp with height of 3.6 m, slope of 10.0 percent and length of 36.0 m, and w
idth of 6 m.
length slope: 36.0 m, length railing: 72.0 m
Volume slope: 855.3599999999999 m3, which is sand: 171.072 m3, and which is soil 684.288 m
3
Area of bottom of slope: 604.8000000000001 m2
```

In [ ]:

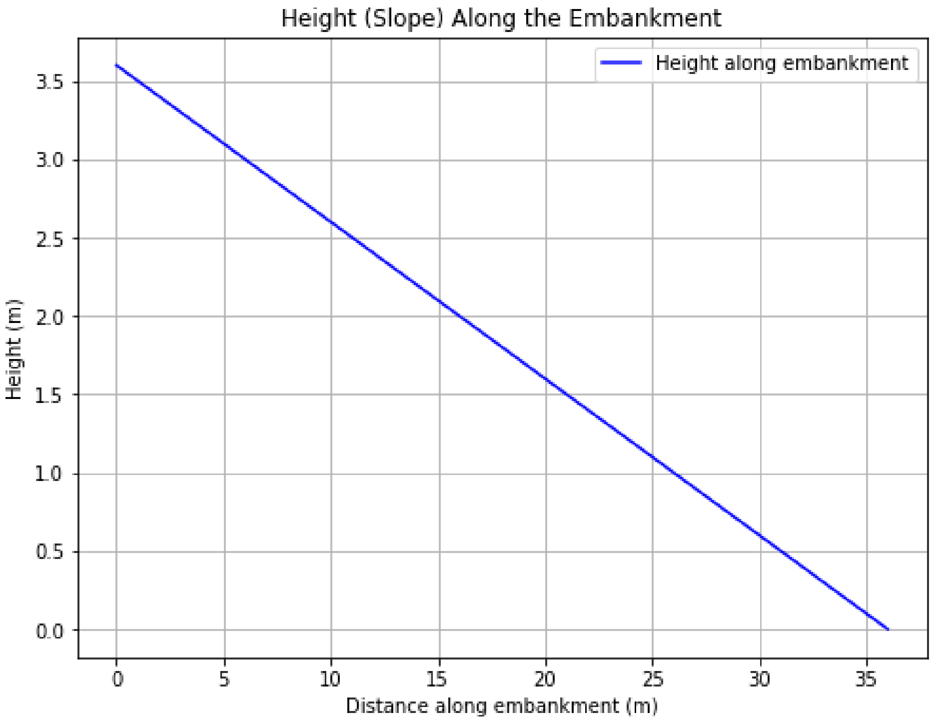
```
import matplotlib.pyplot as plt

# Define the function for the height along the embankment
# (slope in the longitudinal direction)
def height_along_embankment(x):
    return h_max * (1 - x / L_r)

# Create an array of x values along the embankment
x_values = np.linspace(0, L_r, 1000)  # 1000 points between 0 and L_r
height_values = height_along_embankment(x_values)  # corresponding heights at each x

# Plot the slope (height) along the embankment
plt.figure(figsize=(8, 6))
plt.plot(x_values, height_values, label="Height along embankment", color='b')
plt.title("Height (Slope) Along the Embankment")
plt.xlabel("Distance along embankment (m)")
plt.ylabel("Height (m)")
plt.grid(True)
```

```
plt.legend()
plt.show()
```



In [5]:

```
# calculate the volume of concrete for the ramp and columns.

# Define constants
deck_height = 0.45  # thickness of the deck in meters
deck_width = W  # width of the deck in meters
column_diameter = 0.8  # diameter of the columns in meters
column_radius = column_diameter / 2  # radius of the columns
column_spacing = 12  # distance between columns in meters


# Calculate total ramp length based on height and slope
L_r = h_max / slope_length  # total length of the ramp

# Function to calculate the height of the column at any point x along the ramp
def column_height(x):
    return h_max * (x / L_r)  # linear variation of column height along the slope

# Calculate the volume of the deck (as a rectangular prism)
deck_volume = L_r * deck_width * deck_height

# Function to calculate the volume of a single column
# at any point x (cylindrical volume)

def column_volume(x):
    h_c = column_height(x)  # height of the column at point x
    #print(h_c)
    return np.pi * (column_radius ** 2) * h_c
    # volume of the cylinder (pi * r^2 * height)

# Calculate the total number of columns
num_columns = int(L_r // column_spacing) + 1  # +1 for the last column

# Create an array of x positions where columns
# are placed (spaced every column_spacing meters)
column_positions = np.linspace(0, L_r, num_columns)

# Calculate the total volume of all columns
# by summing the volume at each column position
total_column_volume = sum([column_volume(x) for x in column_positions])
```

```
# Calculate the total concrete volume (deck + columns)
total_concrete_volume = deck_volume + total_column_volume #[m3]

# Calculate the volume for foundation piles
foundation_volume = 4*0.25*0.25*num_columns*17.5
#rectangle area of 250x250mm and length of 17.5m
foundation_pilecap_volume = 0.8*0.8*0.5*num_columns
#Pile cap of 0.8mx0.8mx0.5m

#calculate the amount of steel reinforcement
total_steel = 230 * total_concrete_volume #[kg]
steel_deck = 130 * deck_volume #[kg]
steel_column = 100 * total_column_volume #[kg]
steel_pilecap = 100 * foundation_pilecap_volume #[kg]


# Output the results
print('results for a ramp with height of', h_max, 'm, slope of',
      (slope_length*100), 'percent and length of', L_r, 'm, and width of', W, 'm.')
print('length railing:', (L_r*2), 'm')
print('concrete volume deck:', deck_volume, 'm3', '
      and amount of steel', (steel_deck/1000), 'ton.')
print('amount of columns:',num_columns,', concrete volume columns:',
      total_column_volume, 'm3 and amount of steel', (steel_column/1000), 'ton.')
print('volume foundation:', foundation_volume, 'm3')
print('volume pile cap:', foundation_pilecap_volume,
      'm3, and steel', (steel_pilecap/1000), 'ton')
```

```
results for a ramp with height of 3.6 m, slope of 10.0 percent and length of 36.0 m, and w
idth of 6 m.
length railing: 72.0 m
concrete volume deck: 97.2 m3 and amount of steel 12.636 ton.
amount of columns: 4 , concrete volume columns: 3.619114736935442 m3 and amount of steel
0.3619114736935442 ton.
volume foundation: 17.5 m3
volume pile cap: 1.2800000000000002 m3, and steel 0.12800000000000003 ton
```

In [4]:

```
#Calculate the weight of concrete deck and column
total_concrete_weight = total_concrete_volume * 2400 * 0.00981 #[kN]


total_steel_kn = total_steel * 0.00981 #[kN]
print('total weight concrete:', total_concrete_weight, 'kN')
print('total weight steel:', total_steel_kn, 'kN')
```

```
total weight concrete: 2373.685237366408 kN
total weight steel: 227.47816858094743 kN
```

In [5]:

```
#Calculate the weight of concrete deck and column
deck_concrete_weight = deck_volume * 2400 * 0.00981 #[kN]
deck_steel_kn = steel_deck * 0.00981 #[kN]
print('total weight concrete deck:', total_concrete_weight, 'kN')
print('total weight steel deck:', total_steel_kn, 'kN')
G_column = (deck_concrete_weight + deck_steel_kn) / L_r * column_spacing
V_column = 1.3*2.9*W*12
print(G_column, V_column, (G_column + V_column))
```

```
total weight concrete deck: 2373.685237366408 kN
total weight steel deck: 227.47816858094743 kN
804.1453199999999 271.44 1075.58532
```

In [6]:

```
#Volume calculation foundation of bridge
```

C.2. Approach ramp designs

Variant 1

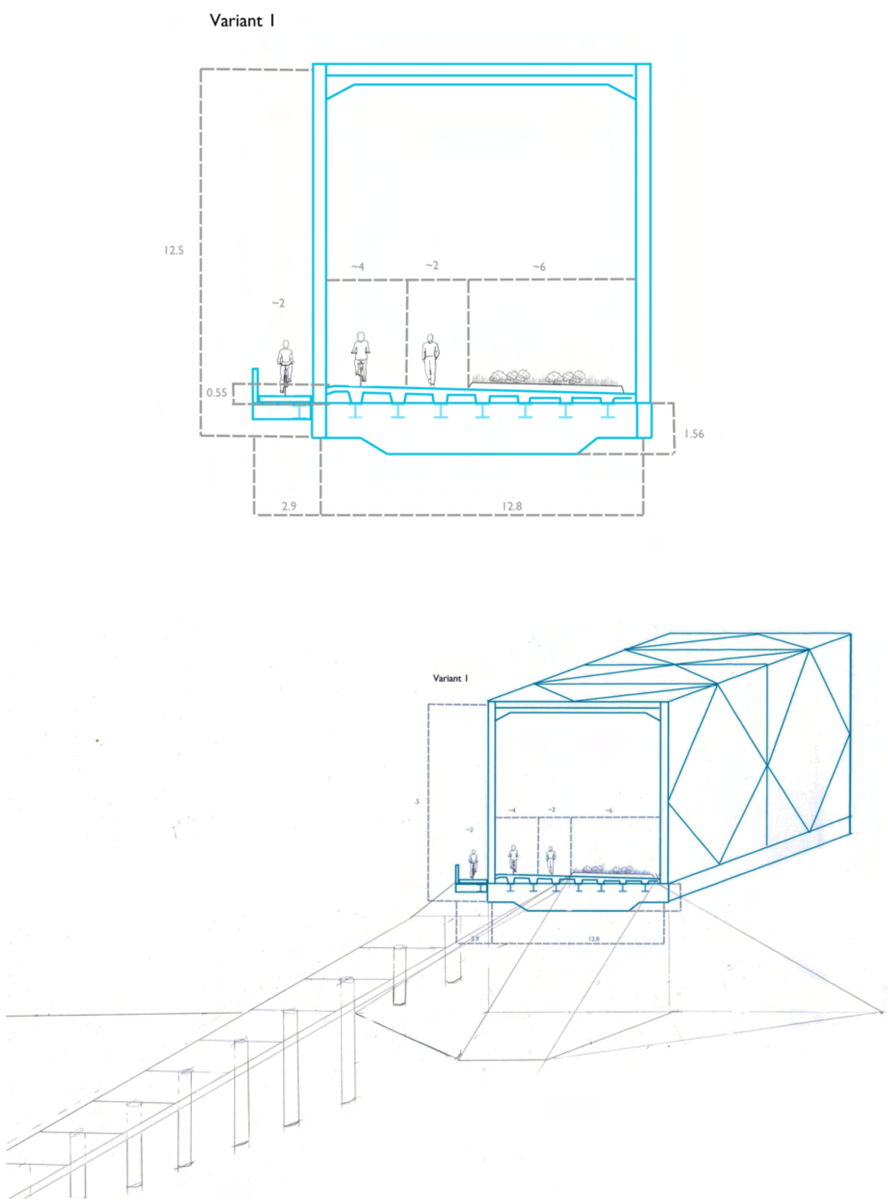
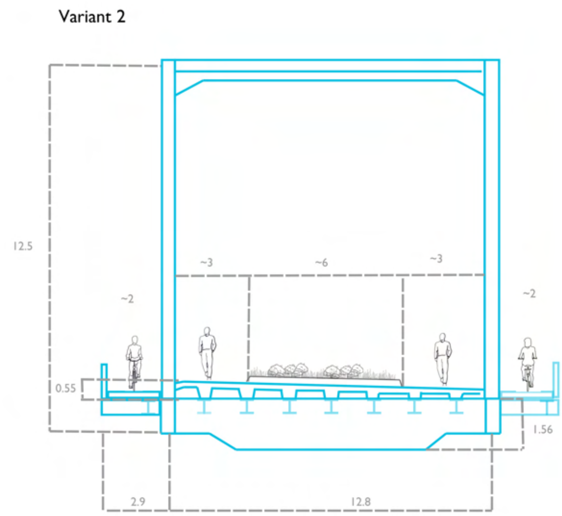


Figure C.1: Design variant 1

Variant 2



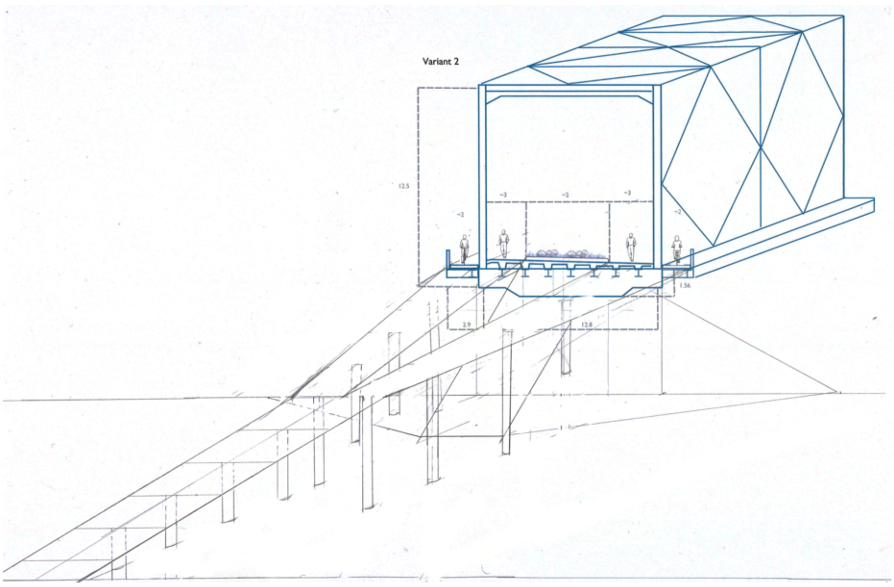


Figure C.2: Design variant 2

Figure C.3: Design variant 2 approach ramps

Variant 3

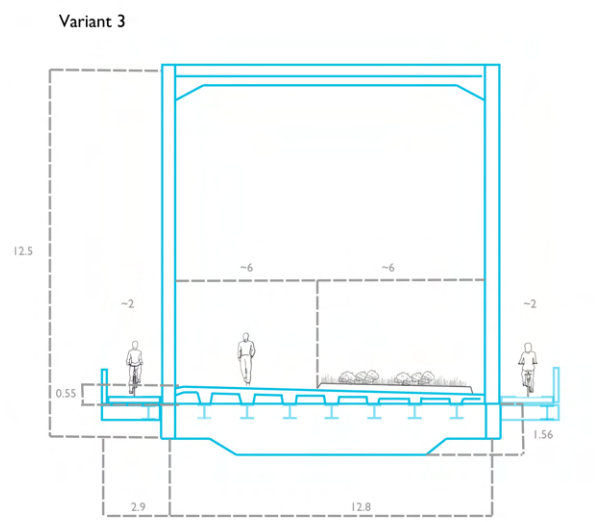


Figure C.4: Design variant 3

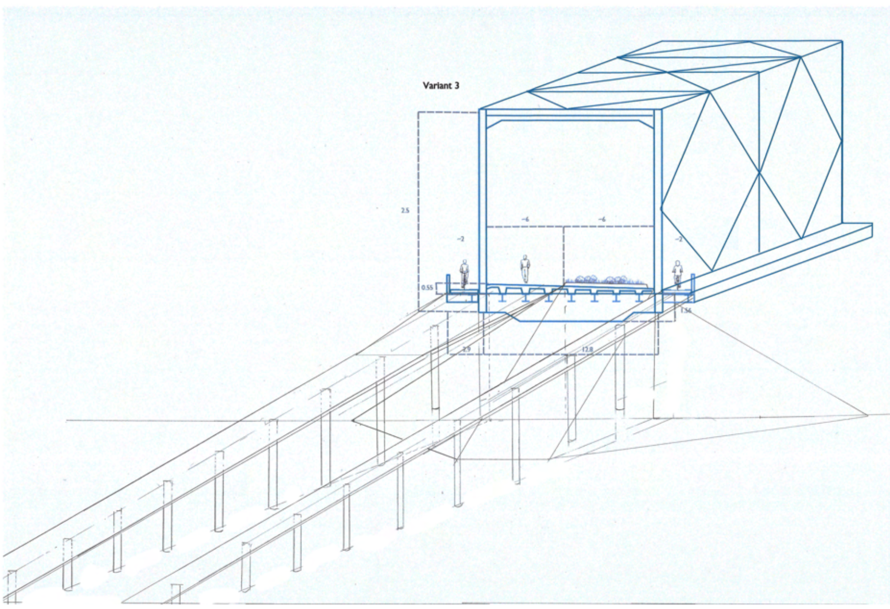


Figure C.5: Design variant 3 approach ramps

Variant 4

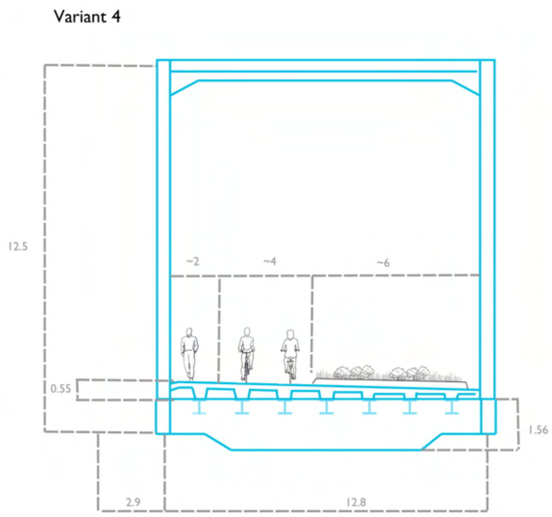


Figure C.6: Design variant 4

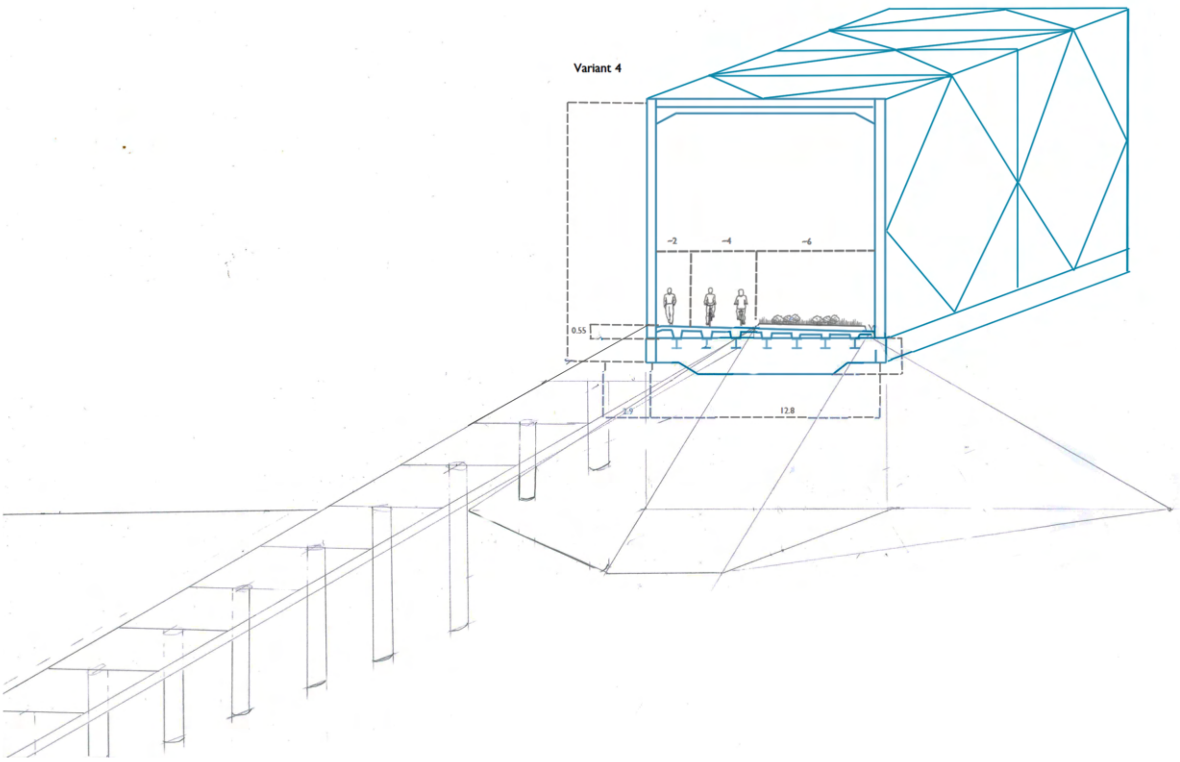


Figure C.7: Desing Variant 4 approach ramp

The approach ramp of this design is similar to Variant 3.

Variant 5

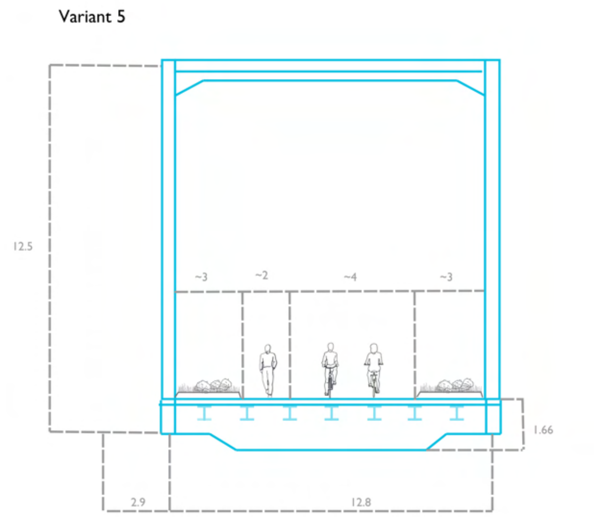


Figure C.8: Design variant 5

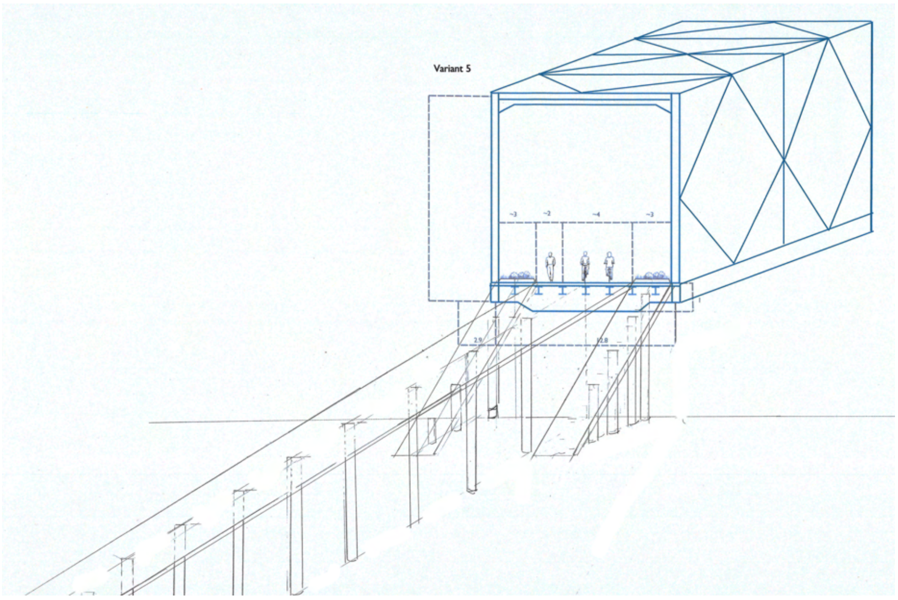


Figure C.9: Design variant 5 approach ramps

Variant 6a and 6b

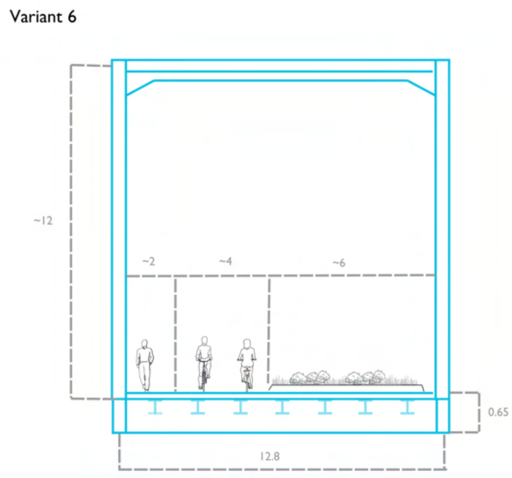


Figure C.10: Design variant 6

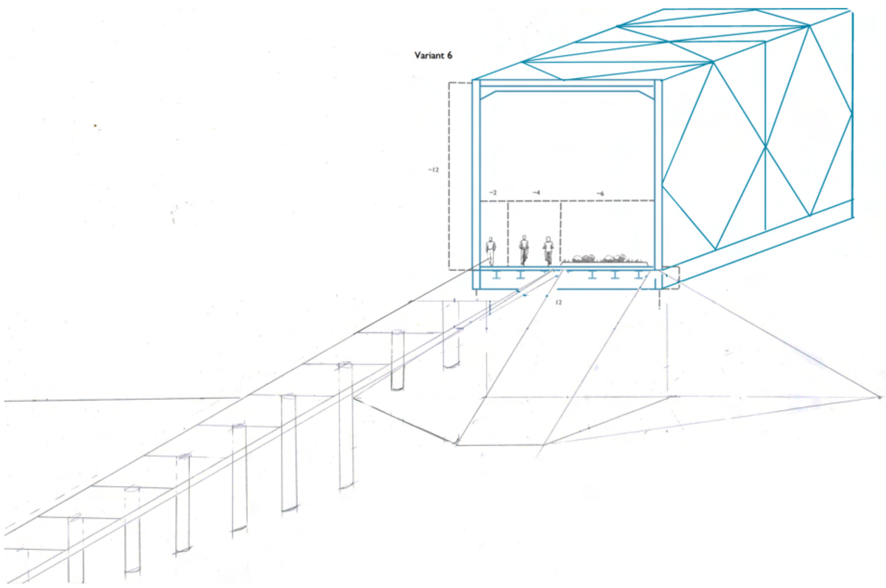


Figure C.11: Design variant 6 approach ramps

Variant 7

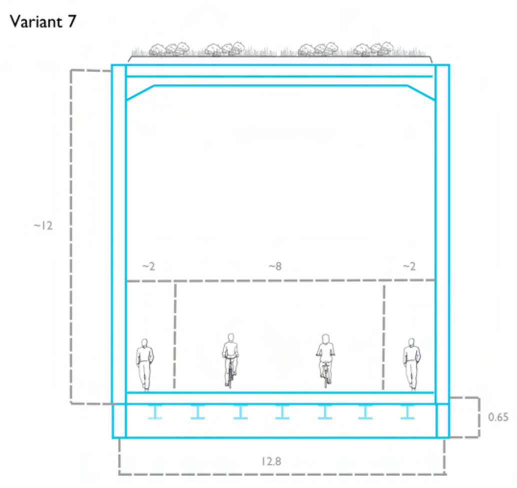


Figure C.12: Design variant 7

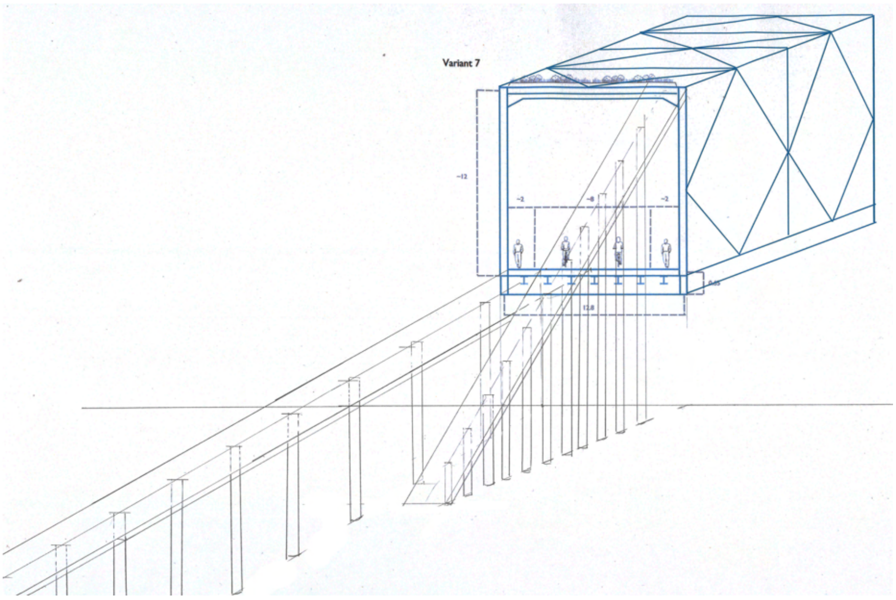


Figure C.13: Design variant 7 approach ramps

Variant 8

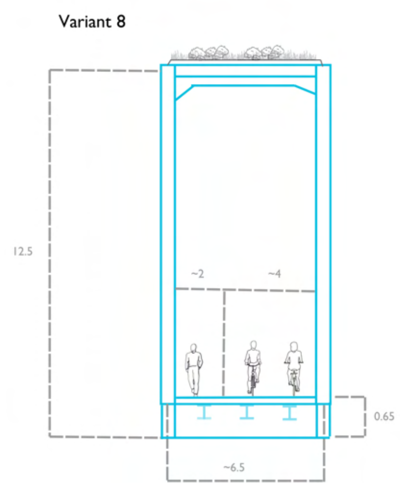


Figure C.14: Design variant 8

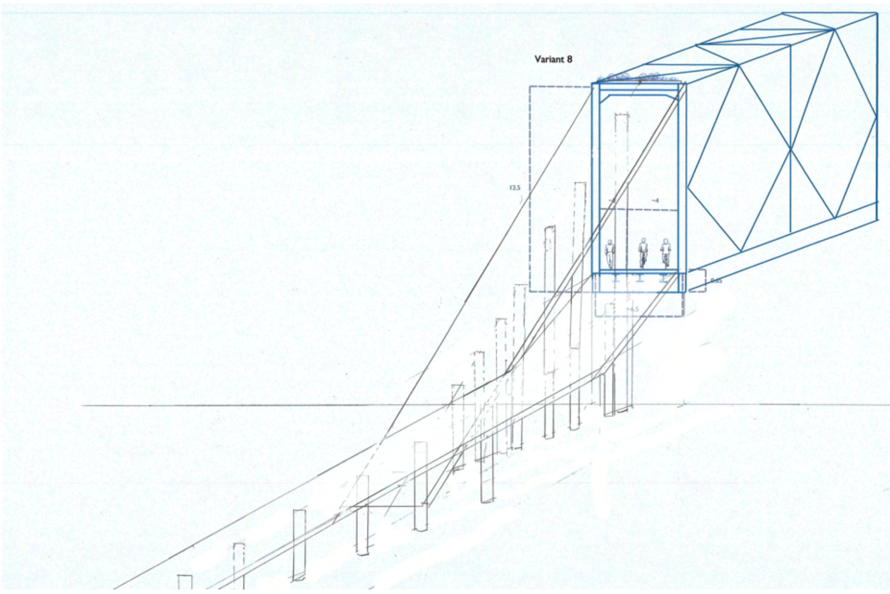


Figure C.15: Design variant 8 approach ramps

Project overzicht				Product overzicht			Meer informatie
Variant	Element niveau 1	Element niveau 2	Product	Datacategorie	Hoeveelheid in project	Eenheid	Omschrijving Element niveau 1
Variant 6b	Wear layer		Slijtlaag	Cat.3 (30%)	1.950.00	m2	
Variant 6b	Paint layer		Natlaksysteem voor staalconstructies	Cat.3 (30%)	26.880.00	m2	
Variant 6b	Transport		Transport per binnenvaartschip	Cat.3 (30%)	540.900.00	tkm	
Variant 6b	Reused steel		Zwaar constructiestaal uit hergebruik 7820 kgm3, incl. conservering	Cat.2	1.534.800.00	kg	
Variant 6b	New bridge deck		Zwaar constructiestaal 7820 kgm3, incl. conservering	Cat.2	256.200.00	kg	
Variant 6b	Concrete deck fauna		Doorgaand Gewapend Beton C3037 CEM III	Cat.3 (30%)	195.00	m3	
Variant 6b	Foundation	Piles	Funderingspalen, Beton; in het werk gestort, C2025; incl. wapening	Cat.3 (30%)	201.60	m3	
Variant 6b	Foundation	Pilecap	Betonmortel voor GWW C3545 CEM III 30% granulaat 2386 kgm3 compleet	Cat.3 (30%)	52.27	m3	
Variant 6b	Foundation	Pilecap	Wapeningsstaal	Cat.3 (30%)	5.23	ton	
Variant 6b	Foundation	Top beam	Betonmortel voor GWW C3545 CEM III 30% granulaat 2386 kgm3 compleet	Cat.3 (30%)	30.72	m3	
Variant 6b	Foundation	Top beam	Wapeningsstaal	Cat.3 (30%)	3.07	ton	
Variant 6b	Foundation	Columns	Betonmortel voor GWW C3545 CEM III 30% granulaat 2386 kgm3 compleet	Cat.3 (30%)	63.36	m3	
Variant 6b	Foundation	Columns	Wapeningsstaal	Cat.3 (30%)	6.34	ton	
Variant 6b	Humans passage west		Ophoogmateriaal, zand	Cat.3 (30%)	252.37	m3	6m wide, 3% inclination, 2.6m height
Variant 6b	Humans passage west		Geotextiel	Cat.3 (30%)	1.196.00	m2	6m wide, 3% inclination, 2.6m height
Variant 6b	Humans passage west		Ophoogmateriaal, grond	Cat.3 (30%)	1.009.49	m3	6m wide, 3% inclination, 2.6m height
Variant 6b	Humans passage west		Balustrades, Staal, gepoedercoat; spijlen	Cat.3 (30%)	173.33	m1	6m wide, 3% inclination, 2.6m height
Variant 6b	Fauna passage west		Ophoogmateriaal, zand	Cat.3 (30%)	539.39	m3	soil ramp fauna 6m wide 5.6m height 10%
Variant 6b	Fauna passage west		Geotextiel	Cat.3 (30%)	1.276.80	m2	soil ramp fauna 6m wide 5.6m height 10%
Variant 6b	Fauna passage west		Ophoogmateriaal, grond	Cat.3 (30%)	2.157.57	m3	soil ramp fauna 6m wide 5.6m height 10%
Variant 6b	Fauna passage west		Balustrades, Staal, gepoedercoat; spijlen	Cat.3 (30%)	150.00	m1	soil ramp fauna 6m wide 5.6m height 10%
Variant 6b	Fauna passage east		Ophoogmateriaal, zand	Cat.3 (30%)	677.22	m3	soil ramp fauna 6m wide 6.1m height 10%
Variant 6b	Fauna passage east		Geotextiel	Cat.3 (30%)	1.482.30	m2	soil ramp fauna 6m wide 6.1m height 10%
Variant 6b	Fauna passage east		Ophoogmateriaal, grond	Cat.3 (30%)	2.708.89	m3	soil ramp fauna 6m wide 6.1m height 10%
Variant 6b	Humans passage east		Ophoogmateriaal, zand	Cat.3 (30%)	390.81	m3	6m wide, 3% inclination, 3.1m height
Variant 6b	Humans passage east		Geotextiel	Cat.3 (30%)	1.581.00	m2	6m wide, 3% inclination, 3.1m height
Variant 6b	Humans passage east		Ophoogmateriaal, grond	Cat.3 (30%)	1.563.23	m3	6m wide, 3% inclination, 3.1m height
Variant 6b	Humans passage east		Balustrades, Staal, gepoedercoat; spijlen	Cat.3 (30%)	206.67	m1	6m wide, 3% inclination, 3.1m height
Variant 6b	Timber deck pedestrians/cyclists		Cloeziana planken, schaalbaar	Cat.3 (30%)	1.950.00	m1	

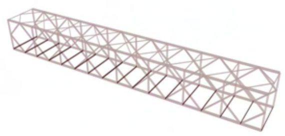
C.3. Dubocalc detailed information

Dubocalc is used for a preliminary investigation into the environmental impact of different design variants. Within the program, different product cards are integrated and can be added to a project. For other engineers to recreate a similar environmental impact analysis for other design projects, an overview of the used products/materials in this research is given below. Since the program is in Dutch, this overview is as well.

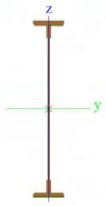
C.4. Unity checks model

Below, the performed unity checks for the simulation of the structure can be found.

Crossbeams / Dwarsdragers



Original cross section



Original Material properties

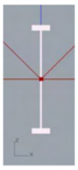
Dwarsdrager hoog 3pl		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	S 235	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	4,4276e-02	
A_y [m²], A_z [m²]	2,3273e-02	1,9559e-02
A_L [m²/m], A_D [m²/m]	4,1760e+00	4,1760e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	1,8035e-02	1,2865e-04
i_y [mm], i_z [mm]	638	54
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	2,3122e-02	9,5296e-04
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	2,6357e-02	1,5511e-03
$M_{pl.y+}$ [Nm], $M_{pl.y-}$ [Nm]	6,19e+06	6,19e+06
$M_{pl.z+}$ [Nm], $M_{pl.z-}$ [Nm]	3,65e+05	3,65e+05
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	1,5179e-05	7,3694e-05
$β_y$ [mm], $β_z$ [mm]	0	0

W_ply [m3]	0.026357
W_ply [cm3]	26357
A [m2]	0.044276
A {cm2]	442.76

Modelled material properties

1. family:'DefaultCroSec' name:'' material:'Steel' applies to elements:'cross beam bottom'; I-Profile: height:60[cm] Flange-width:1[cm] Flange-thick:3[cm] Fillet-radius:0[cm] Web-thick:5[cm] zs:30[cm]

Modelled cross section



Bending moment

$M_{pl,y}\,[kNm]$	6190	U.C	0.264646607
$M_{Ed,y}\,[kNm]$	1310.53	max gamma	4.723279894
Location max	Middle, every crossbeam		
$\gamma_{m2}\,[-]$	1.25		

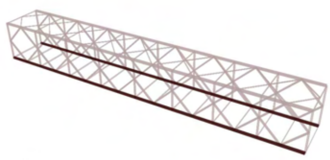
Normal force, tension

$N_{pl,Rd} = A * \frac{f_y}{\gamma_{M0}}\,[kN]$	8323.888	U.C	0.006366015 no combination check with moment necessary
$N_{t,Ed}\,[kN]$	52.99	max gamma	

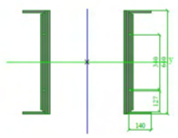
Shearforce

$V_{pl,Rd,z} = \frac{A_{v,z}(f_y/\sqrt{3})}{\gamma_{M0}}$	2122.970056	U.C. z	0.00962331 no combined check necessary
$f_y\,[N/mm^2]$	235	U.C. y	0.178678985 no combined check necessary
$A_{v,z}$	0.019559		
$V_{ED,z}$	20.43		
$V_{pl,Rd,y} = \frac{A_{v,y}(f_y/\sqrt{3})}{\gamma_{M0}}$	2526.094489		
$A_{v,y}$	0.023273		
$V_{ED,y}$	451.36		
$\gamma_{m2}\,[-]$	1.25		

Main beams bottom/ hoofdligger onder



Original cross section

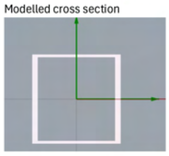


Original Material properties

Hoofdligger RO4		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 vakwerk (zwaar)x1.25	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	7,8824e-02	
A_y [m²], A_z [m²]	1,6101e+00	6,4653e-02
A_L [m²/m], A_D [m²/m]	3,8080e+00	3,9920e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	320
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	3,0254e-03	5,6026e-03
i_y [mm], i_z [mm]	196	267
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	9,4543e-03	1,4006e-02
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	1,3397e-02	2,0891e-02
$M_{pl.y+}$ [Nm], $M_{pl.y-}$ [Nm]	3,15e+06	3,15e+06
$M_{pl.z+}$ [Nm], $M_{pl.z-}$ [Nm]	4,91e+06	4,91e+06
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	1,5157e-04	0,0000e+00
$β_y$ [mm], $β_z$ [mm]	0	0

W_ply [m3]	0.013397
W_ply [cm3]	13397
A [m2]	0.078824
A {cm2]	788.24
Iy [m^4]	0.0030254
Iy [cm^4]	302540

Modelled cross section



$\varepsilon = \sqrt{235/f_y}$	0.813616513	7.322548621
c [mm]	460	
t [mm]	10	
c/t	46	class 1

Modelled material properties

[]-Profile: height:64[cm] Flange-width:46[cm] Flange-thick:2[cm] SWall-thick:4[cm] zs:32[cm]

Normal force, tension

$N_{c,Rd} = A * f_y/\gamma\,[kN]$	22386.016	U.C	0.448177559 combination check with moment necessary
A [m2]	0.078824	max gamma	2.78907316
$f_y\,[N/mm^2]$	355		
$\gamma_{m2}\,[-]$	1.25		
$N_{c,Ed}$	10032.91		

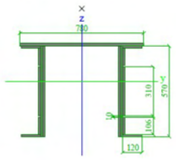
Bending moment

$M_{pl,y}\,[kNm]$	3150	U.C	0.103063492
$M_{Ed,y}\,[kNm]$	259.72		
$\gamma_{m2}\,[-]$	1.25		
$M_{pl,z}\,[kNm]$	4910	U.C	0.040980143
$M_{Ed,z}\,[kNm]$	160.97		
$\gamma_{m2}\,[-]$	1.25		

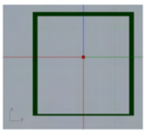
$a = \frac{A - 2bt_f}{A} \leq 0.5$	0.391048412	U.C.	0.15298522	$\left[\frac{M_{y,Ed}}{M_{N,y,Rd}}\right]^{\alpha} + \left[\frac{M_{z,Ed}}{M_{N,z,Rd}}\right]^{\beta} \leq 1$
$n = N_{Ed}/N_{pl,Rd}$	0.448177559			
$M_{N,y,RD} = M_{pl,y,rd}(1-n)/(1-0.5a) \leq M_{pl,y,RD}$	2160.712234			
$M_{N,z,RD} = M_{pl,z,RD}$ for $n > a$	4910			

Main beams top/ hoofdligger boven

Original cross section



Modelled cross section



Modelled material properties

[]-Profile: height:64[cm] Flange-width:64[cm] Upper-thick:2.5[cm] Lower-thick:1[cm] SWall-thick:3[cm] zs:27.78[cm]

Original Material properties

Hoofdligger RB3		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 vakwerk (zwaar)x1.25	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	7,0356e-02	
A_y [m²], A_z [m²]	1,2450e-02	4,7177e-02
A_L [m²/m], A_D [m²/m]	4,4140e+00	4,4140e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	347
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	2,8176e-03	4,5452e-03
i_y [mm], i_z [mm]	200	254
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	8,1192e-03	1,1654e-02
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	1,2449e-02	1,7322e-02
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	2,93e+06	2,93e+06
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	4,07e+06	4,07e+06
d_y [mm], d_z [mm]	0	458
I_t [m⁴], I_w [m⁶]	3,5036e-05	1,6146e-04
$β_y$ [mm], $β_z$ [mm]	-995	0

W_ply [m3]	0.012449
W_ply [cm3]	12449
A [m2]	0.070356
A {cm2]	703.56
Iy [m^4]	0.0028176
Iy [cm^4]	281760

Normal force, compression

$N_{C,Rd} = A * f_y/\gamma [kN]$		13226.928	U.C	0.757446476
A [m2]		0.070356	max gamma	1.650281624
$f_y [N/mm^2]$		235		
γ_{m2} [−]		1.25		
$N_{C,Ed}$		10018.69		
location	III-8c9c			

Bending moment

$M_{pl,y}$ [kNm]	2930	U.C	0.118976109
$M_{Ed,y}$ [kNm]	278.88		
γ_{m2} [−]	1.25		
$M_{pl,z}$ [kNm]	4070	U.C	0.05737715
$M_{Ed,z}$ [kNm]	186.82		
γ_{m2} [−]	1.25		

Normal force, buckling

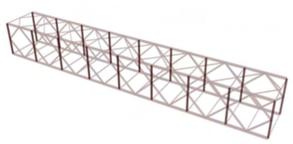
$\varepsilon = \sqrt{235/f_y}$	1		
i [mm]	200	U.C.	0.772904567
Buckling length (0.9*systemlength) L_cr [mm]	5625		
$\lambda_1 = 93.9 \cdot \varepsilon$	93.9		
$\bar{\lambda} = \sqrt{\frac{A \cdot f_y}{N_{cr}}} = \frac{L_{cr}}{i} \cdot \frac{1}{\lambda_1}$	0.299520767		
from graph 6.4 NEN-EN 1993-1-1 χ	0.98	curve b	
γ_{M2} [−]	1.25		
$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}}$ [kN]	12962.38944		

Shearforce

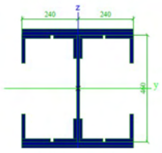
$V_{pl,Rd,z} = \frac{A_{v,z}(f_y/\sqrt{3})}{\gamma_{M0}}$ [kN]	5120.68	U.C. z	0.02138193	no combined check necessary
γ_{M0} [−]	1.25	U.C. y	0.008051232	no combined check necessary
$A_{v,z}$	0.047177			
$V_{ED,z}$	109.49			
$V_{pl,Rd,y} = \frac{A_{v,y}(f_y/\sqrt{3})}{\gamma_{M0}}$ [kN]	1351.35			
$A_{v,y}$	0.01245			
$V_{ED,y}$	10.88			

Vertical beams

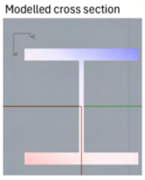
ends



Original cross section



Modelled cross section



Modelled material properties

I-Profile: height:48[cm] Flange-width:48[cm] Flange-thick:5[cm] Fillet-radius:0[cm] Web-thick:2[cm] zs:24[cm]

Original Material properties

Hoofdligger WV1		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 overigx1.05	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	5,2592e-02	
A_y [m²], A_z [m²]	3,7009e-02	9,4772e-03
A_L [m²/m], A_D [m²/m]	3,8760e+00	3,8760e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	2,4332e-03	1,0321e-03
i_y [mm], i_z [mm]	215	140
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	9,5419e-03	4,3006e-03
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	1,1003e-02	5,8655e-03
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	2,59e+06	2,59e+06
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	1,38e+06	1,38e+06
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	2,2126e-05	7,4461e-05
$β_y$ [mm], $β_z$ [mm]	0	0

W_ply [m3]	0.011003
W_ply [cm3]	11003
A [m2]	0.052592
A {cm2]	525.92
Iy [m^4]	0.0024332
Iy [cm^4]	243320
W_plz [m3]	0.0058655
W_plz [cm3]	5865.5

Bending moment

$M_{pl,y}\ [kNm]$	2590		U.C	0.014107143
$M_{Ed,y}\ [kNm]$	29.23			
$\gamma_{m2}\ [-]$	1.25			
$M_{pl,z}\ [kNm]$	1380	II-III C1, C17	U.C	0.040344203
$M_{Ed,z}\ [kNm]$	44.54			
$\gamma_{m2}\ [-]$	1.25		location	1 BC

Normal force, tension

$N_{pl,Rd} = A * \frac{f_y}{\gamma_{M0}} 0 [kN]$	9885.416	U.C	0	no combination check with moment necessary
$N_{t,Ed}\ [kN]$	0			

Normal force, compression

$N_{C,Rd} = A * f_y/\gamma [kN]$	9885.416	U.C.	0.486306292
A [m2]	0.052582	max gamma	2.570396519
$f_y [N/mm^2]$	235		
$\gamma_{M2}\ [-]$	1.25		
$N_{C,Ed}\ [kN]$	4807.34		

Shearforce $V_{ED}/V_{pl,Rd}$

$V_{pl,Rd,z} = \frac{A_{v,z}(f_y/\sqrt{3})}{\gamma_{M0}}$		U.C. z	0.005103664	no combined check necessary
	1028.672827	U.C. y	0.001774945	no combined check necessary
$A_{v,z}$	0.0094772			
$V_{ED,z}$	5.25			
$V_{pl,Rd,y} = \frac{A_{v,y}(f_y/\sqrt{3})}{\gamma_{M0}}$				
	4017.025349			
$A_{v,y}$	0.037009			
$V_{ED,y}$	7.13			

Bending and normal force

$a = \frac{A - 2bt_f}{A} \leq 0.5$	0.452388196	U.C.	0.032351627	$\left[\frac{M_{y,Ed}}{M_{N,y,Rd}}\right]^{\alpha} + \left[\frac{M_{z,Ed}}{M_{N,z,Rd}}\right]^{\beta} \leq 1$
$n = N_{Ed}/N_{pl,Rd}$	0			
$M_{N,y,RD} = M_{pl,y,rd}(1-n)/(1-0.5a) \leq M_{pl,y,RD}$	3347.092589			
$M_{N,z,RD} = M_{pl,z,RD}$ for $n > a$	1380			

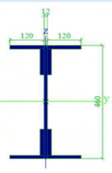
Normal force, buckling

$\varepsilon = \sqrt{235/f_y}$	1		
i [mm]	215	U.C.	0.51190136
Buckling length (0.9*systemlength) L_cr [mm]	5625	max gamma	2.441876693
$\lambda_1 = 93.9 \cdot \varepsilon$	93.9		
$\bar{\lambda} = \sqrt{\frac{A \cdot f_y}{N_{cr}}} = \frac{L_{cr}}{i} \cdot \frac{1}{\lambda_1}$	0.278623969		
from graph 6.4 NEN-EN 1993-1-1 χ	0.95		
$\gamma_{M2}\ [-]$	1.25		
$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}} [kN]$	9391.1452		

Middle

Normal force, tension

$N_{pl,Rd} = A * \frac{f_y}{\gamma_{M0}} [kN]$	3417.088	U.C	0.129987873	no combination check with moment necessary
A [m2]	0.018176			
$f_y [N/mm^2]$	235			
$\gamma_{M2}\ [-]$	1.25			
$N_{t,Ed}\ [kN]$	444.18			



W_ply [m3]	0.00310093
W_ply [cm3]	3100.93
A [m2]	0.018176
A {cm2]	181.76
Iy [m^4]	0.0005949
Iy [cm^4]	59490
W_plz [m3]	0.0031009
W_plz [cm3]	3100.9

Bending moment

$M_{pl,y}\ [kNm]$	729	U.C	0.059972565
$M_{Ed,y}\ [kNm]$	43.72		
$\gamma_{m2}\ [-]$	1		
$M_{pl,z}\ [kNm]$	126	U.C	0.210873016
$M_{Ed,z}\ [kNm]$	26.57		
$\gamma_{m2}\ [-]$	1	U.C. combinec	0.270845581
		max gamma	3.692140725

Shearforce $V_{ED}/V_{pl,Rd}$

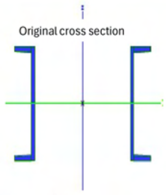
$V_{pl,Rd,z} = \frac{A_{v,z}(f_y/\sqrt{3})}{\gamma_{M0}}$		U.C. z	0.078071337	no combined check necessary
	110.7961043	U.C. y	0.031406925	no combined check necessary
$A_{v,z}$	0.0072226			
$V_{ED,z}$	8.65			
$V_{pl,Rd,y} = \frac{A_{v,y}(f_y/\sqrt{3})}{\gamma_{M0}}$				
	135.3204767			
$A_{v,y}$	0.0088213			
$V_{ED,y}$	4.25			

Hoofdligger WV2		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	St37 overigx1.05	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	1,8176e-02	
A_y [m²], A_z [m²]	8,8213e-03	7,2226e-03
A_L [m²/m], A_D [m²/m]	1,9040e+00	1,9040e+00
$c_{Y,UCS}$ [mm], $c_{Z,UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	5,9490e-04	3,8503e-05
i_y [mm], i_z [mm]	181	46
$W_{el,y}$ [m³], $W_{el,z}$ [m³]	2,5865e-03	3,0558e-04
$W_{pl,y}$ [m³], $W_{pl,z}$ [m³]	3,1009e-03	5,3725e-04
$M_{pl,y,+}$ [Nm], $M_{pl,y,-}$ [Nm]	7,29e+05	7,29e+05
$M_{pl,z,+}$ [Nm], $M_{pl,z,-}$ [Nm]	1,26e+05	1,26e+05
d_y [mm], d_z [mm]	0	0
I_t [m⁴], I_w [m⁶]	5,1265e-06	1,8569e-06
β_y [mm], β_z [mm]	0	0

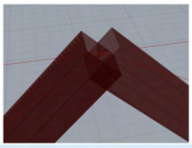
Diagnoals

Modelled material properties

Original cross section



Modelled cross section



Original Material properties

Hoofdligger WD3		
Type	Grafische doorsnede	
Vorm type	Dunwandig	
Onderdeelmateriaal	S 235	
Bouwwijze	Algemeen	
Knik y-y, Knik z-z	d	d
A [m²]	1,6090e-02	
A_y [m²], A_z [m²]	9,3467e-01	1,0046e-02
A_L [m²/m], A_D [m²/m]	2,1343e+00	2,1343e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	0	0
α [deg]	0,00	
I_y [m⁴], I_z [m⁴]	2,6292e-04	1,1811e-03
i_y [mm], i_z [mm]	128	271
$W_{el.y}$ [m³], $W_{el.z}$ [m³]	1,5024e-03	3,4135e-03
$W_{pl.y}$ [m³], $W_{pl.z}$ [m³]	1,8514e-03	4,3364e-03
$M_{pl.y+}$ [Nm], $M_{pl.y-}$ [Nm]	4,35e+05	4,35e+05
$M_{pl.z+}$ [Nm], $M_{pl.z-}$ [Nm]	1,02e+06	1,02e+06
d_y [mm], d_z [mm]	0	0

W_ply [m3]	0.0018514
W_ply [cm3]	1851.4
A [m2]	0.01609
A {cm2]	160.9
Iy [m^4]	0.00026292
Iy [cm^4]	26292

[]-Profile: height:45[cm] Flange-width:45[cm] Flange-thick:0.5[cm] SWall-thick:1.5[cm] zs:22.5[cm]

Normal force, compression

$N_{C,Rd} = A * f_y/\gamma [kN]$	8541.016	U.C	0.39407958
A [m2]	0.030074	max gamma	3.171948162
$f_y [N/mm^2]$	355		
γ_{M2} [−]	1.25		
$N_{C,Ed}$	3365.84		

Normal force, tension

$N_{pl,Rd} = A * \frac{f_y}{\gamma_{M0}} [kN]$	8541.016	U.C	0.392051718 combination check with moment necessary
A [m2]	0.030074		
$f_y [N/mm^2]$	355		
γ_{M2} [−]	1.25		
$N_{t,Ed}$ [kN]	3348.52		

Bending moment

$M_{pl,y}$ [kNm]	435	U.C	0.095689655
$M_{Ed,y}$ [kNm]	33.3		
γ_{m2} [−]	1.25		
$M_{pl,z}$ [kNm]	1020	U.C	0.165625
$M_{Ed,z}$ [kNm]	135.15		
γ_{m2} [−]	1.25		

Bending and normal force

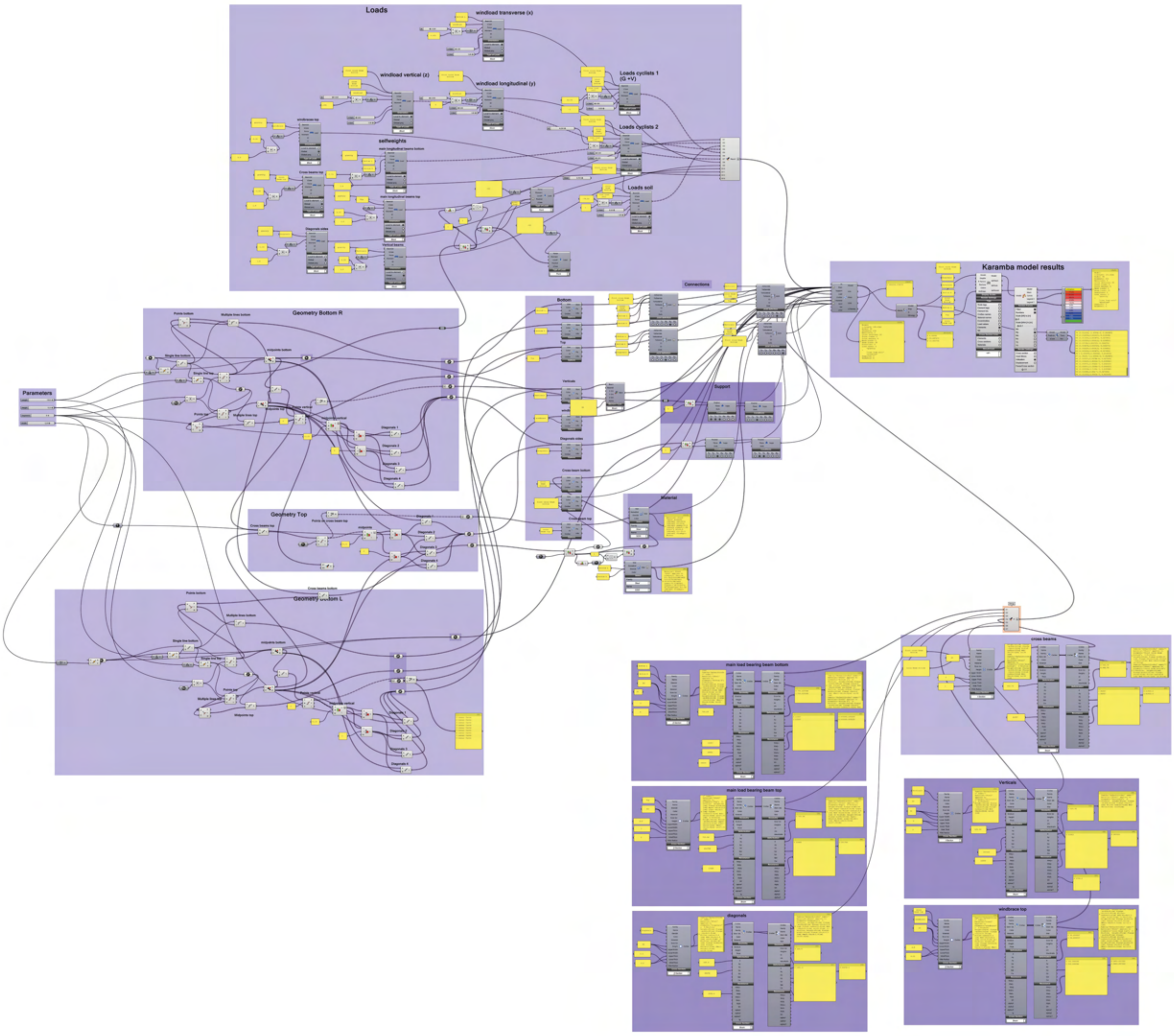
$a = \frac{A - 2bt_f}{A} \leq 0.5$	0.160969546	U.C.	0.14591 $\left[\frac{M_{y,Ed}}{M_{N,y,Rd}}\right]^{\alpha} + \left[\frac{M_{z,Ed}}{M_{N,z,Rd}}\right]^{\beta} \leq 1$
$n = N_{Ed}/N_{pl,Rd}$	0.392051718		
$M_{N,y,RD} = M_{pl,y,rd}(1-n)/(1-0.5a) \leq M_{pl,y,RD}$	287.6053542		
$M_{N,z,RD} = M_{pl,z,RD}$ $for\ n > a$	1020		

Normal force, buckling

$\varepsilon = \sqrt{235/f_y}$	0.813616513		
i [mm]	128	U.C.	0.539835041
Buckling length (0.9*systemlength) L_cr [mm]	7956	max gamma	2.315522158
λ_1=93.9 · ε	76.39859061		
$\bar{\lambda} = \sqrt{\frac{A \cdot f_y}{N_{cr}}} = \frac{L_{cr}}{i} \cdot \frac{1}{\lambda_1}$	0.81357849		
from graph 6.4 NEN-EN 1993-1-1 χ	0.73 curve b		
γ_{M2} [−]	1.25		
$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}} [kN]$	6234.94168		

C.5. Grasshopper file

The graph below shows the complete interface of the grasshopper file of the structural model of the Keizersveerbrug.

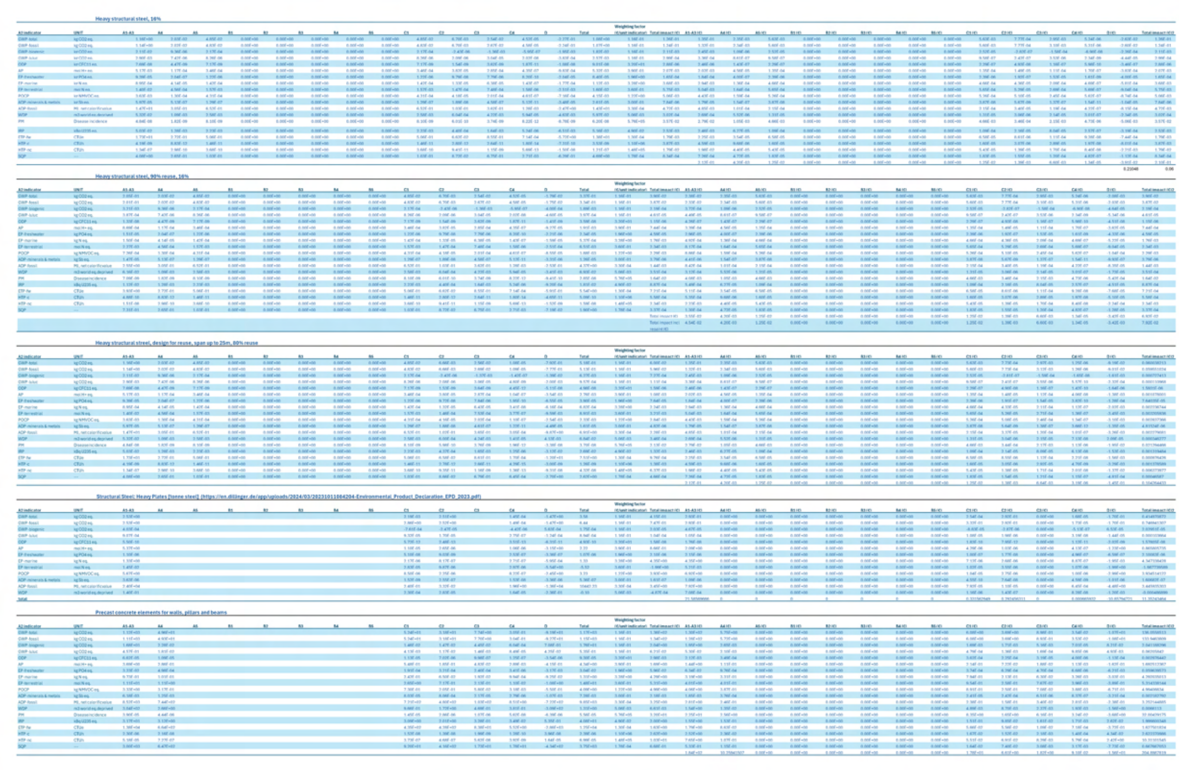


D

Environmental impact analysis

D.1. Environmental Product Declarations

Below, the original values of the used Environmental Product Declarations are shown.



D.2. Concrete design variant municipality Delft

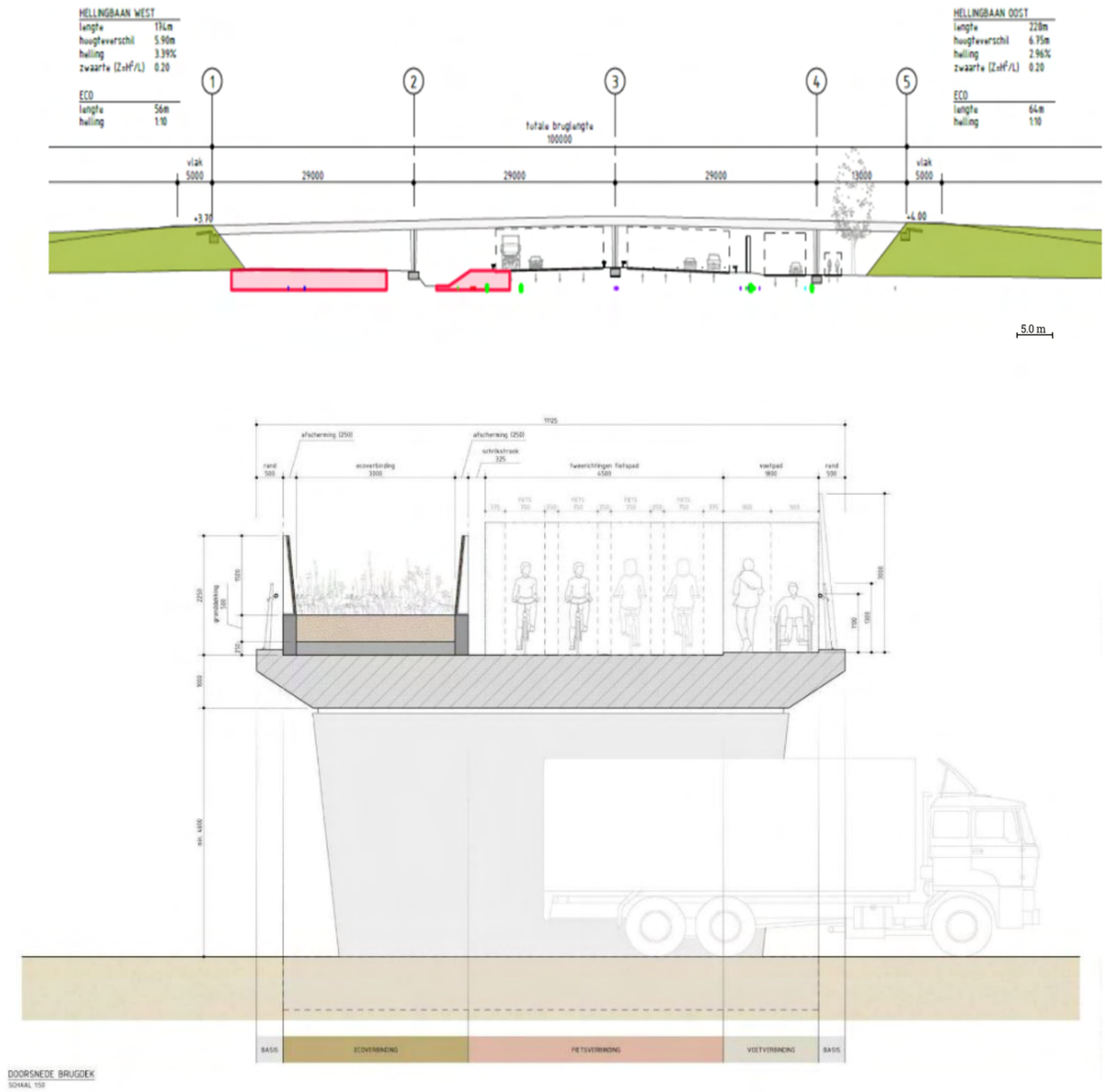


Figure D.1: Concrete design variant for Ackerdijksebrug, Municipality Delft ("Metropolitane Fiets Route Delft – Rotterdam Alexander met viaduct A13 Natuurgroep Ackerdijk Puur Natuur", 2023).