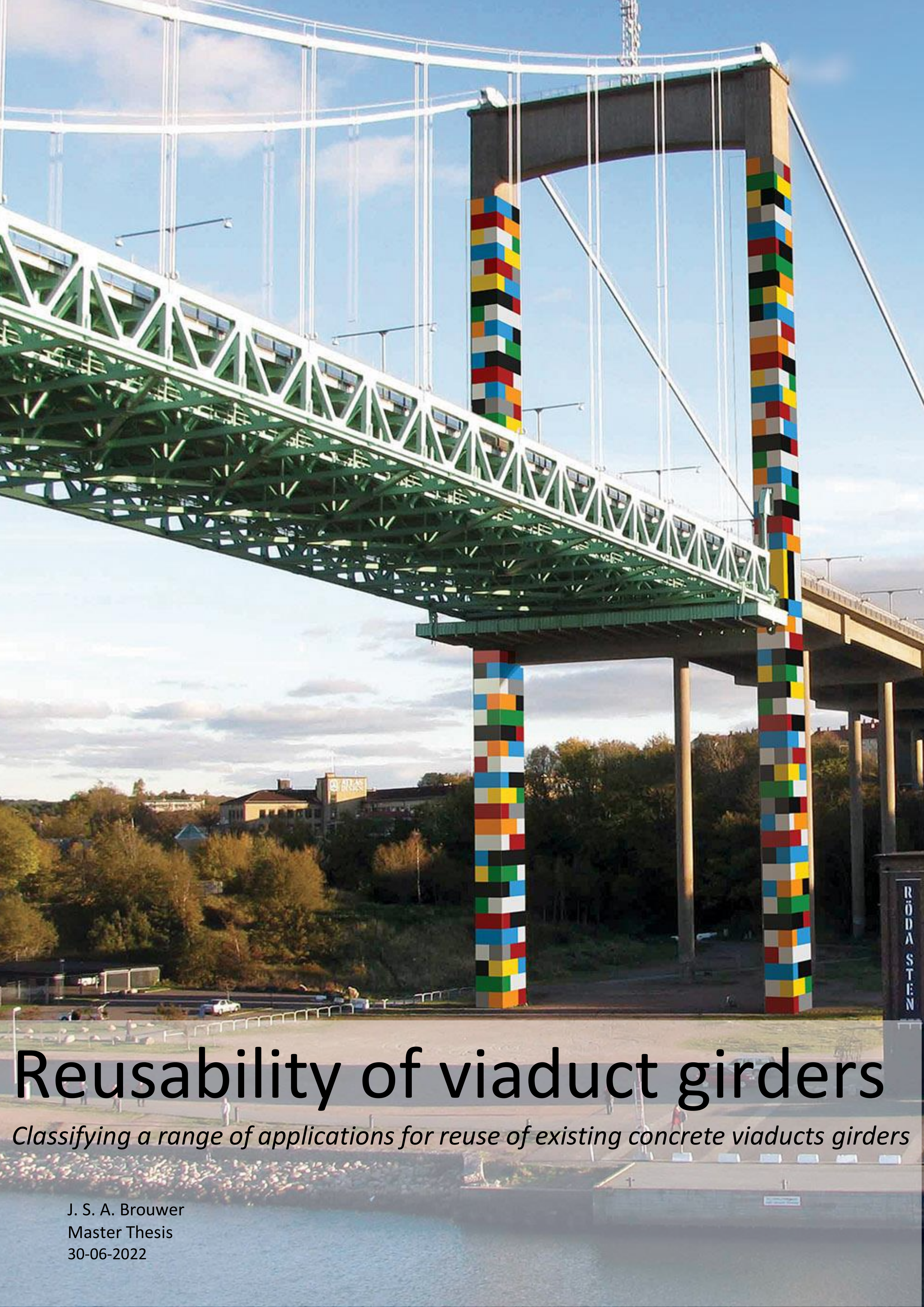

Reusability of viaduct girders

Classifying a range of applications for reuse of existing concrete viaducts girders

J. S. A. Brouwer
Master Thesis
30-06-2022

The world will not evolve past its current state of crisis by using the same thinking that created the situation

- Albert Einstein (1946)

***Image cover page**: Lego's bridge* (Guelov, 2017)

For inquiries regarding this thesis please contact the author

Reusability of viaduct girders

Classifying a range of applications for reuse of existing concrete viaducts girders

By

J.S.A. Brouwer

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering
Building Engineering – Structural Design

at the Delft University of Technology,
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Preface

Before you lies my master thesis *Reusability of viaduct girders: Classifying a range of applications for reuse of existing concrete viaducts girders*. This thesis has been written in conclusion of my master studies in Building Engineering with the specialization of Structural Design at the Faculty of Civil Engineering and Geosciences at the TU Delft University of Technology. I was able to write this research in collaboration with the TU Delft University of Technology and Nebest B.V.

Ever since I was a little kid I enjoyed creating things. Especially with Lego blocks. Little did I know that after years of studying I would end up writing a master thesis which uses Lego blocks as visualization. It feels as if this loop has closed the way it was meant to.

A loop that has not been closed yet however, is the circularity loop. Throughout the (many) years of my education, circularity drew more and more attention each year. It was a new way of thinking and still in its infancy. This therefore piqued my interest and when I came across the initiative 'Closing the Loop' at Nebest I was instantly sold.

First of all, I would like to the thank thesis committee for their experience, helpful advice, criticism and above all their enthusiasm. Where I sometimes considered you as my enemies, you were in fact my allies during this research. At first, I would like to thank Henk Jonkers, for not only being the chair of the committee but also for your calmness, understanding and practical suggestions. Furthermore, I would like to thank Sander Pasterkamp for his open mind, thinking in solutions instead of problems and ideas, which really helped me throughout my research period. I would also like to thank Yuguang Yang. Your knowledge and criticism always tried to make me think one step ahead. Last, but definitely not least, the committee member I want to extend my gratitude to is Wouter van den Berg. You introduced me first to Closing the Loop and stood by my side during the full thesis period. Your enthusiasm, positivity, critical view, strong feedback but above all your patience really helped me to finish this thesis.

Furthermore, I would like to thank my family and friends, and some people in particular. Starting with my parents Bob and Karin. Without you I would never have been able to even start this whole student journey. Because of you I can wear the title of Civil Engineer proudly. Next, I would like to thank my girlfriend, Maegan, for always standing by my side, staying positive and helping me with the most you can. I also want to thank the other graduates at Nebest Thijs, Jens, Thieme and Andries for their laughs and anticipation during the past year. Furthermore, I want to thank my little sisters. At first, Laetitia, for her experience in the English language and providing advice and suggestions regarding my report. Second, Eline, for her help with creating the layout of my thesis.

Second to last, I really want to thank all the different companies for their collaboration and help during my research. Their generosity of sharing knowledge and benevolence of creating available time was really pleasant to experience. With special thanks to Hendrik Herder, from Haitsma Beton, for sharing knowledge, documents and providing a tour around the concrete factory.

Finally, I want to express my appreciation to every other who helped me to stay focused, motivated and helped taking my mind of my thesis from time to time.

I hope you will enjoy reading my thesis,

J.S.A. (Joost) Brouwer
Rotterdam, June 2022

Abstract

We are currently facing a transition of economy. Previous years were focused on a linear economy, consisting of the make-waste concept. The products that are made with raw materials are thrown away after its use. Unfortunately, the Earth does not contain an unlimited source of materials and we need to focus on reusing materials. Concluding to create a circular economy in which waste does not exist at all. To be able to reach this goal, climate agreements have been signed to reach for the transition into a circular economy. RWS took the exemplary role and wants to be fully circular- and energy neutral by 2030. Therefore, an SBIR: Circular Viaducts is launched in which the consortium 'Closing the Loop' created the idea of developing a new viaduct with harvested elements from other viaducts. Researches show that currently more than 70% of the bridges and viaducts are demolished before the end of the lifetime, which means that the different elements are still in fine shape. From a first research the scope of the research is demarcated from 200.000 structures into a variety of 1500 concrete girder viaducts. The obstacles for reuse can be summarized into four main categories: *Lack of knowledge, lack of data, unequal balance* and *no application methods*. With these obstacles in mind, the aim of this research is noted as to *Contribute to the transition into a circular economy through the stimulation of a new way of thinking by determining and classifying a range of applications of current existing girders within a valuable scope in the acreage of RWS*.

The goal is to start with reusing as of today, instead of in the future. In other words, using the current existing elements. However, to do so it must be known which elements are available. Therefore, a data analysis has been done on the current existing structures as well as the future perspective. These analyses combined concluded in a common scope, visualized as a Lego box. This Lego box does not only consist of all the current existing structures (within the determined scope), but also provides a future perspective on the demolishing plans in the near future. With this determined Lego box, the Lego blocks can be specified. Based on a time-consuming manual research a variety of nearly 70 viaducts have been examined. This lead to the summarization of 5 different girder categories: *Box girders, inverted T-girders, Infilled girders, T-girders and remaining*. As a result of a further in-depth study on these girders, are specified into different variants. Based on future applicability, potential reuse, amount of impact and future estimated quantities 5 different variants have been determined: *HNP 75/98; ZIP 700; T-girder; SDK 900* and *SKK 1300*.

With the specific girders known, design applications can be created. The focus on these applications is to think outside the box and reusing a girder in a different function than the original purpose. To be able to compare the way of reusing, a first indication is created on reusing a girder in the same purpose. To create this indication an assessment is done based on three main criteria: *Structural, Environmental* and *Economic*. These criteria act as a red thread throughout the research. This first indication has created positive outcomes regarding the environmental and economic aspects. With this in mind the design applications are created with a brainstorm session. For this session multiple different broad-minded individuals had been invited for an open discussion which concluded in over 20 different design applications. Thereafter, these applications have been examined with the help of an MCDA, based on the three main criteria. This MCDA is executed with the help of multiple different experts with a background regarding one of the three main criteria. With these expert judgements the total amount of design applications has been demarcated to a top 5. Reusing a girder as: *Bicycle bridges, (non-)residential buildings, retaining walls, sound barriers* and *culverts*. With a more detailed elaboration on top of the expert judgement, the final application is chosen to be the reusing of a box-girder into a culvert.

The last research method resulted in a more in-depth elaboration of the application of reusing a box-girder as a culvert. To be able to make a substantiated comparison, firstly a study has been done on creating a culvert concerning BAU. The dimensions and applications of the culvert are based on

common sizes, which are also available in the determined Lego box, combined with different assumptions. Comparing the BAU with the reused box girder led to multiple interesting aspects. It is noted that a big improvement can be made regarding the environmental as well as the economic impact. From the environmental impact it can be concluded that the highest costs are made during the manufacturing phase. With reusing this phase can be removed from the overview, since elements are already existing. This removal creates a big influence, based on the first impressions. The environmental impact can therefore be lowered by a factor of 2, where the realization costs can be lowered by a factor 9. Furthermore, the culvert application is compared to reusing in the same function. Both score an equal saving in shadow costs (determined by the environmental aspects), but the culvert design application creates a larger saving of costs. However, the structural aspect of reusing in the same function will result in less uncertainties and a smaller chance of over dimensioning.

In conclusion, the first impressions regarding reuse in another application seem at least interesting. With the different impact factors determined, the possibility looks very promising. It can be stated that reusing in general will be better for the environment, as well as for your own wallet. Reusing a girder as culvert can in theory be seen as a good reuse application, but not higher in a general value than reusing again as a girder. This is based due to the fact that using the girder as a culvert will take more research in practice, especially regarding structural aspects. However, from this thesis it the first impression conclude in the fact that the impact in costs as well as environmental impacts are bigger when reusing the girder in another function. However, it must be noted that the impact factors are determined theoretically and further specific researches are required. This followed into multiple recommendations for different involved companies and other researchers. These recommendations vary from additional structural assessments with software programs and using different pilots, until creating awareness and using the provided data analysis.

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List of abbreviations

Term	**Meaning**
CE	Circular economy
CO₂	Carbon dioxide
RWS	Rijkswaterstaat
SBIR	Strategic business innovation research
CB'23	Open platform to establish agreements for circular constructing in 2023
CTL	Closing the Loop
SMART	Specific measurable assignable realistic and time-related
CRIAM	Constructief risico indexering afwegings model
EDMS	Engineering documentation management systems
DISK	Data informatie systeem kunstwerken
VenR	Vervanging en renovatie
MIRT	Meerjarenprogramma infrastructuur ruimte en transport
RBK	Richtlijnen beoordeling kunstwerken
ROK	Richtlijnen ontwerp kunstwerken
LCA	Life cycle assessment
ECI	Environmental cost indicator
BAU	Building as usual
MCDA	Multiple criteria design analysis
EPB	Environmental performance buildings
MYPR	Multi-Year program sound remediation
NED	National environmental database

Glossary

Term	**Definition**
Greenwashing	The process of conveying a false impression or providing misleading information about how a company's products are more environmentally sound
Circular economy	An economy which is keeping materials and resources in use and retaining their value, rather than consuming and disposing of them
High value reusability	The process to convert secondary raw materials (either with recycling or reusing) into new materials, components or products with at least the same, but preferred better quality, functionality and/ or higher value
Technical demolition	When the design life is reached, the structure will be demolished based on his structural lifetime
Functional demolition	When the design life time isn’t reach and the structure is demolished based on functional aspects like railroad construction and improving traffic flow
Closing the Loop	A consortium of Nebest, Antea Group, Strukton Civiel, GBN group and multiple knowledge institutions, which aims to close the lifetime loop by focusing on high quality reuse of viaduct elements
Element & Component (Element & Bouwdeel)	An element (*Element*) is a part which fulfills a function (for example: a load bearing structure). A component (*Bouwdeel*) is a part which is physically available (for example: a girder)
Girder vs. Beam	A girder is a primary beam. Its main job is to transfer loads to the columns upon which it rests. A beam is a secondary beam. Its main job is to transfer its loads to girders, which then transfer the load to the columns. If its function is to transfer load to a larger beam, it’s just a beam. If it’s to transfer load directly to the columns it sits upon, it’s a girder (Swanton welding company, 2017)
Reuse	Using a product again. The focus is on the product
Recycling	The processing of a product (or its waste) into reusable material. The focus is on the material
Design application	A possible purpose to reuse a specific element in a way other than its original function
Cradle to grave	Raw material extraction up to waste processing
Cradle to gate	Raw material extraction to manufacturing product
Cradle to cradle	Closed loop recycling

Chapter 1. Research Framework

1 Introduction

These days words like *circularity, sustainability, recycling, reusing* and many more are very trendy. These terms appear a lot in combination with the phenomenon *Greenwashing*. On one had it translates to companies claiming to be sustainable and state that they care about the environment. This gives them a better image and places the company higher on the market. However, on the other hand, their actions do not correspond to their promises. Being circular is more than just a slogan on a market campaign.

Circularity is about reusing instead of wasting. The last century the demand of raw materials has been increased a lot in combination with an improved development. However, this demand will only increase more due to a growing world population and an improving consumption (Rijkswaterstaat, n.d.-e). Where this demand increases, the manufacturing of the raw materials causes an increase of the carbon dioxide (CO_2) emissions with its corresponding climate change effects. Therefore, this economy with a high raw material demand needs to decrease. Or in other words, transition into a Circular economy (CE) is needed. This CE is an economy which is keeping materials and resources in use and retaining their value, rather than consuming and disposing of them (Cheshire, 2016). As mentioned before, it has received an increasing attention worldwide due to the depletion of finite raw materials caused by the current production and consumption model (Ghisellini, Cialani, & Ulgiati, 2015). This circular economy is analyzed further in the next section (Transition to a circular economy).

We, as a society, need to work together to take care of our planet and being able to complete the transition to a CE. This path to a CE and its additional culture change isn't a straight line but requires research. This thesis aims to contribute to this transition by setting in motion a creative process of thinking with using current existing elements. Besides, with focusing on being circular as of today instead of in the future, the first steps are made.

2 Background

2.1 Transition to a circular economy

For a long time the Dutch economy has been a linear economy. A linear economy can be described as an economy which is obtaining raw materials for creating a new product and throwing away the waste after its use (Government, sd). This waste management is elaborated further in Appendix A: Waste management. The origin of thinking regarding circular is owed to Ad Lansink. He created a ladder, based on waste management, to differentiate the way of reusing materials. Using this ladder as a base, a 10R-model is created which showed that the focus on recycling and recovering must be extended. This is elaborated and substantiated further in Appendix A: The main goals within the CE are to not only avoid the waste production, but also to limit the (raw-)material usage (CB'23, 2019). The aim is to reach for *high value reusability*. Or in other words:

High value reusability: The process to convert secondary raw materials (either with recycling or reusing) into new materials, components or products with at least the same, but preferred better quality, functionality and/ or higher value[1]
(CB'23, 2022)

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[1] In this definition the term 'value' leaves an open definition. This will be elaborated later on during this research

Currently the transition into a CE is ongoing, which means the reuse economy is the current state of the economy. Meaning that some of the used products will be recycled. However, the goal is to reach the transition to a CE, where waste doesn't exist at all. These different economies are visualized in Figure 1. Currently the world faces multiple global challenges like waste, pollution and climate change. With the transition to a CE these challenges can be tackled (The Ellen MacArthur Foundation, 2015).

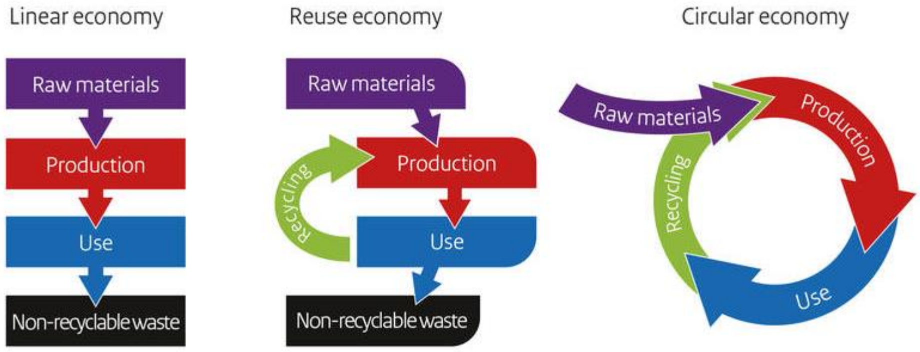


Figure 1 Linear-, reuse- and a circular economy (Government, sd)

According to the council for the environment and infrastructure in the Netherlands, the transition to a CE needs to be done for three reasons. The first one is tackling of the overconsumption of raw material and its following waste caused by human overexploitation and/or mismanagement of critical natural resources. Considering the Netherlands, they are highly dependent on the import of raw materials. About 68% of the raw materials usage is imported from abroad. Moreover, the whole of Europe imports about 90% of its most critical materials from outside the continent (Council for the environment and infrastructure, 2015). This dependency makes Europe vulnerable. Since there is no certainty of the provision and the prices of the materials, it leads to fluctuations in resource prices and even the security of supply. Scarcity of the materials have caused and still increase in prices, which have been doubled since 2000. The current situation between Russia and Ukraine is an example of this. Next to the scarcity of raw materials, the current economy affects the earning capacity of the Netherlands. A smarter reuse of materials can lead to a strengthened earning capacity due to cost savings, innovations and new earning opportunities. The last reason for the transition to a CE is about the growing global demand for resources and the (still) increasing environmental impact due to the expanding world population. This environmental impact is currently already exceeding the sustainability limits of the earth. Therefore, alternatives for resource have to be considered to be able to strengthen the economy. The need for a transition to CE can be summarized in three main topics: Environmental impact (exceeding the sustainability limits of the earth), Economic impact (dependency of other continents) and Structural impact (smarter reuse of materials). These topics will therefore act as a red thread to this research.

2.2 Demolition causes

Going back into 2016 the Dutch government signed, on behalf of the 28 states of the European Union, a new United Nations climate agreement in Paris. This agreement started from the year 2020 on and aims to limit the temperature rise well below 2.0 degrees Celsius and with a clear view on 1.5 degrees Celsius (Rijkswaterstaat, n.d.-a.). The European Union has this goal more specified and aims to reduce the CO_2 emissions by 40%. The Netherlands even levels up their game and stated to have, compared to 1990, a 49% less CO_2 emission in 2030 and a 95% less CO_2 emission in 2050 (RVO, 2018). To be able to reach this goal, a raw materials agreement has been signed in the year 2018. This agreement describes how to run the Dutch economy on reusable materials. To quote (translated from Dutch) the former state secretary Dijksma: "We need to get rid of the 'throw-away-culture' and start thinking from the design on, how to reuse the materials" (Vellinga, n.d.). An overview of the different agreements is shown in Table 1. The raw materials agreement is split up into five different sectors:

biomass, plastics, manufacturing, construction and *consumer goods*. When focusing on the construction sector, it is visible that this sector uses about 50% of the total amount of raw material usage in the Netherlands. Above all, the biggest amount of waste in the construction sector is the demolition waste (Rijksoverheid, n.d.-a)

This demolition waste is especially noticeable at civil engineering (nonbuilding) structures (or: Infrastructure works) like concrete viaducts and bridges. For these structures the design lifetime is approximately 100 years. This is purely theoretical and can be reached when aspects such as load, maintenance and other circumstances all go as foreseen. When the design life is reached in this way, the structure will be demolished based on his structural lifetime. This is regarded as *technical demolition*. Next to that, if a structure is demolished because of the high maintenance load or when the structure is unable to withstand the required demands (e.g., change of standards) it is also regarded as *technical demolition* (Nooij, 2016). However, in practice it turned out that this structural lifetime is almost never reached and the technical demolition barely takes place. In turns out that about 70% of the demolished viaducts were far from their end of the structural lifetime and were demolished for functional aspects (Nicolai, 2019). This is regarded as *functional demolition* The two main categories of functional demolition are railroad construction and improving the traffic flow (e.g., adding an extra lane). An overview of the comparison between functional- (top chart) and technical demolition (bottom chart) is shown in Figure 2.

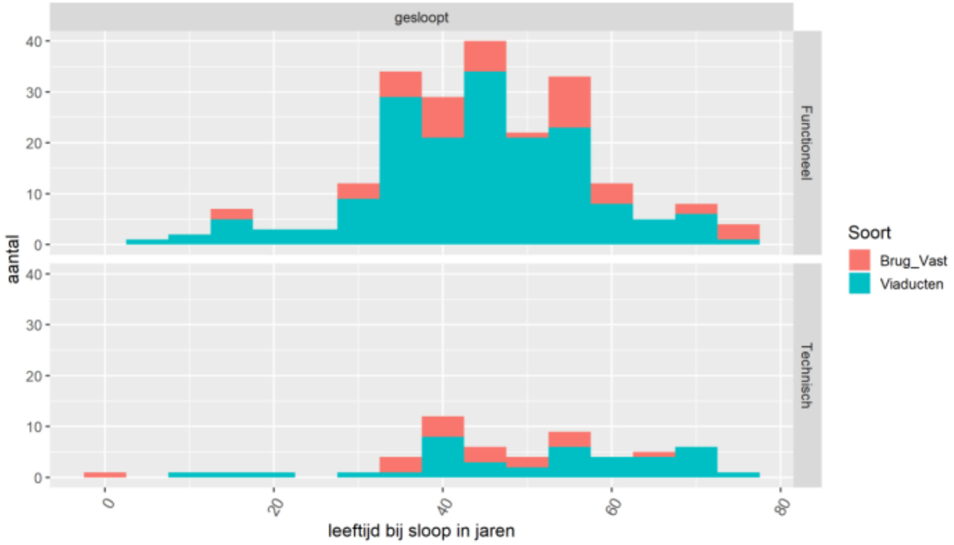


Figure 2 Age of demolished bridges and viaducts, split in functional- (top) and technical (bottom) demolition (Nicolai, 2019)

2.3 Starting with a strategic business innovation research

Rijkswaterstaat (RWS) is the implementing organization of the Ministry of Infrastructure and Water management in the Netherlands. They focus on keeping the country safe, livable, but most important for this report, accessible. RWS is responsible for all the national roads through the country. To fulfil the task regarding accessibility, it is important to provide an optimal performance for the road network as well as for the water ways (Rijkswaterstaat, n.d.-c).

RWS took the exemplary role in the Netherlands and wants to be already circular- and energy neutral by 2030 instead of 2050. From 2030 on, the Dutch government aims to only tender on circular base to prevent overload of the earth and to use resources in a better, more clever and more economical way (Rijksoverheid, n.d.-d). An overview of the different agreements together with the previous mentioned ones are shown in Table 1.

Table 1 Climate agreements demarcated from worldwide to RWS (Rijksoverheid, n.d.-d; Rijksoverheid, n.d.-a; Rijkswaterstaat, n.d.-a.)

Year	Parties involved	What	Goal
2016	United nations	Climate agreement in Paris	Limit the temperature rise well below 2.0 degrees Celsius and with a clear view on 1.5 degrees Celsius from 2020 on
2016	European states	Climate plans	Reduce the CO_2 emissions by 40%
2018	The Netherlands	Raw materials agreement	Compared to 1990: 49% less CO_2 emission in 2030 95% less CO_2 emission in 2050
2018	Rijkswaterstaat (RWS)	Exemplary role	Circular- and energy neutral in 2030

Together with the construction industry, the government created in 2018 an open platform Circular Constructing in 2023 (*in short: CB'23)*. This platform aims to establish nationally, sector wide agreements in 2023 which consists of a common definition framework, clear agreements and measuring methods, focusing on protecting the three main aspects: environment, the material supplies and the current value (CB'23, 2020 - b). The principle of this platform is to have a transparent work frame with all the different parties.

However, since there are not yet standard solutions or working methods for these three aspects, a Strategic Business Innovation Research (SBIR) was launched in February 2020. A SBIR is a method which finances, and thus stimulates, the development paths of innovations. This particular SBIR: CiVi focusses on circular viaducts. At the start 32 contestants were interested in this SBIR and submitted their plan regarding circular product innovations. After a quick selection, of a so called SBIR Team (which is an independent committee), only 10 contestants were able to enter the first phase. Phase 1 is about a feasibility assessment in which the possibility of the plan is elaborated. In January 2021 the first phase of the SBIR is completed and only 3 contestants were remaining for the second phase. Phase 2 is about developing, testing and validating a prototype. Where one of the researches is about modularity, the other two projects are about reusability. One of those 2 reusability projects is Closing the loop (Rijksoverheid, n.d.-c).

2.4 Closing the loop

Nebest B.V. participates together with Antea Group, Strukton Civiel, GBN group and multiple knowledge institutes in the consortium Closing the Loop (CTL). This Consortium aims to close the lifetime loop by focusing on high quality reuse of viaduct elements. The circle applies to the whole lifecycle of a viaduct. From designing to constructing and finishing it off with reusing. This closing of the loop implies not constructing or designing new elements to be circular in the future but focusing on reusing old elements into a new purpose and thus being circular as of today. In Figure 3 the chart of CTL is shown with its five different phases and as for visualization of these phases, Lego blocks are used. Starting from the top and going clockwise, the different phases are: *Acreage knowledge, Reusability scan, Design concept, Construction* and *Reusability*. Each of these phases is further elaborated in Appendix B: Closing the loop (van den Berg, 2021). Within the consortium CTL the reusability scan (*in Dutch: Herbruikbaarheidsscan*) is created in phase 1 of the SBIR. This scan is an inspection tool to determine a degree of reusability for viaducts by using the 10R-model (Appendix A: Waste management). Based on a longlist of CB'23, three main categories are composed: residual lifetime, demount ability and constructive properties. With these categories not only an assessment is done for the reusability of different elements of a structure but also an elaborated data base is created (Span & ter Meulen, 2021).

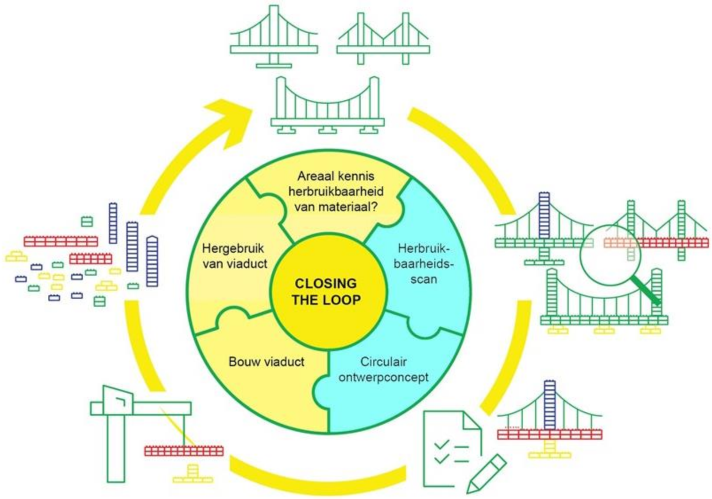


Figure 3 Closing the loop with its 5 different phases (van den Berg, 2021)

2.5 Scope

Throughout the whole country, more than 200.000 infrastructure works are present (Bloksma & Westenberg, 2021). This varies from the biggest bridge, the van Brienenoord bridge in Rotterdam, up to a small culvert underneath a local road. These structures are mostly built between the 1960s and 1980s. With a design lifecycle of about 80 years, the Netherlands is facing a great maintenance/ replacement project in the period of 2025-2050 (See Appendix C: Scope of the research for an elaboration of this scope). Since the reuse economy is currently present and it is impossible to do everything at once, a scope needs to be defined. This scope will provide a valuable playing field which can lead to the most impact on circularity. This playing field will be examined in a later stage in this research. An overview of the demarcation of the infrastructure works is shown in Table 2, which is determined in Appendix C: Scope of the research.

Table 2 Number of structures divided per scale (Bloksma & Westenberg, 2021; Bleijenberg, 2021)

Scale	Amount
Infrastructure works in the Netherlands	213.395
Bridges/Viaducts (Fixed/Movable & Concrete/steel) in the Netherlands	84.573
Infrastructure works in the acreage of RWS	6.237
Viaducts in the acreage of RWS	3.119
Concrete viaducts in the acreage of RWS (which are in use)	3.026

However, 3000 viaducts is still too much to be able to analyze within a single research. Therefore, the viaducts will be separated into smaller pieces. CTL shows that each structure can be seen as a Lego structure, with different types of Lego blocks. However, these blocks need to be defined. With this knowledge a virtual viaduct can be created with the most occurring elements and dimensions to be able to make the biggest impact, without taking everything into account at once.

2.5.1. Construction layers

In contradiction to consumer goods, the infrastructure works and (non-) residential buildings have a way higher residual life time. However, this residual lifetime doesn't really imply to the total construction but must be divided into different components. This way the constructions will last the longest (RVO, 2018; Smit, n.d.)

The division of a building is based on a concept created by Frank Duffy and developed by Stewart Brand (Smit, n.d.). His believe was that there isn't any such thing as a building. A building properly designed consists of several layers built components with different lifecycles (Brand, 1994). Based on this lifecycle aspect he created the layers Site, Structure, Skin, Services, Space plan and Stuff, ordered from longest to shortest lifecycle. The layers are visualized Figure 4. Using this way of thinking and understanding the logic behind it is key for substantiated choices of circular design (Brand, 1994). The idea behind the layers was that no single layer should affect another layer in case of replacement, maintenance or refurbishment. However, in practice, components with a shorter lifecycle are often integrated into the load bearing structure. When these layers are either demolished or altered, they can cause damage to the structure and unfortunately, decreasing its lifecycle.

This shearing layers concept, or so-called theory of layers, can be adapted into the infrastructure works sector. In Figure 5 the layers Site, Surrounding, Skin, Structure, Space plan, Stuff and Social are visible (CB'23, 2020 - b). It is noticeable that there are two layers added, based on a research of Robert Schmidt III (CB'23, 2020 - b). This comparison between the layers is visible in the Table 3.

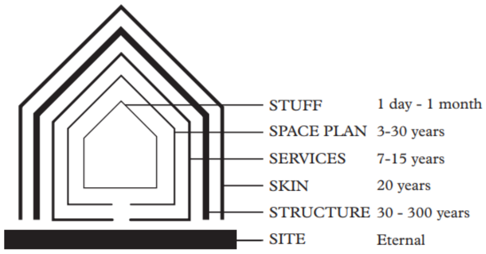


Figure 4 Shearing layers (Brand, 1994)

Figure 5 Shearing layers for infrastructure works (CB'23, 2020 - b)

Table 3 Shearing layers highlighted (Brand, 1994; CB'23, 2020 - b; Smit, n.d.)

Layer	Definition Buildings	Definition Infrastructure works
Social	-	Users, traffic
Stuff	Furniture, random 'stuff'	Surrounding 'stuff' like traffic signs
Space plan	Interior layout like walls and floors	Layout of public space like roads and squares
Services	Installations like air conditioning and elevators	Technical installations like pumps and pipes
Skin	Façade and roof	Top layer, traffic barrier
Structure	Foundation and load bearing structure	Foundation and load bearing structure
Surroundings	-	Ecosystem
Site	Geographical setting of the building	Geographical setting of the building

2.5.2. Decomposition of a viaduct

An application of this theory of layers is visible in a physical decomposition, standardized by the Dutch standard NEN 2767. This standard is mainly focused on a specified condition measurement to inventory the current situation of different elements (NEN 2767, 2017). However, to inventory this, the elements need to be specified at first. This is called a decomposition and in the previously mentioned standard it describes how to subdivide the infrastructure works into 'smaller' elements (Dieleman & Bakker , 2016). In this standard a distinction is made regarding the different parts of a structure. In Dutch these different parts are called: *Element* and *Bouwdeel*. However, both parts translate to 'element' in the English vocabulary. Since this is vague and causing problems in explaining, some clarification is required and thus coming to the following. A structure contains multiple parts which fulfill a function (*Element*). These functional parts are then subdivided into parts which are physical available (*Bouwdeel*). A clarification example is a main load bearing structure (fulfills a function), which is subdivided into girders (physically available). For the ease of the further report, *Element* and *Bouwdeel* are translated into respectively Element and Component. Based on the graph in Appendix D: DISK Graphs, the most common elements that occur on concrete viaducts are shown in Figure 6.

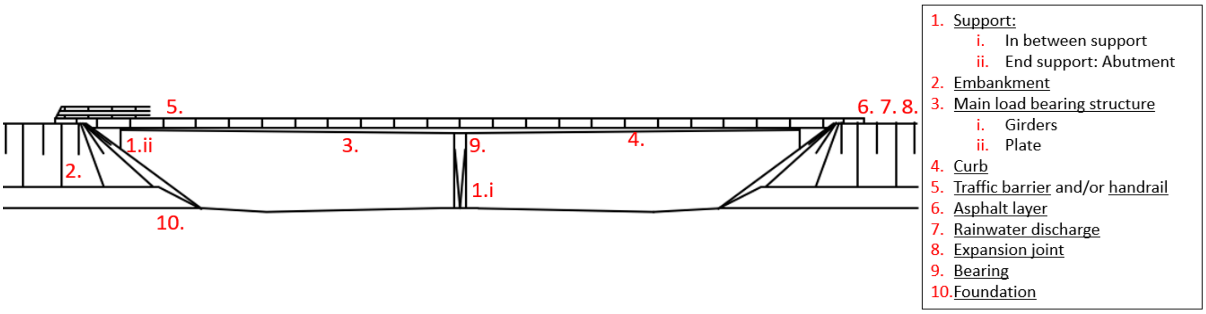


Figure 6 Decomposition of a viaduct, with the top 10 most common elements

Going deeper into detail, every element has its own component(s), which is elaborated in Appendix C: C.2 Concrete viaducts. These elements can be schematized according to Brand, which is shown in the Table 4. From this table it is visible that elements 1, 3 and 10 are interesting from a constructive way of reuse. Next to that, these elements consist of concrete. Research shows that on average 85% of viaducts consists of concrete (Arnoldussen, et al., 2022), which makes it the most interesting to focus further on concrete to make the biggest impact. From experience in the field and from meetings with experts it turns out that supports are in the first place hard to inventory. They are very unique and project specific, which makes it difficult to generalize. Next to that the support are in most cases constructed with in-situ concrete combined with a lot of steel and poured into the foundation. This makes it hard to demount and therefore reuse them (Vergoossen, 2021). This unique specification is also visible for the next element: foundation. This is custom made for every viaduct (Vergoossen, 2021). Next to that, removing the foundation will cause negative influence on the strength of the soil. This leaves only one element left, the main load bearing structure. Therefore, the viaducts in the acreage of RWS are filtered upon main load bearing construction type, which is shown in Figure 7. The most common types are concrete decks and girders and appear each in almost 50% of the cases. It must be noted that this information is obtained from DISK (See paragraph 4.1.3 Data system 3: DISK). However, this is never meant to be as a data system. During the years a lot of notation rules have changed. For example, a box girder is sometimes denoted in different components: wall, roof and floor instead of just longitudinal girder. Since girders have the advantage (compared to deck structures) to be not only precast and therefore easier to demount, but also are they already designed for transport. Next to that, girder already have preload and therefore won't crack when they are demounted (Vergoossen, 2021). In conclusion, this research will focus on the reusability of concrete girders.

Table 4 Graph of the different types of viaducts in the Netherlands

Layer	Definition Infrastructure works	Elements
Social	Users, traffic	-
Stuff	Surrounding 'stuff' like traffic signs	-
Space plan	Layout of public space like streets and squares	-
Services	Technical installations like pumps and pipes	7
Skin	Top layer, traffic barrier	4; 5; 6; 8;9
Structure	Foundation and load bearing structure	1; 3; 10
Surroundings	Ecosystem	-
Site	Geographical setting of the building	2

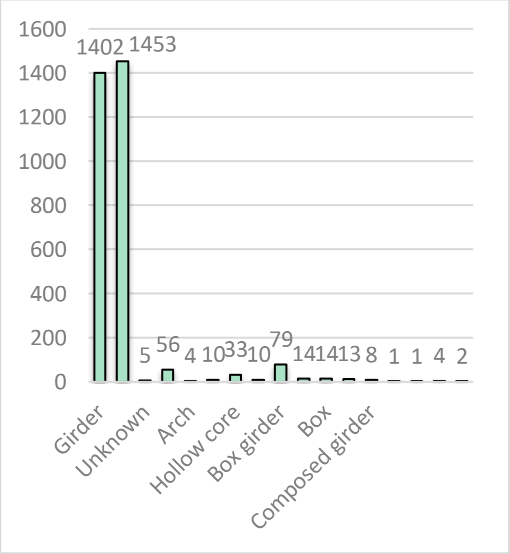


Figure 7 Different viaduct types

2.6 Problem statement

Waste as we know it today in the current economy is based on the so-called take-make-waste concept, described by Braungart & McDonough (EPEA, 2021). Not only in the Netherlands, but in most of the countries worldwide. Materials are obtained, manufactured for usage and in the end disposed as waste. The transition into a circular economy is receiving more attention over the past years but is still in the early stages of the development. Regardless the fact that recycling is mostly seen as downgrading due to the loss of quality (Luscuere & van Veen, 2018), the main focus is still on recycling rather than reusing (Ghisellini, Cialani, & Ulgiati, 2015). The problem statement is summarized and schematized in Figure 8. It all starts with the goals of circularity. However, these goals face obstacles due to the lack of multiple elements.

At first there is insufficient knowledge about how to reach this CE. Especially with respect to the feasibility and the profitability for reusability of civil engineering structures in the infrastructure (Keemers & Looije, 2021). Circularity nowadays is compared to buying a secondhand car with a lot of flaws, concluding into a higher price tag in the end. It is not (yet) attractive to buy a secondhand product. Next to that, reusability has not been done a lot yet, due to the lack of standards. Reusability is new and the standards only make a distinction between existing structure and new structures. Not reused structures. This causes a lack of trust in reused elements. Despite the fact that from the feasibility researches regarding the SBIR it is proven that reusability is indeed possible (van Eck, 2021; van den Berg, 2021).

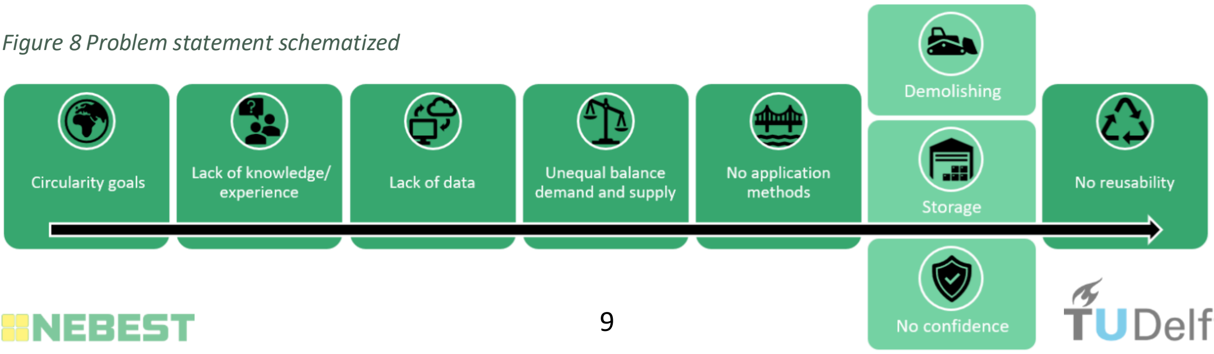
The next obstacle is the lack of data. During the construction peak (1960-1980) all the data was stored manual. Only since a few years, Dutch authorities (e.g. municipalities, provinces, RWS) are obliged to register their assets. Within the development of the reusability scan, as described in Appendix B.2 The reusability scan, the first steps into the gathering of data is made. With obtaining detailed information per structure a basis can be formed and reusability possibilities can be visualized up front.

The third obstacle is the unequal balance between demand and supply. When it occurs that reused elements are required for structural use, the possibility of harvesting another structure at that same time is very small.

The fourth and last obstacle is the lack of application methods. There are not yet ideas, applications or possibilities on how to reuse element in a new life cycle. This is also visible in the CTL (Figure 3), since there is a missing link into the design phase. At the moment the reusability scan only gives an indication about the current state of the elements, but doesn't give design possibilities for future usage

All the obstacles combined causes the fact that reusability is not applied, never mind on a large scale. In the first place, the unnecessary functional demolishing (Figure 2) takes away the possibility of reuse. There is no confidence in reusing. Structurally as well as economical. Might it be the case that elements are indeed demounted, the chance of being able to reuse it is small. Due to the unequal balance and the lack of application methods, this causes a big storage of elements. A cultural change isn't done in a blink of an eye of course. It takes years to develop, implement and as last maintaining a new way of living. However, the goal is to be circular as of today instead of in the future. So, to pretend a big storage of materials due to the waiting for the right reuse possibility, a new way of thinking and therefore reusing needs to be determined. Reusing must become interesting and attractive.

Figure 8 Problem statement schematized



3 Research approach

This research is done on behalf of the Delft University of Technology and Nebest B.V. Nebest is an independent engineering-/consultancy firm, specialized in inspection, technical advice and project management. Not only in terms of civil-, mechanical and electrical engineering but also on architectural projects (Nebest, n.d.). The approach of this thesis is described in this section, divided into multiple sections.

3.1 Research aim

This research aims to contribute to the transition to a circular economy as well as closing the reusability loop by providing design applications for the harvested girders of the (to be) demolished concrete viaducts. An important aspect in this is the difference between demolishing and harvesting. The first step into this CE is to make use of the current existing structures with a high amount of demolition waste and focus on reusing rather than recycling. Due to different specifications, not every reused girder can be applied immediately, causing waste flows. The chart, which is shown in Figure 3 on page 6, shows multiple phases of the lifecycle of a viaduct. Each different phase has multiple subtasks which needs development for a CE. However, this research will focus on the possibilities of the harvested girders and aims to create a bridge between the reusability scan and the design phase. This corresponds to the two phases that are highlighted in blue in this aforementioned chart. To visualize the whole process, the viaducts can be seen as structures built from Lego blocks.

To start with the transition into the CE, a higher demand as well as supply needs to be created for reusability. This will contribute to the prevention of the waste flows. The balance between supply and demand needs to be equal. The goal of this research is to create the demand, by analyzing the supply. This supply will be created by not only looking into the current available structures, but also by analyzing the future release of elements when structures will be demolished or amended. The first steps into combining supply and demand has been done by Nebest, by creating a 'wip' (seesaw), as shown in Appendix B: B.3 The seesaw (*wip*) of Nebest. The goal is to balance this seesaw and creating a match between the harvested elements and the construction phase. With combining the past and the present an interesting inventory of concrete girders applicability in the future can be realized. Meaning that not only the contractor will get new ideas or inspiration about building a new viaduct, but it also makes architects think twice about their project and makes them contribute to the CE. This is currently not the case, since designers only design with new materials. On top of that the goal is to create awareness as well as trust in reusability by providing multiple design applications. With a bigger variety of options, the chance of reusing increases and therefore creates more attractiveness in the harvesting of elements. This research aims to define the value of reusing of different design applications in comparison with building as usual. Providing the first steps into changing the mindset and thinking about designing circular viaducts, will be the start of closing the circular loop. The main research aim will therefore be as follows:

Contribute to the transition into a circular economy through the stimulation of a new way of thinking by determining and classifying a range of applications of current existing girders within a valuable scope in the acreage of RWS

3.2 Research scope

To prevent of not seeing the wood for the trees and it being impossible to solve all related problems, the scope of the research contains the following aspects:

- The reusability scan is already developed by Nebest B.V. and thus won't be optimized;
- The research focusses on concrete viaduct girders within the acreage of RWS;

- It is assumed that the to be harvested girders are qualified in the reusability scan and in a good state for reuse.

3.3 Research questions and methods

3.3.1. Main question

The research aim leads to the following main question of this research:

> *How can a range of applications for reuse be classified for existing concrete viaduct girders from a valuable scope in the acreage of RWS?*

Since this research can't be answered at once, it is split into multiple sub-questions, corresponding to the in blue highlighted words in the main question.

3.3.2. Sub-questions

To be able to answer the previously formulated research question, this research is divided into three chapters: *Research framework*; *Research methods* and *Results and final remarks*. Each of these chapters has its own sub-question to form a base for the main research question. The elaborated questions correspond to the different sections in the chapters. These chapters with its sub-questions and methodologies are elaborated in this paragraph.

3.3.2.1 *Chapter 1: Research framework*

The research framework is not particularly to answer the main question. In this chapter the background study and the current state of the art is provided to point out the problem statement as well as the motive to do this research and write this thesis. This chapter is based on own practical experience within the company Nebest, multiple talks with experts within the consortium CTL as well as colleagues from Nebest. To ensure that the data is valid, contacts have been made with a data analyst from RWS. When the first problems and orientations were done a literature study has been performed to provide a theoretical foundation for the scope as well as the first gathering of information. This chapter is therefore in absence of research questions.

3.3.2.2 *Chapter 2: Research methods*

This chapter includes the different research methods. Each of them is done in another way. Therefore, this chapter is divided into four different phases acting in a chronological order and corresponding to the different sections. Each of these phases contain their own main sub-question to guide the research and will together act as a red thread further on the research. The thought behind and the elaboration of the research questions is further done in the specific sections.

Phase 1: Creating a Lego box

In the first section of this research, a visualization is done with the help of Lego blocks. Meaning that different infrastructure works can be seen as built op Lego models, consisting of different Lego blocks. This research further on focusses on reusability. But to reuse, you need elements that are already exist. Thinking of the visualization of the Lego blocks, the childhood memories came up. A little kid sitting down next to a big plastic container and digging though it for different Lego blocks to create something. This childhood memory is converted into the visualization of a Lego box for the inventory of the different elements. The goal of this research phase is creating this big plastic container, or in other words creating a Lego box of valuable elements.

Phase 1 is therefore an expansion of the previous determined scope. In the research framework the scope was determined to concrete girders. However, before going further into detail of these girders, the original application needs to be known. Which are the viaducts where these girders are harvested from. In other words, the goal is to create a Lego box in which the Lego blocks (elements) can be taken from. This goal is achieved by analyzing multiple data systems to act as a substantiation of the valuable scope. The goal of this valuable scope is to be applicable to as many structures or projects as possible. By inventorying the data based on most common, and most interesting elements the biggest impact can be made. This all comes together in the following research questions.

1. How is the Lego box formed?
    a. Which data systems are available to shape the Lego box?
    b. What is known in the current existing acreage?
    c. What is known from the future plans?

Phase 2: Viaduct girders

Where in Phase 1 the valuable scope is created with different aspects, this phase gets deeper into the future plans to determine the actual scope of future available girders. These girders will then be available for the next phase of this research. By combining an extensive literature study with acquired data, different girders have been inventoried. Following into the determination of the concrete viaduct girders. This and the previous phase combined therefore creates the ability to give an academic substantiated conclusion in the end of the research. The research questions of this phase are as follows:

2. Which girders are going to be used for the design applications?
    a. Which girders are available in the near future?
    b. Which design aspects influence the structural behavior?
    c. Which standard can be created?

Phase 3: Design applications

Phase 3 is split into five different paragraphs, corresponding to the sub-questions, to create the range of applications. The first paragraph is to form a base of the to acquire design applications by determining the assessment. The assessment methods are developed for a following phase of the research to determine the final application. The second phase consists of the organization of a brainstorm session. In this session a group of people is selected based on a broad mindset and with interest in circularity and innovations to come up with different design applications. In the fourth paragraph the design applications are assessed with the help of expert judgements to come up with a top 5 of design application. These five applications are then narrowed down into one final application, which will be elaborated further in phase 4.

3. What are the possible design applications for reused concrete girders?
    a. What are the assessment topics of design applications?
    b. What are the differences between a new and a reused girder?
    c. Which design applications can be thought of?
    d. What is the top 5 design applications?
    e. Which design application is most likely to be possible?

Phase 4: Elaboration of the design application

Phase 4 is about classifying the final determined design application from the previous phase. With the help of multiple experts of the different main categories, as well as the information gathered from previous sections the final design application can be classified. With this classification it is possible to look into the value of reusability.

4. Is the determined design application actually doable?
    a. Is it profitable based on environmental aspects?

b. Is it structurally achievable?
c. What are the total costs?
d. How is this application in comparison to a new element?
e. How is this application in comparison to reusing in the same function?
f. Is it considered high value reuse?

3.3.2.3 *Chapter 3: Results and final remarks*

The main goal of this final chapter is to summarize the whole research and to perform a self-evaluation. By critical thinking a discussion of the gathered results is opened in which the research relevance as well as the research limitations are dealt with. This discussion is then followed by a conclusion in which the research questions are answered. As last, based on mostly the limitations but also new possibilities recommendations are written for different parties who may benefit from this research on firsthand.

3.4 Research outline

The research outline is schematized in Figure 9. The research is divided into three chapters.

Chapter I	Research framework
Chapter II	Research methods
Chapter II	Results and final remarks

Each part is divided into multiple sub-sections. In the research framework the basis is laid for the research, by providing an introduction which flows into the background study. The final section will then provide the research approach. In this approach the four phases with the corresponding research methods are provided. Each phase is created to answer their particular sub-questions as is stated in the previous paragraph. In the final chapter the results of this research are summarized into a discussion and a conclusion and ends with recommendations for companies and further researchers.

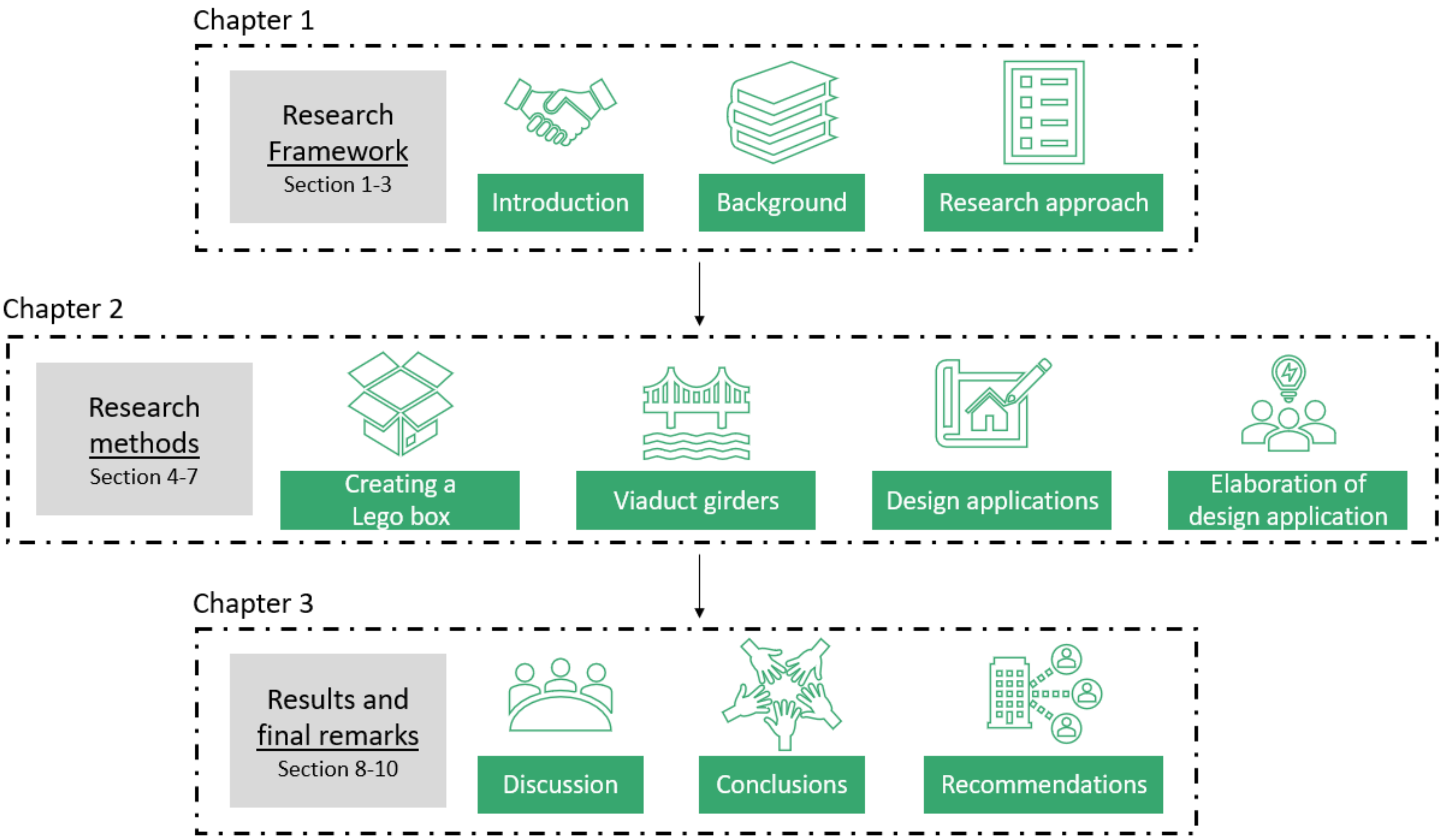


Figure 9 Research outline

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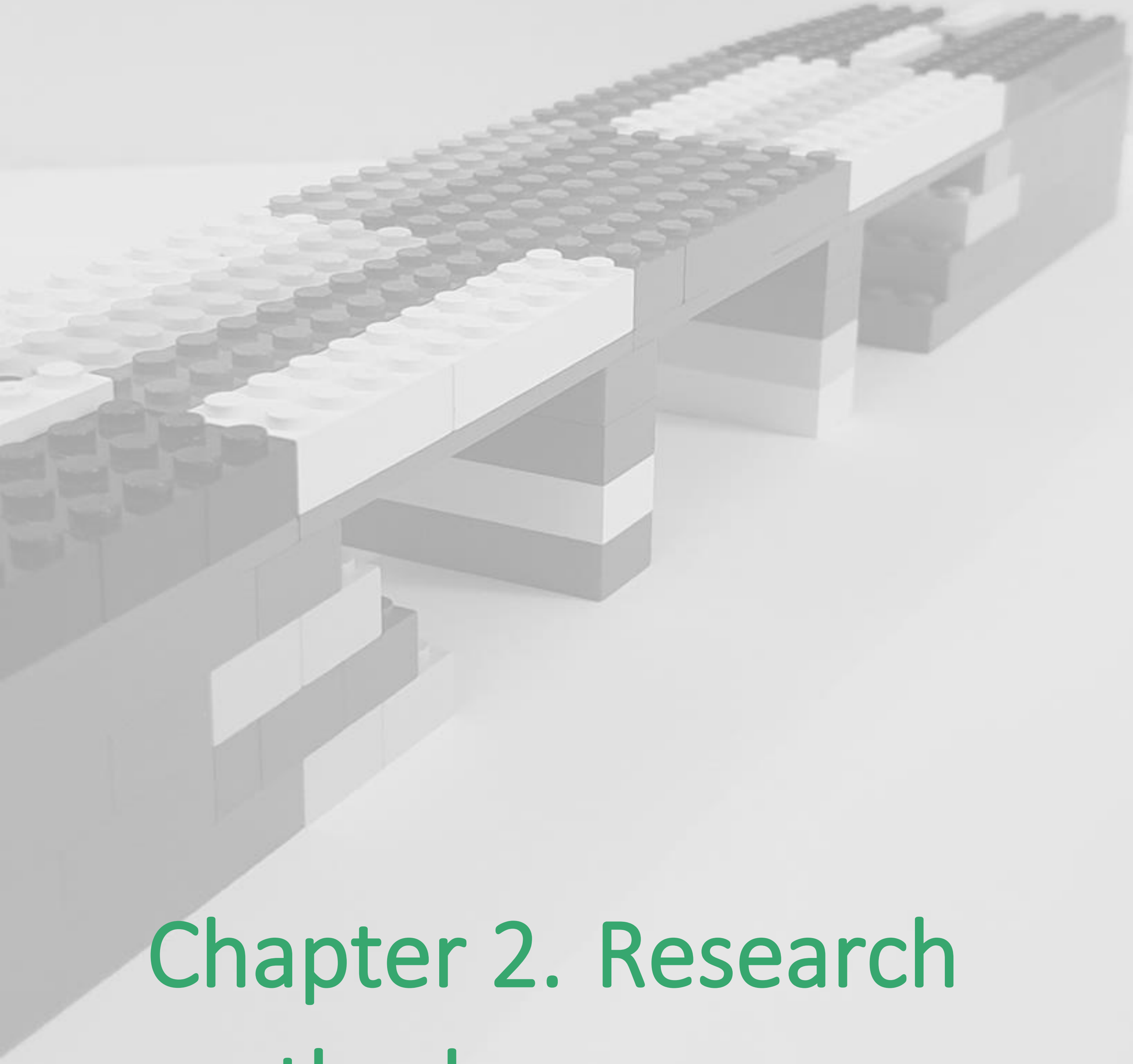


Chapter 2. Research methods

4 Phase 1: Creating a Lego box

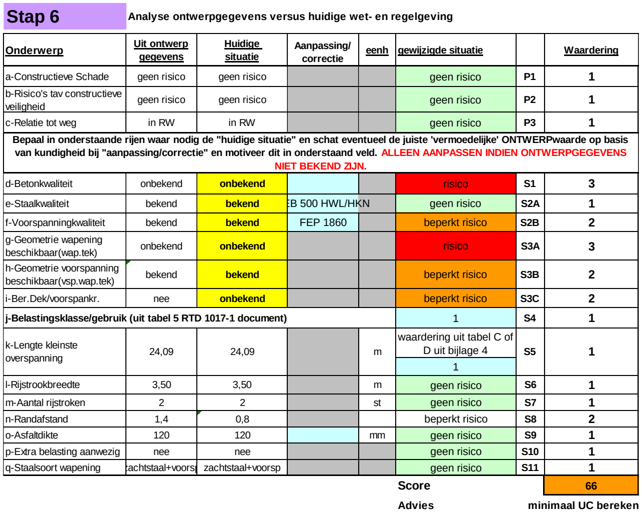
From the background information it is determined that the scope of this thesis will focus on concrete girders from viaducts in the acreage of RWS. However, these viaducts are built in a lifetime of almost a 100 years. The designing of the viaducts developed throughout the years due to different changing aspects like increase of traffic, different locations and new methodologies. Therefore, the first step is to inventory the different types of viaducts. This is done with two different methods. The first method is based on the current acreage to make an overview of the current stock. The second method is based on future perspective to predict what will be harvested in the near future.

4.1 Current acreage

Looking at the current acreage can be seen as a method of inventorying the different structures by focusing on the production. The advantage of this method is that what you see is what you get. For this research the data will be approached based on the SMART-principle (*Specific, Measurable, Assignable, Realistic and Time-related*), which is a project management principle (Randstad, sd). This principle implies a theoretical approach to the data since a lot of data is either missing or not stored well (Arnoldussen, et al., 2022). Also, to prevent looking into a couple of thousand technical drawings for a detailed elaboration. For this method, multiple data systems are taken into consideration. By using the SMART-principle the obtained information is presented. After an elaboration of each data system, a conclusion is made on relevance of the obtained data.

4.1.1. Data system 1: CRIAM

The most infrastructure works are built between the 1960s and the 1980s. Since then, the traffic flows have been increased in weight as well as frequency. This created structural risks on all the concrete structures. In the early years, to determine these risks, every calculation had to be assessed or totally renewed in case of absence. However, in 2006, RWS introduced a risk-based approach instead of damage-based approach (Dieleman & Bakker , 2016). The difference is the increased focus on the cause of the damage instead of just recovery. Another part of this risk-based approach is the introduction to an Excel-model called CRIAM, which stands for *Constructief Risico Indexering Afwegings Model*. This model inventories and determines the size of the risks of concrete structures by filling in 8 different steps (Boer & Booij, 2012). An example of step 6: Analysis design data is visualized in Dutch in Figure 10. This model contains specific data per structure, which are retrieved from technical drawings like reinforcement type and dimensions of the main load bearing structure. With this information a lot about the different structures can be found. Unfortunately, this data cannot be approached in a SMART way (Parsan, 2021). Therefore, this method isn't used to determine a valuable scope.



Stap 6 **Analyse ontwerpgegevens versus huidige wet- en regelgeving**

Onderwerp	**Uit ontwerp gegevens**	**Huidige situatie**	**Aanpassing/ correctie**	**eenh**	**gewijzigde situatie**		**Waardering**
a-Constructieve Schade	geen risico	geen risico			geen risico	**P1**	**1**
b-Risico's tav constructieve veiligheid	geen risico	geen risico			geen risico	**P2**	**1**
c-Relatie tot weg	in RW	in RW			geen risico	**P3**	**1**
Bepaal in onderstaande rijen waar nodig de "huidige situatie" en schat eventueel de juiste 'vermoedelijke' ONTWERPwaarde op basis van kundigheid bij "aanpassing/correctie" en motiveer dit in onderstaand veld. **ALLEEN AANPASSEN INDIEN ONTWERPGEGEVENS NIET BEKEND ZIJN.**							
d-Betonkwaliteit	onbekend	**onbekend**			risico	**S1**	**3**
e-Staalkwaliteit	bekend	**bekend**	B 500 HWL/HKN		geen risico	**S2A**	**1**
f-Voorspanningkwaliteit	bekend	**bekend**	FEP 1860		beperkt risico	**S2B**	**2**
g-Geometrie wapening beschikbaar(wap.tek)	onbekend	**onbekend**			risico	**S3A**	**3**
h-Geometrie voorspanning beschikbaar(vsp.wap.tek)	bekend	**bekend**			beperkt risico	**S3B**	**2**
i-Ber.Dek/voorspankr.	nee	**onbekend**			beperkt risico	**S3C**	**2**
j-Belastingsklasse/gebruik (uit tabel 5 RTD 1017-1 document)					1	**S4**	**1**
k-Lengte kleinste overspanning	24,09	24,09		m	waardering uit tabel C of D uit bijlage 4 1	**S5**	**1**
l-Rijstrookbreedte	3,50	3,50		m	geen risico	**S6**	**1**
m-Aantal rijstroken	2	2		st	geen risico	**S7**	**1**
n-Randafstand	1,4	0,8			beperkt risico	**S8**	**2**
o-Asfaltdikte	120	120		mm	geen risico	**S9**	**1**
p-Extra belasting aanwezig	nee	nee			geen risico	**S10**	**1**
q-Staalsoort wapening	achtstaal+voors	zachtstaal+voorsp			geen risico	**S11**	**1**
					Score		**66**
					Advies		**minimaal UC bereken**

Figure 10 Step 6/8 from a CRIAM model (Internal document Nebest BV)

4.1.2. Data system 2: Meridian

RWS makes use of so-called *Engineering Documentation Management Systems* (EDMS) to be able to manage the technical documents. By doing this, they can provide a broad information supply. Meridian is one of the applications that is used as an EDMS, created by the firm Meridian Systems. For specific technical drawings, this application can be used to retrieve information from. Unfortunately, just like the CRIAMs, is this a method which cannot be analyzed in a SMART way. It is very specific per structure and cannot be 'thrown on a big pile' to run different queries and combine the data sets. The main reason for this is due to the fact that all the drawings are originally made by hand.

4.1.3. Data system 3: DISK

RWS manages about 6000 structures throughout the whole country. To be able to maintain all infrastructure works in this network, RWS makes use of a system called DISK (*in Dutch short for:* Data Informatie Systeem Kunstwerken). This system is used to store all the data regarding inspection and maintenance. With the combination of registered acting risks by inspection results, conditions for safe usage and acreage information DISK will help to create maintenance plans for the long term (10 years) as well as, if necessary, short terms. All the structures containing this system are visualized with black triangles in the open-source program GeoWeb, which is shown in Figure 11.

Figure 11 DISK structures visualized in GeoWeb (Rijkswatersaat, n.d.-d)

In paragraph 2.5 the specified structure for this research is determined to be concrete viaducts. From this determination is built on and, with the use of different queries on the DISK database, an Excel export is made with this information. From this data export multiple graphs are composed, which are visible in Appendix D: These graphs can be used to form the most common superficial dimensions, together with other aspects. This data is summarized in Table 5 to set limits for the most common viaducts.

Table 5 Summarized data DISK

Parameter	Amount	Unit
Relative to highway	In Highway	
Construction year	1965-1970	
Width	14	m
Number of lanes[2]	3	-
Total span length	60	m
Load class	60	-
Number of spans	3	-
Average span length	20	M
Intersection angle	100	gon[3]

---

[2] Including emergency lane and edge elements

[3] Gradian (gon) is a way of expressing the size of an angle. A gon is $\frac{1}{400}$ part of a circle. A 100 gon equals 90° degrees

4.2 Future perspective

As in the previous section is spoken about what you see is what you get (production in the past), the future perspective method focusses on the future demolition plans. It turns out that every year about 10 girder viaducts are demolished, in contradiction to the construction of 40 girder viaducts (Vergoossen, 2021). At first glance, 10 viaducts does not sound much but considered the dimensions of a standard viaduct as prescribed in the previous section, each viaduct consists of approximately 40 girders. This makes a total of about 400 girders on average that gets demolished every year. Applying this future approach, it will be clear which viaducts will be available for harvesting of elements. This is, just like the previous approach, also done by using three different data systems. These systems are being prescribed as follows.

4.2.1. Data system 4: Reusability scan

The goal of the reusability scan is to create a data base in which as much information is stored as possible, regarding the reuse potential of elements. Afterwards this data can be shared with multiple sectors. This reusability scan is currently filled with approximately a hundred infrastructure works. Nebest filled this scan by using previous researches from graduates and also participating in projects like a reusability pilot from RWS. These particular structures are assessed and are therefore considered as the low hanging fruit, since specific information is known (Rademaker, 2021). These structures are now close to practice and the first step into the future plans. These hundred structures are varying from culverts till viaducts across the whole country, shown in Figure 12. As is seen in this graph the structures are mostly located in the west coast of the Netherlands. This is in contradiction to the dots visible in Figure 11 where the structures are all around the country. From a first impression into the elements of the structures within this scan, it turned out that most of the elements were concrete columns or steel girders (van den Berg, 2021) . This is also in contradiction to the general data about viaducts retrieved from DISK. Therefore, this data from the reusability scan is good for a first impression, but not to use for a typical or standard viaduct. It is too much focused on specific projects and therefore not applicable to a general overall view. However, this reusability scan forms the basis of this research and is elaborated further in Appendix B: The reusability scan.

Figure 12 Overview structures reusability scan (van den Berg, 2021)

4.2.2. Data system 5: Vervanging en Renovatie (VenR)

To maintain the safety and availability of the main roads, infrastructure works need to be preserved. In the first place, this is done by regular maintenance. However, these infrastructure works have limited lifecycles. When regular management and maintenance on structures are not applicable anymore, measures need to be taken. Since most of the current structures are built in the 1960s and therefore approaching their end-of-life cycle, RWS (and also the Netherlands) is facing a big replacement and renovation challenge (Bloksma & Westenberg, 2021). To manage this all, the program

VenR is written (*Replacement and renovation*). Based on construction year, inspections and calculations an insight is given per structure on the VenR period. This all is done in multiple phases, which are taken up into MIRT (MIRT, n.d.).

4.2.3. Data system 6: MIRT

The future plans for mobility needs in the (Dutch) infrastructure are very uncertain. There is a contradiction in the idea of what the future will require. On one hand RWS focusses on a so called 'Smart Mobility' movement, where the goal is to let people travel smart (safe and quick) from A to B (Rijkswaterstaat, n.d.-b). With a simple look in the past a realization about the change of traffic flows can be made. These changes cause uncertainties regarding the amount of increasing and the improved demands of the civil engineering works within the infrastructure it will bring with it (Asten, 2021). However, on the other hand it is proven that the current infrastructure works are stronger than we thought (Vergoossen, 2021) and maybe instead of creating whole new structures, adaptation can be sufficient (RVO, 2018).

The current existing future plans of projects regarding improvement of the infrastructure in the Netherlands are stored as multiple projects in an implementation program called *MIRT*, which stands for Multi-year program for Infrastructure, Spatial planning and Transport (*Meerjarenprogramma Infrastructuur Ruimte en Transport)* (MIRT, n.d.). Within this program the ministry of Infrastructure and water management is involved in all the projects, together with regional partners like municipalities or provinces. To maintain an overview in all these projects, the country is split in five different regions as shown in Figure 13.

Figure 13 Overview of different MIRT regions (MIRT, n.d.)

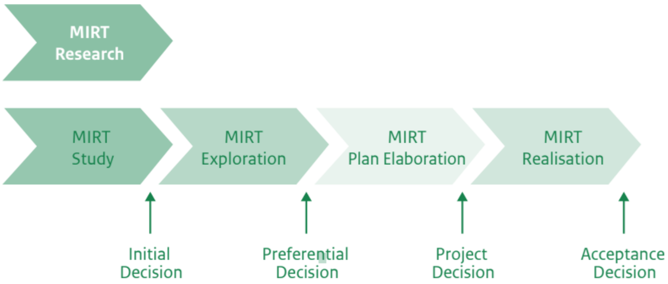


Figure 14 MIRT research phases (Ministry of Infrastructure and Water Management, 2018)

A MIRT project consists of the phases: Study, Exploration, Elaboration and Realization, visualized in Figure 14. Each phase ends with a so called 'political- administrative decision', before going on to the next phase (Ministry of Infrastructure and Water Management, 2018). Up until the project decision a lot can change within the project, since the planning procedures (*in Ducth: Tracébesluit*[4]) is not finalized. Therefore, only the projects that are noted in the realization phase are taken into account in the further development of the research.

According to the Ministry of Infrastructure and Water Management, the key to success of the MIRT projects is to have an open and creative approach (Ministry of Infrastructure and Water Management,

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[4] The planning procedures (*tracébesluiten*) are obtained from www.platformparticipatie.nl

2018).In other words this does mean that in the end of September 2021, the MIRT summary of 2022 appeared and less than one week later the corresponding data files were available on the open website of data storage by the government (Overheid.nl, n.d.). MIRT 2022 consists of a total of 117 projects nationally (shown in Figure 15), divided in 4 different modes of transport: main roads, rail roads, water ways and water in general (Visser & Weyenberg, 2021). Where the main roads, consists of a total of 43 projects, it can be regarded as the biggest of these four.

Figure 15 Overview of all MIRT projects in the Netherlands (Visser & Weyenberg, 2021)

If taken into account only the projects which are regarding the main road category as well as the current phase of realization (the VenR projects), the following table of projects is made.

Table 6 MIRT main road projects in the realization phase

MIRT Number	Project	Area
1	A1/A6/A9 Schiphol-Amsterdam-Almere	Noordwest-Nederland
2	A10 Knooppunten De Nieuwe Meer en Amstel	Noordwest-Nederland
4	A27/A12 Ring Utrecht	Noordwest-Nederland
5	A28/A1 Knooppunt Hoevelaken	Noordwest-Nederland
10	ZuidasDok[5]	Noordwest-Nederland
15	A15 Papendrecht–Sliedrecht[6]	Zuidwest-Nederland
16	A16 Rotterdam	Zuidwest-Nederland
18	A24 Blankenburgverbinding	Zuidwest-Nederland
20	Rijnlandroute[7]	Zuidwest-Nederland
23	A2 Het Vonderen-Kerensheide	Zuid-Nederland
24	A27 Houten-Hooipolder	Zuid-Nederland
30	N65 Vught-Haaren	Zuid-Nederland
31	A1 Apeldoorn-Azelo	Oost-Nederland
34	A12/A15 Ressen - Oudbroeken (ViA15)	Oost-Nederland
42	A7 Zuidelijke Ringweg Groningen, fase 2	Noord-Nederland

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[5] Project 10 is combined with project 42

[6] This project doesn't contain structures which require adaption, since they are already built according to the requirements, stated in the Planning procedures A15

[7] The planning procedures wasn't available and therefore their own website Rijnlandroute is used.

All these projects have their own data set which can be combined with the data of the infrastructure works throughout the Netherlands, as previously shown in Figure 11. This leads to the following overview map of the Netherlands, visible in Figure 16. The black triangles are the infrastructure works and the blue dots represent all the applied areas of the MIRT projects as shown in Table 6.

Figure 16 Overview the Netherlands with RWS structures and MIRT projects

A zoomed-in version of all these particular projects is shown in Appendix E: . Two different layers are now created. When combining these layers, together with the planning procedures of the MIRT projects, a useful playing field of structures is created. These structures are divided in four different aspects: demolished; new structure; unharmed and adjustment. These aspects mean respectively: Structures that are going to be demolished, without building a new one; A new structure on the same place as an old one; the current structure stays unharmed; the current structure requires only adjustment like widening. This leads to the graph in Figure 17 in which the amount of different infrastructure works are sorted by their corresponding aspect. A full version is visible in Appendix E: E.15 MIRT Structures. In the graph the red bars correspond to viaducts and are obviously the majority of these structures. About 400 of the total 600 structures are viaducts. The distribution of viaduct types is also almost 50/50 of girders vs plate structures. Just as shown in the previously research section in Figure 7.

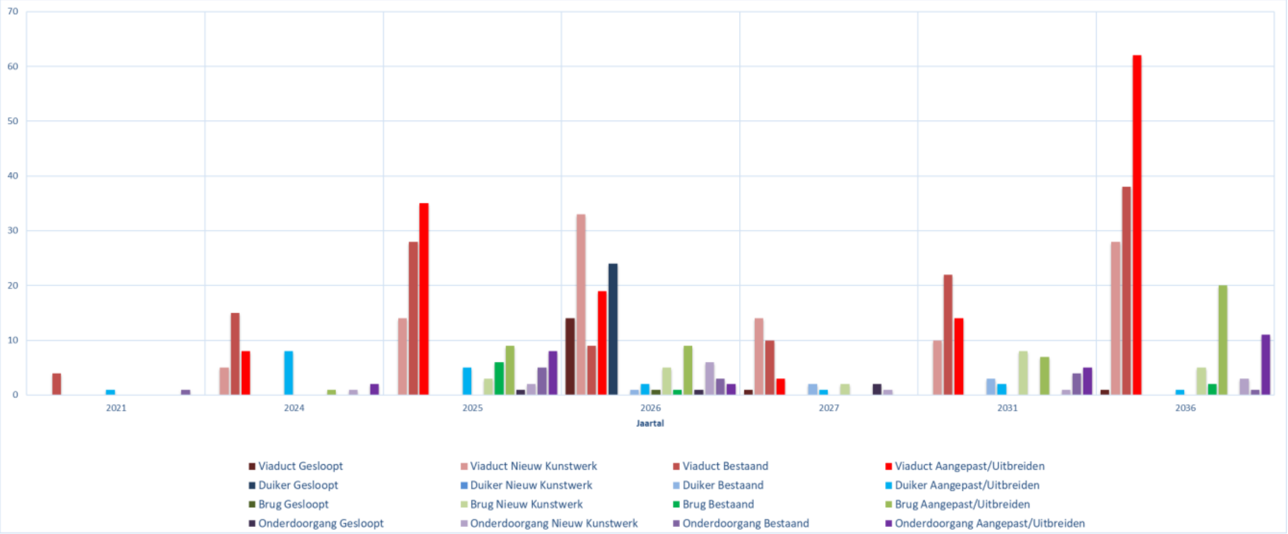

Figure 17 Graph containing the structures from the MIRT database

Since this research only focusses on these concrete viaducts, the graph of Figure 17 can summarized in as shown in Table 7. A total of 420 viaducts are retrieved from the data. However, 33 of these (appearing in MIRT Project 1) have an undefined purpose and thus are not taken into the consideration. It must be noted that the shown years in the table are the completion dates of the total MIRT projects. This means that the elements of the structures will be available sooner since of course demolishing happens before construction. From some verified demolishing years, a difference of about 3-4 years can be taken into account between completion date of the project and the demolishing year of the viaduct. In practice it turns out that the project organization in reusability is, as mentioned, a big bump. Even more due to the Covid-19 pandemic. Therefore, this thesis won't go further in depth on this part of project organization. Besides, multiple other TU Delft students already focused on this which can be found easily in the TU Delft repository.

Table 7 Viaducts subdivided

Year	Viaduct Demolished	Viaduct new	Viaduct unharmed	Viaduct adjusted	Total
2021	0	0	4	0	**4**
2024	0	5	15	8	**28**
2025	0	14	28	35	**77**
2026	14	33	9	19	**75**
2027	1	14	10	3	**28**
2031	0	10	22	14	**46**
2036	1	28	38	62	**129**
Total	**16**	**104**	**126**	**141**	387

Since these viaducts are now known, graphs can be plotted with help of a SMART data analysis, just as is done with the retrieved data from the DISK database. In Table 8, an overview is provided of this data with the most occurring characteristics.

Table 8 Summarized data MIRT

Parameter	Amount					Unit
Aspect	*Demolished*	*New*	*Unharmed*	*Adjusted*	*All combined*	-
Relative to highway	In	In	In/Over	In	In	-
Construction year	1975-1980	1965-1970	1975-1980	1965-1970	1965-1980	-
Width	15	12.5	15	12.5-17.5	12.5-17.5	m
Number of lanes	4	3	4	4	4	-
Total span length	40-50	60-80	60-90	60-80	50-70	m
Load class	60	60	60	60	60	-
Number of spans	2	3	3	3	3	-
Average span length	20	20	25	20	20	m
Intersection angle	100	100	100	100	100	gon

4.2.4. Summary

Combining all the previous found data about the viaducts, the desired Lego box can be created. This Lego box will be virtually shaped in the form of a viaduct. This viaduct contains the most applicable scope, with the most common elements and dimensions. From the data combination of DISK and MIRT, the Lego box is in both cases shaped in the same way. It can be seen that this viaduct is a 3x3 viaduct. This implies a viaduct with 3 different spans, all containing of 3 highway lanes. An overview of the combined data and therefore the determined scope is shown in the Table 9 and visualized in Figure 18. Different aspects of each parameter will be elaborated in a later stage in this research.

Table 9 Final Lego box of viaduct parameters

Parameter	Amount	Unit
Relative to highway	In	-
Construction year	1960-1970	-
Width	14	m
Number of lanes	3	-
Total span length	60	m
Load class	60	-
Number of spans	3	-
Average span length	20	m
Intersection angle	100	gon

With this combination of retrieved data, the scope is determined on which the design applications will be applied. It is assumed that this is the most common viaduct with its specific dimension, to be able to make the most impact with the design applications. Because, if for example it was assumed that each girder is 10m long (instead of 20m as shown in the table), then it could be possible that only on a small amount of the in the future harvested girders can be reused. This is not the aim of this research. However, before being able to think of multiple design applications, the girders need to be defined more. Since in this phase the Lego box is defined, the next step is to collect all the 'girder shaped' Lego blocks.

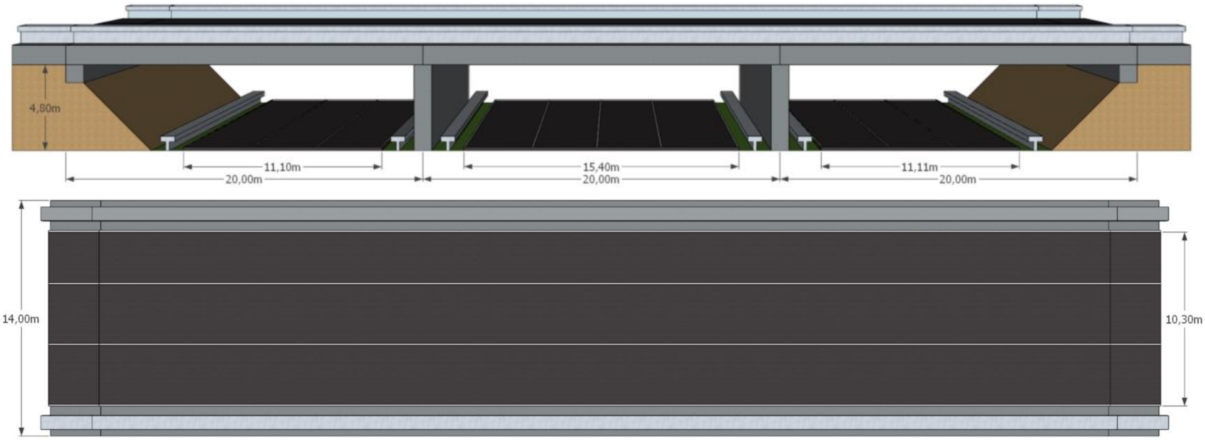

Figure 18 Side and top view of viaduct scope

5 Phase 2: Viaduct girders

In the previous phase, the Lego box is defined by taking into account about 400 viaducts. For the usage of the upcoming phase these viaducts are demarcated into the viaducts that are planned to be demolished in the upcoming 15 years. This are the two columns 'demolished' and 'new' combined from Table 6. This leads to the summation of a total of 120 viaducts that will be demolished in the upcoming years. The consisting elements will be crushed to debris if reusability will not be encouraged. Out of these 120 viaducts, 65 are labelled as girder viaducts and will be looked into further. This is done with the use of the program Meridian (see paragraph 4.1.2 Data system 2: Meridian) which provides technical drawings. An overview of these viaducts is shown in Appendix F: Viaduct girders. From this appendix it can be concluded that the 65 girders consist together a total of about 2800 girders, which have the possibility to be harvested instead of demolished. In this section the viaduct girders have been elaborated.

5.1 Different girder types

Throughout the Netherlands, about 210.000 infrastructure works are created of which about 85.000 are viaducts. These are all managed by different owners which all have their own demands on the design. These demands are in the first place based on constructive requirements. However, mostly due to costs or safety aspects, there is (almost) always an addition to these requirements. This results in different designs of infrastructure works. In Dutch the structures are called *'kunstwerken'*, which translates to artwork and is based on the fact that (almost) every structure is unique in its own way. Nevertheless, in this section an overview has been made to obtain the most common girders.

In Chapter 1.Research Framework the total amount of viaducts was determined to be about 3000. Due to the substantiated demarcation, only 65 viaducts are left. These 65 viaducts will be examined in a more detailed way. This is done by using the previously mentioned data system Meridian. With use of Meridian, the technical drawings are collected to see the different types of girders and being able to categorize them. This in-depth study resulted in the main girder types as is visible in Figure 19. Per main girder type a further elaboration is done.

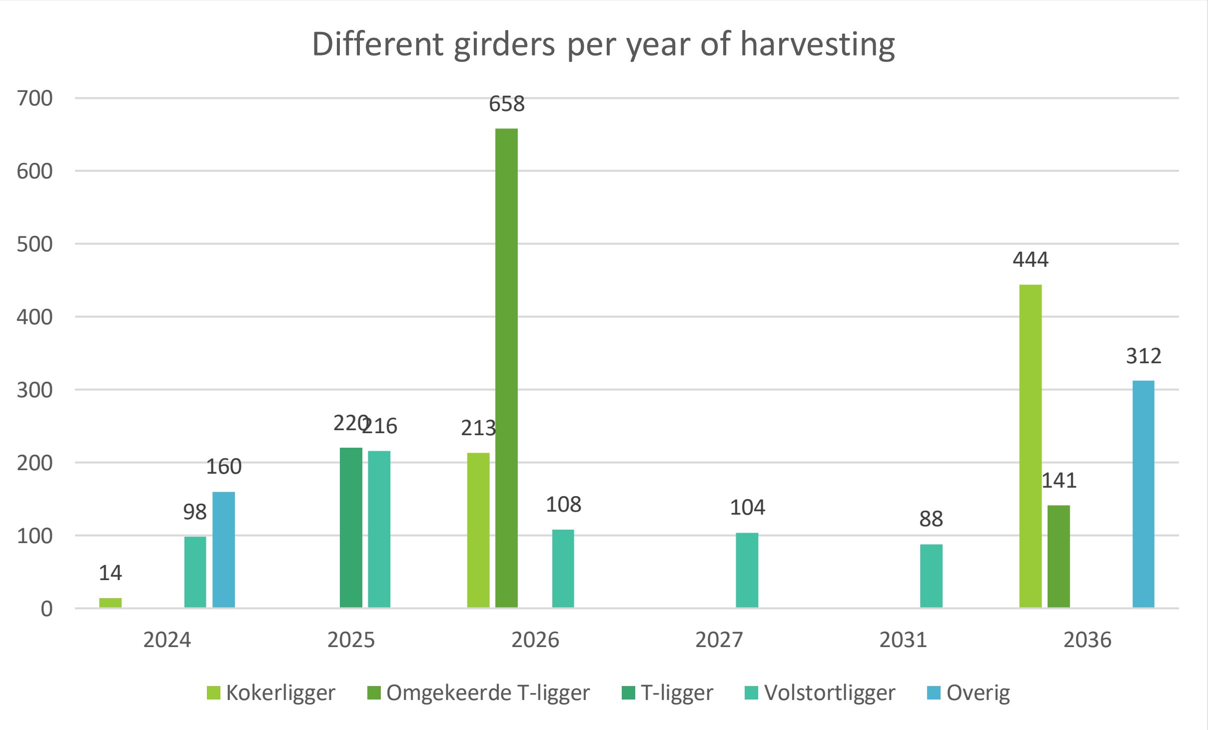

Figure 19 Different girders per year of harvesting of the examined viaducts

5.1.1. Inverted T-girders (Omgekeerde T-ligger)

From the graph it can be seen that 799 of the in total 2776 girders are defined as inverted T-girders. These are also referred to as *rail girders*, due to their shape where they look like rail tracks. It can be seen that about 30% of the viaducts that are on the list of demolition, consists of inverted T-girders. However, not every girder is the same. This is shown in Figure 20, where the girders in the examined viaducts are split per type, length and year of availability[8]. In Table 10 the total amount of girders is shown.

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[8] Note: As mentioned in paragraph 4.2.3 this is the completion date of the project and therefore not the exact release date of the girders

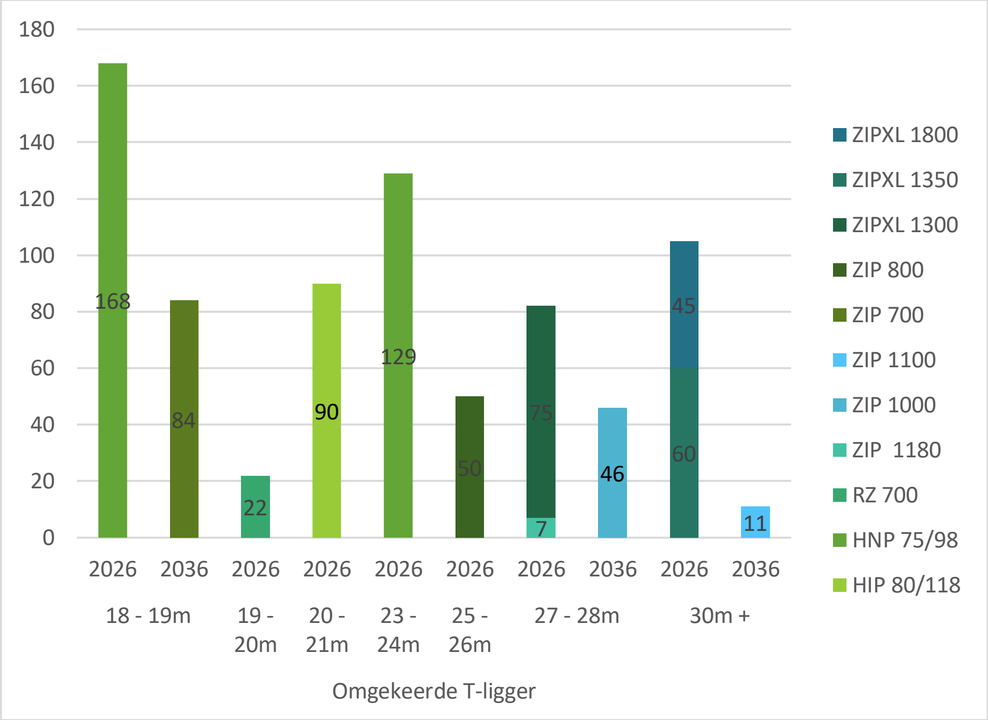

Figure 20 Graph of the different inverted T-girders, split by length and release date

Table 10 Amount of T-girders

T-girder	Girders
HIP 80/118	90
HNP 75/98	297
RZ 700	22
ZIP 1180	7
ZIP 1000	46
ZIP 1100	11
ZIP 700	84
ZIP 800	50
ZIPXL 1300	75
ZIPXL 1350	60
ZIPXL 1800	45
Total	**787**

In Figure 21 the different cross sections of the inverted T-girders are depicted. The cross sections in blue and grey are designed by Spanbeton. This was a concrete factory, focused on precast elements with prestressing. Spanbeton created about 70% of the girders of the viaducts from RWS (Vergoossen, 2021). Unfortunately, they have withdrawn from the infrastructure within the Netherlands and thus their concurrent, Haitsma concrete, took almost the monopoly. The yellow cross sections are designed by Haitsma. The RZ 700 profile (Table 10) is a specific profile, designed by Romein concrete and won't be taken into consideration further.

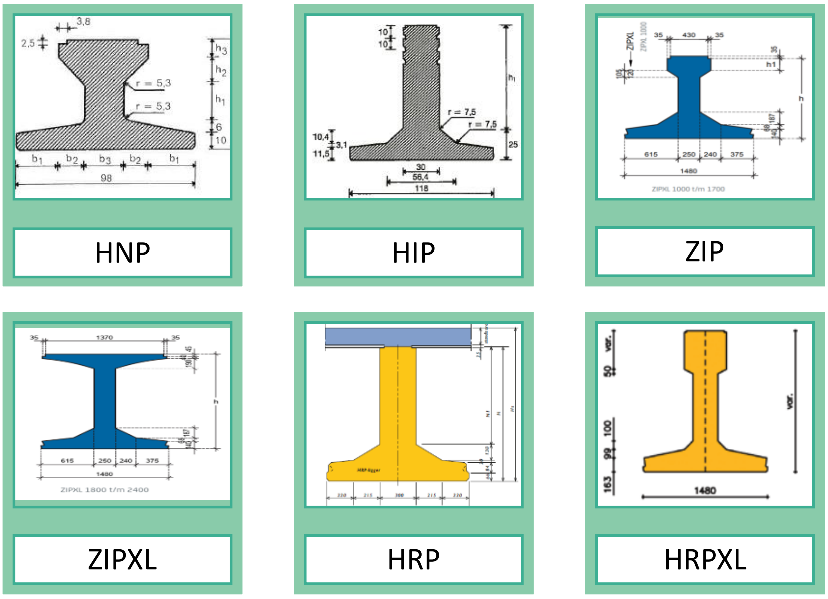

Figure 21 Cross sections of different inverted T-girders (Spanbeton, n.d.-a; Spanbeton, 1992; Haitsma beton, n.d.-b; Spanbeton, n.d.-a)

Although there are different profiles, the basics of designing a viaduct with inverted T-girders is all the same. It consists of a combination of prefab girders and an in-situ concrete compressive layer on top. The prefab girders are longitudinal prestressed in the factory, causing a camber to reduce the effect of sagging. An additional advantage is a better rainwater discharge. For the realization of the viaduct, the precast members are laid next to each other while resting with the use of (mostly rubber) bearings on the supports. By casting concrete in the rabbets (Figure 22 bottom right) these girders are connected to each other. Next to that, the prefab girders are provided with extended stirrups, which are visualized on top of the girder in Figure 22. These stirrups, combined with the rough upper layer of the girder makes it possible to take the shearing forces between the girder and the in-situ concrete compressive layer. Formwork (depicted in Figure 23) is placed at the location of the supports (on both ends of the girder) and in the rabbet between the girders. With this formwork both the transverse girder and the concrete compressive layer can be casted. Unfortunately, the formwork cannot be removed and is therefore seen as lost formwork. The transverse beam at the supports is reinforced by using the holes in the girder (visible in Figure 22) and connects the girders to each other. This way a viaduct is constructed to withstand the different loads in both vertical as horizontal directions. Since the different inverted T-girders (Figure 21) do not only have similarities, they are shortly elaborated.

Figure 22 Haitsma concrete girder with extended stirrups

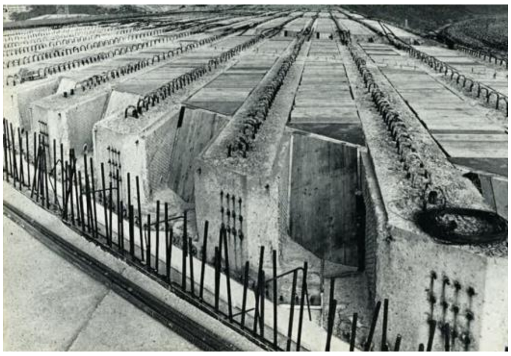

Figure 23 Concrete girders with formwork (Spanbeton, n.d.-a)

5.1.1.1 *HNP girders*

A total of 297 out of the 777 inverted T-girders are HNP profiles. HNP girders can be seen as the first generation of precast girders in the infrastructure works. They are used by Spanbeton in the period of 1965-1972 and consist of little (negligible) to no stirrup reinforcement. Causing them to be more vulnerable for shear forces. The precast concrete is designed by the RVB 1962 (regulations method regarding design viaducts). The different HNP-profiles are defined based on load class and span. The load classes are designed with the VOSB 1962 and are subdivided in classes 30, 45 and 60. This can be related to a class 60 which can withstand the highest load (heavy traffic) and class 30 isn't designed for heavy traffic. Theses load classes correspond to equivalent loads which the viaduct has to be able to withstand. The span of these girders varies from 13 to 29 meters. All different profiles have a constant width of 1000 mm, but a varying height difference between 500 and 1000 mm (Spanbeton, n.d.-a). Nowadays this girder profile isn't constructed anymore due to the demands in the current design codes, mostly due to the absence of the stirrup reinforcement.

5.1.1.2 *HIP girders*

In 1970 the HIP girders were introduced by Spanbeton. This design was the expansion to HNP girders to be able to not only fulfill the question of bigger spans but also to create a more economical solution (Quartel, 2011). In contrast to the HNP girders, the HIP-girders have a constant width of 1200 mm and can therefore span up to 40 meters with a profile height difference of 500-1400 mm. The load classes are also (just as the HNP) designed by the VOSB 1962, but the precast concrete is based on the RVB 1967. However, also this profile has little to no stirrup reinforcement and is therefore unfavorable to shear strength (de Meijer & Vergoossen, 2012). Nowadays, just as the HNP profile, this HIP profile isn't constructed anymore, since it doesn't fulfil the current design codes

5.1.1.3 *ZIP girders*

Where about 40% of the profiles shown in the graph in Figure 20 are HNP girders, about 50% is taken by the ZIP girders. In 1973 the ZIP girders were introduced by Spanbeton which consists of the same system of the previously mentioned HIP girders (Quartel, 2011). However, the Z stands for *Zwaar*, which means heavy in Dutch. The purpose of these girders was to create heavier elements to be able to withstand higher horizontal forces due to collision. And if the girders are on their specific location even more vulnerable for collisions, the space on the edge can be filled up to provide more strength. This is made visible in the grey area in Figure 24. Furthermore, this girder contains of a width of 1200 mm and a height varying from 500-900 to be able to span up to 25 meters. On top of that, this profile of girders also contains a XL variant, which of course contains more concrete and is therefore able to have a bigger span. With a constant width of 1500 mm and a varying height of 1000-2400, this profile is able to span op to 65 meters (Spanbeton, n.d.-b). It must be noted that these ZIP girders are designed for static determinate structures. Nowadays the ZIP as well as the ZIP XL isn't constructed anymore, since Spanbeton has withdrawn themselves from the infrastructure market.

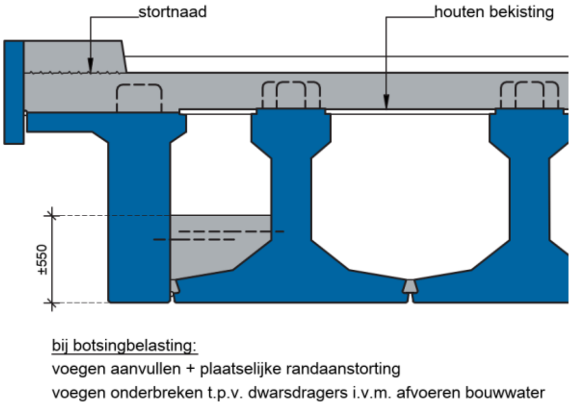

Figure 24 Cross section ZIP-girder with extra strengthening (Spanbeton, n.d.-b)

5.1.1.4 *HRP girders*

HRP stands for *Haitsma railligger profiel* and is in fact the same concept as the ZIP profile. It is mostly used when construction height is not a problem and an economic solution can be created. They have a standard with of 1200 mm and can span 15-40m by varying the height from 500-1600mm. This profile also has an expansion into HIP profiles. These types are suitable for spans between 40-65m with a width of 1500mm and a varying height of 1200-2000mm (Haitsma beton, n.d.-b). The HRP as well as the HIP can be used for static determinate and indeterminate structures. These girders are still available on the market to construct but as is seen in Figure 21 these girders won't be available in the upcoming years.

All the inverted T-girder profiles are summarized in the Table 11 with an overview of the differences. It is noticeable that during the years the improvement in span has increased. The design codes and load classes are elaborated further in paragraph 5.2.1.

Table 11 Summarized T-girder profiles

Inverted T-girder	c.t.c distance [mm]	Height [mm]	Span [m]	Design code	Load class
HNP	1000	500-1000	13-29	VOSB 1963	60
HIP	1200	500-1400	13-40	VOSB 1963	60
ZIP	1200	500-900	10-30	NEN-EN 1992-2[9]	NEN-EN 1991-2
ZIP XL	1500	1000-2400	10-60	NEN-EN 1992-2[10]	NEN-EN 1991-2
HRP	1200	500-1600	20-40	NEN-EN 1992-2	NEN-EN 1991-2
HRP XL	1500	1200-2000	45-60	NEN-EN 1992-2	NEN-EN 1991-2

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[9] The ZIP girders were designed from 1973 on. In this year the designed code was GBV 1962. During the years, this code changed multiple times before the Eurocodes were applied. These girders were built up to circa 2020 and therefore these girders are constructed over the years, based on multiple design codes.

[10] See footnote 8

5.1.2. Box girders (Kokerliggers)

About 25% (671 out of 2776) of the girders from the graph in Figure 20 are defined as box girders. A box girder is shaped as a box and is seen as a closed element with less intrusion of dirt and moist resulting in a better lifecycle. The box girders are also (constructively) hollow on the inside, which can be created in two different ways. The first one is to cast the concrete in two phases. The first phase consists of a U-shape concrete profile and when this is hardened (after circa 3 hours) the deck is casted on a lost formwork. The second way of creating this box girder is by using polystyrene blocks as a core (de Boer, 2001). The hollow space is than not actually hollow, but the weight of this polystyrene can be neglected. The hollow core of this box girder causes a big reduce in the weight of the girder compared to solid girders. This use of polystyrene blocks has the advantage to create a girder which is casted all at once and is therefore in absence of a construction joint. This results in a constructive better girder (Haitsma beton, n.d.-c). The box girders are mostly prestressed with post-tension steel in transverse direction and prestressed with pre-tensioned steel in longitudinal direction. The combination of these prestressing steel creates a concrete deck consisting of two prestressed directions. When demounting the structures, these cables need to be cut. This can form a risk since these cables are under a high tension load. A big advantage of the box girders is that they create a fully concrete deck and thus an extra concrete compressive layer isn't needed. To finalize the girders and connecting them to the supports, both ends of the box girders are solid over a distance of about 1 meter. A big advantage of these box girders is that they are better resistant for buckling load in comparison to a girder with the same weight. Therefore, these girders can withstand higher loads. However, it must be noted that the cost of box girders is higher than the rail girders. The different box girder profiles that will have the opportunity to be harvested in the near future are shown in Figure 25 and Table 12.

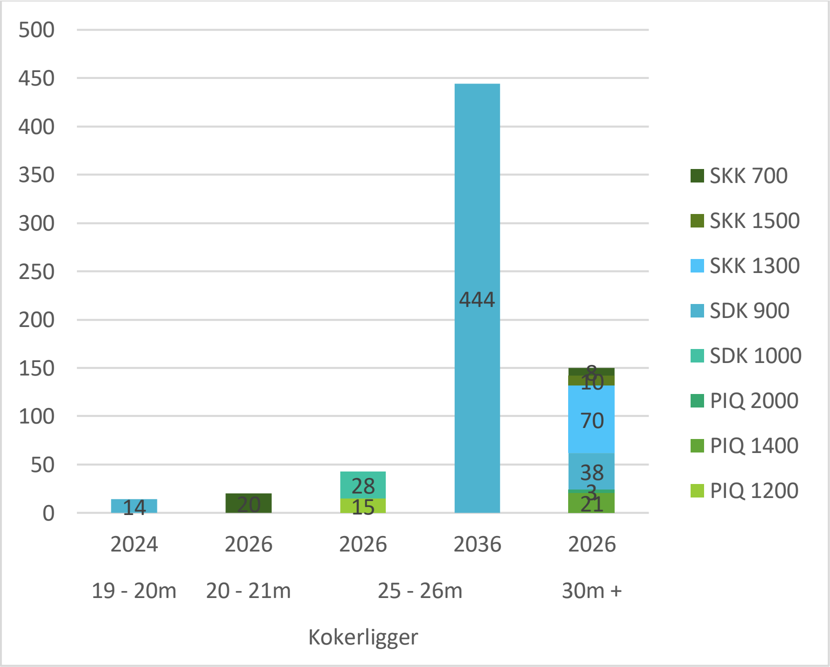

Figure 25 Graph of the different box girders, split by length and release date

Table 12 Amount of box girders

Box girder	Girders
PIQ 1200	15
PIQ 1400	21
PIQ 2000	3
SDK 1000	28
SDK 900	496
SKK 1300	70
SKK 1500	10
SKK 700	28
Total	**671**

The different box girder profiles mentioned in this graph and table are shown in Figure 26 and elaborated further underneath the image.

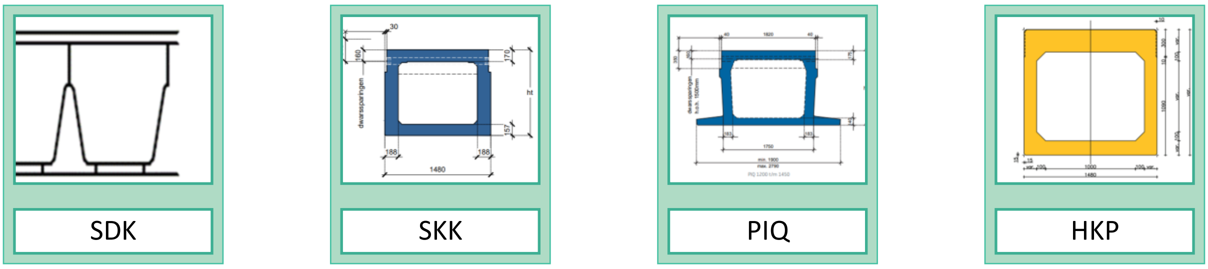

Figure 26 Cross sections of different box girders (Spanbeton, n.d.-d; Haitsma beton, n.d.-c)

5.1.2.1 *SDK girder*

About 500 of the total of 671 box girders are SDK (*Spanbeton Dywidag Kontaktsysteem)* girders. In 1975 the SDK system was introduced to the infrastructure works. This system was based on creating girders with high quality and relatively slender construction height and to be able to have a short construction time. There were two different types available in which the type number corresponds to the construction height. The SDK 650 is a fully casted girder and the SDK 900 has a hollow core. This SDK 900 was able to span up to 30 meters (Quartel, 2011). This profile isn't made anymore, since it underwent further development into the SKK profile. Up to only a few years after this development, the SDK profiles were only used when a time factor was decisive. For example, when creating a railway viaduct (Quartel, 2011).

5.1.2.2 *SKK girder*

As an extension to the SDK 900, the SKK girders were created around 1980. From the previous graph it is visible that about 100 girders are designed with this profile. With a constant width of 1200 mm and a height varying between 700-1400mm, spans of 45m could be reached. The deck of a viaduct was created by laying the girders next to each other with a rabbet of about 30 by 300mm. This rabbet was then filled with concrete and after hardening, the tension could be applied to make the box girders work together as a full deck.

5.1.2.3 *PIQ girder*

The PIQ box girders are very specific and were not used a lot in the Netherlands. In the previous graph it can be seen that this profile only appears to 20 girders. It has the same functioning as the SKK girder, but it has more width causing to create a deck with less girders. By using lost formwork, the girders can be connected together by a small cast in-situ layer.

5.1.2.4 *HKP girder*

With the new possibilities at Haitsma concrete, designers were able to design bigger infrastructure works with the use of the HKP (*Haitsma Koker Profiel*) girders. This profile is optimized in such a way that spans up to 70m can be reached with a varying height of 800-2200 mm and a standard width of 1500mm (Haitsma beton, n.d.-c). Just as the Haitsma inverted T-girders, these HKP profiles are still available on the market to construct but as is seen in Figure 26 these girders won't be available in the upcoming years.

5.1.3. T-girders (T-liggers)

In 2025 more than 200 T-girders will become available due to a project in Groningen in the Netherlands. These girders are divided into two different spans as shown in Figure 28. A cross section of these T-girders is shown in Figure 27. T-girders are in general used for viaducts with a lower load class and when the available construction height isn't limited. With laying these girders next to each other a concrete compressive layer is provided to create a concrete deck structure. It must be noted that these girders are only applicable for static determinate structures. At the supports the girders get horizontally connected by and in-situ transverse girder (de Meijer & Vergoossen, 2012). The girders have a relatively small bottom flange, compared to the top flange. Therefore, these girders are not only vulnerable for turning over but also to collision. De bottom flanges are not connected to each other. When a collision happens, only one girder has to take the full load. Since the requirements for collision have been improved over the years, these girders are not made anymore (de Boer, 2001).

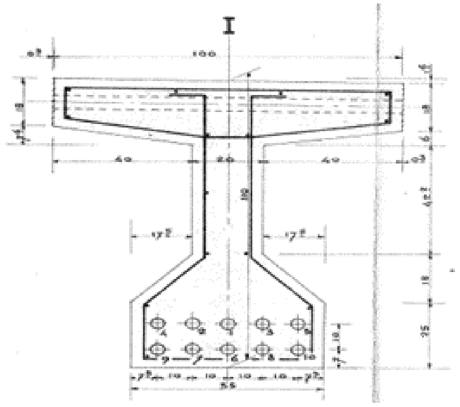

Figure 27 Cross section of T-girders

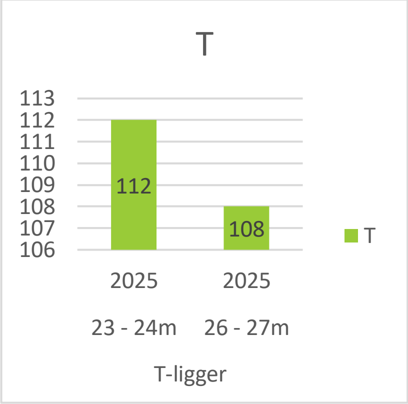

Figure 28 Graph of the T-girders, split by length and release date

5.1.4. Infilled girders (Volstortliggers)

The second place of most occurring girders are the infilled girders. In the near future about 25% of the available girders are infilled girders. Also in this case, there are multiple different infilled girder profiles, as can be seen in Figure 29 and the Table 13.

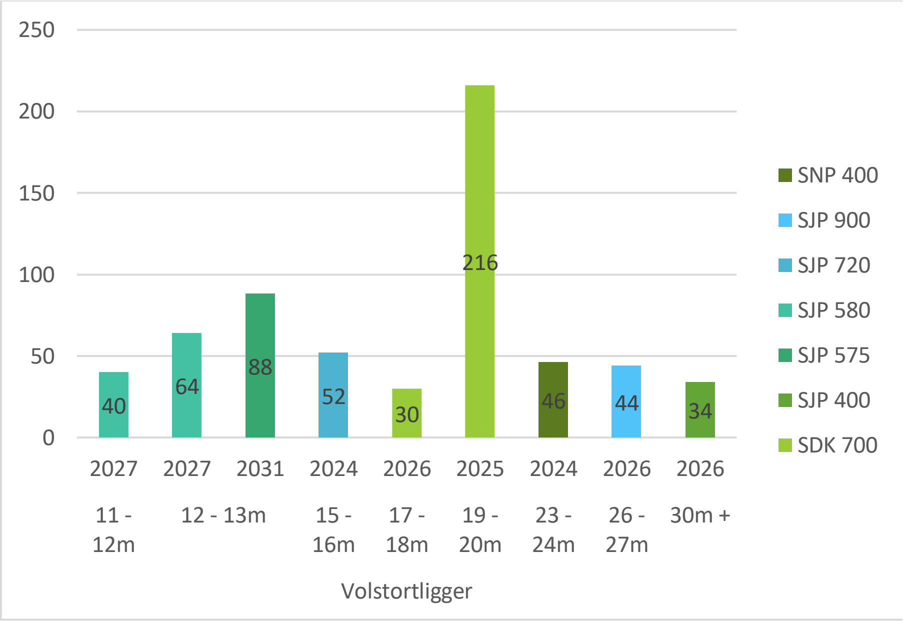

Figure 29 Graph of the different infilled girders, split by length and release date

Table 13 Amount of infilled girders

Infilled girder	Girders
SDK 700[11]	246
SJP 400	34
SJP 575	88
SJP 580	104
SJP 720	52
SJP 900	44
SNP 400	46
Total	**614**

The infilled girders are mostly used in the infrastructure works since it is the most economical solution. The basis of the girders is determined by minimal prefab elements with longitudinal prestressing steel. On top of these girders an in-situ concrete layer is casted which reaches up to circa 80mm above the height of the prefab elements. The advantages of prefab are combined with the advantages of cast in-situ. Using prefab elements has advantages for reinforcement connection and limited use of formwork and with the usage of the cast in-situ layer the price is kept low. The combination of these two is also very beneficial for the construction time. With the use of the holes in the girders (as seen Figure 30) the bottom transverse reinforcement is realized. Combining all these aspects, these girders can in fact be specified as a solid deck. During the realization of this deck, the girders aren't in fact there anymore. This make it harder to reuse, since it is all covered in concrete. In longitudinal direction, this solid deck

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[11] Due to the solid cross section, the SDK 700 is considered as an infilled girder. However, it can also be classified as a T-girder due to its shape.

is still a prestressed deck, but in transverse direction a reinforced deck is created. In longitudinal direction the height of the deck is the height of the infilled girder plus about 80mm of the in-situ layer. In transverse direction this height is about 12cm lower due to the height of the bottom flange. The joint in between the bottom flanges of the girders won't be filled with the in-situ concrete which is also visible in the Figure 30 (de Boer, 2001). These infilled girders are mostly used in the structures with smaller spans, since they can reach spans between 5-20m.

Figure 30 Infilled girders

Cross sections of the different infilled girder profiles are shown in Figure 31. The first profile is created somewhere in the 1960s and was the predecessor of the different profiles. This profile underwent development by Spanbeton and turned into the SJP (Flex) girder. Next to that, Haitsma created the yellow profiles HKO and HKO-XL. Due to the fact that the profiles don't differ that much and these girders can be seen as a solid deck, the different profiles won't be elaborated further

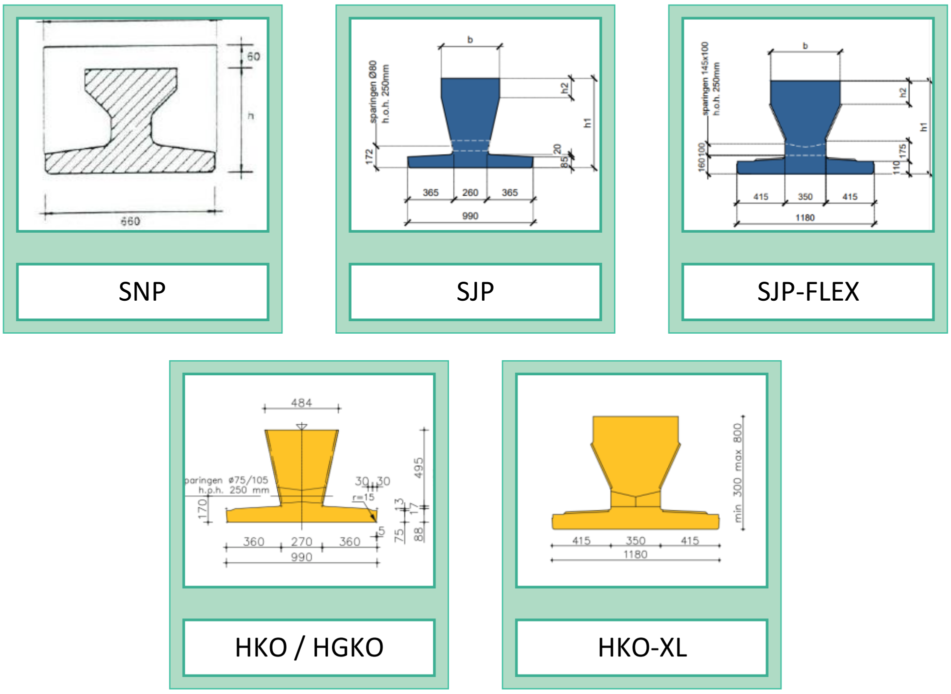

Figure 31 Cross sections of different infilled girders (Spanbeton, n.d.-c; Haitsma beton, n.d.-a; Ergon, n.d.)

5.1.5. Remaining (Overig)

It can be noticed from Figure 19 that there are also some girders marked as 'Remaining'. This is divided into two different profiles. Both these girders are very specific and used in a small amount of infrastructure works. The first one is the preflex girder (Figure 32). This profile was introduced in de

1950s as a combination between concrete and steel. After multiple uses it was concluded that mostly the concrete part did all the work and have not been used further on. The second profile is shown in Figure 33. This profile looks like a standard inverted t-girder, but a maximum width of 500mm could not be classified. Both these profiles are excluded from further research.

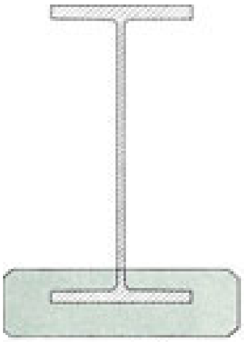

Figure 32 Preflex girder cross section (Quartel, 2011)

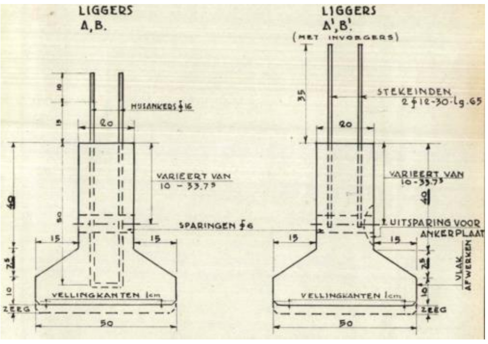

Figure 33 T-girder A&B and A'&B

5.2 Structural behavior viaducts

In this research the focus is about reusing girders in another function, different than the original. However, to do so the original function must be looked into first. This will provide a better understanding of the girders and can therefore result in the realization of more optimized design applications. In the previous paragraph the different girder types are elaborated. This paragraph will focus on the structural behavior of viaducts itself. This structural behavior will not be into much detail, since it is mostly applicable to the design of new viaducts. This will not be the case when thinking of design applications in another function. Nevertheless, the original function of the girders needs to be known, since they are optimized for that purpose and designed in such a way to withstand the loads. Therefore, background information is required before another design can be made.

5.2.1. Design standards

To design and assess viaducts in the Netherlands, multiple standards are written. These standards are summarized in the Figure 34 with the help of an upside-down pyramid. On top of this graph the contract is depicted. The contract has the highest influence on the design standards. The specific client can ask anything regarding specific demands, with the minimum level of the law. This means he can always ask for stricter demands. The other design standards are shortly elaborated further, by going from bottom to top.

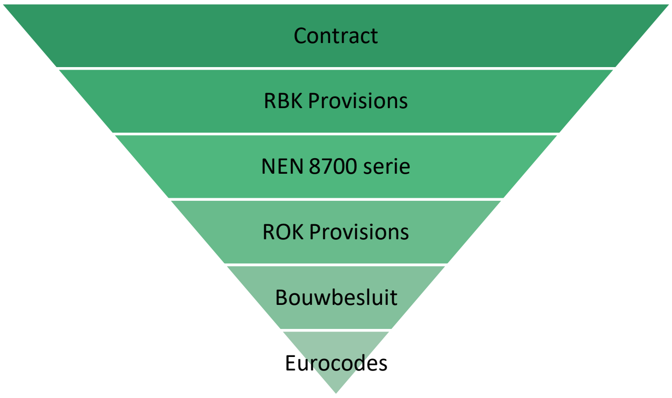

Figure 34 Design standards viaducts ordered on influence

5.2.1.1 *Eurocodes*

In 1912 the first regulations regarding reinforced concrete were written in the Netherlands: the GBV 1912 (*Gewapend Beton Voorschriften*). Since this version, the regulations of the GBV has been revised 4 times (1918; 1930; 1940; 1950) before the release of the last version GBV 1962. After this last version the GBV changed into the VB (*Voorschriften Beton*). From 1974 to 1983 different individual reports were published, each with their own focus area. After these publications, the VB 1984 was published containing a combined version with particular revisions. The biggest difference between the VB and the GBV was the trust that was gained in the concrete and the concrete knowledge. This led to a reduction of the safety coefficients. In 1990 the transition to the VBC (*Voorschriften Beton. Constructieve Eisen en rekenmethoden*) was created. This VBC 1990 was referred to by a new document: The Bouwbesluit. The most important aspect was to create a more unambiguous procedure and determination. This VBC 1990 was revised in 1995 and a VBB 1995 (*Voorschriften Beton – Bruggen*) was created. This VBB was revised once, in 2009. In April 2012, exactly 100 years after the GBV 1912, the VBC was withdrawn and the era of the specific Dutch regulations was over (Gijsbers J. , 2012).

Currently viaducts are designed according to the Eurocodes. In the Eurocodes safety requirements are noted for new to build structures. Eurocodes 1 and 2 are applicable to viaducts. These Eurocodes are European standards for the assessment of the structural safety of all possible building structures. Eurocode 1 is about the different loads where the NEN-EN 1991-2 is specific applicable to traffic loads on bridges (and viaducts). Eurocode 2 is about the design and detailing of concrete structures. The NEN-EN 1992-2 is specific about concrete bridges (NEN, n.d.-a). However, these Eurocodes also create the opportunity to determine differences per country in certain safety aspects. In the Netherlands this is done in the National annexes, recognizable on the abbreviation NEN before the standards.

5.2.1.2 *Bouwbesluit 2012*

As is shown in the pyramid, the Bouwbesluit 2012 is placed above the Eurocodes (van den Broek, 2021). Since a structure must not fail and causing causalities the Dutch government wrote the Bouwbesluit. This Bouwbesluit contains regulations about safety, health, user ability, economic aspects and the environment (Rijksoverheid, n.d.-b). A structure must always satisfy these regulations. To prove the fulfilling of these regulations the Eurocodes, as describes before, can be used. There are also other options (for example designing by testing), but these elaborations will be left out further.

This Bouwbesluit is split into new- and existing constructions. For new constructions the Bouwbesluit specifies, determined of the user ability, a confidence level which can be seen as a chance of failure in a certain period (Vergoossen, 2021). Reaching this specific level can then be proved with the calculations from the Eurocode 1 and 2. For existing structures the Bouwbesluit describes that an owner of a certain structure is not allowed to bring its conditions below a level of disapproving (Vergoossen, 2021).

5.2.1.3 *RWS guidelines*

The top of the chart in Figure 34 is about contract level. RWS did this for all their assets and wrote their demands in two separate documents. The ROK and the RBK. In these documents RWS specified certain demands which they want on top of the basic Eurocode regulations. The ROK stands for *Richtlijnen ontwerp kunstwerken* and focusses on the design aspects of new to build structures. RBK stands for *Richtlijnen beoordeling kunstwerken* and focusses on the assessment of current existing structures. An example of a demand in the ROK is that all the viaducts of RWS must be classified as consequence class 3, which is explained in paragraph 5.2.5.

5.2.1.4 *NEN 8700 series*

The NEN 8700 series provide standards for existing constructions and refurbishment (NEN, n.d.-b). Where the NEN 8700 is all about the basic principles, the NEN 8701 is about the different loads. The NEN 8700 is usable at three different levels. The first one is about the structural assessment of the design models of structural works. The second one is about the assessment of an existing building to a specific performance level. The third one is about the assessment of the previous mentioned level of disapproving.

5.2.1.5 *Conclusion*

The biggest challenge in the current economy is the lack of standards for reusability. Despite the fact that the NEN 8700 series provide an article about rebuilding, this is still quite vague since most of the time still determinations for new constructions have to be sustained (Vergoossen, 2021). Due to the upcoming popularity of reusing, some definitions in the Bouwbesluit are not straightforward anymore. For example, the term for building a new construction with reused elements is not fully rebuilding, but neither it is a fully new construction. In conclusion, from this point on in the research, the assumption is made that the reused elements need to satisfy the new construction standards regarding load classes. The NEN 8700 is based on a lower limit of a specific chance of surviving of people in case of an accident. The standards for a new construction are also more based on economic certainty.

5.2.2. Loads

Mentioned in the previous paragraph, the Eurocode NEN-EN 1991-2 describes the standards of traffic loads on viaducts. However, during the years, also these regulations have changed. In 1920 the first general conditions were taken into account. Before these conditions, the asset owners had their own standards (Weemaes, 2018). The previous standards through the years are summed in Table 14.

Table 14 Previous load standards summarized (Weemaes, 2018)

Standard	Elaboration	Weight vehicle	Distributed load
1920	General conditions	14 tons	4.0 kN/m^2
VOSB 1938	Traffic class A: Bridges in highway, diverting traffic excluded	Vehicle with 3 axles of 20 tons	4.0 kN/m^2
	Traffic class B: Bridges in highway, possibility of class A vehicle	Vehicle with 2 axles of 10 tons and 1 of 20 tons	4.0 kN/m^2
	Traffic class C: Bridge not intended for very heavy vehicles	Vehicle with 2 axles of 10 tons	3.5 kN/m^2
	Traffic class D: Bridge only intended for light weight vehicles	Vehicle with 2 axles of 5 tons	3.0 kN/m^2
	Bicycle/ pedestrian bridge	-	4.0 kN/m^2
VOSB 1963/1995	Traffic class 60: Bridges in highway, diverting traffic excluded	Vehicle with 3 axles of 200 kN	4.0 kN/m^2 With a max of 12 kN/m lane
	Traffic class 45: Bridges in highway, small possibility of class 60 vehicle	Vehicle with 3 axles of 150 kN	3.0 kN/m^2 With a max of 9 kN/m lane
	Traffic class 30: Bridge not intended for very heavy vehicles	Vehicle with 3 axles of 100 kN	2.0 kN/m^2 With a max of 6 kN/m lane
	Bicycle/ pedestrian bridge	-	4.0 kN/m^2
NEN 6706: 2007	Only one Load model (LM1) prescribed. Due to the idea of every heavy vehicle must be able to drive everywhere	Simultaneously presence of maximum 3 vehicles of 600, 400 and 200 kN	9.0 kN/m^2 on ‘heavy lane’ and 2.5 kN/m^2 on other lanes

As mentioned before, the current situation is the application of the Eurocode NEN-EN 1991-2 in combination with the NEN 8700. In these standards the consequence class needs to be determined at first. This consequence class has effect on the load carrying elements of the viaduct. This class then prescribes different load factors which need to be used for different load combinations, with the fundamental combinations shown in equation (1), based on the NEN-EN 1990: Basis of structural design (NEN 1990, 2019).

$$\begin{aligned} &\sum\nolimits_{j>1} \gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot \psi_{0,1} Q_{k,1} + \sum\nolimits_{i>1} \gamma_{G,i} \psi_{0,i} Q_{k,i} \qquad (6.10a) \\ &\sum\nolimits_{j>1} \xi_j \gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot Q_{k,1} + \sum\nolimits_{i>1} \gamma_{G,i} \psi_{0,i} Q_{k,i} \qquad (6.10b) \end{aligned} \qquad (1)$$

Where:

γ	partial factor
G	permanent load
P	prestress load
Q	variable load
ψ	factor for variable load
ξ	reduction factor for unfavourable permanent loads

The load factors take into account traffic loads, but also wind and remaining loads. It must be noted that these load factors are based on rebuilding or rejecting. This was mentioned before and is an obstacle when looking into reusability. For the loads, different load models (LM1-LM4) are prescribed in which the LM1 is most used for viaducts (Weemaes, 2018).

Loads on concrete girder decks of viaducts act in vertical as well as horizontal directions. Both directions are influenced by multiple loads. These loads can be divided into 3 different aspects, summarized in Table 15. Each load has another effect on the design of the girders, which is taken up into the Eurocodes.

Table 15 Different loads acting on a viaduct

Loads	Vertical		Horizontal
Permanent	Self-weight	Dead loads	Prestressed
Varying	Traffic load		Traffic load
Extraordinary			Collision

What is clear from the distinction of this section is the big difference in the original purpose of the viaduct and therefore the girders. The girders that are taken into account are constructed over an era of more than 60 years, causing them to differ a lot in the design. Nevertheless, from Table 14 it is clear that most viaducts are designed with traffic class 60. Therefore, this class is taken into account in the next phase as original load class. This is in contradiction to the design standard Eurocode which is taken into account.

5.2.3. Connections

Two different methods are possible for the connections of the girders. The first one is the wet cast connection. This connection is made by cast in-situ concrete which monolithic connects the precast elements and the reinforcement. This is a very strong connection and after hardening of the connection both elements can be regarded as one. Causing it to be a clamped supported girder on the end. A disadvantage of this connection is the labour intensiveness. The other method of connection is based on a dry cast connection in which the connection consists of a simple support (placement on a rubber bearing). Advantages of this support is that it has less labour intensiveness and the connection is easier to make, since it has an instant connection. This also causes it to be easier demountable. The different type of connection therefore has an effect of the reusability of the girders. Both connection types require a different way of demounting and is therefore an important aspect for further design of the reused girders. Both types of connections have an effect of way of supporting and vice versa.

5.2.4. Supports

With a wet cast connection, as mentioned in the previous paragraph, a statically indeterminate structure is created. In this connection the girders can be seen as one big girder which reaches multiple spans. Concluding it to be regarded as a continuous element. This continuous element causes a hogging moment at the middle support and sagging moments in the spans. Therefore, the girders need top- as well as bottom reinforcement (TU Delft, 2022). When a dry cast connection is used, the deck can be regarded as simply supported which means only sagging moments occur in the midspans. Therefore, reinforcement in the bottom of the girder is enough. The way of supporting the structure, due to the chosen connection, has effect on the demount ability and therefore the reusability of the girders. For the simply supported girder are no problems foreseen, but when splitting the continuous girder there is. The moment line of the continuous girder will turn into the one of the simply supported girder and therefore lowering the maximum load bearing capacity. The different structures are shown in Figure 35. From the inventorying of the viaducts in the first phase of this research (next to own experience in the field) it turned out that most of the viaducts in the scope are constructed with dry cast connections. A rubber bearing is placed, which allows the girder to move freely in all horizontal directions.

Figure 35 Moment lines of continuously (left) versus simply (right) supported girder

5.2.5. Consequence classes

By assessing infrastructure works, the consequence classes have to be taken into account. These consequence classes are based on multiple criteria like building type and height. The purpose of these classes is to provide an appropriate level of safety and quality control. There are three classes defined based on consequences of loss of human lives and financial damage. The classes are shown in Table 16. RWS stated in the ROK that all its viaducts need to have CC3.

Table 16 Consequence classes

Class	Consequence	Examples of buildings
CC3	High consequence	Stadiums and concert halls for 5,000+ people, buildings storing hazardous substances
CC2	Medium consequence	Most multi-story residential and commercial buildings, hotels, hospitals, education establishments and car parks
CC1	Low consequence	Agricultural or storage buildings

5.2.6. Compressive layer

A viaduct constructed by girders is in need of a concrete top layer. If for example only inverted T-girders are used, there is no possibility to cross the viaducts. For this top layer a compressive layer is used. This is a (two-way) reinforced concrete in-situ cast layer. With the use of lost formwork, this layer can be casted. This compressive layer has multiple purposes, next to creating a monolith deck structure by connecting the girders. The most important are the spreading of the loads and increasing the load bearing capacity. Previously, this layer was designed with concrete with a quality of K300 (corresponding to C19/22). Currently this concrete layer is designed with class C28/35 or C30/37. These compressive layers are approximately 200-250mm thick (Spanbeton, n.d.-b; Haitsma beton, n.d.-b; Spanbeton, n.d.-a).

5.2.7. Environmental categories

Environmental categories are based on the surroundings of the concrete structure/element. These categories are based on three deterioration principles: Reinforcement, Reinforcement & concrete and concrete itself. Dependent on the situation, multiple categories can be applied. These environmental categories are described in the *CUR 118: Specialist maintenance techniques – concrete repairment* which refers to the standard *NEN-EN 206: Concrete specification.* A total of 18 environmental categories are divided into 6 main classes, shown in Table 17. For concrete girders environmental categories XC4, XD3, XD4 and XF2 are applied. (Spanbeton, n.d.-b)

Table 17 Environmental categories (CUR 118, 2015)

Deterioration principle	Main class	Explanation
No deterioration	X0	For concrete without reinforcement or in an indoor environment
Reinforcement deterioration	XC1-XC4	Corrosion initiated by carbonation
	XD1-XD3	Corrosion initiated by chlorides, different from seawater. For example de-icing salts
Deterioration reinforcement & concrete	XS1-XS3	Influence of salt originating from seawater
Deterioration concrete	XF1-XF4	Influence of changes in frost and thaw, with or without de-icing salts
	XA1-XA3	Chemical deterioration due to aggressive environment. For example sewage or fertilizer

5.3 Summary

A total of almost 2800 girders will become available for reuse in the upcoming 15 years. About 30% of them are inverted T-girders. From different experts it also turned out that about half of the viaducts that are built between the 1960s and 1980s are built with inverted T-girders (Vergoossen, 2021). Combining both these facts leads to a big impact when these girders are taken into account in the next phase. Two different inverted T-girders are most common, namely the ZIP and the HNP. Both of them are in principle designed the same way but with different load factors. This must be taken into account in a next phase. The specific girder types are HNP 75/98 and ZIP 700 that will be taken into account further.

Concerning the box girders, the actual inflow of available girders will come probably some years later. The biggest use of these girders was made in the 1980s and therefore are not yet already at their theoretical end of lifetime. However, the SDK 900 girders are well represented in the upcoming years. Next to that, the inability to not use these anymore in the original purpose makes them interesting for further research. Next to these SDK 900 girders, the most common box girder is the SKK-girder. From the analysis it turned out that the SKK 1300 variant is most common in the girders regarding the upcoming years. Unfortunately, this variant is designed for spans of about 40m. This is not in comparison with the determined scope from the previous sections, which stated to have spans of 20m. However, this 20m was an average of the total length divided by the number of supports. The length of 40m is still within the margin of the total span of 60m, but the different spans will not be equally divided. In practice this is almost never the case. Combining this and looking on further future perspective, this variant will also be taken into account further on. At last, these box girders provide an extra possibility into different design applications due to the 'hollow core'.

From the normal T-girders it is seen that there is a low availability (in contrast to other girders) in the near future. However, due to the fact that they aren't made anymore and also won't be used into the infrastructure works, they are highly interesting for the next phase of this thesis. Since they won't be used anymore it gives the perfect chance of reusing in a different function.

The infilled girders as well as the remaining girder types will not be taken into account in the design phase. The remaining girders are too specific and therefore will not reach an impact that was searched for regarding sustainability. As for the infilled beams, in this chapter it was stated that these can be seen as solid deck structures. Therefore, these girders fall outside the scope and also will not be taken into account anymore.

The cross sections of the girders that are taken into account for the next phase are summarized in Figure 36. The number of girders of these relevant girders is plotted in the graph in Figure 37, summed up to a total of 1177 girders. Lastly the dimensions and properties are summarized in Table 18.

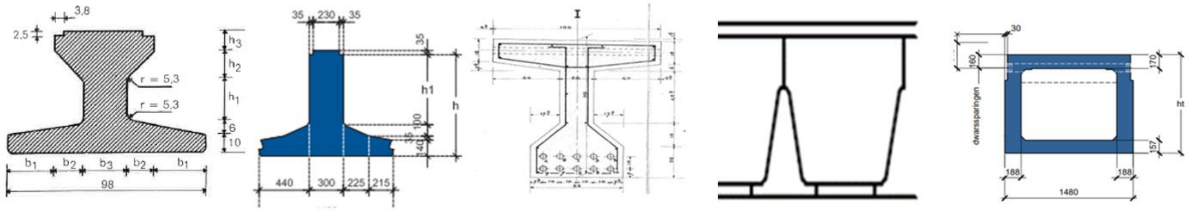

Figure 36 Cross sections of the girders that are taken into account

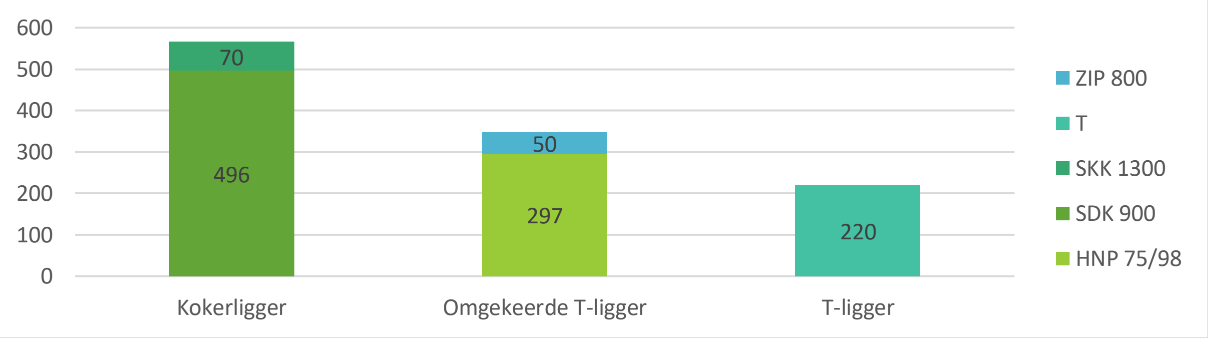

Figure 37 Graph of the girders that are taken into account

Table 18 Girder types with dimensions & properties (Virginia, 1991; Spanbeton, n.d.-a; Spanbeton, n.d.-d; Spanbeton, n.d.-b)

	Unit	HNP 75/98	ZIP 700	T	SDK 900	SKK 1300
Category		Reversed T-girder	Reversed T-girder	T-girder	Box girder	Box girder
Amount	[-]	297	84	220	496	70
Height	[mm]	750	700	1100	900	1300
Width top	[mm]	480	300	1000	895	1420
Width bottom	[mm]	980	1180	550	600	1480
Self-weight	[kg/m]	742	950	1213	1440	2420
Design span	[m]	25	25	25	30	52
Area cross section	* 10^3 [mm2]	16435	389	505,4	643	865
z_top	[mm]	388,3	475	488	483,5	635
z_bot	[mm]	361,7	225	612	419	665
Ib	* 10^6 [mm4]	7031,4	16230	2586,2	44000	188000
Wtop	* 10^6 [mm3]	18,1	34	5,3	91	296,1
Wbot	* 10^6 [mm3]	19,4	66	4,2	105	282,7
Concrete class		K600	C60/75	C53/65 or C40/50	-	C60/75
Prestressing steel		QP 190	QP 190	QP 170	Dywidag 12*0,52	FeP 1860
Reinforcement steel		QR 40	FEB 400/500	QR 40	-	FEB 400/500

6 Phase 3: Design applications

In the previous phase the complete scope is determined. From a large amount of girders a selection is made into 5 different types. These types are going to be taken into account in the following phase, the design applications. In this section, based on the girder types, different design applications will be conceived. At first the classification aspects will be determined to make a demarcation of the different applications in a later stage. These aspects are subdivided in criteria, based on circular strategies as described in Appendix G: G.1 Circular strategies. In this section this will be taken into further elaboration. With these classification aspects a comparison is made between reusing a girder or creating a new girder. This will provide a comparison in the later stage. Thereafter, design applications are conceived with the use of multiple interested persons with different backgrounds. On top of that, the applications are assessed with the help of experts. At final this leaves one design applications to look into in the next phase.

6.1 Classification aspects

To be able to classify the different design applications in a later stage, firstly the classification aspects need to be formed. In an earlier state of this research the specific definition of the value of high valued reusability is left open. In most cases, reusability is valued based on structural performance. However, reusability can be seen as depending on multiple categories. These categories each have their own contribution into the possibility and feasibility of reusing. The three main categories are: Structural, Environmental and Economic. This are the three main categories that are also taken into account in the evaluation of the SBIR: CiVi as mentioned in paragraph 2.3. The assessment of the design applications is done based on superficial level. For a real assessment, specific knowledge is required from the exact harvested girders as well as the exact new application/project. Moreover, this in detail elaboration is also required when designing new structures and thus does not imply more work. Concluding that a superficial level to start with will satisfy the needs. Leading to the assumption that the assessment will be done in the draft design phase. This phase follows the kickoff of a project and is used to visualize the different ideas and creating the first concept. After this phase the preliminary design phase is reached in which a more in-depth feasibility assessment is done.

6.1.1. Structural

The most important aspect of creating a new design application is the structural aspect. Is in fact the application of a harvested girder in a new function, possible? Is the girder good enough for the reuse, or is adaption needed? And if so, how much adaption is needed to guarantee a safe, new structure? Unfortunately, in advance specific aspects cannot be created for the design applications. The goal is to create design applications by thinking outside the box. Therefore, the structural assessment will be based on the structural feasibility of that particular design, following the Eurocode standards. To still be able to assess the design applications, multiple criteria based on structural feasibility are formed. These are based on talks with different students, experts, colleagues and researches. The main criteria for the structural aspect are: Structural safety, Residual lifetime, and Demount ability.

6.1.2. Environmental

Environmental aspect is the core of this research. As is mentioned at the start of this research, a transition into a CE is ongoing. These environmental aspects are based on the following main categories: Scalability, Environmental impact and value of Reusability. For the Environmental aspect the measurement becomes not only more important in the consideration process, but also in monitoring the circularity performances. Therefore, the environmental aspects need to be assessed in a uniform way. By providing a uniform assessment method, big steps for the transition into a CE can be made. Causing circularity to be determined quantitively to prevent the phenomenon of greenwashing. The aim is to reach high valued reusability, unfortunately, this is not always possible and therefore multiple circular strategies are composed.

6.1.2.1 *Circular strategies*

A circular strategy can be denoted as an action with an aim to reach circularity and to contribute to the CE (CB'23, 2020 - b). The goal of these strategies is to enlarge the possibility of circular usage of different materials/elements. A list of the circular strategies, including an elaboration is visible in Appendix G: G.1 Circular strategies. With these circular strategies two different measuring methods are composed.

6.1.2.2 *ECI and LCA methods*

Life Cycle Assessment (LCA) is a worldwide tool, defined by the standard ISO 14040. With this tool it is possible to determine environmental impacts through the stages of the life cycle of a product/element. However, there are multiple life cycles that can be taken into account, which are elaborated further in Appendix G: G.2 Life cycle assessment and Environmental cost indicator. With the use of different impact categories, an assessment can be made to determine what a constructed girder will 'take' from the environment. This way the best option can be chosen. Unfortunately, these aspects are all in different units. Therefore, the Environmental Cost Indicator (ECI) is created. This indicator translates the environmental 'costs' (such as CO_2 emission) into euros, so called shadow costs. This way a price tag can be given to multiple ideas/designs/elements to determine which one is the best. In environmental aspects as well as in costs. In case of the upcoming design applications, the ECI is moreover based on what to save or replace. The different applications are not particular decisive, but what did the original design cost in case of environment.

6.1.2.3 *Core measuring method*

From research with stakeholders and parties from the building section it turned out that the desired circular construction section can be divided in three core goals. These goals, which are in line with the previous mentioned topics, are focused on protecting three main aspects: the environment, the material supplies and the current value (CB'23, 2020 - b). These three main goals are divided in a total of seven indicators to measure circularity per main goals. Each indicator is followed by another subdivision which leads to a total of 34 aspects. This is further mentioned as the *core measuring method*, created by CB'23 and elaborated further in Appendix G: Improved measuring method. This method measures the impact of different circular strategies onto the three circular goals. It must be noted that this method does not provide a total summarized score due to the unknown underlying factors between the core goals. Per company it differs which goal is regarded as most important and thus has a higher valued factor.

6.1.3. Economic

In the end, the economic aspect is the final aim and the crucial issue in this world. Therefore, a big and important aspect to take into account for the assessment of a design application. If the design application is possible in a structural point of view, good for the Environment, but it costs ten times more than using new materials, no one is going to apply this application. For this Economic aspect multiple costs will be taken into account to compare differences. These differences will be elaborated later on. The two main categories for economic aspects are the potential to sales market and the possibility of reusing in a next life cycle.

6.2 Reusing a girder in the same function

The goal is to make a valid conclusion on the possibility of a specific design application. Therefore, a comparison needs to be done. This comparison consists of two aspects. The first one is comparing the reused element with new, raw materials. The second one is the comparison between reusing in another function and reusing in the same function. With this comparison a conclusion can be made regarding the aspect high valued reusability. Since, in first instance, every interviewee has negative thoughts on reusing girders in another function. In their eyes it is regarded as low valued reusability and we must aim for a one-on-one reusability. Or, in other words, reusing a girder again as a girder since this element is optimized for this function. However, these thoughts are fully based on a structural aspect. In the previous section it is stated that beneficial reuse is dependent on a total of three different aspects. To be able to make a valid comparison, this section will focus on reusing a girder in the same function.

To do so, the first step is to visualize the differences between constructing a new girder from scratch (raw materials) and reusing an 'old' girder. Or in other words, comparing Building As Usual (BAU) with reuse. To make this comparison, the life cycle from cradle to gate is taken into account (see Appendix G: G.2 Life cycle assessment) for BAU. For a reused girder the lifecycle from harvesting till re-applying is taken into account. The difference here is the way of receiving or retrieving the basic materials. The data to compare is shown in Table 19 on the next page. The quantified comparison will be based on the aspects economic and environmental.

Due to a not specified project or an exact defined reuse plan, a structural consideration cannot be done into detail. This means that some cells in Table 19 are left blank. However, important aspects regarding structural assessment are derived. In the environment aspect field it can be seen that the ECI value of an inverted T-girder is shown. This is done based on the standard which is given in the environmental database. This database contains multiple standard elements combined with their ECI values. Based on multiple researches and research into different elements in this database, it is determined that about 75-85% of the ECI score is based on the manufacturing phase. Therefore, an assumption is made that the ECI score for a reused girder can be set to 20% of the total. This is also proven by CE Delft (Bruinsma & Bijleveld, 2021). For the environmental category, the focus is on the total euros (in which all the aspects are taken into) as well as the CO_2 emission particular. These are considered the two main aspects of this category.

Table 19 Criteria values comparing girder BAU with reuse

Main criterium	Criterium	New girder	Unit	Reused girder	Unit	Source
Economic	Manufacturing	€ 1.000,00[12]	$/m^3$	€ 0,00	-	(Herder, 2022)
	Demolishing	€ 37,51	$/m^3$	N/A	-	(Peereboom, 2021)
	Sawing construction	N/A	-	€ 120,00	/m width	(Peereboom, 2021)
	Sawing deck	N/A	-	€ 70,00	/m length	(Peereboom, 2021)
	Repairing	N/A	-	€ 500,00	$/m^2$	(Teeuw & Dijcker, 2017)
	Concrete compressive layer demolishing	€ 208,73	$/m^2$	€ 208,73	$/m^2$	(Peereboom, 2021)
	Research quality	€ 0,00		€ 1.000,00	/girder	(Nebest B.V. Internal document, 2021)
	Applying on location	N/A[13]		€ 1.100,00	/girder	(Span & ter Meulen, 2021)
	Transport	N/A[14]	-	€ 1,48	/km	(Span & ter Meulen, 2021)
	Using Storage hubs	N/A[15]	-	to be determined	-	-
	Adjusting	N/A	-	to be determined	-	-
Structural	Effort	Already optimized	-	Extra research required	-	-
	Standards	Existing	-	Not yet	-	-
	Damage	N/A	-	Dependent	-	-
Environmental	MKI score	100%	-	20% Of new material	-	(Nationale Milieu Database, n.d.)
	Prefab girder inverted T - 25m	€ 45,55	/m	€ 9,11		(Nationale Milieu Database, n.d.)
	Concrete compressive layer	€ 17,33	/m	€ 17,33	/m	(Nationale Milieu Database, n.d.)
	Availability	Infinity		799		MIRT Research
	CO2 manufacturing	300	kg CO_2/m	0	kg CO_2/m	(Nationale Milieu Database, n.d.)
	CO2 transport	28	kg CO_2/m	28	kg CO_2/m	(Nationale Milieu Database, n.d.)
	CO2 building phase	10	kg CO_2/m	10	kg CO_2/m	(Nationale Milieu Database, n.d.)
	Residual lifetime	80-100 years	-	Based on research	t = 80 – (2022– construction year)	

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[12] This concludes the total process from cement paste up to placement on location

[13] Included in constructing costs

[14] See footnote 11

[15] On site of the concrete factory

In the Dutch national database, three prefab girders are defined varying in span up to 25, 35 or 45 meters. From the previous section it is determined that the most common viaducts are consisting of 3 lanes and with 3 spans of each ~20m. This most common viaduct will be used to determine the difference between the girder as reuse and BAU. The ECI value of the inverted T-girders up to 25m are used, which corresponds to the ZIP 700 (see graph Appendix H: H.1 Graph ZIP girders). For this viaduct a total of 36 girders is required. Based on this amount the balance can be made. This balance is shown in Table 20 and the underlying math is visible in Appendix H: H.2 Maple sheet comparison BAU and Reuse. In this overview the costs (for constructing and shadow based) are taken into account. However, since they apply to both cases, they are not required to take into account in a next comparison. The same applies for the CO_2 emission in the transport and building phase. Based on this first visualization it is very promising to look further into reuse of concrete girders, since a total of almost €150.000 and 6000 kg CO_2 can be saved by reusing 36 inverted T-girders. This means that per reused girder about €4200,- and 170 kg CO_2 emission can be saved. Referring this back into the more than 2700 girders that are on the planning to be demolished, a difference can be reached of about €11.6 million euro's[16]. In Table 20 it is visible that the most savings is done based on manufacturing the girders. However, it must be noted that not all aspects are taken into account. For example '*Adjusting*', which is dependent on the state of the girder and the damage that has been done. This can in a later stage influence the total savings.

Table 20 Cost comparison of an inverted T-girder between BAU and reuse

Main Criterium	Criterium	Girder BAU	Girder Reuse	Difference
Economic	Manufacturing	€ 280.080,00	€ 0,00	€ -280.080,00
	Demolishing	€ 0,00	€ 57.120,00	€ 57.120,00
	Adjusting	€ 0,00	€ 0,00	€ 0,00
	Top layer	€ 177.337,01	€ 177.377,01	€ 0,00
	Research quality	€ 0,00	€ 36.000,00	€ 36.000,00
	Applying on location	€ 0,00	€ 39.600,00	€ 39.600,00
Environment	Transport	€ 0,00	€ 0,00	€ 0,00
	Prefab girder inverted T - 25m	€ 32.796,00	€ 6.559,20	€ -26.236,80
	Concrete top layer	€ 14.723,57	€ 14.723,57	€ 0,00
	Availability [number of girders]	36	50 in 2026	-
	CO2 Manufacturing [kg CO_2]	6000	0	-6000
	CO2 Transport [kg CO_2]	560	560	0
	CO2 Building phase [kg CO_2]]	200	200	0
	CO2 Total [kg CO_2] **Total costs [€]**	**6760** **€ 504.936,58**	**760** **€ 357.576,58**	**-6000** **€ 147.360,00**

For the structural aspect it is determined, based on feasibility research from RHDHV (van Eck, 2021), that reusability of physical unchanged concrete inverted T-girders is technically feasible. For this research RZ 700 girders are used which are dimensioned according to the VB 1974 standard. These RZ 700 girders correspond with the ZIP 700 girder type. With the use of the NEN 8700, section renovation, it is proven that these girders can be reused. However, in the previous section it is shown that multiple different girders are taken into account. To determine the possibility of reusability, these girders with their structural aspects are therefore analyzed theoretically to inventory their structural challenges as seen in Table 21. Before being able to determine the structural reusability, the girders must be assessed on moment capacity, shear force capacity, shear stress capacity, anchorage check and the time dependent prestress losses (van Eck, 2021). These prestress losses occur due to creep, shrinkage and relaxation.

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[16] Hypothetical approximation with assuming all girders are the same

Table 21 Structural challenge regarding scope girders

Girder	Structural challenge(s)
HNP 75/98	Designed with standard GBV 1962; Not designed with stirrup reinforcement for shear force; Designed for load class 60; Concrete quality of K600, corresponding to ca. concrete class C50/60.
ZIP 700	Shape of the pre-tensioned steel affects the demount ability of the girder; Prestressed with pre-tensioned steel: Force is transferred by steel-concrete bond; During the years due to elastic deformation a loss of prestressing force occurs.
T-girder	Since the requirements for collision have been improved over the years, these girders are not made any more for viaducts.
SDK 900	Underwent development and thus this type isn't used anymore. Not much is known from this type.
SKK 1300	Hollow cross section and thus lower shear force resistance. Therefore both ends of the girders are solid. This has influence on the demount ability; Another aspect of demount ability is the prestressed post-tensioned girders. These must be released from tension, before cutting them.

6.3 Brainstorm

The goal of this thesis is to create design applications for the reuse of girders, with a focus on different functions. The proverb 'A fool can ask more questions than seven wise men can answer' is in this case used as a starting technique. To be able to come up with original, creative and new design applications a brainstorm session has been organized with people who are broad-minded. Next to that the focus area is of course reusability and circularity. Combining these aspects, the two criterium for the brainstorm guests are made.

6.3.1. Invited guests

Due to the Covid-19 pandemic, a brainstorm session is held within Microsoft Teams. Since with this program, only one person can talk at the time, a maximum of people for this session determined. It is aimed to be limited to about 20 people to prevent it becoming a chicken coop in where everyone talks at the same time. The approach of this meeting was to at first make the participants familiar with the subject. By pointing out the importance of reusability, the discussion was started. This meeting is done in week 6 of 2022, which corresponds to the week of circular economy. In this week multiple companies and organizations held events like lunch lectures to talk about circularity. The goal was to spread awareness as well as sharing information and studies to prevent everyone inventing the wheel over and over again. The participants are anonymously shown in Table 22 with their corresponding company and job function. The people are selected based on broad-minded and with interest in circularity, reusability and innovations.

Table 22 Invited guests Brainstorm session

Company	Profession
Province Noord-Holland	Project leader and advisor innovations
Nebest	Product owner and innovation manager
Arup	Circular designer and bridge engineer
Nebest	Project employee 3
Royal HaskoningDHV	Project manager bridges and circularity
Stichting MRPI	Director - Sustainability & structural design
TU Delft en Heijmans	Graduate Building Engineering
Avans hogeschool	Graduate Civil Engineering

Breda University of Applied Sciences	Student Built Environment - Mobility
Studente Mobiliteit BUas	Student Built Environment
Bevepro	Director Engineering and commerce
Royal HaskoningDHV	Business development manager
Compass Infrastructuur Nederland	Manager strategic and innovation
Strukton Civiel	Graduate Business administration and engineering
Avans hogeschool	Graduate Civil Engineering
Nebest	Graduate Building Engineering
Nebest	Project leader IAK
RWS	Government Procurement Trainee
RWS	Advisor circular economy

6.3.2. Overview

During the brainstorm session, the specific girder types have not been elaborated yet. This caused an open-minded brainstorm, without limitations. Only the different girder types were made clear on which to focus on, since the goal was to match the current girders into new possibilities. Quite soon, during the brainstorm, the focus of design applications was split into two main categories. The first category was focusing on the current bearing capacity of the girders. The second one was focusing on big, robust and heavy girders. Or in other words: strength versus mass. Both these categories lead to multiple very different design applications, which are shown in Figure 38. In the Table 23 the applications from the sketches are noted with their corresponding numbers.

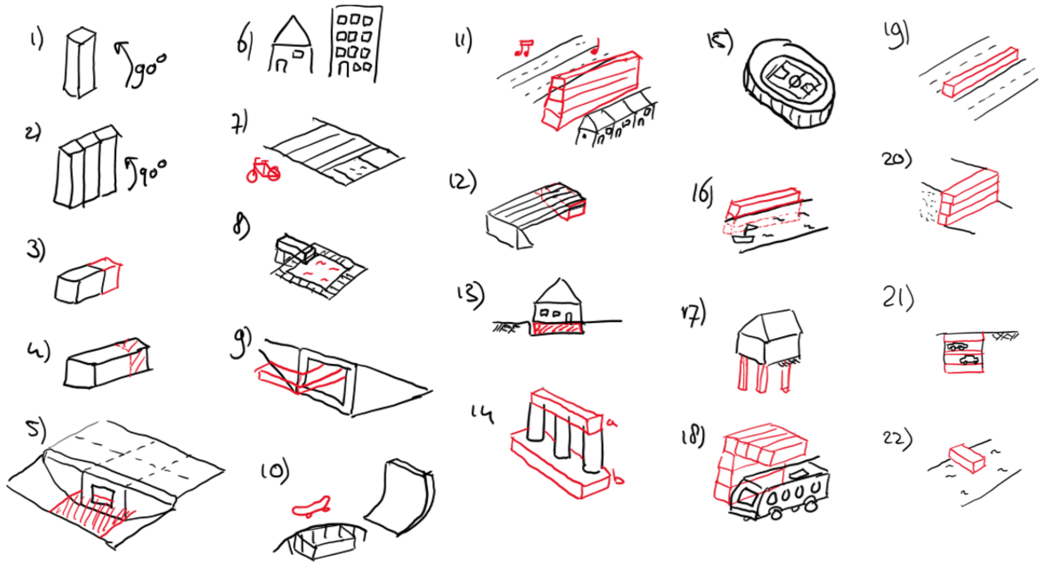


Figure 38 Sketch drawings of Brainstorm output

Table 23 Design applications from Brainstorm session

1. Column	6. (non)-residential structures	11. Sound barrier	15. Stand in a stadium	19. Traffic barrier
2. Wall (combined multiple girders)	7. Bicycle bridge	12. Abutment	16. Quay wall	20. Retaining wall
3. Elongating	8. Diving board in a pool	13. Foundation	17. Foundation pile	21. Parking garage
4. Shortening	9. Wildlife tunnel	14. Transverse girder	18. Roof/ Canopy	22. Pier
5. Culvert	10. Skatepark			

6.4 Expert Judgement

The output of the brainstorm session includes 22 different applications. From this total cloud of ideas, a demarcation needs to be done to determine which applications have a possibility for realization. This demarcation is done with the help of experts in three different knowledge fields, corresponding to the earlier divided categories: Environment, Economic and Structural. Before going into these expert meetings, the total applications have been reduced to 18. The applications 'elongating' and 'shortening' (number 3 and 4) will not be seen as a particular application, but as a way to possibly fulfill an application. Where shortening already automatically happens by demounting certain girder types, elongation is not that easy as it seems. Concrete girders are designed with an optimal height/length ratio. A rule of thumb for calculating the maximum moment in a girder span is $M = \frac{1}{8}ql^2$. The length squares in the formula and therefore has a greater effect on the occurring moment. Another application that has been removed is reusing as a wall (number 2). This application can be seen as the same as the column application but then multiplied. The final application that didn't make the cut is the diving board in a pool (number 8). This application is seen as the same reusing level as a skatepark.

6.4.1. Grading applications

The applications of course vary widely. In application as well as possibility. Therefore, a reasonable top 5 will be determined to increase a chance of possible reusability. To be able to choose a top 5 of design applications, the applications need to be assessed. This is done with a multiple criteria design analysis (MCDA). With this analysis it is possible to assess aspects which have nothing in common. Which is done by using multiple criteria. These criteria are based on the circular strategies, which are elaborated in Appendix G: . These strategies are furthermore rated based on the core goals of the core measuring method from CB'23. This grading can be found in Appendix G: G.3.2 Circular strategies on core indicators. Based on the highest grading criteria, the circular strategies are translated into criteria for grading the different design applications. These criteria are translated into a score sheet in which the experts of different knowledge fields could give a score from 1 to 5. This sheet is visible in Dutch in Appendix I: Score sheet design applications. The criteria are written in such a way that the higher the score (5), the better it is for reusing. The application with the highest score is then seen as the best application.

Table 24 Score criteria based on circular strategies

Main category	Circular strategy	Criterium
Environment	Reusability	Way of reuse
	Scalability	Amount of impact
	Upgradeability	Addition needed of (primary) materials
	Adjustability	Deviation of original function
	Durability	Life cycle
Structural	Scalability	Structural challenge
	Downgrade ability	Damage dependency
	Removability	Influence on harvesting elements
	Demount ability	Demount ability new cycle
	Durability	Residual lifetime
Economic	Demount ability	Possible to extra life cycle
	Adjustability	Extent of adjustability
	Accessibility	Accessibility
	Availability	Potential sales market

6.4.2. Experts

Where the grading criteria have been determined in the previous paragraph, the next step is to verify the applications with experts. As mentioned before, this has been done on three different main categories and therefore this verification is also done in multiple sessions. The aim for this expert judgement was to reach 4-5 different participants per category. This way a discussion can be created by experts with different infield practice, but with the same background knowledge. Unfortunately, this number of participants is not achieved for the economic part. Therefore, this score is multiplied by $\frac{3}{4}$ to receive a slightly more average grading. The background of the participants of the expert judgements are summarized anonymously in the Table 25. Since the participants did not know each other either, multiple discussions opened up with sharing different experiences. On top of that, none of them yet experienced reusability in focusing on another function.

Table 25 Participants expert judgement

Main category	Company	Profession
Structural	BAM Infraconsult	Design leader civil engineering
	Ingenieursbureau Amsterdam	Concrete engineer
	RWS	Technical advisor circular structures
	Ingenieursbureau Amsterdam	Specialist structural engineer
Environmental	Stichting Insert	Circular project employee
	Nebest BV	Sustainable concrete
	Dura Vermeer	Circular Urban Mining
	SGS Intron	Senior consultant sustainability
Economic	Strukton	Contractor big maintenance bridges

Before these expert judgements could take place, the sketches from Figure 38 have been updated into more advanced images. Since a picture says more than a thousand words, these images created a better understanding of the subject. This way the purpose of the new design application was clear and the focus of the meetings could be on the discussions. These images are numbered in Figure 39. The numbers correspond to the application as described in Table 26. Both the figure and the table are visible on the next page. It must be noted that these are the images used for the expert judgement as an impression. In most of the images, the box girder is used to visualize the reused girder. However, for different applications, multiple girders can be used and for some applications it is also possible that not all the previously determined girders are applicable. Next to that, different applications require different methods to be able to use the design application and require some out of the box thinking. For example, to rotate the girders 90° in design application 11, the retaining wall.

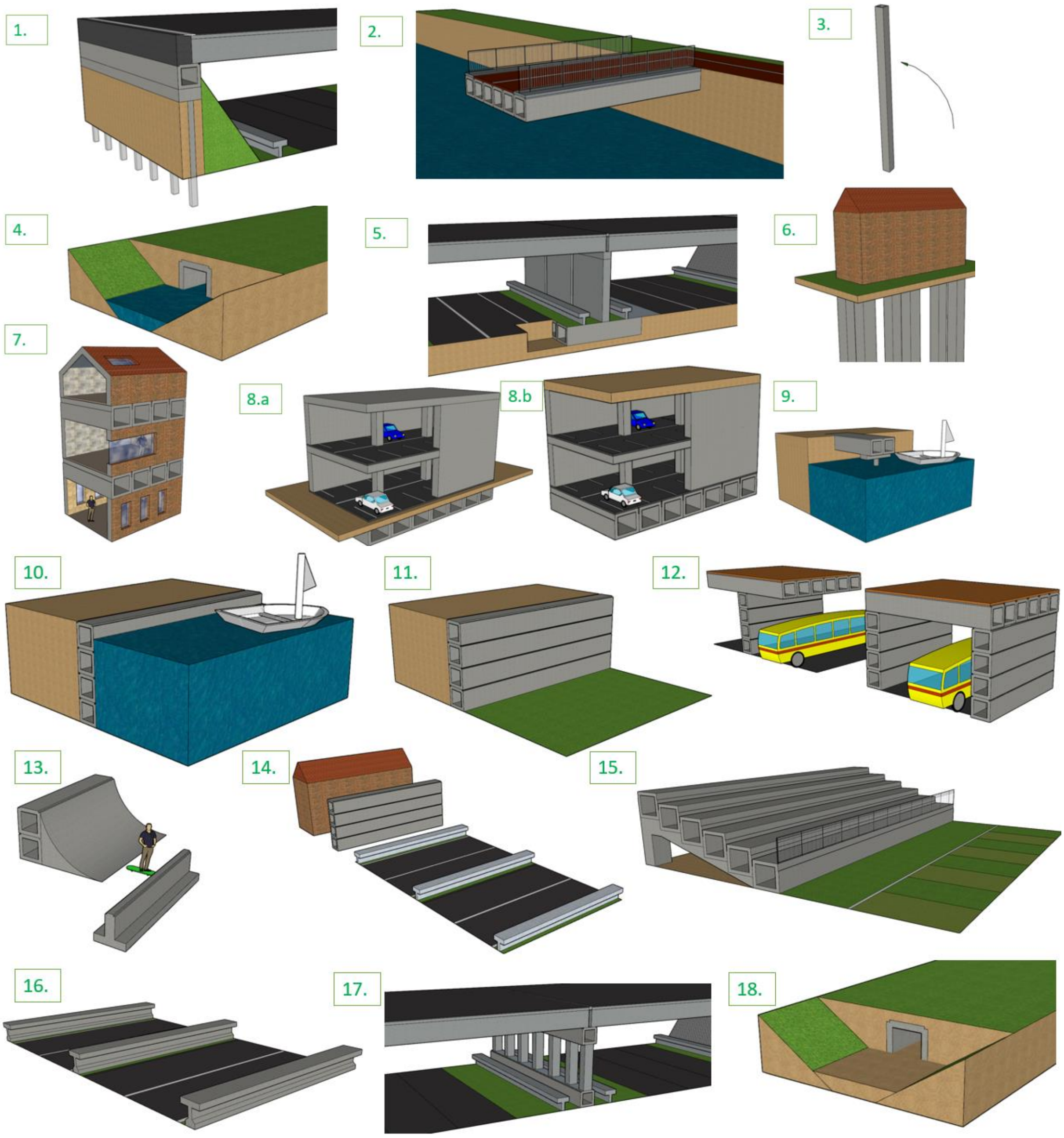
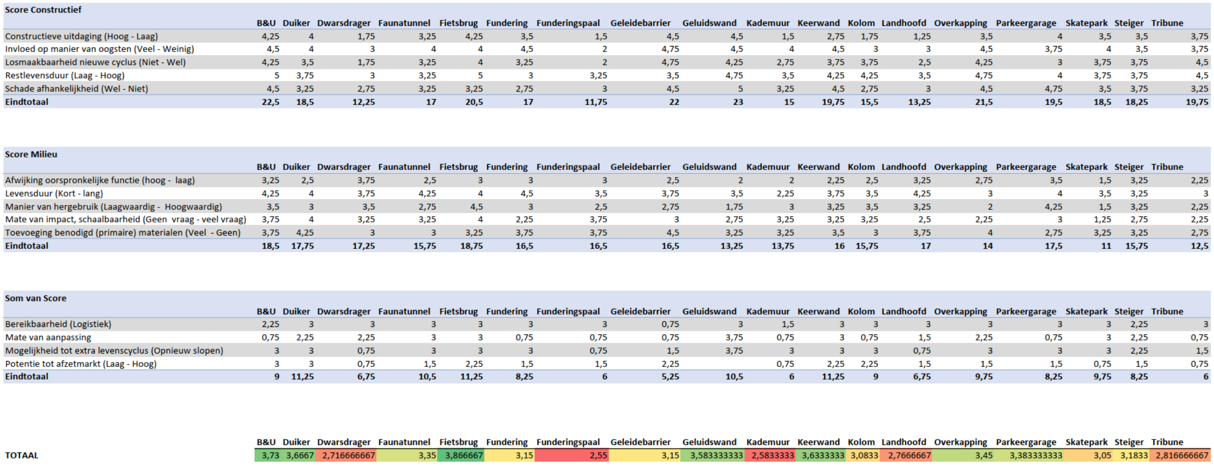


Figure 39 Numbered design applications, drawn schematically with box girders

Table 26 Design applications summary

Design application	Design application
1. Abutment	10. Quay wall
2. Bicycle bridge	11. Retaining wall
3. Column	12. Roof/ Canopy
4. Culvert	13. Skate park
5. Foundation	14 Sound barrier
6. Foundation pile	15. Stand
7. (non-) residential	16. Traffic barrier
8. Parking garage a. Above ground b. below ground	17. Transverse girder
9. Pier	18. Wildlife tunnel

With the help of the experts, the assessment is done for the design applications. Each application has been given a score on the specific main category and (dis)advantages have been discussed. Having an open discussion about the applications and combining multiple expert knowledge, lead to new insights and ideas on how to reuse concrete girders in a good way. This followed into the grading of all the applications. Each expert graded an application on 4 or 5 different criteria (depended on the expertise). Per criterion a total grade was obtained by adding the grades of the different participants. Next up, an average grade was obtained by dividing the total grade of that criterion by the number of experts. This follows in the fact that each application has 4 or 5 average (criterion) grades per main category. Afterwards, these 4 or 5 grades are added together and then divided by the number of criteria to give one specific grade per category. Concluding in three different scores (one per main category). In this research each aspects counts just as much as the other since there won't be any benefit from a particular rating. Therefore, the weighting factors of each category is $\frac{1}{3}$. As final, the overview scheme as presented in Figure 40 is created. This scheme is enlarged presented in Appendix J: J.1Appendix I: , with the addition of the previous mentioned text in an elaborated example Appendix J: J.2. Besides the grading aspects, each application also had its (dis)advantages or other possibilities. For example, some applications are (from experts' view) more likely to been seen as a temporary solution, instead of having a high long term reuse potential. These discussion notes were on top of the already mentioned criteria and are therefore summarized in Appendix J: J.3. An interesting approach to note is that all the experts agreed on the fact that in basic, all the possibilities of reuse are better than crushing the concrete into debris for recycling. After all the grading is done and the summarization of the dis(advantages) a top 5 for reuse design applications has been created.



Score Constructief

	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
Constructieve uitdaging (Hoog - Laag)	4,25	4	1,75	3,25	4,25	3,5	1,5	4,5	4,5	1,5	2,75	1,75	1,25	3,5	4	3,5	3,5	3,75
Invloed op manier van oogsten (Veel - Weinig)	4,5	4	3	4	4	4,5	2	4,75	4,5	4	4,5	3	3	4,5	3,75	4	3,5	3,75
Losmaakbaarheid nieuwe cyclus (Niet - Wel)	4,25	3,5	1,75	3,25	4	3,25	2	4,75	4,25	2,75	3,75	3,75	2,5	4,25	3	3,75	3,75	4,5
Restlevensduur (Laag - Hoog)	5	3,75	3	3,25	5	3	3,25	3,5	4,75	3,5	4,25	4,25	3,5	4,75	4	3,75	3,75	4,5
Schade afhankelijkheid (Wel - Niet)	4,5	3,25	2,75	3,25	3,25	2,75	3	4,5	5	3,25	4,5	2,75	3	4,5	4,75	3,5	3,75	3,25
Eindtotaal	**22,5**	**18,5**	**12,25**	**17**	**20,5**	**17**	**11,75**	**22**	**23**	**15**	**19,75**	**15,5**	**13,25**	**21,5**	**19,5**	**18,5**	**18,25**	**19,75**

Score Milieu

	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
Afwijking oorspronkelijke functie (hoog - laag)	3,25	2,5	3,75	2,5	3	3	3	2,5	2	2	2,25	2,5	3,25	2,75	3,5	1,5	3,25	2,25
Levensduur (Kort - lang)	4,25	4	3,75	4,25	4	4,5	3,5	3,75	3,5	2,25	3,75	3,5	4,25	3	4	3,5	3,25	3
Manier van hergebruik (Laagwaardig - Hoogwaardig)	3,5	3	3,5	2,75	4,5	3	2,5	2,75	1,75	3	3,25	3,5	3,25	2	4,25	1,5	3,25	2,25
Mate van impact, schaalbaarheid (Geen vraag - veel vraag)	3,75	4	3,25	3,25	4	2,25	3,75	3	2,75	3,25	3,25	3,25	2,5	2,25	3	1,25	2,75	2,25
Toevoeging benodigd (primaire) materialen (Veel - Geen)	3,75	4,25	3	3	3,25	3,75	3,75	4,5	3,25	3,25	3,5	3	3,75	4	2,75	3,25	3,25	2,75
Eindtotaal	**18,5**	**17,75**	**17,25**	**15,75**	**18,75**	**16,5**	**16,5**	**16,5**	**13,25**	**13,75**	**16**	**15,75**	**17**	**14**	**17,5**	**11**	**15,75**	**12,5**

Som van Score

	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
Bereikbaarheid (Logistiek)	2,25	3	3	3	3	3	3	0,75	3	1,5	3	3	3	3	3	3	2,25	3
Mate van aanpassing	0,75	2,25	2,25	3	3	0,75	0,75	0,75	3,75	0,75	3	0,75	1,5	2,25	0,75	3	2,25	0,75
Mogelijkheid tot extra levenscyclus (Opnieuw slopen)	3	3	0,75	3	3	3	0,75	1,5	3,75	3	3	3	0,75	3	3	3	2,25	1,5
Potentie tot afzetmarkt (Laag - Hoog)	3	3	0,75	1,5	2,25	1,5	1,5	2,25		0,75	2,25	2,25	1,5	1,5	1,5	0,75	1,5	0,75
Eindtotaal	**9**	**11,25**	**6,75**	**10,5**	**11,25**	**8,25**	**6**	**5,25**	**10,5**	**6**	**11,25**	**9**	**6,75**	**9,75**	**8,25**	**9,75**	**8,25**	**6**

	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
TOTAAL	3,73	3,6667	2,716666667	3,35	3,866667	3,15	2,55	3,15	3,583333333	2,5833333	3,6333333	3,0833	2,7666667	3,45	3,383333333	3,05	3,1833	2,816666667

Figure 40 Summary scoring sheet design applications

6.4.3. Highest graded design applications.

If we zoom in on Figure 40, and plot a graph of the total scores of all the applications, Figure 41 is obtained. By using the graph next to the color scheme, it is visible that there is a clear top 5 of possible design applications, which are highlighted in blue in the graph. These 5 applications will be looked into a bit deeper to define a design application which looks the most interesting. For these top 5 design applications multiple girders can be applied. However, just like the schematic images, the box-girders are used. The final remaining application will then be looked into in detail in the final phase.

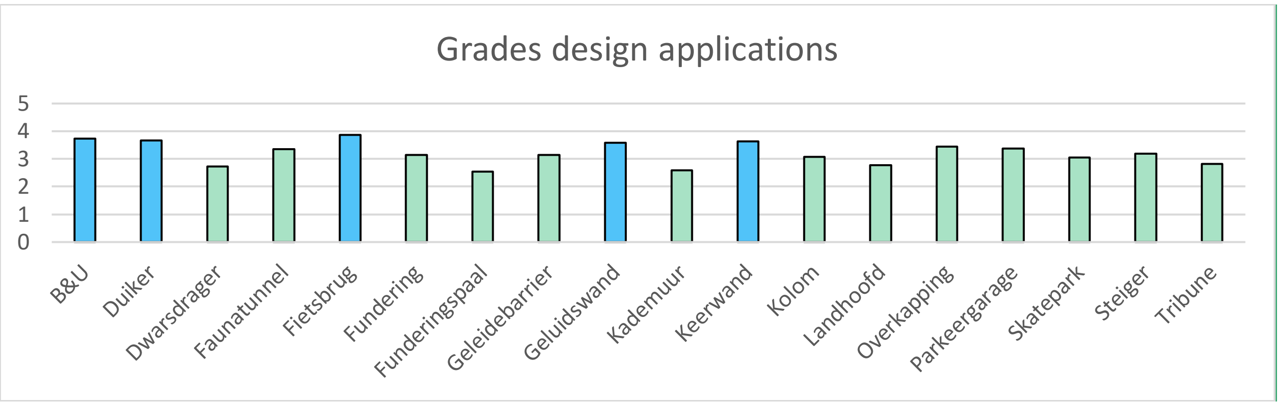


Figure 41 Graph grading overview design applications

6.4.3.1 *Bicycle bridge*

Figure 42 Design application bicycle bridge

A bicycle bridge (or in Dutch: *Fietsbrug*) is a bridge designed for bicycle traffic, pedestrians and if the width allows it, emergency services like ambulances. In theory it is designed in the same way as a viaduct. The girders need to span a certain distance in which a load transfers from the top, horizontally to the supports. Therefore, the girder is loaded in the same way and will also deflect in the same way. However, from Table 14 (page 34) it is seen that during the years the standards made a division in the load on heavy traffic bridges compared to bicycle bridges. This difference is also visible in the Eurocode, which prescribed a distributed load of 5 kN/m^2 for pedestrian bridges versus 9 kN/m^2 for viaducts (this is a difference per square meter of about 400 kilograms). This 5 kN/m^2 is mostly based on the weight of large pedestrian groups, since these are determinate. The load scheme and the deflections are shown in the Figure 43. For illustration of the differences/comparison a bicycle is used versus a car as applicated load.

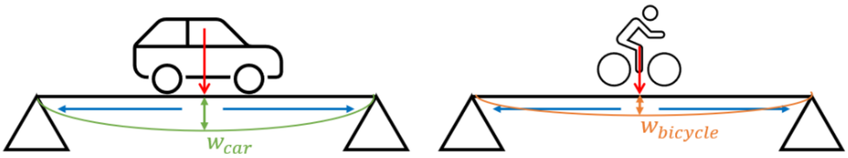


Figure 43 Deflection scheme viaduct versus bicycle bridge

So, in first instance it seems really interesting to reuse concrete girders from viaducts into bicycle bridges. Certainly, when the harvested girders encountered some damage and will not be able to fulfil the requirements of a viaduct anymore. Or when a girder type is harvested that doesn't fulfill the current standards anymore, like a HNP girder. However, over dimensioning plays a big role in this decision. Girders which were designed for almost 2 times more load, will be way bigger and thus heavier than needed. This will translate into more (heavier, bigger) supports and/or foundations. These elements will then require more 'new' materials to be used for being able to maintain the extra load of the over dimensioned girders. In the end stage, the reusability of these girders will then cause the same or maybe even more materials than when 'normal' designed girders were used. Besides, bicycle bridges are also already designed with different materials to obtain lighter (and more esthetically) bridges.

Combining all this, this application won't be elaborated further. However, as mentioned in an earlier paragraph, the reuse of a concrete girder as a new girder will be taken into account, meaning that this bicycle bridge application will therefore still be partially elaborated.

6.4.3.2 *(non-)residential buildings*

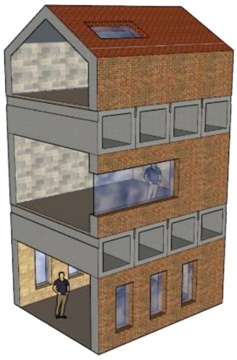


Figure 44 design application (non-) residential buildings

Within (non-)residential buildings multiple different structures are defined, based on two main categories. Residential buildings can be split into: *detached houses; semi-detached houses; serial houses* and *apartments/multi-family houses*. For non-residential buildings the building types are: *company buildings; offices; educational buildings; care buildings* and *stores* (Arnoldussen, et al., 2022). Each building has their own specific standards and dimensions, but they are all depended on the Environmental Performance Buildings (EPB) which translates to MPG in Dutch (*Milieu prestatie gebouwen*). This EPB is part of the total ECI. Where the ECI determines the total life cycle and structure, the EPB of a building is expressed in euros/m^2/year. Since January 2013, this EPB calculation is an obligatory part in the request of an environmental permit, which translates to the permit to construct a building which possibly causes nuisance to the environment (RVO, n.d.). From July 2021 a change in the Bouwbesluit occurred, which states that the limit of this EPB is 0.8, instead of 1.0. The goal is to halve this limit to 0.5 by 2030 (RVO, n.d.). It is clear to see that the requirements for these buildings are stricter than for the infrastructure. This also translates in lower materials (elements) usage for the structures. However, reusing materials/ elements does have a positive influence on a lower EPB score.

For residential buildings in general the demand is currently very high, due to the housing shortage. In contradiction to non-residential building of which is stated that the production of these buildings will all decrease in the upcoming years. With care buildings for example, the production is quite low due to the limited budgets and the production of the educational buildings is low due to the decrease inflow of new students (Arnoldussen, et al., 2022).

This increasing demand of residential buildings makes it of course interesting to look into the possibility of reusing materials. Unfortunately, these structures also involve some additional design aspects. Starting with the span of the buildings. The average spans are in a range of 5-10 meters (exceptions excluded), which are half or even a fourth of the average spans of viaduct girders of 20 meters. This therefore brings extra difficulties in the demounting (sawing) of the girders. In serial housing these girders have the possibility to be designed in a continuous way, to acquire more need of bigger spans. However, this causes a hogging effect in the middle of the beam (as explained in paragraph 5.2.4). This requires reinforcement in the top of the beam, which currently is not present. For non-residential buildings the span differs per category. In offices spans of about 7-10 meter can be realized (which still does not take the previous mentioned problem away) where in stores, care and educational buildings bigger spans can be required. Unfortunately, these are in a lot of cases supported by columns instead of walls. This involves extra difficulties regarding supporting girders. For example, an extra transverse girder is required which in their turn increase the building height. Due to the specific building heights of buildings per floor, the requirement is to keep the floor heights as low as possible.

Next to the stricter requirements, the difference in applied loads is also an issue. In Appendix J: J.4 Vertical variable loads on floors and roofs, a table is shown. In this table the vertical variable loads on floors and roofs are described, divided in different categories corresponding to the earlier mentioned building categories. From this table it is clear to see that the distributed- as well as the concentrated vertical load is way lower than the design loads of viaducts. With simple rules of thumb, a first estimation of beams can be determined. On average the height of a beam in a (non)-residential building equals $h_b = \frac{1}{20} * span$. For a house with a span between 5-10m a height of 250-500mm is required. Translated to the inverted T-girders from the viaducts, this translates into ZIP 500 as lowest type. This is way lower than the average girder type, which therefore causes a big amount of over dimensioning in the building. This then translates into the use of bigger (stronger) supports and eventually the foundation.

Although the sales market seems quite interesting regarding residential houses, this application won't be used for the final stage of this research. The main criteria is the already fully designed building industry in which minimum materials is used to provide as slender as possible elements. The viaduct girders can be seen as a bull in a China shop if they will be reused in houses. They are too big and will only cause either additional damage or a lot of adaptions to supports and foundations that the point of lessen materials will be missed. If the load bearing capacity doubles per foundation pile, the area of this pile almost also doubles.

6.4.3.3 *Retaining wall*

A retaining wall (or *Keerwand* in Dutch) is a wall which provides stability of the soil (or water) pressure of a higher elevated ground level. Examples of this application can be a specific hill or a dike. The failure of this structure can be split into four different categories: Failure based on total shearing, rotation, particular shearing or failure of the foundation. These are illustrated in Figure 46 from top left to bottom right. For the illustration in Figure 45 as well as the failure scheme, box girders are used.

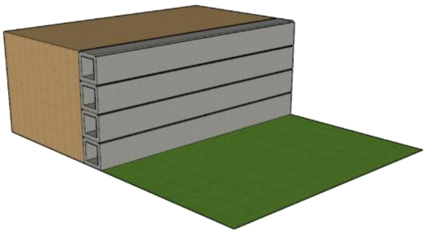


Figure 45 design application retaining wall

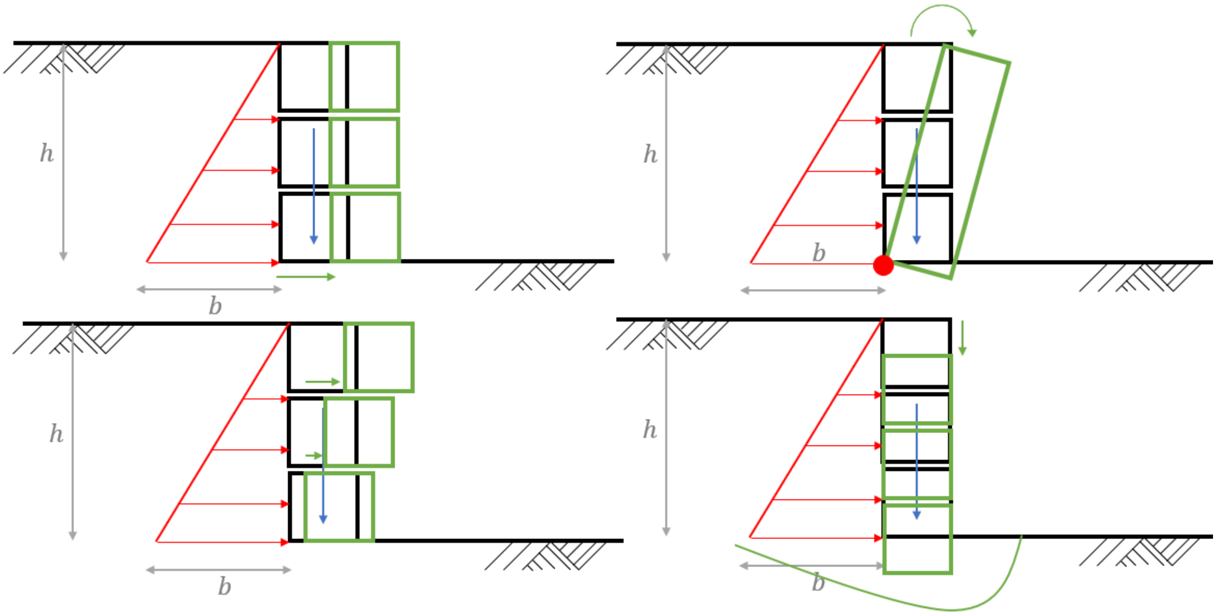


Figure 46 Failure schemes retaining wall

Currently new retaining walls are designed in an inverted T- or L-shape. This limits the chance of failure of rotation, since the soil then not only causes a horizontal pressure, but also a vertical one creating an opposite momentum. Unfortunately, this shape isn't there for all the harvested girders and thus the shear failure needs to be prevented with either sufficient friction or an additional intermediate layer. The friction coefficient of concrete is determined to be between 0.5-07, determining of the condition (wet versus dry) and the movement (at the start versus continuous). The most unfavourable coefficient is then 0.5 (van Staverden, 1983). With the formula for friction $F_f = \mu * F_V$ the required weight of an element can be determined regarding the horizontal force. The 0.5 factor translates to the fact that the girder needs to be twice as heavy as the occurring horizontal soil pressure to prevent shearing.

The vertical soil pressure can be determined using the principle of soil pressure equals grain pressure plus pore pressure. In formula form this is written as $\vartheta_{soil} = \vartheta_{grain} + p$ where the grain pressure equals the vertical pressure. The horizontal pressure is determined with a λ-coefficient which is dependent on the soil type. For sand this λ-coefficient is 0.4 (Verruijt & Broere, 2011) . Pore pressure of water is equal in all the directions due to the liquid state. Every material has its own determined volume weight. For dry sand this equals 17 kN/m^3 and for wet sand this equals 19 kN/m^3, dependent on the water level. Since the soil pressure is linear over the depth of the soil, the total horizontal soil pressure can be determined by multiplying the area of the red triangle (as seen in Figure 46). Using h as the height of the soil give the soil pressure on the bottom expressed in $b \ = \vartheta_{soil} * h$. Combining this all the formula for the equivalent horizontal load can be described as $F_H = \frac{1}{2} * (0.4 * \vartheta_{soil} * h) * h = 0.2 * \vartheta_{soil} * h^2$ [kN/m]. Assumed a soil elevation of 5 meters which need to be blocked by a retaining wall consisting of stacked SKK 1300 girders. To achieve a height of 5m, 4 girders need to be stacked. With a self-weight of 2420 kg/m per girder, the total vertical weight will be 96.8 kN/m. This translates to a horizontal load bearing capacity of 48.4 kN/m. The horizontal load is determined by the soil pressure and by using the previously derived formula $F_H = 0.2 * 19*5^2 = 95$ kN/m (Assumed wet sand as soil). This gives a unity check of 95/48.4 = 1.96 which is way bigger than acceptable (UC must be ≤ 1).

Rotating of the structure can be calculated by the sum of moments around the bottom corner of the structure, displayed with the red dot in Figure 46. This rotating however, is dependent on the shape of the wall, which translates in the shape of the girders. For example, inverted T-girders look more like the preferred shape of a retaining wall. However, an additional difficulty is the ability to stack these girders. Box girders can be stacked more easily, but don't provide an additional eccentric loading to prevent rotating. Next to this, the connection in between the girders is of high importance to prevent the shearing of individual girders on top of each other.

The final assessment needs to be done based on the load bearing capacity of the underlying soil. To prevent failure of the soil and causing sagging or sliding, the load bearing capacity of the soil must be bigger than the weight of the structure. The load bearing capacity of the soil is depended on the cohesion of the soil, the soil cover and volume weight.

Summarizing these notes of reusing girders as a retaining wall follows in the decision to not take this application into further detail. There are multiple project depending variables to determine the feasibility. Next to that, vertical retaining walls are currently optimized with the use of *reinforced soil*, or more known as *terré armée* from the French language. In this wall the concrete elements are anchored with the use of steel strips to withstand horizontal forces by friction.

6.4.3.4 *Sound barrier*

Currently (until approximately 2027) RWS is performing a Multi-Year Program Sound Remediation (MYPR, or in Dutch: *Meerjarenprogramma Geluidsanering*, MJPG). Alongside all the highway roads, noise pollution occurs in the surrounding houses. From research it is concluded that the noise pollution is above the remediation level of 65 decibel (dB) and thus needs improvement (Rijkswaterstaat, n.d.-f). This project makes it quite interesting to search for reusability options for girders as sound barriers. This application is based on the principle of big heavy elements, which can be stacked to form a wall. However, the biggest questions are the sound-proof ability of the concrete and the way of stacking the particular elements, just like the design application of the retaining wall. On top of that, the esthetics also plays a big role. A schematic overview is given in Figure 48.

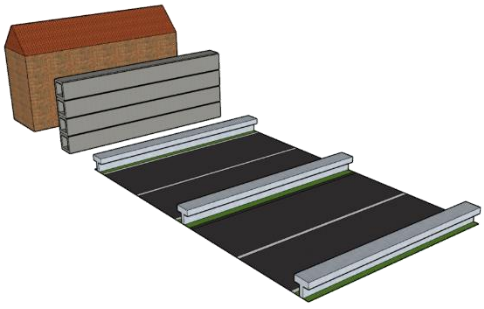


Figure 47 Design application sound barrier

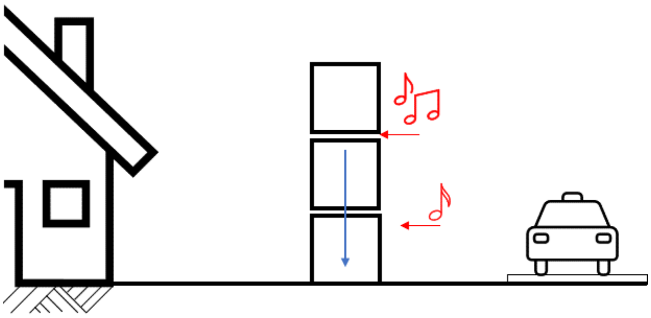


Figure 48 Schematic overview sound barrier

The amount of sound proofing is dependent by the mass. In turns, this mass is dependent on the amount of granular material. The more granular material, the lower the mass. Concrete has a lot of mass and is therefore interesting for sound isolation. In practice a closed structure of 10 kg/m^2 delivers a sound absorption of 15 dB (van Beers & Alsem, 2019). For each 3 to 4 extra dB, the mass needs to be doubled. In the MYPR it is stated that the remediation level is 65 dB. This would require a total mass of 24.160 kg/m^2. With a self-weight of the SKK girders (the heaviest as seen in Table 18) of 2420 kg/m, this is nowhere nearby. However, the total amount of noise doesn't need to be absorbed. In general, a sound isolation of 25 dB should be enough. This correspond with 40 kg/m^2 and can easily be reached. Unfortunately, this isn't the only variable regarding the feasibility of a concrete reused girders as a sound barrier. Next to the weight of the structure (and thus material), the pitfalls are in the dilatation joints and the possible application of safety doors and other elements. Next to this, the underlying distance to the source takes a big part in the designing.

Next to the required mass for sound proofing, these girders also need to be stacked on top of each other. This either causes small holes in between the stacked girders due to either different cambers or an additional intermediate layer in between the girders is required. These holes are obviously not desirable when designing a soundproof structure.

Based on the previous mentioned remarks, the sound barrier won't be taken into account in the next phase of the research. From a structural point of view, the girders don't need to withstand a big load and the most interesting aspect is making the girders soundproof. Or at least, absorbing enough. This can for example be done by pouring soil in between the layers, which also improves the esthetics.

6.4.3.5 *Culvert*

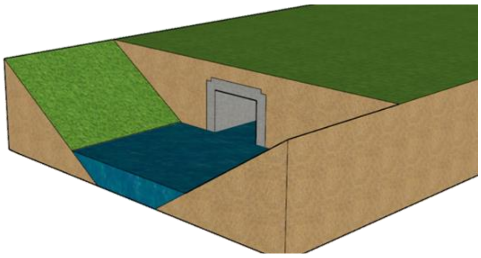


Figure 49 Design application culvert

The final design application in the top 5 is the culvert. A culvert is a structure with as main goal connecting two different waterways, without causing hinder to the above located layer. There are two different sorts of culverts: normal culvert or sinker. A culvert is placed straight ahead under the particular soil. A sinker on the other hand is constructed with a kink in the beginning and the end. In this research only the normal culvert is taken into account. The advantage of using a culvert is the easy application of constructing a (rail)road above a particular waterway. Culverts are available in all materials, sorts and sizes, depending on the application. The schematic scheme of the cross section of a culvert is visible in Figure 50. The red arrows are soil pressure, where the green arrows represent the soil weight on top of the culvert plus the weight of the traffic and asphalt layer. These loads are, together with the change of settlement the most determinant loads to verify in this design application.

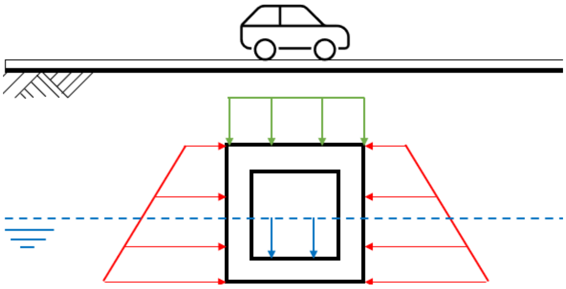


Figure 50 Structural scheme culvert

Culverts can be designed with transition slabs. These are placed perpendicular to the length of the culvert. The purpose of these transition slabs is to prevent the negative effects on possible settlements relative to the above located highway for example. From the previous phases a demarcation is made into 5 different girders, which all differ in shape. The application of the girders with a *non-open* core into culverts will be harder, more challenging and takes extra steps into detailing. These girders are not provided with a hollow section and therefore need some out of the box thinking for applying.

Culverts are designed by attaching different modules to each other with the use of post-tensioned prestressing steel. The most common culvert elements have a length between 1-3m. This length provides a better withstanding of unequal soil settlements as well as an easier and quicker assembly. Nevertheless, there are examples of element lengths of 12 meters. This makes it therefore interesting to look further into this design application.

The most important aspect of designing a culvert is of course the waterproofness. A leak in the culvert will cause soil intrusion. Due to the water flow this soil will be drained, causing settlement in the soil around the culvert and thus for the above located layer (highway for example). The waterproofness is critical in the connection in between the different elements. It is most common to either use a rubber or plastic ring in between these elements.

6.5 Final design application

In the previous paragraph the top 5 applications have been elaborated a bit further. Each design applications has both advantages as well as disadvantages. Next to that, the possibility for each design application is also dependent on the type of girder which will be reused. For example, the T-girders are very hard to be used for the designing of a culvert and the SKK girders are way too big for using in (non)residential buildings.

Based on the previous mentioned comments per design application, the final application is chosen. The reusing of the concrete girders as a culvert will be looked into more detailed. This design application has some potential of reusing and will also be a good challenge. From practice it turns out that the dimensions of the girders are not out of proportion, since culverts are used up to an internal diameter of 3.5 meters.

7 Phase 4: Elaboration of design application

All the previous sections combined lead to the final design application: reusing a girder as a culvert. In this last phase of the research this application will be looked into a bit further. The aim of this section is to elaborate the differences between constructing with reuse and BAU. However, to do so, at first the scope needs to be determined with its particular dimensions. In this way, a supported assessment can be done which follows into a proper conclusion. The main focus in this section is to answer the question: Is it possible to reuse a girder as a culvert? This will then follow into the determination of the different comparing details.

7.1 Dimensions

To be able to elaborate a design application, different dimensions and properties need to be determined and prescribed. The different dimensions are split into three categories. As first the girder itself is pointed out. Following into the determination of the culvert dimensions and as last the assumed area in which the application will be integrated is prescribed.

Research into DISK (the data system of RWS) gives the graph as shown in Figure 51. From this graph it can be seen that between 1960-1980 the most culverts are constructed. However, an upward trend is visible starting from the year 2005 until now in the increasing number of culverts. Therefore, it can be assumed that the reuse potential of culverts also has an influence on the near future and will therefore be able to make an impact in the transition to a CE.

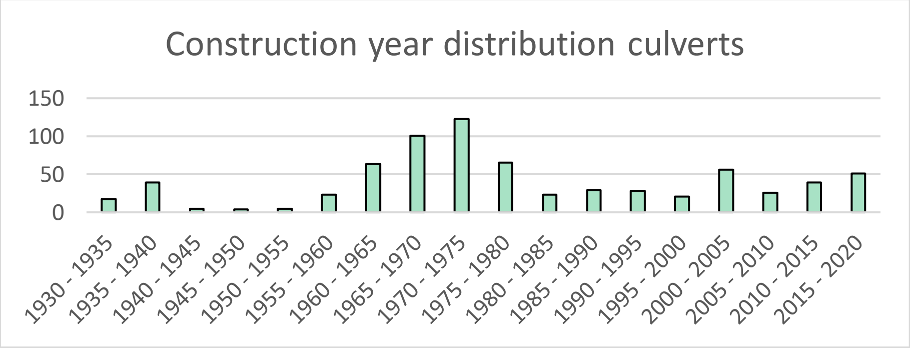


Figure 51 Construction year distribution culverts

7.1.1. Girder

From the previous phases, 3 different categories of girders: *Inverted T, normal T* and *box* girders are determined for reusability. Each specific category has its own (dis)advantages regarding the reuse application of a culvert. Therefore, these girders are elaborated shortly on the possibility of reusing.

7.1.1.1 *Inverted T-girders*

Inverted T-girders are mostly used in the construction of viaducts. The girders that are taken into account are the HNP 75-98 and the ZIP 700. Their shape is optimized for the withstanding of the determinant traffic loads. Through the years these girders underwent multiple adjustments, which causes a still used profile in the current days. The girders are prestressed with pre-tensioned steel. The starting points of these cables vary over the cross section causing the occurrence of kinks in these cables over the length of the girder.

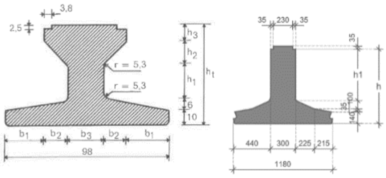


Figure 52 Cross section reversed T-girders for final application

Unfortunately, as is clearly seen on the previous image, there isn't a hollow section present. There are two possibilities to create a hollow section in which water can flow through. The first one is by preventing to cut the concrete topping layer and placing 2 (or maybe more) girders next to each other. The second variation is by rotating one of the two girders by 180°. Both possibilities are shown in Figure 53 with the use of the HNP girder. The same applies for the ZIP variant. Of course, both approaches take a complete other detailed defining.

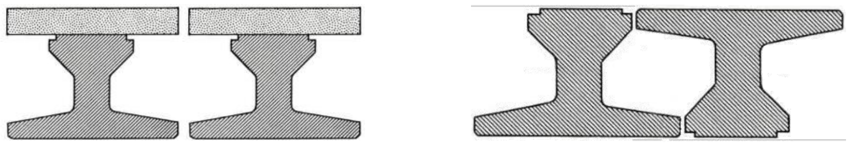


Figure 53 Two possibilities of creating a hollow section with HNP girders

7.1.1.2 *T-girder*

The T-girder is a profile that hasn't been used a lot in the Netherlands. Mostly due to their construction height and the lower bottom flange width compared to the top flange. Due to the fact that the bottom flanges cannot be connected to provide horizontal stability, these girders are not applied anymore into new viaducts. Causing it to be interesting to look into further. Unfortunately, due to its shape, this girder isn't applicable for reusing as a culvert. The possibilities regarding the inverted T-girder do not apply. The T-girders themselves are already provided with a concrete topping and flipping the type upside down will cause the biggest weight on top of the structure.

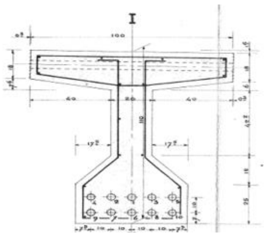


Figure 54 Cross section T-girder for final application

7.1.1.3 *Box girder*

Box girders are constructed since about 1975. The first types were the SDK 900, but soon (within 5 years) these were adjusted to the SKK types. An advantage of box girders is the 'hollow' core in between. This makes the application of the girders into a culvert easier, compared to the previous mentioned girders. However, this hollow core is not hollow in all cases. Most of the times a polystyrene layer is used to construct these girders. This layer needs of course be removed when water needs to flow through. Another aspect of these girders is the addition of so-called bulk heads. These are used to divide the total length of the girder into different compartments to provide stability during the casting of the concrete.

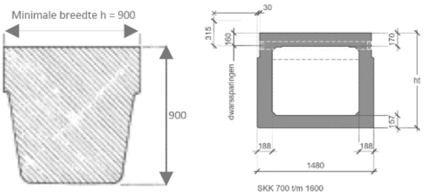


Figure 55 Cross section box girders for final application

7.1.1.4 *Final girder*

An impression of all the examined girders, reused as a culvert is visible in Figure 56.

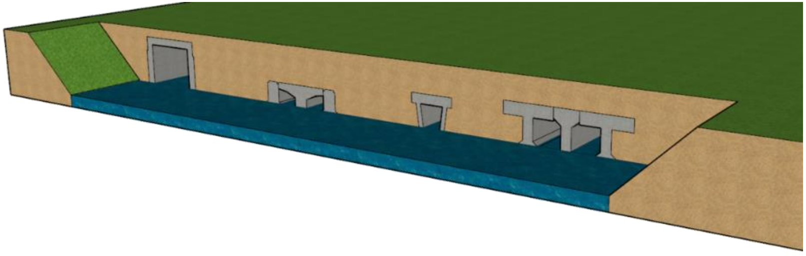


Figure 56 Examined girders reused as culverts

Combining the previously comments on the different girders, the most promising girder for reuse in a culvert is stated to be the SKK girder. From the previously selected girders, this comes down to the SKK 1300 box girder. This girder was designed by Spanbeton and the cross section with its dimensions is shown in Figure 57, with h_t = 1300 mm. The length of the girder is determined from section 5 in which and will be 40 meters. The internal dimensions will then be 1104x973 millimeter (width x height).

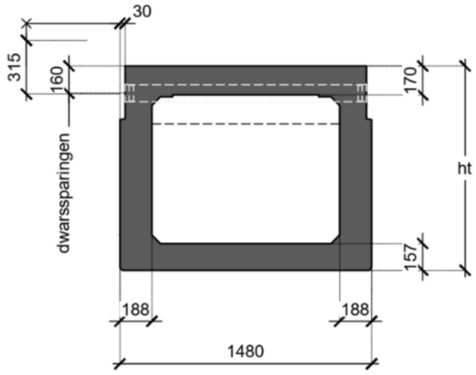


Figure 57 Cross section SKK 1300

7.1.2. Culvert

Since the harvested girder is determined in the previous paragraph, the next variable is the culvert itself. For determining the most common dimensions of culverts in the Netherlands, the system DISK is used. From this system an export regarding superficial culvert data is obtained. With this data file the graphs as visible in Table 27 till Table 30 are made. From these graphs the dimensions of the most common culvert are determined. It is assumed that the culvert has a width of 0-2.5m, a length of 40m and is constructed in the highway. Giving a total area of about 80m^2.

Table 27 Culvert width distribution

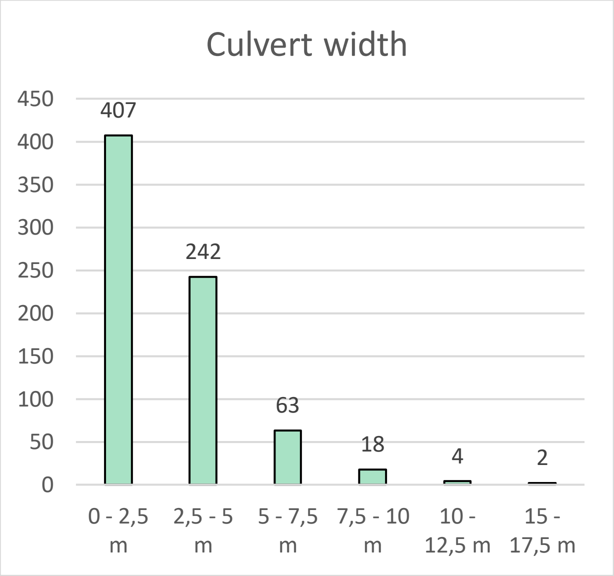


Table 28 Culvert length distribution

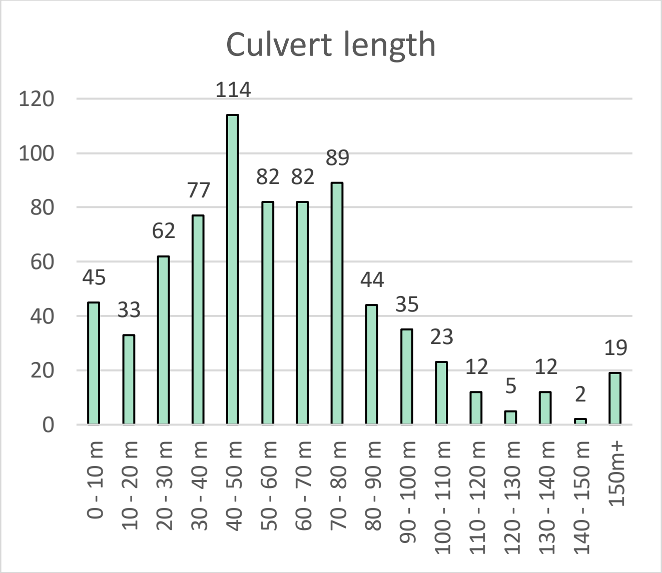


Table 29 Culvert in relation to highway

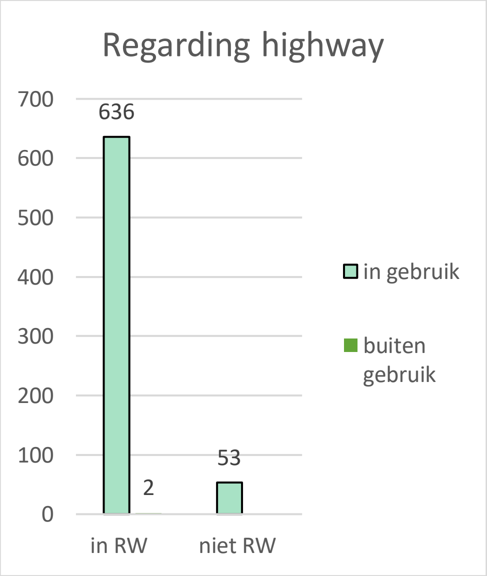
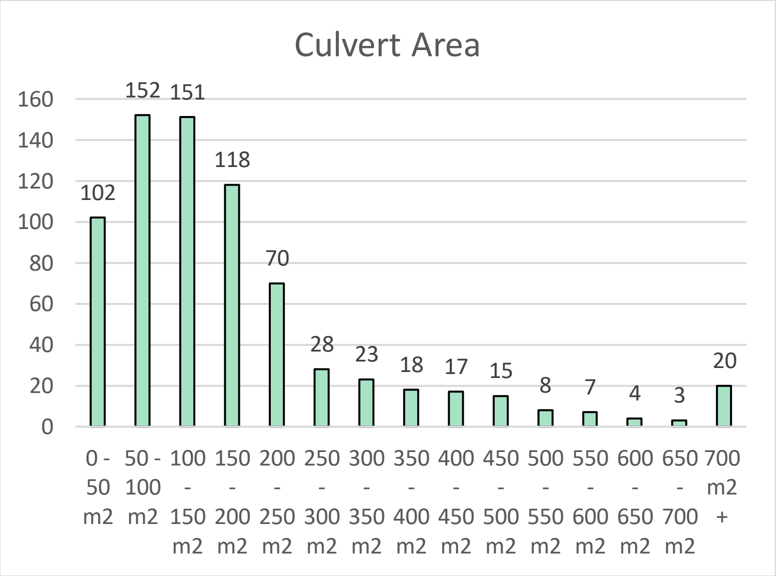


Table 30 Culvert area distribution



7.1.3. Area

In the Netherlands the soil consists of multiple different layers. This soil structure is depended on the particular location in the country. The soil structure with its dominating soil layer is schematized in Figure 58. In this figure the yellow layers are dominated by sand, the blue by clay, purple by peat and the dark brown consists of loess. Regarding these layers, the sand structure provides the most stability and is in about 50% of the country the dominating soil layer. The soil layers can be schematized as shown in Figure 59. A water layer depth towards ground level of 1.5m is assumed.

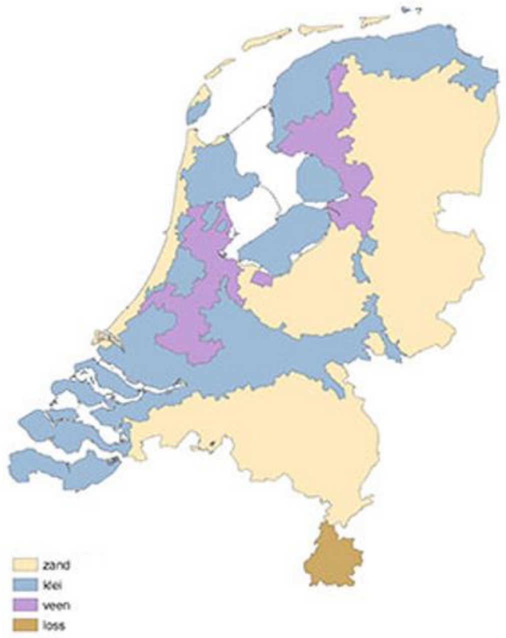


Figure 58 Dominating soil structures in the Netherlands (RIVM, n.d.)

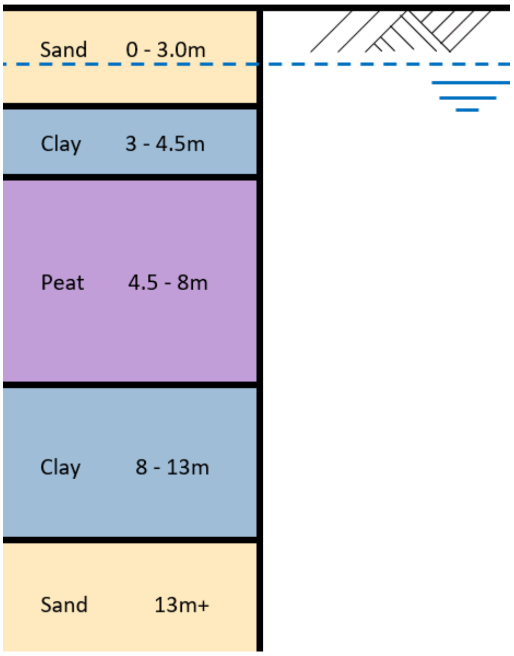


Figure 59 Soil structure layers

Regarding the fact that more dan 90% of the girders are built underneath the highway, this will also be at the determined area of application. The culvert will be placed 1m below ground level, which translates to the fact that transition slabs are not required. This also takes away the structural design of an addition console on which this transition slab needs to be supported. In other words, the culvert will be founded on grade.

7.2 Using new materials

Before looking into reusing the box girder as a culvert, the current situation is analyzed. What is the current effort of constructing a new culvert, based on new, raw materials. This analysis is done based on the three main categories: Structural, Environmental and Economic. Starting off with the structural aspect.

7.2.1. Structural

Currently the design of culverts is completely developed and refined. If a culvert is required on a specific dimension with specific water flow requirements, a lot of options can be chosen of. Multiple companies provide different standards of prefab elements with specific internal dimensions, based on the requirements. The two main categories of designed culverts are circular shaped tubes and rectangle shaped prefab elements. The circular tubes are constructed with a connection by sliding a spigot end into the socket end (Houtman, 2020), visible in Figure 60. In between this connection an additional layer (mostly a rubber ring) is placed to provide waterproofness in the culvert. The advantage is the circular shape. This causes a better connection of the rubber ring, even when large rotations occur. An example of this shape is given in Figure 61.

The other culvert that is often used is the rectangular shaped culvert. This culvert consists of multiple prefabricated concrete elements and has varying internal dimensions up to 3.5 meter. The different prefab elements are connected by using either prestressed post-tensioned steel without insertion, as is visible in Figure 62, or a rubber ring with a spigot-socket connection.

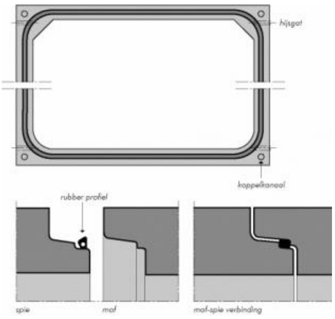


Figure 60 Spigot-socket connection with rubber ring (Giverbo, n.d. - b)

Figure 61 Circular tubes with a spigot and socket end (Giverbo, n.d. - a)

Figure 62 Rectangular concrete elements with prestressed post-tensioned steel (Waco, n.d.)

Currently rectangular box culverts are assessed with the use of the standards NEN EN 14844 in combination with the NEN EN 1992-2 for performing design and detailing rules, the EN 13369:2004 for common rules for precast concrete and the EN 206-1:2000 for Specification, performance, production and conformity. Summarized in short it states that the culverts must be designed with a minimum strength class of C30/37. However, the RBK states that this strength class must be a minimum of C35/45. Further in-depth study on the structural behavior for culverts will be done on the reused material. If assumed a girder of 40 meters with internal area of 1,08 m^2 (1,104 * 0,973), the culvert *Koppelduiker R2* of *Romein beton* can be applied (shown in Figure 63). This culvert is designed by the required standards and satisfies the needs for the concrete class, the consequence class CC3, the internal dimensions and is able to withstand the particular traffic loads of highways. The elements have a length of 2.5m and thus a total number of 16 elements is required to fulfill the 40m span. It can be assumed that these required elements are able to be built on the desired location, without any further elaboration on forehand. In Figure 64 the different elements of the culvert are highlighted. For further comparison between a new constructed girder and reuse, the orange highlighted elements will be left out. These elements will be needed in both systems and therefore balance each other out in a comparison.

Figure 63 Applied culvert: Koppelduiker R2 (Romein, 2018)

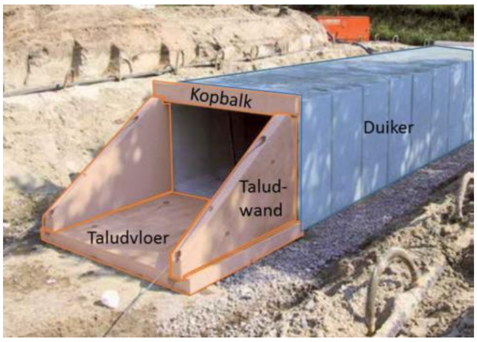


Figure 64 Different elements of the applied culvert (Bruinsma & Bijleveld, 2021)

7.2.2. Environmental

The environmental aspect of the culvert will be done based on two different methods, which are prescribed earlier. The first one will be the worldwide popular LCA method, following the ECI calculation. This will be done with the help of the national environmental database. The next methods will be the core measuring method as described by CB'23.

7.2.2.1 *ECI method*

The ECI method is based on the LCA. The national environmental database (NED) consists of multiple standard elements with a correspond ECI score. This ECI score is based on the life cycle assessment of the environmental aspects, multiplied by the weighing factors as summarized in Appendix G: G.2 Life cycle assessment and Environmental cost indicator. It must be noted that these values, corresponding to category 3 in the NED, are raised by a factor of about 30% to provide general data indications. Specific suppliers can create girders with less environmental impact, but for a general comparison the full ECI value satisfies. For concrete culverts, the standardized culvert in the NED is divided into multiple cross section varies. The ECI value of these standardized culverts also include the orange highlighted elements in Figure 64. The options are also divided into a possible addition of a transition slab. The lowest valued element level is based on the internal dimension of 1250 x 750 mm and does not fulfil the requirements of the culvert (internal width is 973 millimeter). Therefore, a level higher is reached for, meaning the culverts with internal dimensions up to 1500x1000 millimeters and excluded from a console to support the transition slab. This leads to a ECI score of €259,5526 per meter. This ECI method is based on the *cradle to grave* lifetime and therefore includes the waste processing. However, this is based on a combination of the girder elements over a span of 1 meter, a set of embankments on both sides, a transition slab on both sides and 2 consoles to support these slabs. It turns out that only 25% of this ECI score is based on the girder elements (see Appendix K: Culvert design with raw materials) and including the console (Bruinsma & Bijleveld, 2021). Comparing the weight of the culvert with console (2856 kg) with the weight of the culvert without a console (2577 kg) leads to a percentage of 10% console weight (see Appendix K: K.1 Environmental influences) . The final ECI score for the full girder (with a span of 40m) will then be $€259{,}5526 * 25\% * (100\% - 10\%) * 40m = €2335{,}97$. The ECI score without the additional 30% will be €1635,18.

7.2.2.2 *Core measuring method*

The core measuring method is composed by platform CB'23 and is elaborated in Appendix G: G.3.1 Core measuring method. The idea behind this method is to inventory the material input as well as the material output (CB'23, 2020 - b). This material output is based on reusability and recycling. However, for the current research this output is not taken into account, since a specific culvert will not be demounted and reused. The reusability of both culverts (from raw materials and reused girder) is not determined and requires additional research, which is beyond the scope of this research. For creating a culvert, Table 31 can be composed containing the material input. Unfortunately, this summary isn't very interesting. It is assumed that all the materials are new raw materials and therefore all the input is stored in the primary indicator. The total amount of tons is reached by multiplying the load per meter of the culvert (2577kg/m as prescribed before) with the total span of 40m and dividing by 1000 to get tons as unit.

Table 31 Core measuring method - Material input BAU

Number	Indicator	Ton	%
1	Total input	103,08	100
1.1	Primary	103,08	100
1.1.1	Non-renewable	103,08	100
1.1.2	Renewable	0	0
1.1.2a	Sustainable manufactured renewable	0	0
1.1.2b	Non-sustainable Manufactured renewable	0	0
1.2	Secondary	0	0
1.2.1	Secondary from reuse	0	0
1.2.2	Secondary from recycling	0	0

7.2.3. Economic

The economic part of the assessment of the newly constructed culvert is the final category. Of course, this is in certain sense the part where it is all about. If the costs are too high, another option or even total rejection of the structure will be possible. The costs are determined by the *Bouwkostenkompas*. This is a cost database in the Netherlands on a superficial level. This database contains costs for (non-)residential buildings as well as the infrastructure works. For the determination of the total costs of a culvert, it is assumed to be in the province *Noord-Brabant*, since there is the sand layer dominating, as prescribed before. The cost overview is visible in Appendix K: K.2 Economic database. The average cost is determined to be €3.700,- as base costs. However, this includes aspects like dewatering and excavation of the soil. These factors can be excluded, since these are applicable to both culvert applications. This leaves an average cost of €2.233,-. With a total length of 40 meters, the costs of a newly culvert can be estimated on €89.320,-

7.3 Using reused elements

In the previous section a new culvert is designed. With standard dimensions corresponding to the specific requirements a cross section can be chosen out of multiple prescribed designs. This new culvert is then assessed to the other two main criteria. However, reusing a box girder as a culvert is a new application and has not been done before. This section will focus on the designing as well as the assessment of the box girder, reused as a culvert. This is once again done with respect to the three main categories: Structural, Environmental and Economic.

7.3.1. Structural

At first the structural aspect of this box girder will be taken into account. The girder will be assessed based on the application on a culvert, which differs a lot of the original function of a girder. Since there isn't a specific project in which this box-girder-culvert will be used, this assessment will be done based on a fictitious application with provided substantiated assumptions. The structural assessment is done based on a two-way verification with transverse- as well as the longitudinal direction. In the transverse direction the bending moment capacity and the shear force resistance are assessed, where in the longitudinal direction the deflection and crack width are assessed. All the worked-out maple[17] sheets with calculations are visible in Appendix L: .

7.3.1.1 *Dimensions*

Starting with the assessment, the dimensions of the box girder are required. These are shown in the schematic scheme visible in Figure 65. Besides the cross-section dimensions, the length of the box-girder-culvert is 40 meters, as prescribed in the previous paragraph.

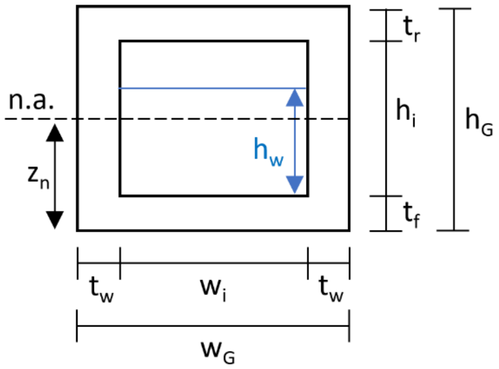


Figure 65 Mechanical scheme with parameters box girder

Dimensions in [mm]

Roof thickness	$t_r = 170$
Floor thickness	$t_f = 157$
Wall thickness	$t_w = 188$
Height girder	$h_G = 1300$
Height water	$h_w = 600$ (assumed)
Height internal	$h_i = h_G - t_f - t_r = 973$
Width girder	$w_G = 1480$
Width internal	$w_i = w_G – 2^* t_w = 1104$
Neutral axis	$z_n = 665$

Before being able to reuse the box girders, some challenges are encountered. The first one is already shortly described in paragraph 7.1.2. The box girders in viaducts are namely constructed with different bulkheads to provide structural stability. Unfortunately, these bulk heads need to be removed to provide a water flow through the girders. This can be done by either removing the bulk head or cutting the box girder just before and after the bulk head. Another challenge regards the core of the box girders. This core is filled with a polystyrene layer concluding that removing this will also require extra actions, which will be elaborated further in paragraph 7.3.2. As final challenge, the box girders are constructed with solid concrete blocks at the supports on each end of the girder. This takes about 1m length per end. Since the assumed girders are of 40 meters length, this leaves a length of 38m.

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[17] Maple is a computer program which is suitable for computer algebra

Bulk heads

The distance between the different bulk heads varies a lot due to the company who made the girders. From research it shows that within halfway the length of a certain variable L_0 the placement of a bulk head is unnecessary for the structural stability (Janssen & Veldpaus, 1970). This value can be calculated with the use of equation 1. And will be used as an estimation of the length of the elements that remains.

$$L_0 = \frac{\pi}{\alpha_0}$$

With

$$\alpha_0^2 = \frac{1}{2}\sqrt{\frac{3}{1-v^2}} \cdot \sqrt{\frac{t_1^3 \cdot t_2^3}{b_1^2 b_2^2 (b_1 t, + b_2 t_2)(b_1 t_2^3 + b_2 t_1^3)}} \tag{2}$$

Where:

L_o	Length of girder [mm]
v	poisons ratio = 0.2 [-]
t_1	thickness wall (t_w)
t_2	thickness roof (t_r)
b_1	half height girder (0.5 * h_G)
b_2	half width girder (0.5 * w_G)

With the use of Maple, this formula is elaborated and a value of L_0 = 3.2 is reached. Therefore, for further assessment it will be assumed that every 4 meter a bulk head is placed. Following in girder elements with a length of circa 4 meters for reusing these girders into culverts.

Foundation

In the previous section the foundation type is already discussed. Culverts can be either founded on grade or on concrete piles. Both methods can be schematized in another way, effecting multiple parameters. Where the foundation on piles can be schematized with different supports, the foundation on grade can be schematized as a continuous elastic supported beam (also known as the *Hetényi* problem) visible in Figure 67. Along the length of the girder, the soil can be schematized with the help of springs (Figure 67). These springs correspond to the elastic supporting of the soil. This elastic support is determined by the foundation modulus (k), which is dependent on the modulus of subgrade (c). For a sand layer this c-value is equal to 10^7 N/m^3, which follows in $k = w_G * c = 1.48 \cdot 10^7\ N/m^2$. The deflection w of the beam can be determined with the use of (ordinary) differential equations (ODE). However, before applying this method, some more parameters need to be determined.

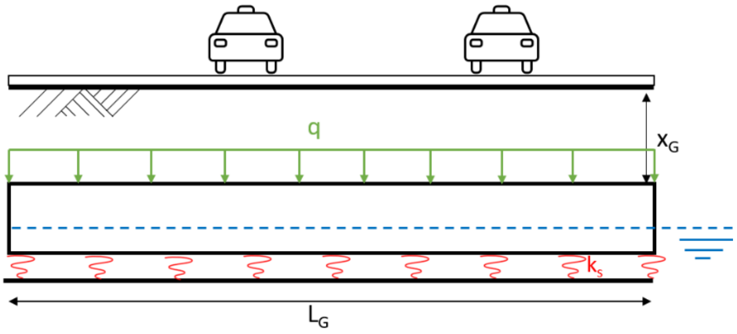


Figure 66 Longitudinal cross section

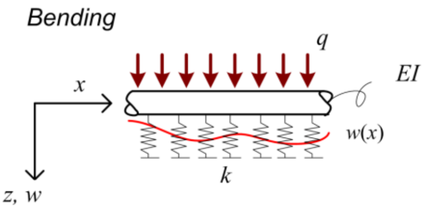


Figure 67 Theoretical scheme bending beam continuously elastic supported

To complete a culvert of 40 meters, multiple elements of the box girder are required. These elements need to have a watertight connection in between. This can be done for example with the addition of either a rubber ring or a spigot and socket connection. This connection will be disregarded from this thesis and assumed to be functional. With this connection, the multiple elements are able to work together when carrying loads. This way the maximum deflection will be lower. Since this connection is not design or optimized, girder element lengths of 4 meter will be taken into account for further assessment. This way the worst-case scenario is taken into account, concluding that in practice it will be a better application.

Modulus of elasticity

With the length of the particular spans determined, the EI value needs to be determined of the concrete girders. This is a multiplication of the modulus of elasticity and the moment of inertia. This moment of inertia, I, is given for different standards. The elasticity modules is dependent on the concrete class (cc) that is applied. For the design of box girders, there are two minimum concrete classes mentioned. The NEN standards prescribe a minimum C30/37 concrete class, which corresponds to an E = $33*10^3$ N/mm^2. On the other hand, the RBK describes a minimum concrete class C35/45 with a corresponding E = $34*10^3$ N/mm^2. However, the deciding class is of course of the box girders itself, which is C60/75 (Spanbeton, n.d.-d). This corresponds to E = $39*10^3$ N/mm^2. Multiplying with I=$188*10^4$ mm^4 (Spanbeton, n.d.-d) gives an EI = 73.3 kNm^2

Reinforcement and prestressing steel

All the different box girder types have the same width and a varying height. Meaning that the height depends on the span of the application. With this height also the amount of reinforcement as well as the prestressing is determined. Most of the different girder types (with varying height) have the same amount of steel in it. Since a specific project is in absence, the girder type HKP 1500 is used as an example. The technical drawings of this girder are visible in Appendix M: .This is a box girder, designed by Haitsma concrete, which delivered the technical drawings to use as first impression. However, this girder has a concrete area of 20% more than the used HKK 1300. Therefore the (prestressing)steel areas are lowered by a factor 0.8. The box girder is prestressed with pre-tensioned steel, which provides a kinked tendon profile, schematized in Figure 68. The dimensions are not to scale. It must be noted that in the solid concrete part, the steel forms a horizontal line. For the girder prestressing steel Y1860S7 is used. During the designing of the viaduct a prestress force is determined. This prestress has occurred different losses during the years. On top of that, due to the cutting of the girder a chance of prestress loss due the shortening of the steel occurs. The steel however is bonded to the concrete and this loss shall be small. To take into account these total losses, a reduce factor of 0.8 is taken into account. The starting value of the prestress will be $\sigma_{p\infty} = 1208\ N/mm^2$, as determined by the RBK.

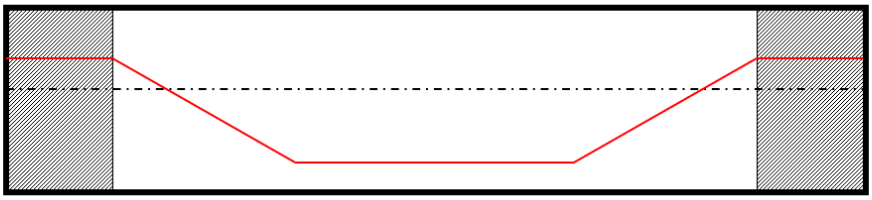


Figure 68 Kinked tendon profile applied with pre-tensioned steel

A summarization of all the different parameters and dimensions are visible in the maple sheet, which can be found in Appendix L: L.1 Parameters.

7.3.1.2 *Loads*

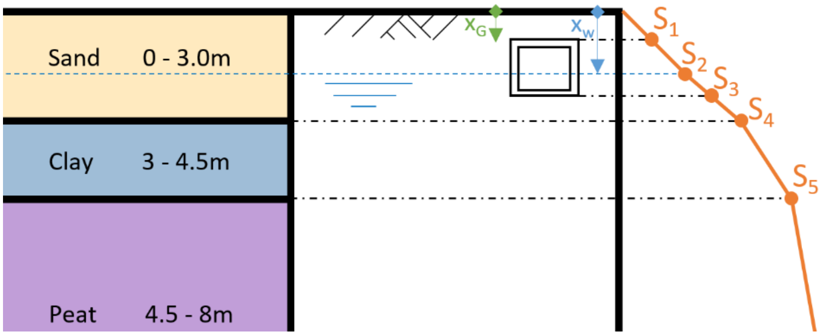
With the known dimensions, the different loads can be determined which act on the culvert. The loads both in transverse as longitudinal direction required. The permanent loads consisting of the soil layer and the asphalt layer. The variable loads are traffic loads. Other loads, like the permanent load of a traffic barrier have not been taken into account. The different loads are composed as distributed loads along the culvert. For the distributed load along the length of the culvert, a factor of 0.5 is applied, since the culvert consists of a box girder with two concrete walls. Each wall will need to carry half of the applied load.

Distributed load - asphalt

The distributed load of the asphalt can be determined by multiplying the area with the weight of the asphalt (23 kN/m^3). An average height for an asphalt layer is 200 mm. For the longitudinal distributed load, the width of the girder is taken into account for the applied area. For the transverse direction a width of 1m is taken into account. The distributed loads for the transverse and longitudinal direction will then respectively be $q_{asphalt\_T}$ = 4.6 kN/m and $q_{asphalt\_L}$ = 6.8 kN/m and thus $q_{asphalt\_L}$ = 3,4 kN/m per concrete wall.

Distributed load – soil layer

The load acting by the soil can be determined with the scheme as drawn in Figure 69. With using the weight of the sand layer (17 kN/ m^3 for dry and 19 kN/ m^3 for wet) and the weight of the clay (16 kN/ m^3) the values of S_1 up to S_4 can be determined by using the soil pressure. This pressure is determined by the height multiplied with the self-weight of the layer material. As mentioned before, the culvert is at 1m depth (x_G = 1m) to prevent the usage of transition slabs. The elaboration of the calculation of S1 up to S4 is visible in appendix L.3. The distributed load due to the soil is the multiplication of S1 and the width of the girder. The distributed loads of the soil are q_{soil_T} = 17.0 kN/m and q_{soil_L} = 12.58 kN/m.



S_1 = 17.0 kN/m^2
S_2 = 26.2 kN/m^2
S_3 = 40.6 kN/m^2
S_4 = 53.9 kN/m^2
S_5 = 77.9 kN/m^2

Figure 69 Soil structure with correspond soil pressure levels

Distributed load – traffic UDL (uniformly distributed load)

From Eurocode NEN-EN 1991-2:2021, Table 32 is obtained. This table prescribes the characteristics for load model 1. From this table it is seen that a subdivision is made between the different lanes. It must be noted that this is a theoretical approach to determine the traffic loads and is not the same as in actual practice. The dominating distributed load of 9 kN/m^2 only applies to lane 1, corresponding to a width of about 3.5m (standard width of highway). Combining this with the fact that for the other lanes a distributed load of 2.5 kN/m^2 can be taken into account, this distributed load is not uniform over the complete length of the culvert. However, for the simplification of the assessment, the dominating load of 9 kN/m^2 will be used. For the dominating distributed load on Lane 1, multiplied by the width gives $q_{traffic,UDL\_T}$ = 9.0 kN/m and $q_{traffic,UDL\_L}$ = 6.66 kN/m.

Table 32 Load model 1: Characteristic values (NEN 1991, 2021)

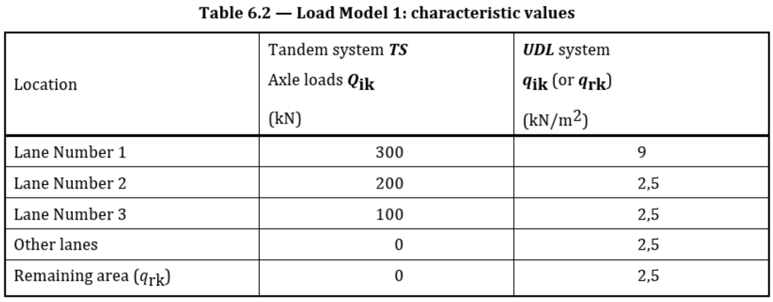


Table 6.2 — Load Model 1: characteristic values

Location	Tandem system ***TS*** Axle loads Q_{ik} (kN)	***UDL*** system q_{ik} (or q_{rk}) (kN/m^2)
Lane Number 1	300	9
Lane Number 2	200	2,5
Lane Number 3	100	2,5
Other lanes	0	2,5
Remaining area (q_{rk})	0	2,5

Distributed load – traffic tandem system (TS)

For determining the distributed load for the tandem system, the axle loads as prescribed in Table 32 can be taken into account. The tandem load is split into two wheels and therefore the load per wheel will be $Q_1 = 150$ kN for lane 1. From the relation between the different lanes, it can be stated that $Q_2 = \frac{2}{3} Q_1$ and $Q_3 = \frac{1}{3} Q_1$.

The footprint of the tandem systems can be schematized according to the Eurocode, as shown in Figure 70. The application of these tandem loads is applied to the box-girder-culvert. This is visible in Figure 71. The most unfavourable application is when the first axle (F1 and F2) is placed on top of the first (left) wall (depicted with the dotted black lines). Due to the fact that the width of the girder (w_G) is smaller than 1.2 meters, the next axle (F3 and F4) is located in the span between the two walls. For the transverse direction, only one wheel per axle (F1 and F4) are taken into account, since 2.0 meters is bigger than the 1.0 width that has been taken into account.

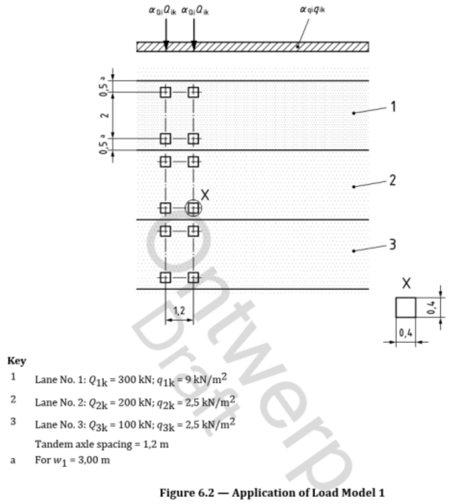


Figure 70 Footprint tandem systems LM1 (NEN 1991, 2021)

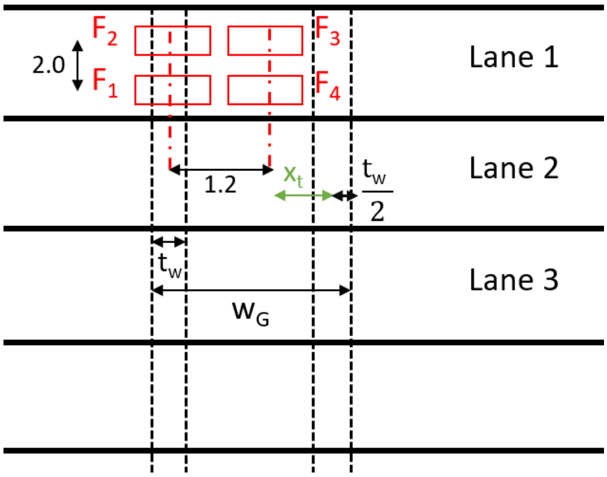


Figure 71 Footprint standards applied to reused box girder (not to scale)

Since these traffic loads are applied as patch loads[18], they can be seen as a uniform distribution of the whole contact area up to the centroid of the girder (NEN 1991, 2021). The tandem systems are applied on a surface of 0.4*0.4m. However, for modelling these loads, the actual surface needs to be determined. This surface is determined by the range (*Spreidingsbreedte*) s_b depicted in Figure 72. The same method is applied for the transversal cross section. However, it turned out that the range of the transversal direction was more than the actual width of the girder. Therefore, the distributed load is halved, since it only applies to the culvert. With the image shown the traffic loads due to the tandem system are $q_{traffic,\,TS\_T} = 53.46$ kN/m and $q_{traffic,\,TS\_L} = 130.06$ kN/m.

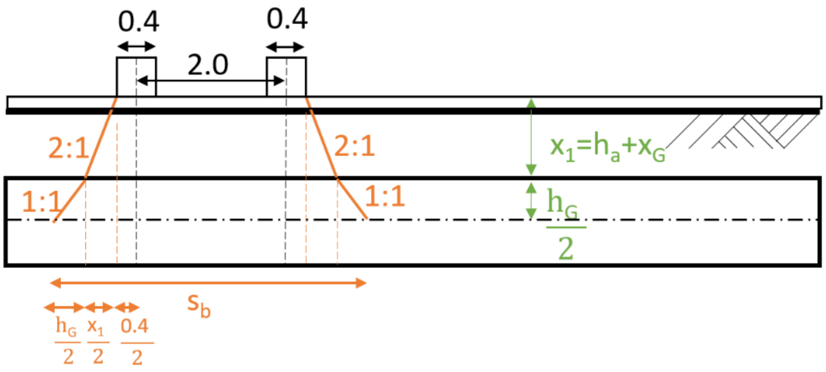


Figure 72 Mechanical scheme of the surface on which the load is applied

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[18] A concentrated load perpendicular to the flanges of a girder

The total distributed load is a summation of the different q-loads. The total distributed loads for the transversal and longitudinal directions equals: q_{total_T} = 84.06 kN/m and q_{total_L} = 152.70 kN/m. With the known loads and the dimensions, the structural assessment can be done.

7.3.1.3 *Assessment*

The assessment is based on four different categories. Each category is described shortly and elaborated with the use of Maple. The maple sheets are visible in Appendix L: L.3-L.7.

Shear force assessment

The shear force assessment states that the occurring shear force (V_{Ed}) must be lower than the shear force resistance (V_{Rd}) of a concrete element. The aim is to reach a unity check $\frac{V_{Ed}}{V_{Rd}} \leq 1.0$. The occurring shear force, V_{Ed}, is determined by the load on the girder element. The resistance is determined by the concrete and the steel properties. The following equations together with the determined parameters will provide a unity check of 0.8, which is close to the 1.0 and therefore properly dimensioned.

$$v_{Rd,c} = \max\,(v_{min}; v_{ed,c})$$

$$v_{min} = 0.035 * k^{\frac{3}{2}} * \sqrt{f_{ck}} \tag{3}$$

$$v_{ed,c} = 0.12 * k * (\rho * f_{ck} * 100)^{\frac{1}{3}}$$

$$V_{Rd,c} = v_{rd,c} * b_{eff} * d \tag{4}$$

$$V_{Ed} = \frac{1}{2} * q * L \tag{5}$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0\;;\ \rho = \frac{Asl}{b_{ef} \cdot d} \tag{6}$$

Where:

k	size effect coefficient [-]
d	effective depth [m]
f_{ck}	characteristic cylinder compressive strength concrete [kN/m^2]
Asl	longitudinal reinforcement area [m^2]
ρ	reinforcement ratio of the longitudinal reinforcement based on the web, width and the effective depth d of the cross-section [-]
b_{eff}	effective width (2*thickness of the walls) [m]
q	distributed load in transversal direction [kN/m]

Bending moment capacity assessment

To determine the bending moment resistance (M_{Rd}) of the culvert, the sum of the moments around the green dot (Figure 73) must equal to zero in the cross-sectional area. This means that N_{cu} can be neglected and P_{∞} and N_P need to be determined. Starting with the value of $\sigma_{p0} = 1208$ as mentioned before. This follows into the P_{∞} by multiplying it with the prestressing steel area (A_P) and the factor of 0.8 for prestress losses. To determine the concrete compression zone, a value of σ_p is assumed to start with. This value corresponds to the green line in Figure 74 to be able to meet halfway. Combining these graphs and the equations (7)-(10), the elaboration is done with the help of maple. This gives a unity check for the moment resistance of 0.02, which is way lower than 1.0 and therefore implies over dimensioning.

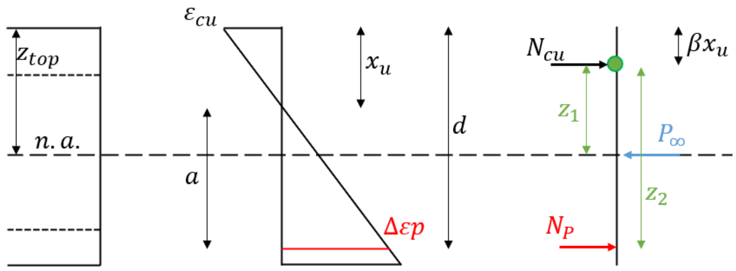


Figure 73 Cross sectional area

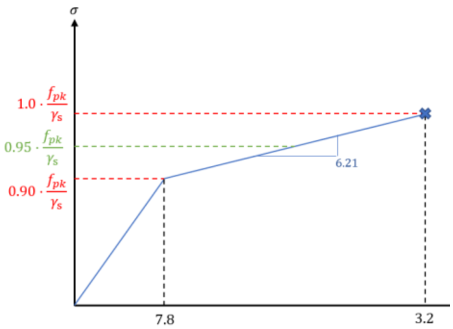


Figure 74 Bi-linear stress-strain diagram for concrete in compression

$$x_u = \frac{A_p * \sigma_p}{\alpha * b * f_{cd}} \tag{7}$$

$$\Delta\varepsilon_P = \frac{\varepsilon_{cu}}{x_u} * a;\ \varepsilon_P = \frac{P_\infty}{A_p * E_p} * a \tag{8}$$

$$\varepsilon_{Ptotal} = \varepsilon_P + \Delta\varepsilon_P$$

$$\sigma_{Ptotal} = 0.9 * \frac{f_{Pk}}{\gamma_s} + (\varepsilon_{Ptotal} - 7.8) * 6.21 \tag{9}$$

$$\sum T_{dot} = M_{Rd} = P_\infty \cdot z_1 + A_P \cdot \Delta\sigma_P \cdot z_2 \tag{10}$$

Where:

A_p	area prestressing steel [mm^2]
x_u	concrete compression zone [mm^2]
σ_p	prestress [N/mm^2]
α	0.67 [-] (depended on C60/75)
f_{Pk}	tensile strength prestressing steel [N/ mm^2]
f_{cd}	design cylinder compressive strength of the concrete [N/ mm^2]
b	width [mm]
P_∞	compressive force [N]
$\Delta\varepsilon_P$	increase of the strain in the prestressing steel [-]
ε_P	strain of the prestressing steel [-]

Tension assessment due to soil settlement

Prefab girders are designed with a camber, provided by the prestressing. This camber gives a little upward curvature of the girder to prevent bigger deflections when the live loads are applied. This is visualized in Figure 75. When the girder is demounted, the camber is lower than the original, since prestress losses have occurred during the years.

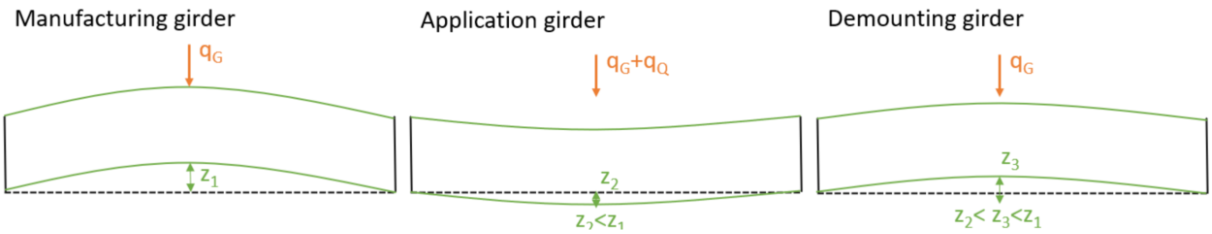


Figure 75 Different phases box girder

This camber in the manufacturing phase (z_1) is designed in such a way that no tensile stresses occur in the top of the girder. Therefore, additional reinforcement is not required. Unfortunately, when this girder will be applied in the new situation a possibility of soil loss occurs due to leakage in between the element (visualized in Figure 76). As noted before, this is dependent on the connection between the elements. However, to take the worst-case scenario only one element will be taken into account. In real practice the multiple elements can be schematized with hinged connections where they act together.

Figure 76 Possibility of soil settlement in between the elements

There are two possibilities for the soil loss underneath the culvert. The first one describes the loss on one side and the second possibility is the loss on both sides of an element. These are both depicted in Figure 77 and Figure 78, together with their schematization. The values of a and x are exaggerated displayed to make the idea visualizable. Due to this exaggerated soil loss, it gives an idea of a stability problem. This is not the case, since the elements are in practice connected on the left side to other elements. The loss of the soil causes a hogging effect in the beam, which gives the possibility for cracking with all the associated consequences like corrosion of the prestressing steel. In both situations the stress on top of the beam (at S_1 and S_2) must be lower than zero to prevent tension or at maximum lower than the tensile strength of the concrete itself. This assessment can be done with the equations (11) and (12).With the usage of maple it is determined that the stresses will not reach the critical values and therefore the culvert will not crack due to the soil loss.

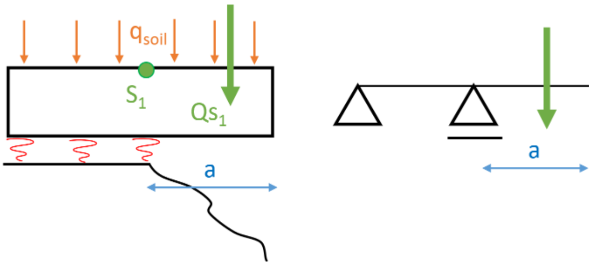


Figure 77 Situation 1: Soil loss on 1 side with exaggerated value a

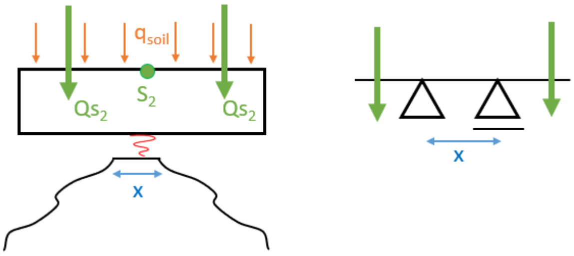


Figure 78 Situation 2: Soil loss on both sides with exaggerated value x

$$\sigma_{c,top} = -\frac{P_\infty}{A_p} + \frac{M_p}{W_{C,top}} + \frac{M_{G_{self}}}{W_{C,top}} + \frac{M_{G_{soil}}}{W_{C,top}} \leq 0 \; or \leq \; f_{ctm} \qquad (11)$$

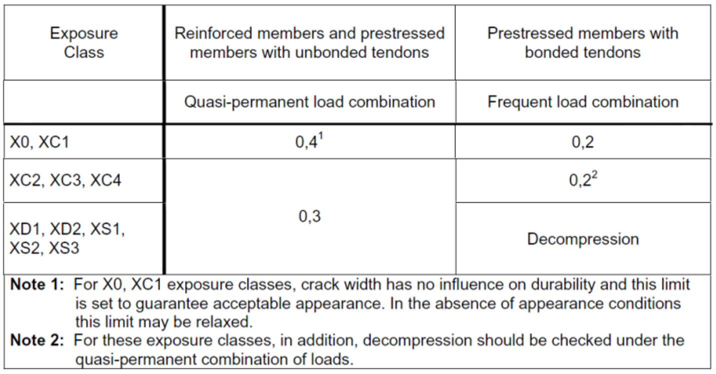
$$\sigma_{c,bot} = -\frac{P_\infty}{A_p} - \frac{M_p}{W_{C,bot}} - \frac{M_{G_{self}}}{W_{C,bot}} - \frac{M_{G_{soil}}}{W_{C,bot}} \leq 0.6 * f_{ctm} \qquad (12)$$

Where:

A_p	area prestressing steel [mm^2]
σ_C	concrete stress
P_∞	compressive force [N]
W_C	section modulus [mm^3]
M_P	bending moment prestressing [Nmm]
M_{selft}	bending moment self-weight [Nmm]
M_{soil}	bending moment soil [Nmm]

Crack width

In the previous assessment it is determined that the girder will not crack due the fact that the occurring stresses are not higher than the tensile strength. However, since this assessment consists of multiple assumptions, the occurring crack width will be compared with the maximum allowed crack width. This maximum crack width is based on the environmental classes as prescribed in Table 17 on page 37. These classes with correspond maximum crack width are shown in Figure 79. With an environmental class of either XC3 or XC4 and bonded tendons, the maximum crack width is set to w_{allowed} = 0.2 mm. The occurring crack width can be determined with equation (13). All the parameters are worked out in the maple sheet. For the variables of α and β it is assumed to be in the crack formation stage with a long-term loading. With the elaboration in Maple it turned out that a maximum crack width of 0.18mm will occur, which is lower than the limited 0.2 mm.



Exposure Class	Reinforced members and prestressed members with unbonded tendons	Prestressed members with bonded tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0,4[1]	0,2
XC2, XC3, XC4	0,3	0,2[2]
XD1, XD2, XS1, XS2, XS3		Decompression

Note 1: For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.

Note 2: For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.

Figure 79 Recommended values of $w_{allowed}$ [mm] (NEN 1992, n.d.)

$$w_{\max} = \frac{1}{2}\cdot\frac{f_{ctm}}{\tau_b}\cdot\frac{\emptyset}{\rho}\cdot\frac{1}{E_s}\cdot(\sigma_s - \alpha\sigma_{sr} + \beta\varepsilon_{cs}E_s) \tag{13}$$

Where:

σ_s	steel stress in a crack under external tensile load[N/mm^2]
σ_{sr}	maximum steel stress in a crack in the crack formation stage [N/mm^2]
ε_{cs}	shrinkage of the concrete [-]
ρ	reinforcement ratio As / Ac [-]
f_{ctm}	mean tensile strength of the concrete [N/mm^2]
α	influence factor based on loading and crack stage (assumed 0.5)
β	influence factor based on loading and crack stage (assumed 0)
τ_b	bond strength steel-concrete (assumed 1.6*f_{ctm})
E_s	Youngs modules steel
$\emptyset$	reinforcement diameter [mm]

Deflection assessment

For the deflection in longitudinal deflection the ODE for a beam, loaded in bending, can be formulated as follows:

$$ODE: EI * \frac{d^4w}{dx^4} + kw = q \tag{14}$$

Where:

k	foundation modulus [N/m^2]
w	displacement [m]
q	distributed (external) load [kN/m]
EI	composed value of Modulus of elasticity and Moment of Inertia [kNm^2]

Solving this ODE has been done with maple. With this maple sheet the used formulas are elaborated. Due to the high foundation modulus of the soil, the settlement of the girder is only 0.01 millimeter. With the limit of a maximum soil deformation of 0.15 meters (NEN 1997, 2021), this deflection is acceptable and can even be neglected.

7.3.2. Environmental

In the previous paragraph the structural possibility of reusing concrete box-girders as a culvert is assessed on a superficial level. In this paragraph the environmental aspect will be elaborated in slightly more detail. Just as is done with the BAU, this paragraph will be split into two sections.

7.3.2.1 *ECI method*

In previous sections it is determined that the ECI of a reused girder can be seen as 20% of the total new application. However, in this application there will not be an element that is going to be reused in the same function. Therefore, some extra focus must be laid on this method. Unfortunately, the NED does not provide an ECI value for box girders. Therefore, the ratio between inverted T-girders and box girders will be defined, based on area and therefore self-weight. The self-weight contains all the materials available in concrete. This is the most important aspect of the ECI value, since it is determined based on raw material usage.

As is shown in paragraph 6.2, the ECI-value of an inverted concrete T-girder equals €45,552. This is applicable to spans up to 25 meters and can therefore be applied to the ZIP 700 girders. These girders contain a self-weight of 950 kg/m. The considered box-girders SKK 1300 contain a self-weight of 2420 kg/m. This is a factor of 2.5 higher. Combining these concerns and multiplying it with the length of the girder, an ECI value of €45.552 * 2.5 * 40 *20% = €911,04.

Unfortunately, this doesn't contain the total ECI value. The core of the box girder is constructed with polystyrene material. These need to be removed to create a hollow core where water can flow through. There are different ways of removing this layer, which can be done by multiple specialists. The way of removing will not be elaborated further but can be seen as an important aspect regarding the reusability of the box girders. Nevertheless, from the NED it is determined that the whole life cycle of polystyrene material costs €10,5194/m^3. For the box-girders with an internal area of 1.124x0.973 =1.09m^2 and a total length of 38m (40meter minus the 2 solid concrete ends), a total of €437,17 is assumed for the life cycle of polystyrene. Multiplying this value by 20% to leave out the construction phase, the ECI value of the removal of polystyrene blocks is assumed to be €87,40. A total ECI value for reusing concrete box girders as a culvert is estimated to be €998,44. This is without the other aspects for application on location (just as is done with BAU)

7.3.2.2 *Core measuring method*

For the core measuring method only the reused box girder is taken into account. The other aspects (as depicted in orange in Figure 64 on page 60) are also applicable for the construction of a culvert and therefore not required for comparison. However, this would give more insights in the total usage of the materials. The material input for a reused girder is provided in Table 33. For the total tons of concrete secondary reused, the weight of the girder/m (2420 kg) is multiplied with the total length (40m).

Table 33 Core measuring method - Material input Reuse

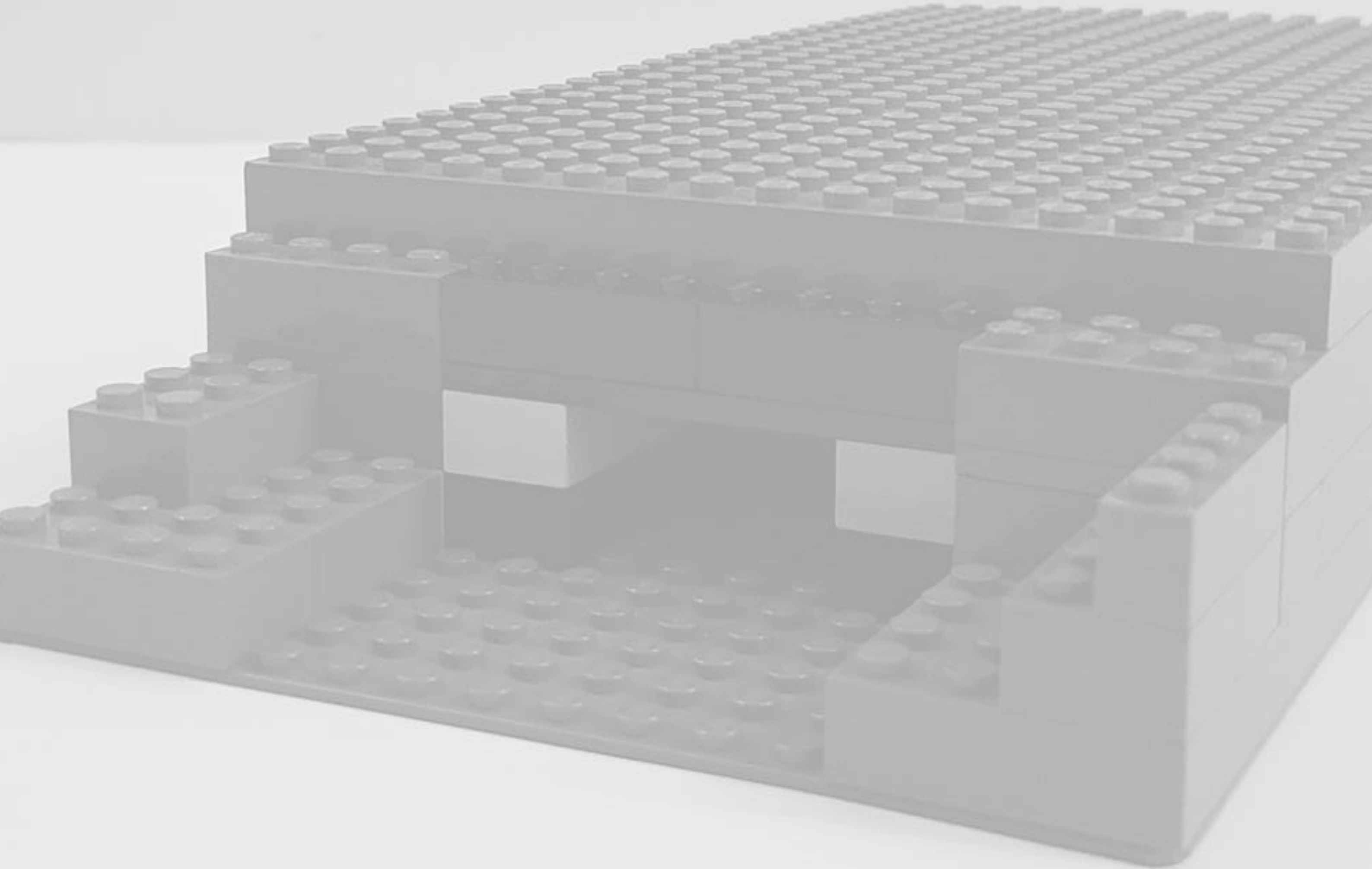
Number	Indicator	Ton	%
1	Total input	96,8	100
1.1	Primary	0	0
1.1.1	Non-renewable	0	0
1.1.2	Renewable	0	0
1.1.2a	Sustainable manufactured renewable	0	0
1.1.2b	Non-sustainable Manufactured renewable	0	0
1.2	Secondary	96,8	100
1.2.1	Secondary from reuse	96,8	100
1.2.2	Secondary from recycling	0	0

7.3.3. Economic

The costs of reusing a girder are already elaborated in the comparison between reusing girders versus BAU in Table 34. It was concluded that the costs were mostly dependent on the demount ability from the current structure. The costs that were composed for reusing the inverted T-girders are also taken into account for the box-girder. In this case it is again assumed that the girders are harvested from a (3x3)-type viaduct. A big difference between the inverted T-girders and the box-girders is the absence of a concrete topping layer. This takes a way additional costs. The calculations that have been done are shown in Appendix L: L.8 Economic calculations. Due the solid parts in the box-girder, the length of 40m cannot be obtained. Therefore, an extra girder is taken into account to form the total costs. In this comparison the principles are based on the compared values. Costs for excavation and transport for example, are assumed to be the same and therefore have not been taken into account in a comparison.

Table 34 Economic criteria reused girder

Criterium	Girder Reuse
Manufacturing	€ 0,00
Demolishing	€ 5.955,20
Adjusting	€ 0,00
Top layer	€ 0,00
Research quality	€ 2.000,00
Applying on location	€ 2.200,00
Total	**€10.155,20**



Chapter 3. Results and final remarks

8 Discussion

In the following section the discussion is started regarding the total research. During this research multiple phases have been gone through, each with their own different approach. At first the basis of the research is formed with an in-depth study and subsequently a data analysis has been done. This analysis created the starting points for different meetings with multiple experts. By using the knowledge of these experts (theoretically as well as practically), multiple design applications have been created and assessed. This led to a final possible design application which is further elaborated to provide a basic idea and a first possible outcome. All these phases are discussed in this section, based on two main categories: Research relevance and research limitations.

8.1 Research relevance

8.1.1. Transition to CE

In the introduction of this research it is stated that the government aims to work circular in 2050 and RWS strives for this achievement to be reached by 2030. The goal is to perform a transition from a linear into a circular economy. It is determined that the building sector, in particular the infrastructure, takes a big part of the current waste productions. Unfortunately, the infrastructure sector has insufficient knowledge about the value of reusing elements. This research contributes to this transition by allowing people from different design levels to broaden their knowledge as well as skills regarding reusability. With the reusability of girders from viaducts taken into account, not only the raw material depletion will be reduced but also other multiple environmental aspects like CO_2 emission.

8.1.2. Overview of acreage

An important aspect of reusability is to have elements which can be reused and thus being able to provide reusability as of today. Therefore, it is not only valuable to know which elements there currently are, but to know when these elements will be available as well. From multiple interviews along the research period, it turned out that there is a lack of an overview of both current used elements as the future availability. This caused an unequal balance between supply and demand, since it is unclear when the supply will be available. This thesis contributes to the reusability and the transition into the CE by providing a specific data analysis. This analysis is translated into a Lego box filled with different Lego blocks. With these Lego blocks inventoried, specific plans and designs can be made with reused elements. This will influence future projects of different market participants in the building sector to take reusability of concrete girders into account. With the current and future acreage summarized, speculations turned into facts.

8.1.3. Improving confidence in reusing

Currently the general thoughts about circularity and reusing are very negative. Old elements are seen as unreliable and score esthetically lower than new elements, which both are seen as extra investment costs. Combining this with the unequal balance of supply and demand, the confidence in reusing is very low. Within this thesis it is shown that based on the three main criteria, reusing is at the very least interesting to look further into. During this thesis period multiple experts from different companies have been interviewed to not only spread awareness but also to create a new way of thinking. It turned out that these people were on one hand very interested in the out of the box way of thinking, but on the other hand also a bit sceptic. The people who were already familiar with reuse thought only of reusing in the same function, without looking into further applications. There needs to be a cultural change on the value of reusing without people looking into it as second hand ‘garbage’. With new ideas, insights, more people involved and different design applications, the confidence in reusing is improved. Causing a higher chance of reusing instead of demolishing.

8.1.4. High- versus low value reusability

The aim of reusing is to go for high value reusability. However, this term is used in all sorts of matters without exactly knowing how to determine it. In paragraph 2 Background on page 22 the definition of high value reusability is formulated. In this definition the term 'value' is used, which is a vague term. In this thesis this value is determined to depend on the three main categories: Structural, Economic and Environmental. The particular value differs per category. The structural value depends on the extent of over dimensioning, the economic value depends on cost differences and the environmental value depends on the environmental damage. If a particular application scores a high value on all of the categories, it can be regarded as high value reusability. If the application scores a low value on all of the categories, it is regarded as low value reusability. With this way of thinking the reusability of materials and elements can be better quantifiable. Leading to better demarcations and inspirations in future projects. Everything in between is regarded as potential reuse and will always be better than grinding the concrete into debris.

8.2 Research limitations

The first research limitations are described in paragraph 3.2 Research scope. In addition to these limitations, within this research more impediments occurred along the road. These are elaborated in this paragraph.

8.2.1. Scope

The scope of the research is demarcated from the top all the way to the concrete girder viaducts by using multiple data systems. Since these data systems are based on the manual infill of information, there can be uncertainties within the data analysis. The MIRT 2022 that was used for the focus on future harvest probability is changing every year. This MIRT is based on multiple indications and provides a summary based on the data from specific (and more detailed) project plannings. Due to the current economic different times this future perspective is not very clear. Next to this, the release dates of the projects is not equal to the release dates of the elements. This differs of about three to four years. After the analysis with the data programs which were available at that time, an in-depth study is done manual. Looking deeper into the different technical drawings provided a distribution in different girder types. Furthermore, the scope describes a limit to the broad applications. It is aimed for to reach the biggest possible impact, however there are of course more elements and structures within the Dutch infrastructure.

8.2.2. Economic uncertainty

Currently the economy fluctuates enormously. The 'price tags' that have been created for the different purposes are based on multiple (substantiated) assumptions. These are therefore not precise and must not be used for further development. However, since the different purposes are defined with the same assumptions it can be used for a comparison. For this comparison only the values that differ have been taken into account. For example, transport costs have not been taken into account. It is stated that the transport from the factory to the location of a viaduct is equal to the transport from viaduct A to viaduct B (or culvert). Unfortunately, there is a very big chance that the elements need a storage location after demounting. Causing an increase in the costs as well as the CO_2 emissions.

8.2.3. No specific case study (structural uncertainty)

The aim of this research was to create impact and contribute to the transition to a CE. However, this cannot be done for the whole infrastructure sector at once. Therefore, based on multiple substantiated assumptions and directions a scope is created. The aim of this scope was to make as much impact as possible and therefore consists of the most common or most important/interesting structures and elements. However, since this scope is created with a bird's eye view the assessments do not contain that much detail. This is especially visible in the structural assessment, which turned out to be superficial and based on multiple assumptions. The structural assessment concluded therefore in a theoretical based and superficial recommendation of reusing.

8.2.4. Environmental uncertainty

Currently the reuse economy is ongoing, as stated in Figure 1 on page 3 of this research. Along the years, the previous linear economy is fully optimized for the structural aspects as well as the costs. Reusability on the other hand still needs a lot of development in the ongoing years, especially reusing in another function. The information and data that have been used in this research are based on the NED and different assumptions. This all is not yet optimized and leaves a lot of free interpretation. For example, the mentioned addition of 30% in the NED.

8.2.5. Choices based on interviews

For as well the creating of as the verification of the design applications, interviews have been held with multiple people with different backgrounds. However, this is still limited to these participants. Since it is a new way of thinking which nobody is familiar with, everyone has their own thoughts on certain aspects. In this research the opinions, thoughts and guidelines of these participants and experts are used as an underpinning for creating and verifying the design aspects. Leaving out the possibility of maybe more applications or a different view on certain aspects.

8.2.6. Most promising application

The most promising application, reusing as a culvert, is determined on expert meetings and a superficial substantiation. This means that it is not per definition the most promising, but it was at least interesting to look further into. For example, reusing in a bicycle bridge seems very feasible, since this application is not very different than the original function. Next to that it looks interesting to also check of reusing the big girders in factory halls, or other applications where a big span is required.

9 Conclusions

In this section the conclusion of the research is formed. This is done based on the in advance drafted main- and sub-questions. The core of the research is created by the different phases with different research methods, guided by the sub-questions. The sub-questions were composed to substantiate the main question and provide a clear, brief and to the point overview of the conclusions.

9.1 Sub-questions

To prevent not being able to see the wood for the trees, the different sub-questions were split up in multiple smaller questions. These are already answered throughout the research.

9.1.1. Phase 1: Creating a Lego box

1. How is the Lego box formed?

The goal of this phase was to create a valuable scope. This scope is based on multiple data systems from RWS, which were divided into two focus categories: current acreage and future plans. On firsthand the data systems regarding the current acreage were taken into account. Unfortunately, in practice it turned out that this current acreage method wasn't the best way to look into different types of girders. DISK was never designed as a data storage system, but only used to store results from inspections. Therefore, DISK contains multiple superficial information of structures within the Netherlands. This superficial information was used to form the first outlines of the Lego box. For requiring specific data about a particular structure, almost everything can be found. However, to find data of multiple structures at once and aiming to combine it all, is horrible. All the data is fragmented throughout different data systems.

This concluded in the use of another data analyzing method. This method was mostly focused on the MIRT 2022. In this report it is visible which projects will be established in the upcoming years. Despite the fact that this method was very labour-intensive it did create an insight in the upcoming available materials in the near future (up to 15 years). It was concluded that more than 2700 girders from 65 viaducts, varying between different sorts of girder variants have the possibly to be harvested. In the end, both methods combined (analysis of DISK and MIRT) lead to superficial information for creating a most common viaduct. It consists of a total length of 60m and a width of about 14 meters resulting into 3 lanes (Figure 18 on page 23). This most common viaduct was then visualized to be the shape of the Lego box in which the different elements are present. However, these Lego blocks are still attached to each other in the Lego box and require further demounting.

9.1.2. Phase 2: Viaduct girders

2. Which girders are going to be used for the design applications?

Phase 2 was the following of the data analysis that has been done in phase 1. In phase 1 the Lego box was determined and shaped as a particular viaduct. In this phase the particular Lego blocks were elaborated, focusing on the Lego blocks shaped as girders. An extensive manual in depth study in the technical drawings of 65 viaducts had been done. This study led to different available girder types, divided in 5 different categories: *Inverted T-girders, Box girders, T-girders, infilled girders* and *remaining*.

In addition, the structural behavior of concrete viaducts has been elaborated, providing a better understanding of the girders to create more optimized design applications. The most important aspect was the difference in the design standards during the last decades. This has an effect on the feasibility of reusing an element in either the same or in another function. Based on multiple criteria, different girder types have been chosen for the creating of different design applications. Two types of inverted T-girders (*ZIP 700* and the *HNP 75/98*) were selected based on three aspects. The high availability in the future, the fact that these ZIP girders are already chosen a lot to reuse in the same function and the fact that the HNP girders are rejected to use in the same function. For this last reason the *T-girders* as well as the *SDK 900* girders were taken into account. The final type that will be used for the design applications is the *SKK 1300*, based on the high availability.

9.1.3. Phase 3: Design applications

3. What are the possible design applications for reused concrete girders?

Before creating and assessing design applications a way of assessing is determined based on the three main criteria which act as a red thread throughout the research: Structural, Environmental and Economic. This assessment method is applied to the reuse of a girder in the same function to provide a comparison in the final stage. From first impressions it is determined that reusing in the same function (as a girder) gives a high value on both environmental and economic aspects. The structural value is also regarded as high, since the girder is loaded in the same way. Due to the fact that the linear economy is fully developed on less material usage for the lowest costs, it is assumed that this application is therefore not over dimensioned. It is determined that an environmental reduction of about €800,- is reached and a cost reduction of €3.400,- per girder. Concluding in a total of 3 high valued assessments, the reusing can be regarded as high valued.

With this one-on-one application in mind and the assessment methods known, the design applications had been created. This is done with the use of a brainstorm session with about 20 people with different backgrounds. This led to 22 different applications of reusing a girder in another function. The applications were categorized in two different categories: reusing due to the bearing capacity of the girders versus reusing due to the big, massive and bulky concrete elements. With the use of expert meetings these applications were brought to a top 5 design applications. Reusing a girder in *(non-) residential buildings, a culvert, a bicycle bridge, a retaining wall* or in *a sound barrier.* With a first structural assessment combined with future perspective, the top 5 applications were brought down to one final design application: Reusing a girder as a culvert.

9.1.4. Phase 4: Elaboration of design application

4. Is the determined design application actually doable?

The design application is determined in the previous phase and will be the reuse of a box girder as a culvert. To answer the question, the design application should be compared to constructing a new culvert as well as reusing the girder as a new girder. This way it gives a good impression of how to reuse.

In phase 4 the elaboration is done on a superficial level, regarding the three main categories: Structural, Environmental and Economic. Before being able to do these assessments, the dimensions of the fictitious case study had been determined. The culvert will be designed with a SKK 1300 girder with a length of 40 meters and a width of 1.5m, placed 1m below the surface level.

At first, designing a culvert from raw materials is taken into account and assessed based on the three main criteria. Next, the culvert constructed with the box-girder is assessed. The structural assessment looked very promising for reuse. However, due to the fact that the unity checks were way lower than zero, it is assumed to be over dimensioning. The combination of the steel and concrete in the girders are probably too much for the application and thus the value regarding structural reuse is regarded as low. In contrast to this structural value, the environmental value as well as the economic value can be regarded as high value reuse. The environmental impact is lowered by a factor of 2.3 (€2300,- versus €1000,-) and the costs were lowered even more by a factor of 9.0 (€90.000,- versus €10.000,-). However, additions to make the girder actual fit as a culvert were not taken into account. The watertight aspect as well as the sawing of different elements will need more research. In general, it is shown that both economic and environmental assessments lead to a positive change and given that in the future reusability is a must, this looks really promising.

In conclusion, reusing in general is better for economic and environmental aspects. Reusing as a culvert looks promising structurally, saves about the same on shadow costs as reusing as a girder but has a much higher cost difference (which unfortunately leaves some remarks). Due to the structural obstacles and based on these first impressions, reusing a girder as culvert can theoretically be seen as a good reuse application, but it is not higher in a general value than reusing again as a girder.

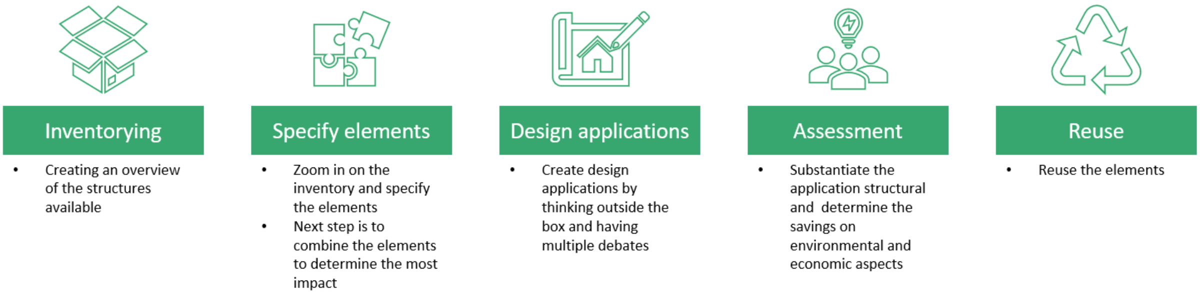
9.2 Main-question

The main-question of this research is formulated as follows:

How can a range of applications for reuse be classified for existing concrete viaduct girders from a valuable scope in the acreage of RWS?

This research question is interpreted into two categories: procedural and feasible. The first category is based on the ‘how-question’ and focusses on the complete process to achieve the classifying of reusability. On the first hand, classifying implies a systematic way of dividing applications in different groups or categories. However, classifying also translates into a systematic way of thinking regarding the approach. From this thesis it turned out that the classification required more than only providing a systematic approach by thinking outside the box. To be able to come up with a classification the aspects to classify needs to be known at first. This appeared to be a very time-consuming process.

This research provides the first starting points for further elaboration in the shape of the determined Lego box. With this Lego box a classification is made based on the three main criteria: structural feasibility, environmental impact and economic benefit, which acted as a red thread throughout the research. These main categories formed the scoring sheet (Appendix I: Score sheet design applications) to create a multi criteria analysis for different applications. For further research regarding reusability, the following roadmap can be used:



Inventorying
- Creating an overview of the structures available

Specify elements
- Zoom in on the inventory and specify the elements
- Next step is to combine the elements to determine the most impact

Design applications
- Create design applications by thinking outside the box and having multiple debates

Assessment
- Substantiate the application structural and determine the savings on environmental and economic aspects

Reuse
- Reuse the elements

Figure 80 Roadmap reusability

The second category is based on the 'can-question'. Is it really an option to reuse concrete girders in another application than the original function? The assessment of reusing a girder as a culvert is at first a superficial elaborated design application. This assessment, based on the three main criteria, piques at least the interests for further development. It is determined that reusing a girder is beneficial on the economic as well as the environmental aspect. The main issue will be the structural assessment, regarding adaptability and possible over dimensioning.

In conclusion, this research provides multiple possibilities of reusing concrete girders from viaducts within a valuable scope in the acreage of RWS. This scope is based on the most interesting and most common elements which are as well currently existing as 'soon' available. With the created reuse possibilities, classifying possibilities, and first assessments, a broader awareness of reusability is created. This translates to the fact that the reusability of elements can be taken to a whole new level in the transition into a circular economy.

10 Recommendations

This research is the first research about the reusability of concrete girders in another function. Where not only reusability is a new and interesting development, this reaches goes a step further by creating non-standard design applications. From multiple interviews it is concluded that this out of the box thinking creates interest by the interviewees and the first awareness has been set out. During this research multiple side notes of this main topic *circularity* were stumbled upon. Since the subject is very broad and currently a hot topic, everyone contacted had its own ideas and thoughts on the subject. Therefore, it is required to conduct more research regarding this subject. Based on the faced problems during this research, recommendations are given for further research to follow up on. The recommendations are split in two paragraphs: recommendations for companies and recommendations for other researchers.

10.1 For companies

10.1.1. Rijkswaterstaat

Due to the exemplary role of RWS regarding the circular goals in 2030, the scope of this thesis is aimed within the acreage of RWS. However, during this research, multiple obstacles have been stumbled upon which could be improved to reach these circular goals.

10.1.1.1 *Organize the data sets*

From this research it can be concluded that inventorying the data was very time consuming due to the big amount of manual work. Information is fragmented over multiple data systems. This makes it harder to combine the data. This research has focused on viaducts, but there are more structures within the acreage. If the accessibility and the usability improves, these structures can also be easier inventoried for further reuse purposes. On top of that, if the data is well organized, some sort of marketplace (an improvement of the current *Bruggenbank*) can be created to combine supply and demand with the building industry.

10.1.1.2 *Be the pioneer in reuse assessment*

From this thesis it can be concluded that the assessment of reusability is not easily done. This applies already for reusing in the same function let alone reusing in another function. Since RWS took the exemplary role regarding the climate agreements, it would be smart to also be the pioneer in the assessment of reusing. From the past it is known that design standards take multiple years to be published. RWS already created their own additions to the design of new and the assessments of current structures (RBK and ROK), thus an additional guideline for reusing will not be far off. To realize this the next recommendation can also be taken into account.

10.1.1.3 *Create the possibility for experimenting*

Every year 40 viaducts are demolished. This already leaves a lot of materials and elements to experiment on, since there has not yet been a development plan for everything. With creating for example different pilots or case studies, further research can be done. This will also stimulate reusing and thinking out of the box.

10.1.1.4 *Improve awareness and reuse possibilities*

Another recommendation is to improve not only the awareness into reusability, but also improve the possibilities for reusing. This can for example be done by either providing storage hubs for elements (maybe in cooperation with concrete factories) or by rewarding reusability. It is seen that a lot of possible hubs (owned by RWS) are available throughout the whole country. This will not only decrease costs of reusing, but also lower environmental emissions due to less transport. With rewarding reusability in different projects, it will be not only attractive to reuse, trust and confidence in reusing will increase as well. Both aspects will provide positive changes in the transition to the CE.

10.1.1.5 *Improvement of the designing of elements for a second lifecycle*

In this thesis the focus is laid on the reusability of current existing materials. The first impressions and possibilities are provided to reuse concrete girders in another function, which appear hopeful. Unfortunately, the structural assessment requires multiple adaptions. For RWS it is recommended to focus on these adaption possibilities and to design (together with the infrastructure industry) new elements in such a way that reusing can be easier. For example, with easier demountable structures to save costs on environmental as well as economic aspects.

10.1.2. Nebest B.V.

10.1.2.1 *Development of the reusability scan*

This research is based on creating a bridge between two phases with CTL: the reusability scan and the design phase. This reusability scan is a tool which underwent a lot of updates during this research period and has already been used many more frequent in different projects. This research can be used as a basis for further research and further development of this reusability scan. It would be interesting to work out multiple design applications for different elements and adding these worked out applications to the reusability scan. If an element is labelled as potential reuse in this scan, the different applications can pop up to stimulate designing with reused elements. This way the bridge between the two phases as described in Figure 3 will actually be created.

10.1.2.2 *Use the data inventory*

This research provides a time-consuming, manual inventory of multiple structures within the Netherlands. For the upcoming 15 years four different main structures have been summarized, based on the future demolishing plans. With this information known, Nebest can take their advantage and improve their spot in the market as well as tendering on promising projects or pilots.

10.1.2.3 *Experiment with remaining girders*

Nebest (particularly CTL) is already participant in multiple different projects. Especially in projects regarding reusability. Since the reusability scan does not always approve all the elements, different elements will remain unused. With these elements experiments can be done (maybe in collaboration with RWS) to improve and substantiate structural assessments. This will conclude in more trust regarding reuse, which will improve the transition into the CE.

10.1.3. Asset owners

10.1.3.1 *Uniform naming method*

In the Netherlands a lot of information is stored per different structure. However, when the focus is into multiple structures at once, it is hard to obtain the data. This data is spread over multiple data sources and therefore hard to combine. In first instance this can very easily be tackled by using a uniform naming method of all the infrastructure works. RWS already uses a uniform method of naming their structures, based on location, and complexes. These codes are displayed like 45B-145-01, regarding their location throughout the country. Unfortunately, other asset owners throughout the country do not use the codes. This makes it very difficult to get an overview in the future ability of structures. Which further translates in an unclear overview of different elements. If a uniform method is used it will be easier to combine supply and demand.

10.1.3.2 *Create collaborations*

More than 200.000 structures are realized in the Netherlands. In this research the acreage of RWS is taken into account, which only consists of approximately 6000 structures. This means that there are many more left owned by different asset owners. It is recommended for these asset owners to get together and inventorize the structures. Next it is important to share the knowledge. This way reusing can be improved and the usage of raw materials decreased.

10.1.4. Policy makers

10.1.4.1 *Improve design standards*

What accounts for RWS, totally accounts for the policy makers. There is not a clear standard on assessing and verifying reusability. Uncertainties have occurred the last years. These can be taken away by for example design by testing. This is a verified method within the Eurocode to prove the ability of reusing. The first steps into these standards have already been made with the use of CB'23, which has written multiple guidelines. The best way would be to create a new Eurocode or national annex regarding the reusability of elements in the same function as well as in a new application.

10.1.4.2 *Definition high- and low value reuse*

A lot of uncertainties occur for the specific definition of high- and low value reuse. During this research multiple discussions have been done, based on this aspect. A lot of people have different opinions and almost everyone uses it (on purpose or not) for their own use. Somebody who works in a concrete factory will think different of this term than a worker in the demolition industry. To be able to compare different approaches, designs or ideas, a uniform definition needs to be established.

10.1.4.3 *Elaboration of the NED*

Currently the NED is a tool used for first impressions. As already mentioned, an extra factor of about 30% is added on top of the ECI values to let other companies come out a better way. On top of that, an improvement of the broad applicability would be recommended to create better and faster impressions regarding reusability. From this research for example, the absence of a box girder was unfortunate.

10.2 For further researchers

In the previous paragraph, multiple recommendations are given for different companies. These recommendations are also applicable to other researchers. In the following paragraph some additional recommendations are given, which are not specified to particular companies.

10.2.1. Improve classification of design applications

In this research a first impression of a classification has been done, regarding reuse possibilities of different design applications. However, this is also a time-consuming method, since multiple discussions and interviews have been executed. It is recommended to perform an improved MCDA for the applications as mentioned in this research. Therefore, relevant ideas can be substantiated more qualitatively instead of quantitively and interesting as well as promising applications can be created.

10.2.2. Further investigating of the culvert

10.2.2.1 *Structural assessment by software*

In this research the reusability of concrete girders is elaborated on a superficial level. However, the devil is in the details. Therefore, additional research is required in the actual possibility of reusing a concrete girder as a culvert. The first aspect is the structural assessment. To have a reliable and substantiated research, a verification with the help of different calculation methods like finite element methods or SCIA needs to be provided. To verify this software, a specific case study could be executed.

10.2.2.2 *Take away the main obstacles*

The first main obstacle is the connection in between multiple elements. As mentioned in the research, this connection needs to be watertight. Otherwise, the whole idea of the culvert is gone. Possibilities of this water tightness can be to either use a specific rubber ring or to create an external connection over and around the girders. The second obstacle is the sawing of the girder into different elements. This sawing affects the (prestressing) steel in the box girder. This would be interesting to work out further to create a conclusion on how this can be done in practice. The third obstacle is the polystyrene layer in the core of the box girder. What is the best way to remove this layer and is it possible to reuse again?

10.2.2.3 *Adjust the parameters*

In this research multiple assumption have been made. Starting with the use of a box girder. It could be possible that another girder would be better for this application. Furthermore, the application on a soil layer and therefore foundation on grade is assumed. It would also be interesting what the outcome will be if the culvert needs to be supported on concrete piles or when another layer (peat for example) is used. Would it still be sufficient?

10.2.3. Taking into account other girders, structures or elements

In this research the final chosen girder for reuse is determined to be a box girder. However, the girders that cannot be reused in the same function again are very interesting to investigate further. These are almost mandatory to be reused in another function.

Furthermore, this research has been focusing on concrete girders from viaducts. The total acreage of infrastructure works consists of more than 200.000 structures, corresponding to even more different elements. These structures, with corresponding elements, can also be interesting for reuse applications. In the same function as well as in another function. Next to these structures the remaining girders are also very interesting to look into further. Especially the girders which.

10.2.4. Further elaboration of other design applications

This research has been providing multiple different design applications. One of these has been chosen to point out. However, it would also be very interesting to see an elaboration of the other design aspects, especially one of the top 5. For example, reusing as a retaining wall can maybe be realized by different designs. A possibility to make this application work can be by using ZIP girders, which have the preferred inverted T-shape, but have a difficulty in stacking the different girders. Another possibility can be to rotate the box girders in a way that the horizontal soil pressure acts in the same direction on the girders as the traffic load of the viaduct did. This causes the reinforcement to act in the right direction. As final it could be an idea to turn the girders 90 degrees, forming a wall in this way.

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Appendices

Appendix A: Waste management

The amount of concrete supply for buildings as well as non-building engineering structures is huge. Currently the ‘waste’- concrete after demolishing will be almost fully (95%) recycled. However, the biggest amount of this concrete is grinded to debris and recycled into foundations underneath the road. This is seen as a waste of concrete elements. Next to that, all the different concrete types are mixed together into one general pile of debris. Causing to have not only different concrete types (e.g. normal concrete versus high strength concrete) but also different conditions (e.g. concrete affected by chlorides) mixed all together (Nedeljkovic, Schlangen, & Fennis, 2021). This recycling is visualized in Figure 81. In this image GWW (*Grond-, weg- en waterbouw*) is translated to infrastructure works and B&U (*Burgelijke en utiliteitsbouw*) contains the (non-) residential buildings. The recycling process into embankments be regarded as waste, since these embankments can for example also be made by soil, which has a lower CO_2 emission.

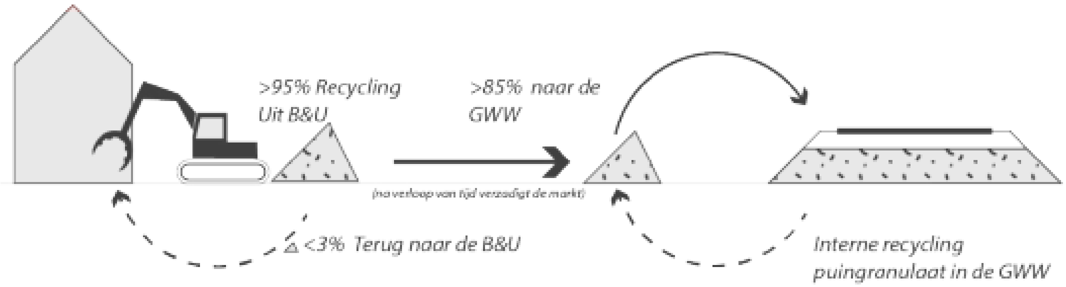


Figure 81 Current concrete recycle process (Dijcker, Crielaard, & Schepers, 2018)

In Figure 82 a schematization is visible of the aforementioned concrete recycling possibilities. In this image each white square represents one million tons of concrete. Therefore, the biggest challenge is not particular to cause recycling, but using a high-grade recycling method and looking further than that before labelling it as circularity (PBL, n.d.).

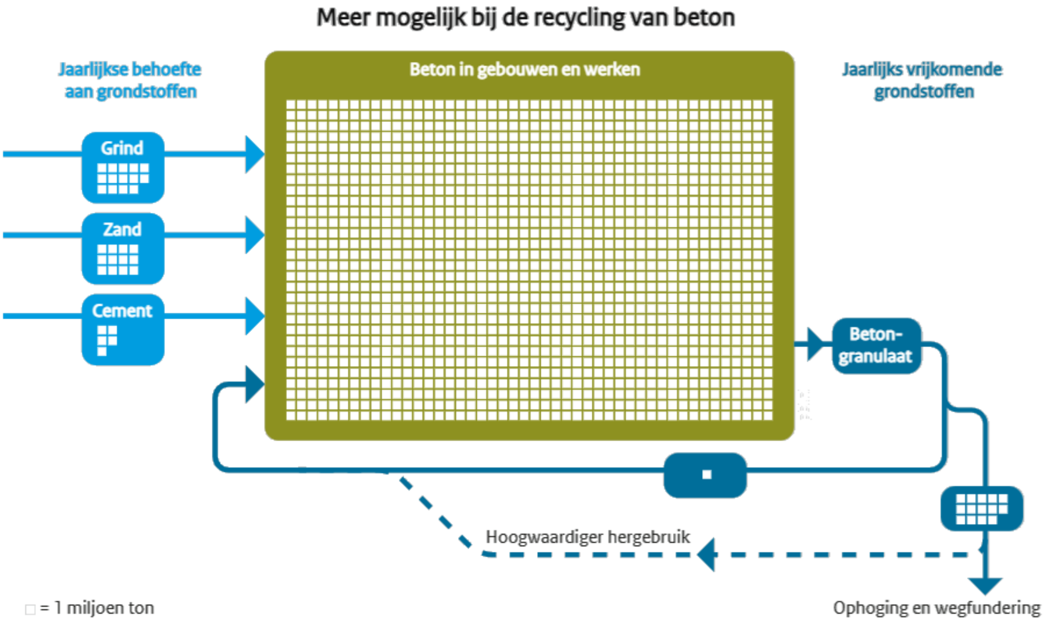
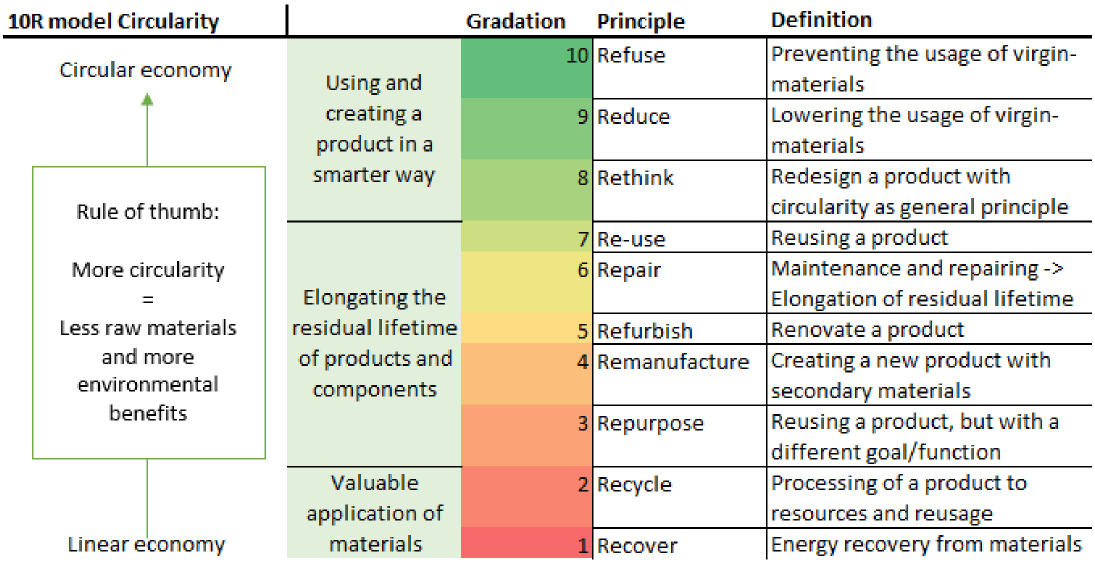


Figure 82 Possibilities of concrete recycling (PBL, n.d.)

Someone who did look further than recycling, despite many others, was a member of the Dutch parliament, Ad Lansink. He proposed a fundamental system to the waste management in 1979. From 1993 on, his method is incorporated in the Dutch policy and called the ‘ladder of Lansink’ or the ‘waste hierarchy’. This tool evaluates the processing methods of waste, with the most preferable option on top of the ladder. The ladder differentiates in three main categories on how to cope with waste. The highest priorities are the top two: prevention and reusing. Next to that recycling and high-end energy production, while the least favorable are burning or dumping (disposal) of waste (Lansink, n.d.). This ladder is shown in Figure 83.

Figure 83 Waste hierarchy or Ladder of Lansink (Lansink, n.d.)

A further in-depth study on the waste hierarchy by prof. dr. J. Cramer (Cramer, 2014) lead to a model for high-end reusability, called the 10R-model. This model contains 10 different circular principles. These R-principles encourage thinking and improving of circularity (CB'23, 2020 - b). As a rule of thumb, a higher principle on this model (shown in Figure 84) equals more circularity and therefore defines a higher circular potential (CB'23, 2019). The Netherlands (and also the world) is currently in the reuse economy due to the transition into the circular economy. In this reuse economy the processes recycling (processing and reusing of materials) and recovering (recovering energy from materials) are noted as the most important. However, it is clear to see that, due to the gradations in the 10R-model, these principles belong to the bottom two levels of circularity (Council for the environment and infrastructure, 2015). The circular economy clearly includes more circularity processes. In an ideal economy, all the materials in a harvested element remain their original state and remain their quality. This way the elements can be immediately reused into a new design (CB'23, 2019).



10R model Circularity		Gradation	Principle	Definition
Circular economy	Using and creating a product in a smarter way	10	Refuse	Preventing the usage of virgin-materials
		9	Reduce	Lowering the usage of virgin-materials
Rule of thumb: More circularity = Less raw materials and more environmental benefits		8	Rethink	Redesign a product with circularity as general principle
	Elongating the residual lifetime of products and components	7	Re-use	Reusing a product
		6	Repair	Maintenance and repairing -> Elongation of residual lifetime
		5	Refurbish	Renovate a product
		4	Remanufacture	Creating a new product with secondary materials
		3	Repurpose	Reusing a product, but with a different goal/function
	Valuable application of materials	2	Recycle	Processing of a product to resources and reusage
Linear economy		1	Recover	Energy recovery from materials

Figure 84 10R-Model Circularity, adapted from (CB'23, 2019; PBL, n.d.)

Since this research focusses on current existing elements, the principles *Refuse, Reduce* and *Rethink* (gradations 8-10) are disregarded. Where the first one (Refuse) focusses on doing nothing, the other 2 principles are based on the construction phase. These phases are therefore not applicable and this research focusses on the next highest principle: Re-use.

Appendix B: Closing the loop

Nebest B.V. participates together with Antea Group, Strukton Civiel, GBN group and multiple knowledge institutes in the consortium Closing the Loop (CTL). This Consortium aims to close the lifetime loop by focusing on reuse of viaduct elements. This implies not constructing or designing new elements to be circular in the future but focusing on reusing old elements into a new purpose and thus being circular as of today. In Figure 85 the chart of CTL is shown with its five different phases. Lego blocks are used for a visualization of these phases.

B.1 Five phases to Close the loop

The first phase (on top in the chart) is about gaining knowledge. To start the feasibility assessment regarding circularity, the current elements need to be known to design new structures. By doing research based on the to be demolished structures, the basis of circularity is formed. Due to the first analysis of structures, already more than 60 extra structures were scaled to a ‘promising’ level, which means they will be demolished or replaced before the year 2030 (Keemers & Looije, 2021).

The second phase (going clockwise) is the reusability scan. Where the first phase explained the need for potential structures, this phase goes deeper into element detail. The first step is about determining which ‘Lego blocks’ the structure is built off, followed by an assessment of each of these different Lego blocks (elements). The reusability scan is elaborated further in the next paragraph.

The third phase consists of the circular design concept. This phase is about combining supply and demand. Where the supply is created in the first two phases, the demand will be based on the design of a new viaduct. By providing possibilities for the harvested elements, the design concepts can be influenced and opportunities for scalability occur. The goal is to being able to know which Lego block can be placed where and how to combine and connect them.

The fourth phase will be the construction of the viaduct. A feasibility scan based on technical as well as financial aspects will be done on the design concepts before the final construction takes place. Not only the construction is considered but also the future demount ability of the structure. In other words, stacking and connecting the Lego blocks.

The fifth and last phase is about decomposing of the newly constructed viaduct. Or in other words, the reusability of the viaduct or visualized as removing the Lego blocks. With the demount ability taken already into account in the design, and the supply is already known, the circularity loop can be closed after this phase (van den Berg, 2021).

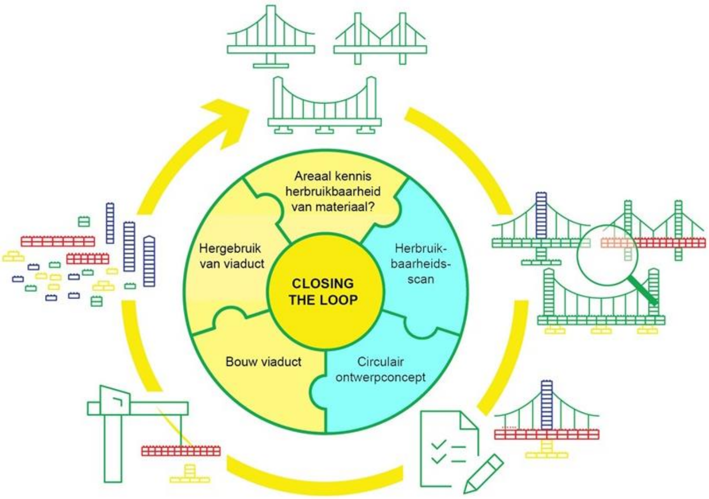


Figure 85 Closing the loop chart of Nebest (in Dutch) with highlighted phases (van den Berg, 2021)

The five previous mentioned phases were combined in the feasibility assessment for phase 1 of the SBIR. This research concluded that circular concrete viaducts are not only feasible, but also have a big impact on the environment. By average of the first scans, per circular viaduct there will be a reduction of: 62% on the environment cost indicator; 49% carbon dioxide (CO_2) emission and 93% abiotic material[19] (van den Berg, 2021)

Closing the loop reached phase 2 after concluding the feasibility of the concrete viaducts in phase 1. In this second phase the gathered information will be applied in practice and a prototype needs to be build, which in this case means a fully circular viaduct.

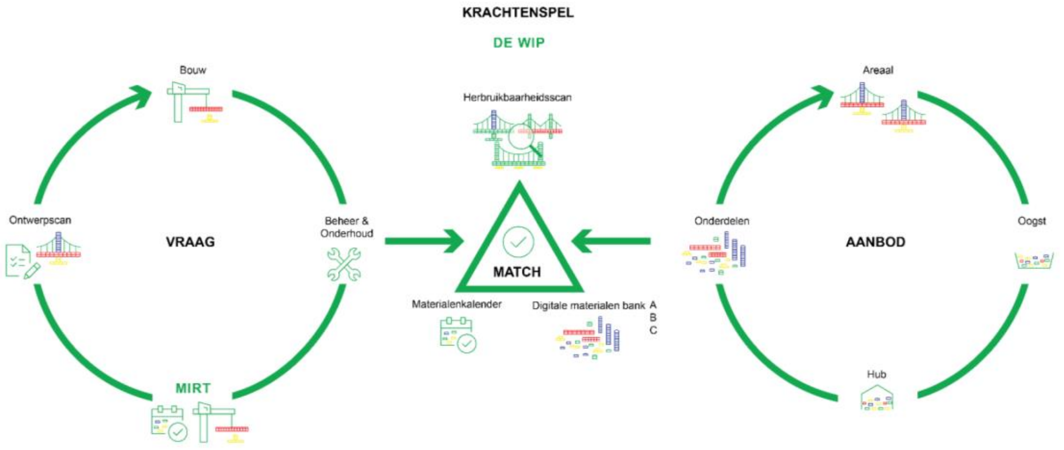
B.2 The reusability scan

To be able of being circular as of today, a reusability scan is created in phase 1 of the SBIR. This reusability scan is an inspection tool, made by Nebest, to determine a degree of reusability for civil engineering structures. On the first hand only infrastructure works, but later on also (non-) residential buildings. By using three main categories, based on a longlist from CB'23: residual lifetime, demount ability and constructive properties, an assessment is done for the reusability of a structure.

Currently al the basic information about structures is stored in DISK, the data system of RWS. This information is stored in rough lines (e.g. the total span or the number of supports) and contains not that many details (e.g. number of girders and their length per span). In the reusability scan, the structure is decomposed according to the Dutch standard NEN-2767. This decomposition is mostly used by the asset managers in the civil engineering sector and describes the underlying components per element. With the reusability tool an expected demolition year will be determined per *structure*, but dimensions will be clear on *element level* (Span & ter Meulen, 2021). Since the first step into circularity and reusability requires knowledge of data, the goal of this reusability scan is to create a data base in which as much information is stored as possible and can be shared with multiple sectors. Therefore, an early detection of reusability is possible which creates a better transition to circularity. With the reusability scan chances of reusability can be noticed in early stages which is an important factor to be able to let reusability succeed (Span & ter Meulen, 2021).

The different elements of each structure are assessed based on the 10R-model (as mentioned in Appendix A: Waste management). With the use of this method, the first determination is made into the reusability of an element. From this scan it is assessed if an element is reusable or not. This research will go further on this assessment and therefore will not take into account further possible damage symptoms.

B.3 The seesaw (*wip*) of Nebest



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[19] A non-living part of an ecosystem that shapes its environment, for example water, temperature and minerals

Appendix C: Scope of the research

C.1 Aging infrastructure

The total civil infrastructure in the Netherlands is aging, but until recently, exact numbers were unknown. In the reconstruction period after the second world war, a lot of infrastructure works were built throughout the country. Until this very moment, the Netherlands still keep continuing building. These civil structures were designed and constructed mostly using concrete and/or steel. Each of these infrastructure works has an estimated lifetime of 80-100 years, depending mostly on the location, quality and maintenance. Considering the expected lifetime as well as the building period, a huge maintenance/ replacement project in the period of 2025-2050 is expected. However, the specific impact of the maintenance/ replacement project is unknown. Only since July 2017, Dutch authorities (e.g. municipalities, provinces, RWS) are obliged to register their assets (e.g. roads & structures). This registering had to be done in the *Basis register topografie* (BGT) (Bloksma & Westenberg, 2021). With the research of Bloksma & Westerberg the total amount of infrastructure works is determined on approximately 213.000 (Bloksma & Westenberg, 2021). This includes everything from the biggest bridge in the Netherlands, the Van Brienenoord bridge, up to a small culvert underneath a local road (Bleijenberg, 2021). Note that, this BGT isn't fully reliable. The data is uncertain and not complete. However, it is the only national data source in which the infrastructure works are registered (Arnoldussen, et al., 2022).

With the obtained data the graph in Figure 86 is made. After the reconstruction period, starting in 1945, the first construction peak of the infrastructure is visible between 1960-1980 due to the emergence of the car. However, not only the aging is a concern on the old structures. With an unforeseen huge increase of the freight traffic (in quantities and in weight) the current load on the structures is way more than the load used in calculations back then. After a small decrease the growth of a new peak occurred in the period of 2000-2010 due to the need of better integration. More tunnels for example and complex junctions were required for a better traffic flow (Bleijenberg, 2021).

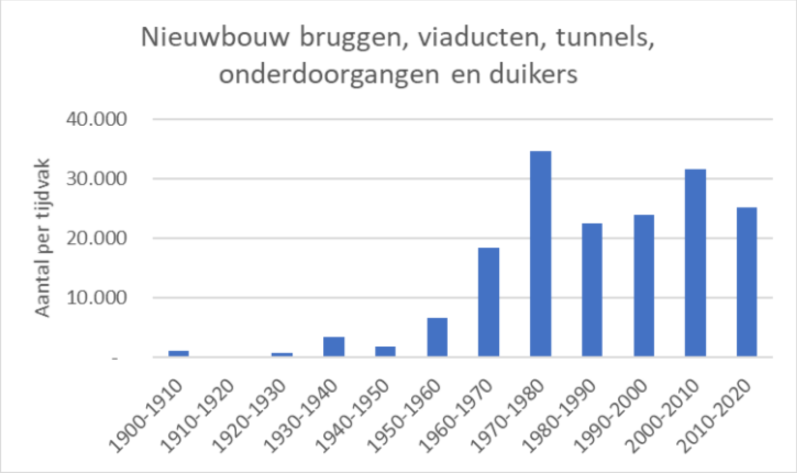


Figure 86 New structures built per decades throughout the years (Bloksma & Westenberg, 2021)

C.2 Concrete viaducts

Based on the fact, mentioned in the paragraph 2.2, that at least 70% of the demolished viaducts were demolished for *functional* aspects, the first defining is done into concrete viaducts and bridges. In March 2021 it is concluded that the Netherlands contain about 85.000 bridges and viaducts (Bloksma & Westenberg, 2021). This corresponds to about 40% of the total amount of structures. These structures are located throughout the whole country and managed by multiple different authorities like municipalities and provinces. With a total of about 6000 structures, RWS manages as biggest authority the largest amount. The other structures are split into multiple asset owners. About 3100 of these structures from RWS are Viaducts, following from an output data set retrieved from DISK. It must be noted that this is filtered upon viaducts which are in use (thus not under construction or demolished). An overview of the number of structures, including the first demarcation, is visible in Table 35.

Table 35 Number of structures divided per scale (Bloksma & Westenberg, 2021) (Bleijenberg, 2021)

Scale	Amount
Infrastructure works in the Netherlands	213.395
Bridges/Viaducts (Fixed/Movable & Concrete/steel) in the Netherlands	84.573
Infrastructure works in the acreage of RWS	6.237
Viaducts in the acreage of RWS	3.119
Concrete viaducts in the acreage of RWS (which are in use)	3.026

C.3 Concrete girders

In this section a comparison is made between the 10 most common elements within a viaduct, summarized in the Table 36 on the next page. This is done by using the graph in Appendix D: D.1 Different elements per viaduct. These elements have multiple components which are prescribed in the NEN-2767. From multiple interviews combined with own experience from the working field, the most common components are summarized. Each element is then assessed on its (dis)advantages regarding reusability. Comparing these with each other, the demarcation of the scope is determined to focus on concrete girders.

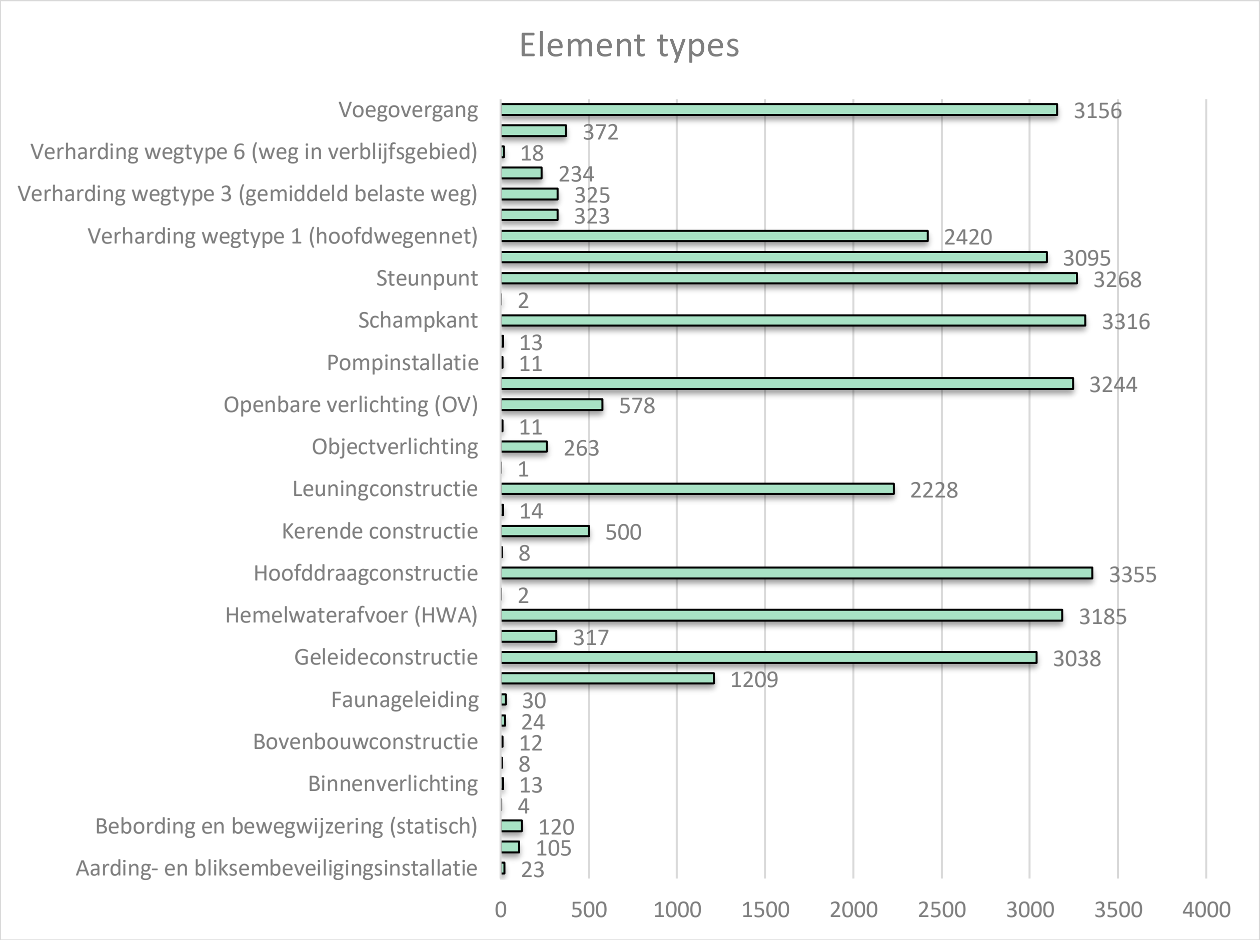
Table 36 Viaduct elements with their (dis)advantages regarding reusability

Element	Most common components	(Dis)advantages reusability
1. Support	I. In between support (like columns or walls) II. End support: Abutment	+ Structural element + Lots of concrete - Project specific - End supports are made in-situ and therefore hard to demount - Not designed for transport
2. Embankment	I. Embankment, general II. Cover	- Non constructive element - A lot of sand - Cover of grass or tiles
3. Main load bearing structure	I. Girder II. Deck	+ Structural element + Consist the most concrete of the viaduct + Can withstand high loads + Prefab elements are easy to demount and designed for transport - Standards have changed over the years - Lots of different types
4. Curb	I. Curb, general II. Curb strip	- Small quantity - Probably additional rail on top + Mostly consisting of prefab elements
5. Traffic barrier and/ or handrail	I. Traffic barrier (concrete or steel) II. Handrail (Normal or vehicle withstand able)	- Non constructive - Mostly made of steel + Standard design + Easy demountable
6. Asphalt layer	I. Underlayer (DAB) II. Top layer (ZOAB)	+ Good for recycling, bad for reusing
7. Rainwater discharge	I. Rainwater discharge, general	- Not visible most of the times - Very limited
8. Expansion joint	I. Joint rubber II. Multiple different types	- Relative shorter life span - Designed one way and therefore hard to reuse in another function - Integrated in deck
9. Bearing	I. Hinged II. Roller bearing III. Clamped	- Relative shorter life span - Specific and therefore hard to reuse
10. Foundation	I. Foundation	- Hard to remove and causing negative influence on the soil - Specific element

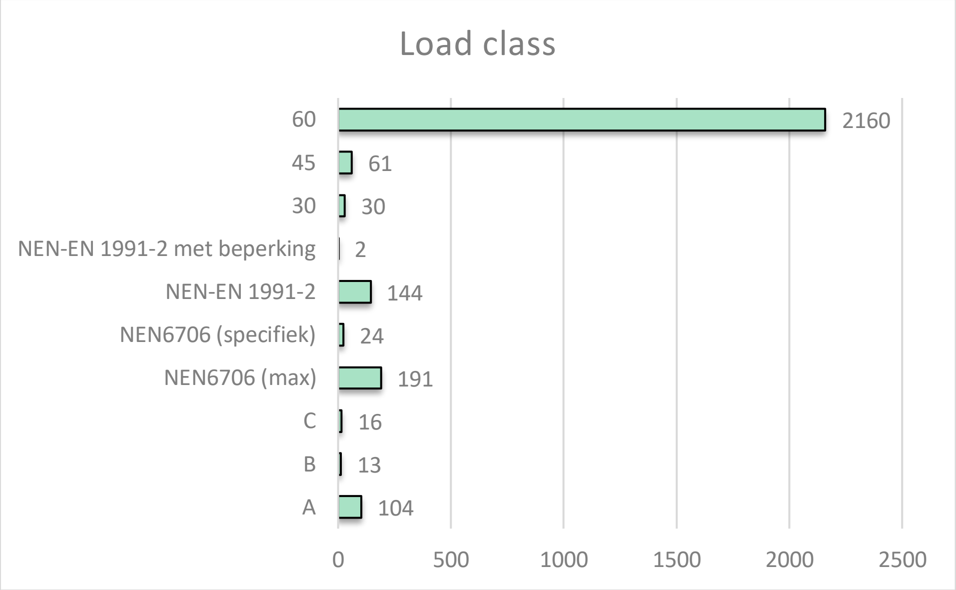
Appendix D: DISK Graphs

This appendix consists of multiple graphs which are created by the data set retrieved from a data list within DISK. This data list is retrieved with the help of a DISK data analyst Patrick Parsan, combined with personal access (obtained for own field experience at Nebest) to DISK. With the possibility of running different queries, it was possible to have an overview of the combined data. This data is split into multiple graphs along this appendix.

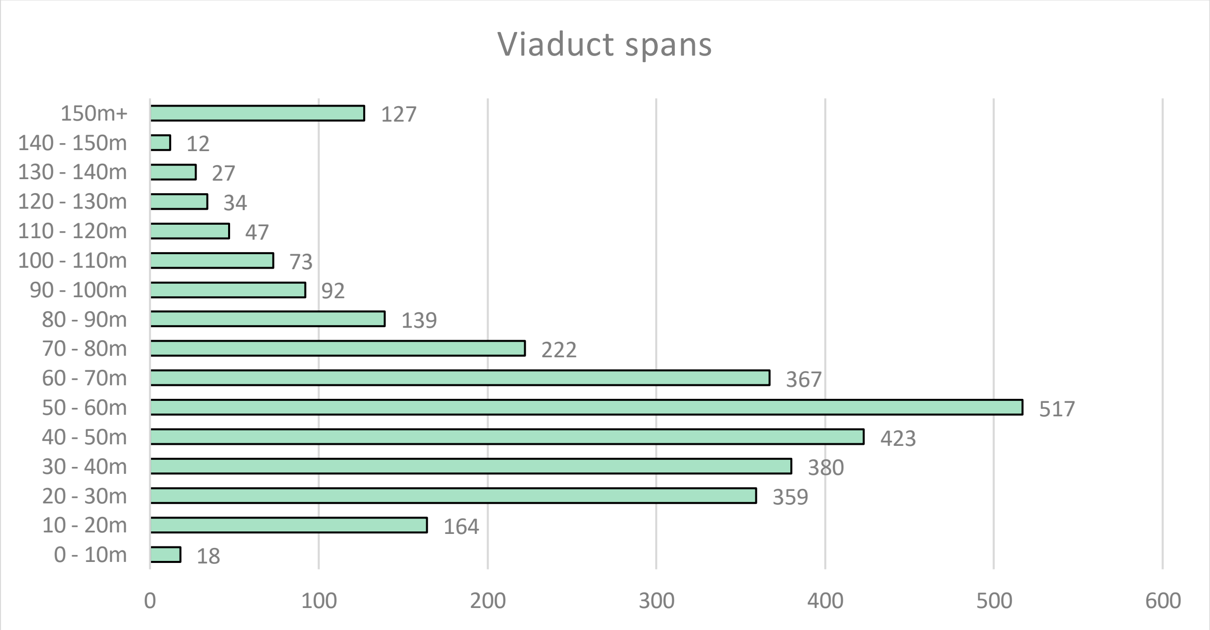
D.1 Different elements per viaduct



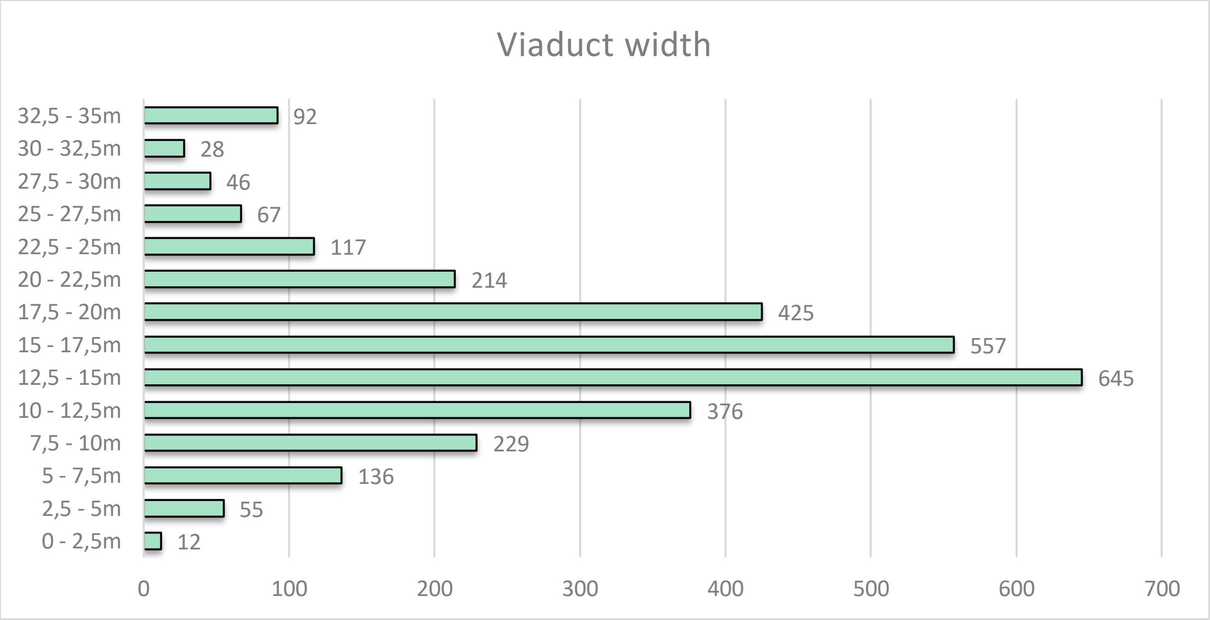
D.2 Occurring load classes



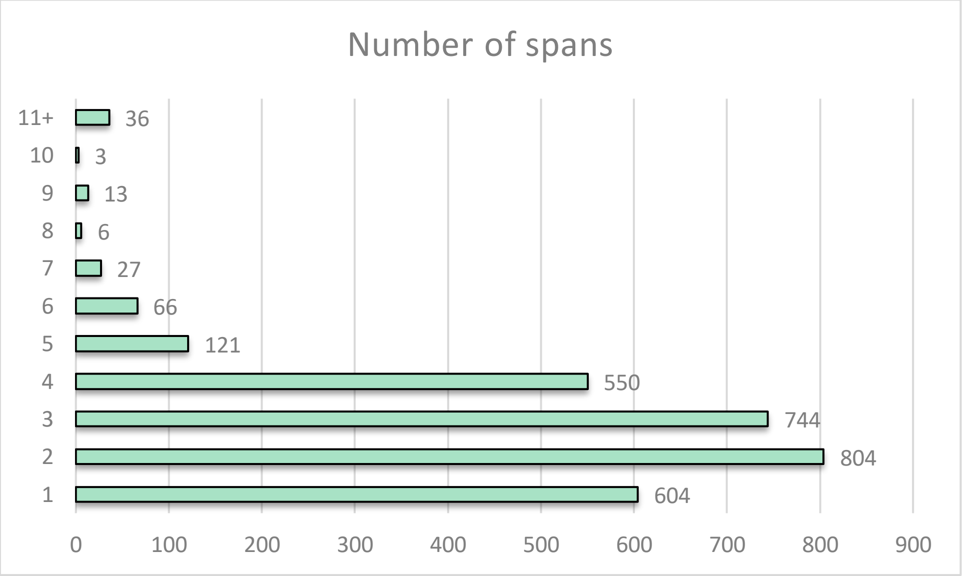
D.3 Viaduct length



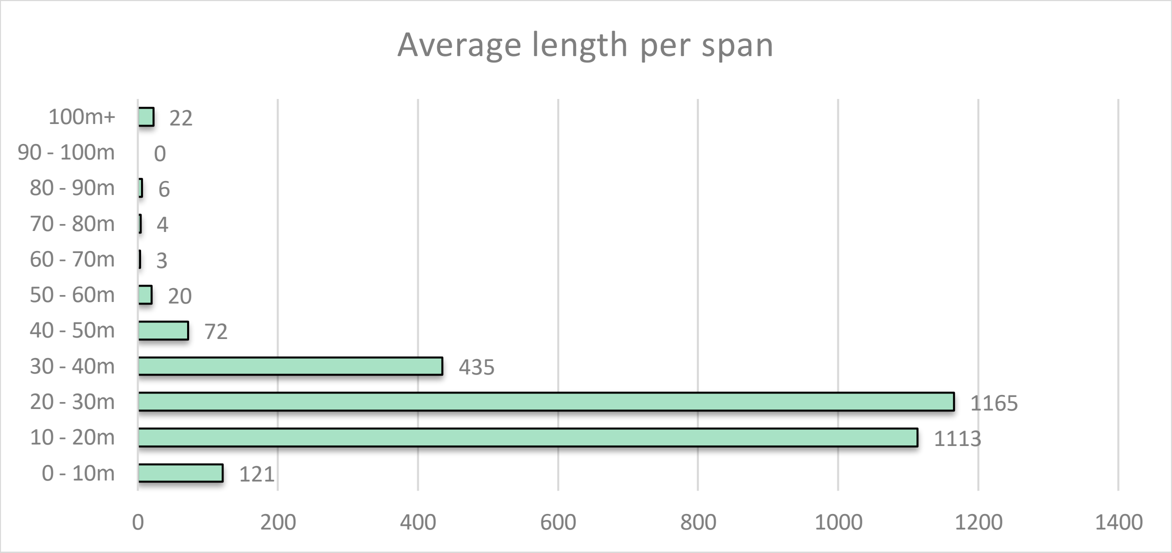
D.4 Overview of viaduct widths



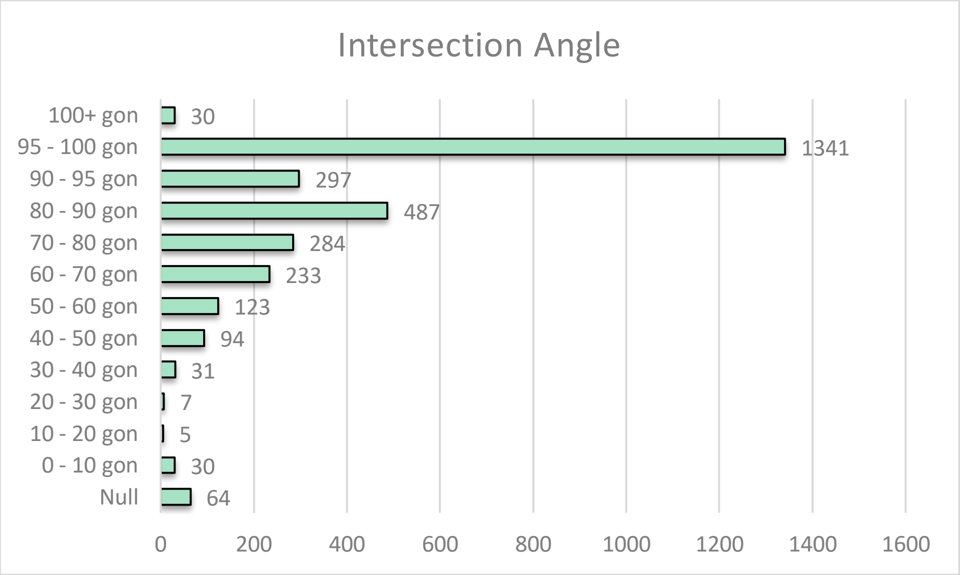
D.5 Overview of viaduct spans



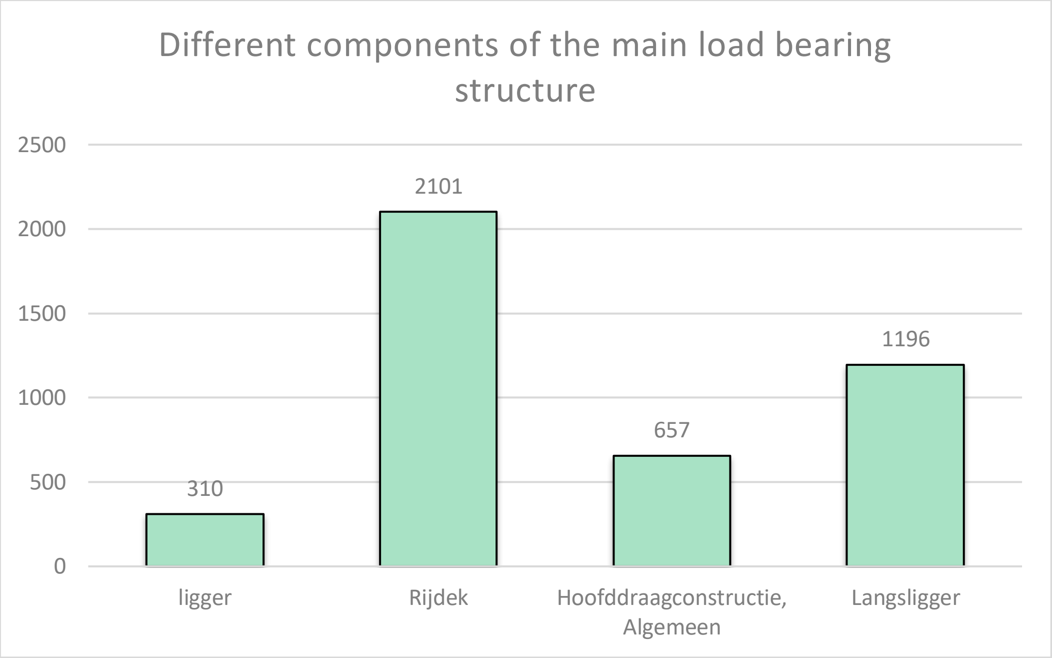
D.6 Average length per span



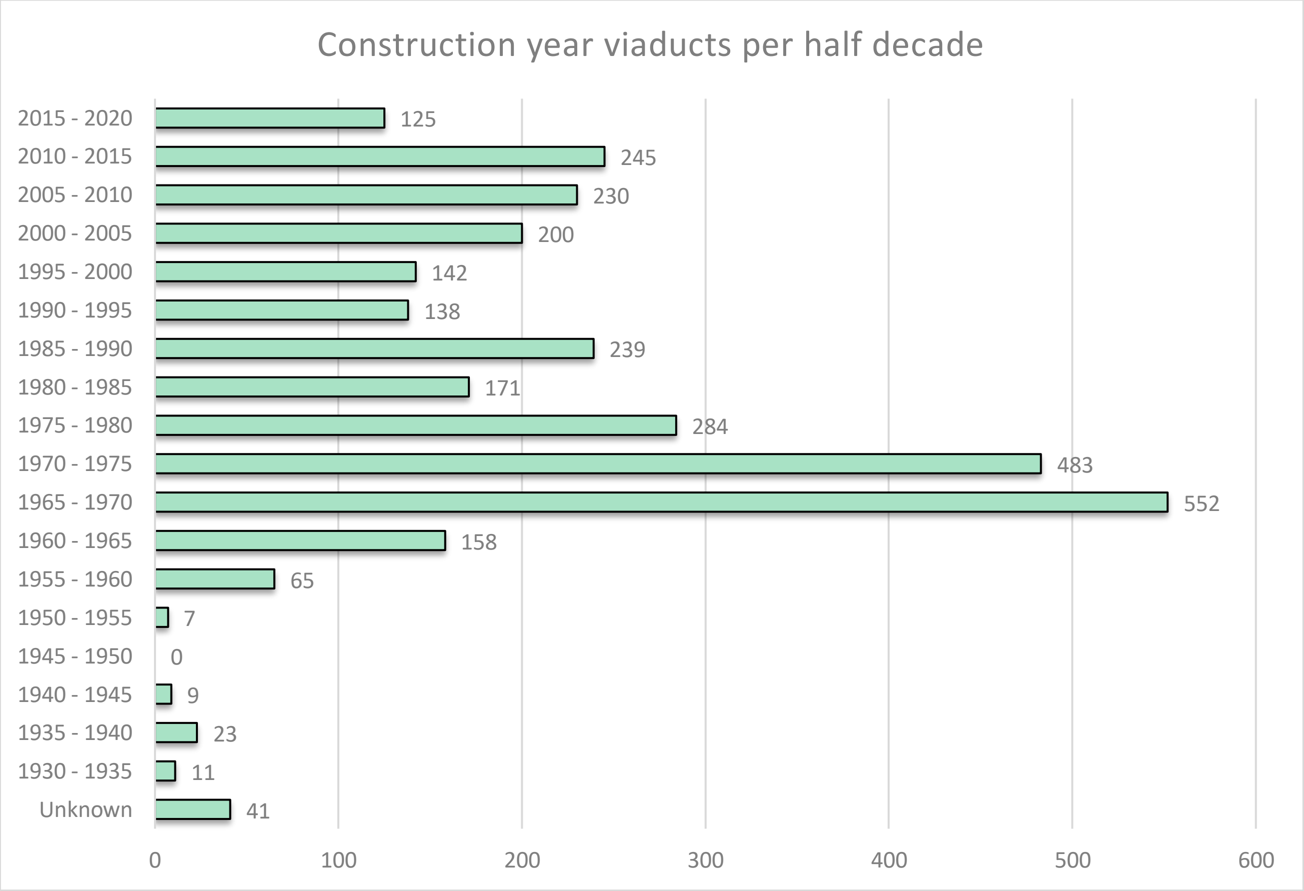
D.7 Intersection angles



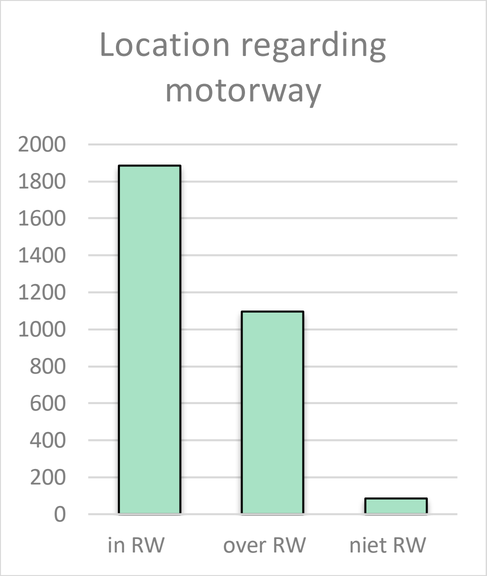
D.8 Main load bearing structure components

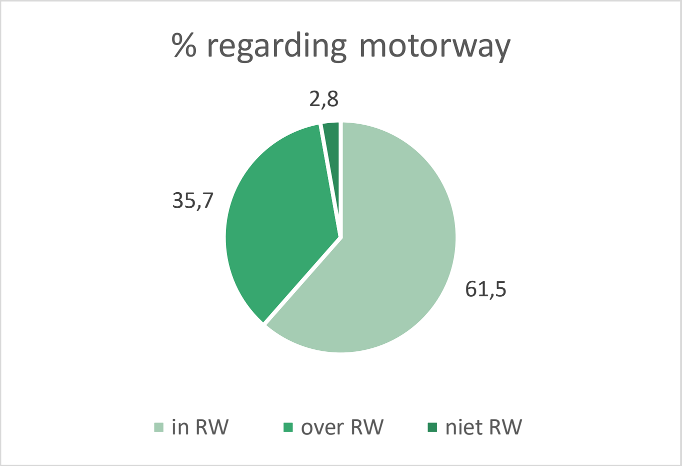


D.9 Main load bearing structure components



D.10 Viaduct location regarding the motorway


Location regarding motorway
2000
1800
1600
1400
1200
1000
800
600
400
200
0
in RW
over RW
niet RW


% regarding motorway
2,8
35,7
61,5
in RW
over RW
niet RW

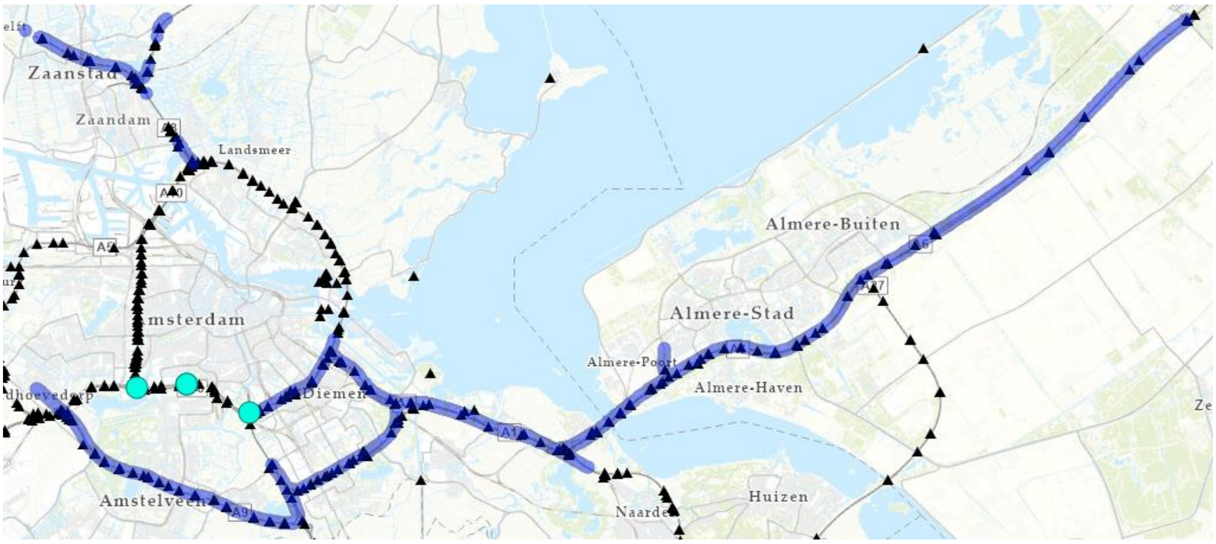
Appendix E: MIRT Elaboration

For the analysis of future perspective, the map of the structures from RWS is used as a base layer. In this base layer the structures are depicted with black triangles. This is shown in Figure 16 on page 21. On top of this layer, an extra layer is added. This extra layer contains the data sets of the different MIRT projects and is visualized with blue half transparent lines. This way it is visible which structures take part in the described MIRT projects, since they overlap in the map.

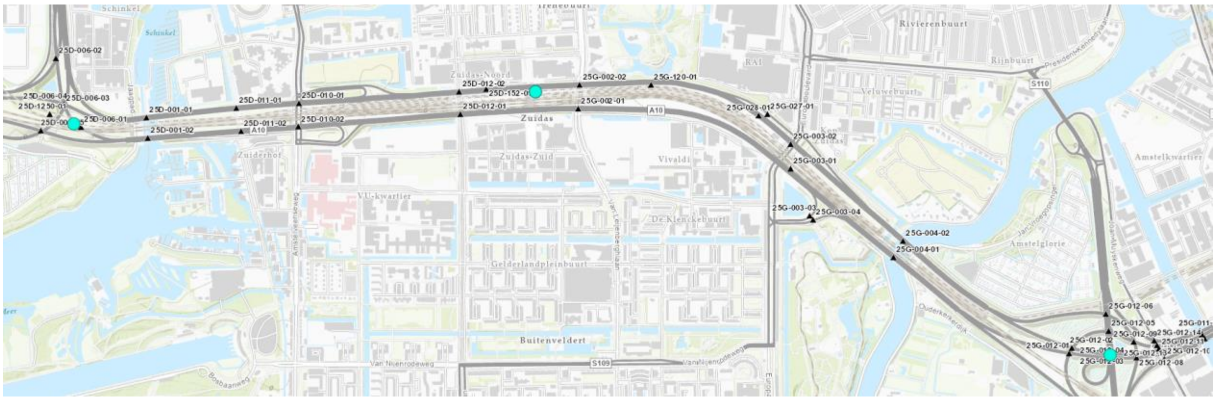
This appendix consists of zoomed in pictures of the different MIRT projects, depicted on the map of the Netherlands. With the use of the planning procedures, available at platformparticipatie.nl, it can be determined in which category the structures belong, which is shown in the graph in Appendix E.15 MIRT Structures.

The blue lines are the data sets which can be retrieved from the open source data.overheid.nl as CSV files. The map of the Netherlands with its infrastructure works of the Netherlands can be retrieved from the open source RWS Maps - DISK. In here it is also possible to upload CSV files as an additional layer.

E.1 Project 1: A1/A6/A9 Schiphol-Amsterdam-Almere



E.2 Project 2: A10 Knooppunten De Nieuwe Meer en Amstel

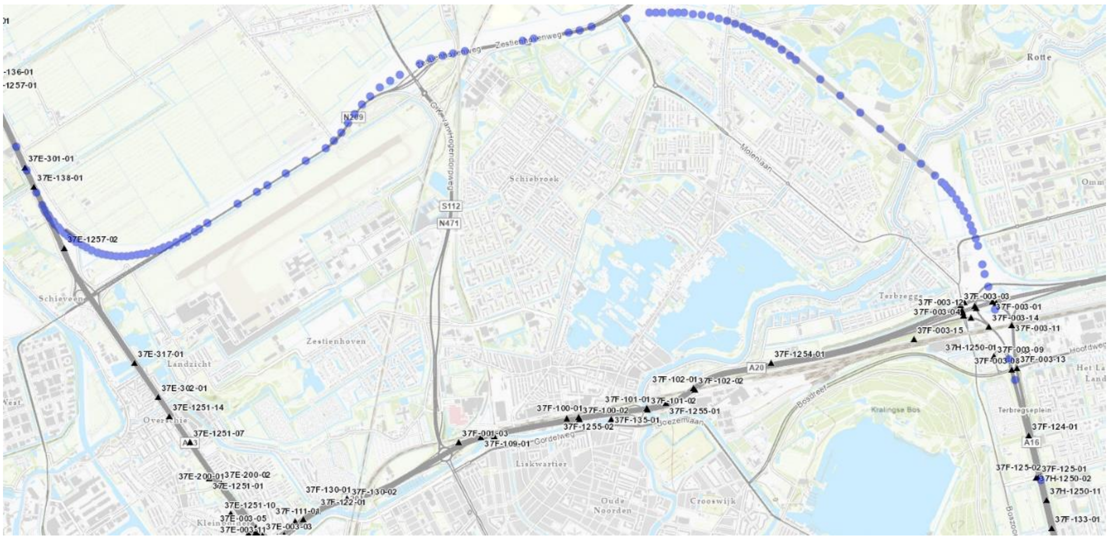


E.3 Project 4: A27/A12 Ring Utrecht

E.4 Project 5: A28/A1 Knooppunt Hoevelaken

E.5 Project 15: A15 Papendrecht–Sliedrecht

E.6 Project 16: A16 Rotterdam

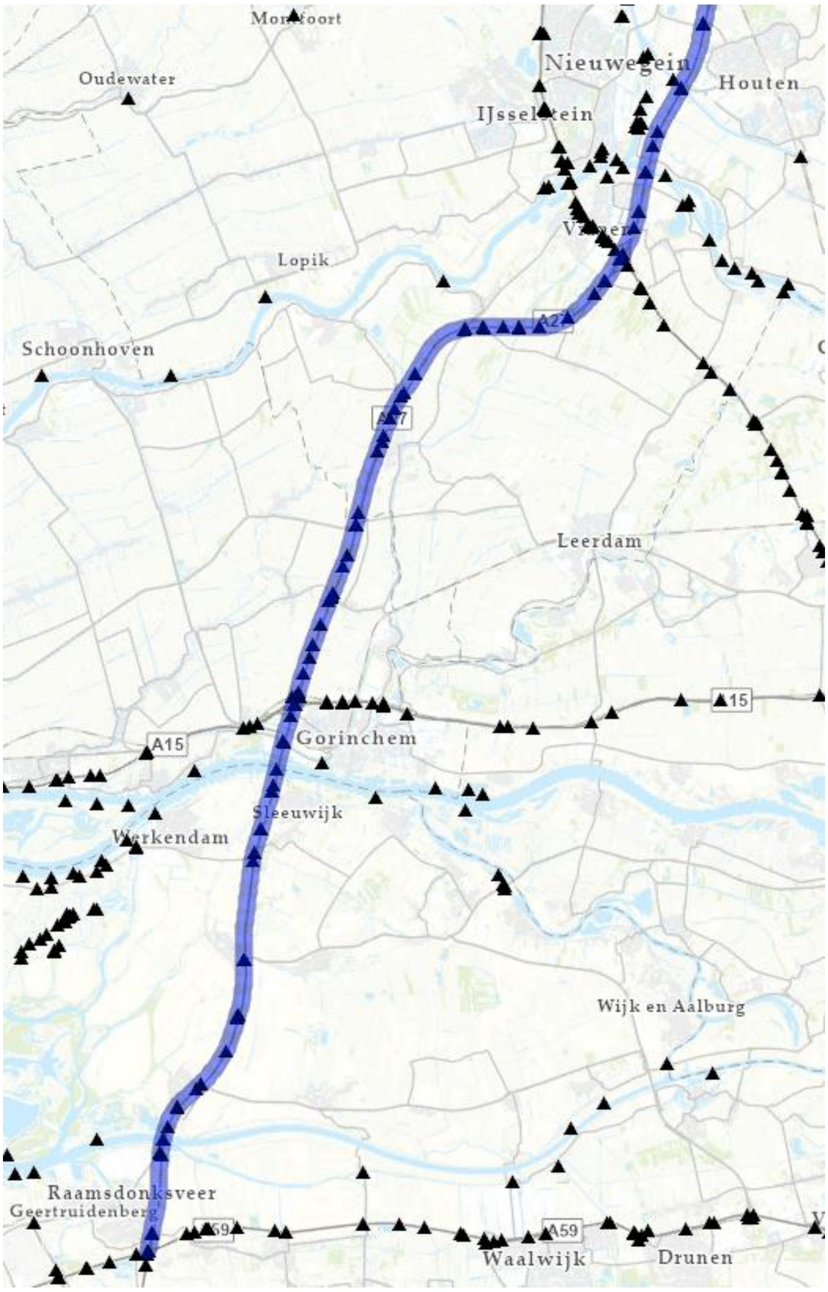


E.7 Project 18: A24 Blankenburgverbinding

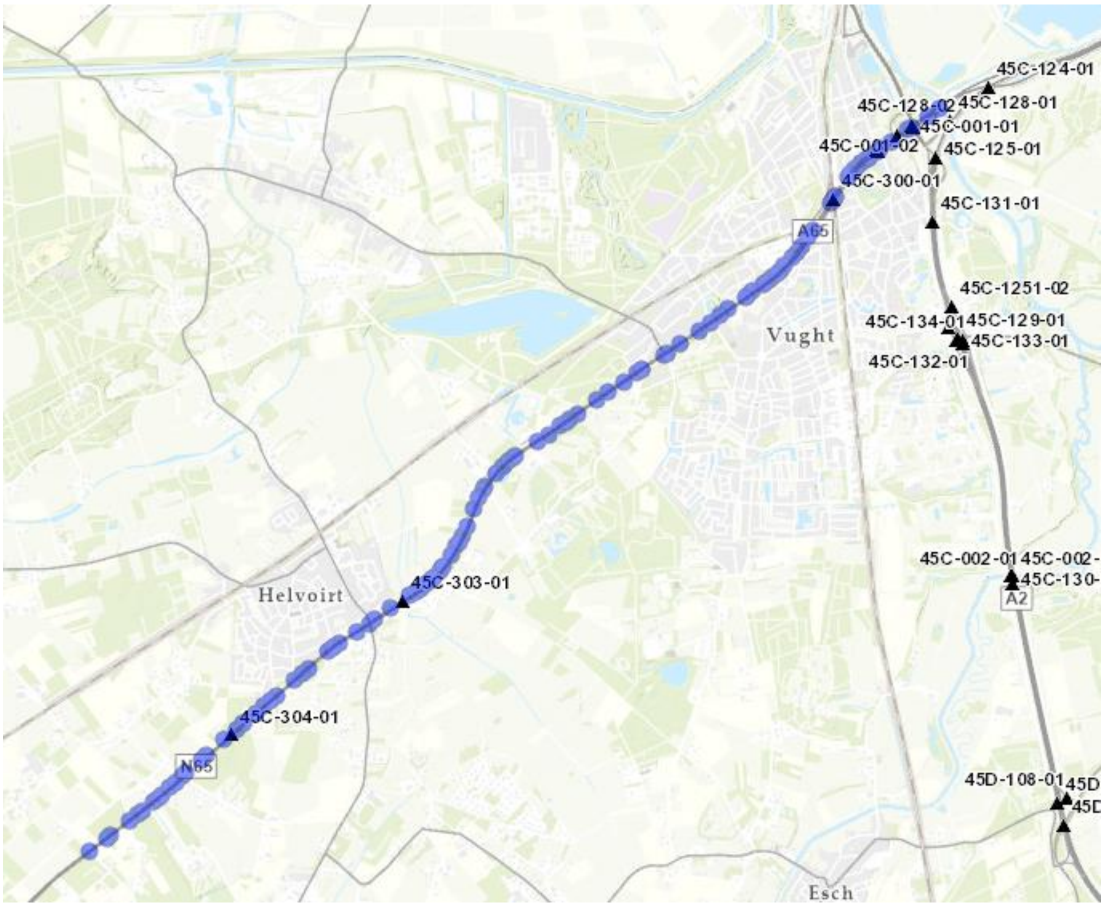
E.8 Project 20: Rijnlandroute

E.9 Project 23: A2 Het Vonderen-Kerensheide

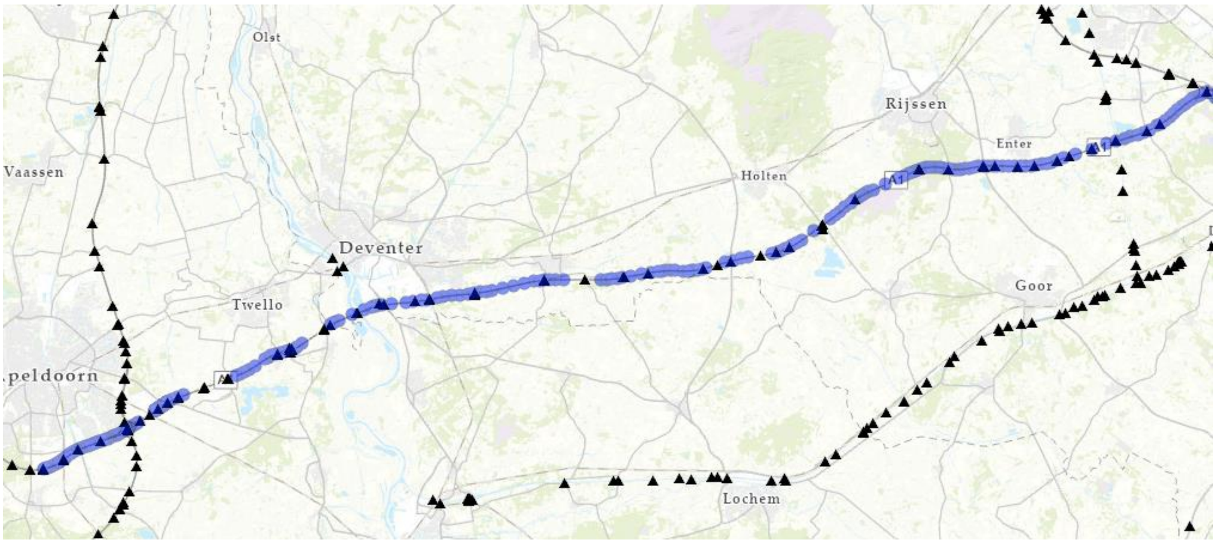
E.10 Project 24: A27 Houten-Hooipolder



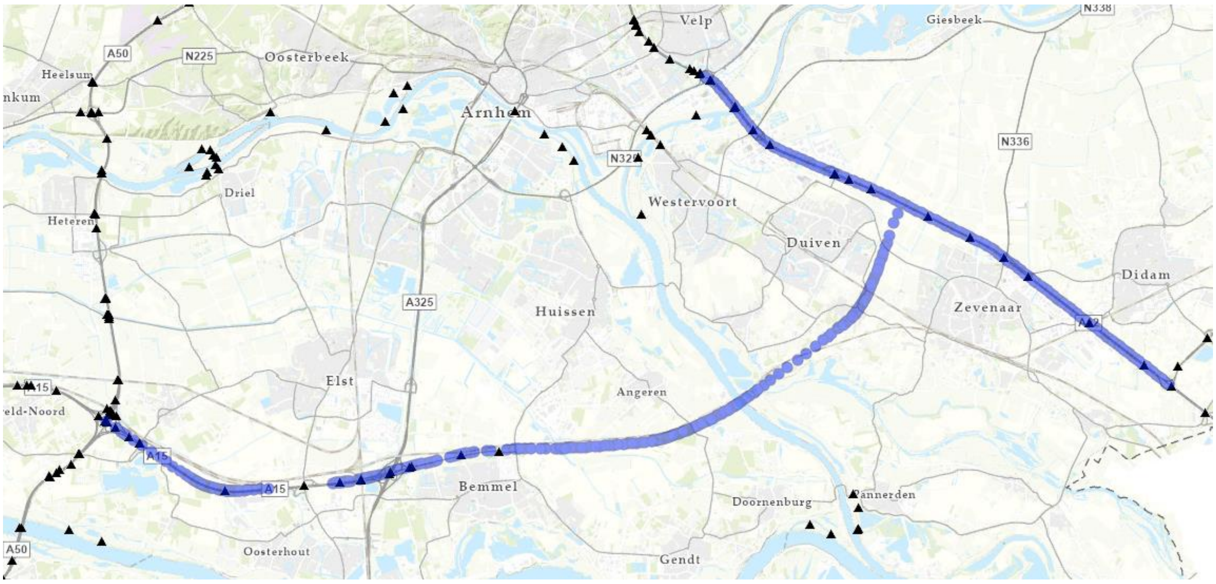
E.11 Project 30: N65 Vught-Haaren



E.12 Project 31: A1 Apeldoorn-Azelo



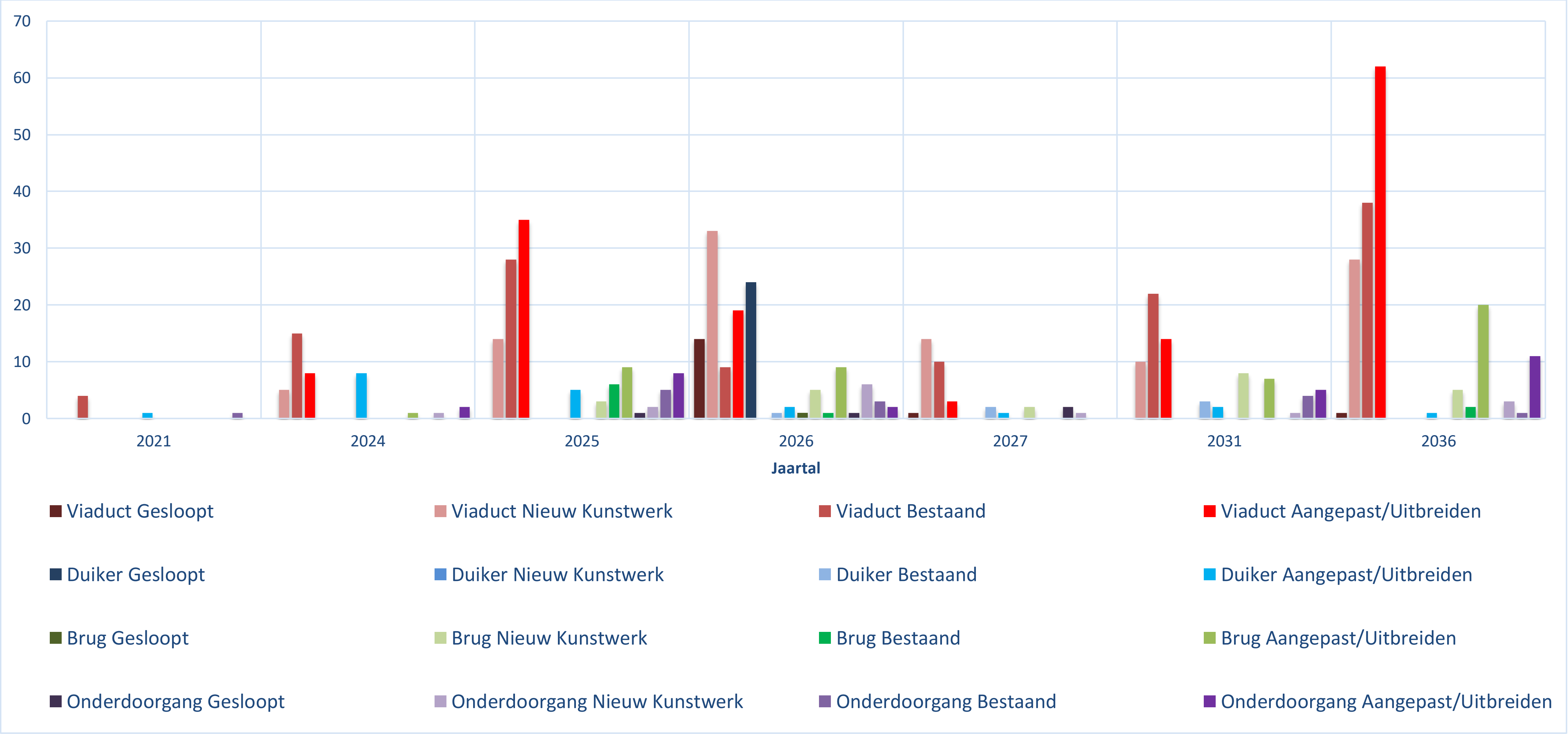
E.13 Project 34: A12/A15 Ressen-Oudbroeken (ViA15)



E.14 Project 42: A7 Zuidelijke Ringweg Groningen

E.15 MIRT Structures

The following graph contains about 600 structures which are categorized in two phases. The first phase is based on the structure type. In red the viaducts, in blue the culverts (*Duiker*), in green the bridges (*Brug*) and in purple the underpasses (*Onderdoorgang*). The next categorizing is done based on future perspective. Is the structure going to be demolished (*gesloopt*), demolished and a new structure will be built on the same place (*Nieuw Kunstwerk*), nothing will be done with it (*Bestaand*) or adjusted/expended (*Aangepast/ Uitgebreid*). These phases are visualized with the color schemes of the particular colored structure.



Appendix F: Viaduct girders

An overview of the concrete girder viaducts that are taken into account into phase 2. In general, the most important information is shown. For an extensive excel document, contact the author.

Structure code	MIRT	Delivery date	Construction year	Life cycle	Viaduct type	Category girder	Total girders
07D-105-01	42	2025	1965	60	4x2	T-ligger	32
07D-105-02	42	2025	1965	60	4x2	T-ligger	32
07D-106-01	42	2025	1965	60	3x2	T-ligger	24
07D-106-02	42	2025	1965	60	3x2	T-ligger	24
07D-108-02	42	2025	1967	58	9x2	T-ligger	54
07D-108-03	42	2025	1967	58	9x2	T-ligger	54
25D-159-01	1	2026	1968	58	3x3	Omgekeerde T-ligger	51
25D-159-02	1	2026	1968	58	3x3	Omgekeerde T-ligger	51
25D-159-03	1	2026	1968	58	3x1	Omgekeerde T-ligger	27
25D-161-01	1	2026	1968	58	4x4	Omgekeerde T-ligger	84
25D-161-02	1	2026	1968	58	4x4	Omgekeerde T-ligger	84
25G-001-03	1	2026	2013	13	2x4	Volstortligger	44
25G-005-04	1	2026	1977	49	1x3	Kokerligger	28
25G-006-02	1	2026	1977	49	1x4	Volstortligger	30
25G-012-05	2	2036	1987	49	2x4	Omgekeerde T-ligger	46
25G-012-09	2	2036	1987	49	1x	Omgekeerde T-ligger	11
25G-014-01	1	2026	1987	39	2x6	Omgekeerde T-ligger	12
25G-017-01	1	2026	1987	39	5x	Kokerligger	0
25G-152-03	1	2026	1979	47	1x2	Omgekeerde T-ligger	7
25G-154-02	1	2026	1979	47	1x2	Omgekeerde T-ligger	22
25G-163-03	1	2026	2017	9	1x2	Kokerligger	8
25G-163-04	1	2026	2017	9	1x4	Kokerligger	12
25G-163-05	1	2026	2017	9	1x1	Kokerligger	8
25G-176-01	1	2026	1973	53	3x3	Omgekeerde T-ligger	90
25H-002-06	1	2026	2017	9	2x4	Omgekeerde T-ligger	38
25H-002-07	1	2026	2017	9	2x2	Omgekeerde T-ligger	12
25H-002-08	1	2026	2017	9	1x1	Kokerligger	5
25H-002-09	1	2026	2017	9	1x1	Kokerligger	5
25H-004-06	1	2026	2017	9	3x2	Omgekeerde T-ligger	27
25H-004-07	1	2026	2017	9	2x2	Omgekeerde T-ligger	18
25H-116-01	1	2026	2017	9	1x3	Volstortligger	34
25H-116-02	1	2026	2017	9	1x9	Omgekeerde T-ligger	60
25H-117-01	1	2026	2017	9	5x5	Omgekeerde T-ligger	75
26A-002-01	1	2026	1999	27	4x4	Kokerligger	40
26A-002-02	1	2026	1999	27	3x2	Kokerligger	30
26B-315-01	1	2026	1990	36	2x2	Kokerligger	38
26C-309-03	1	2026	2017	9	3x2	Kokerligger	3
26C-309-04	1	2026	2017	9	5x2	Kokerligger	15
26C-309-05	1	2026	2017	9	3x2	Kokerligger	21
31H-132-01	4	2036	1970	66	3x3	Overig	78
31H-132-02	4	2036	1970	66	3x3	Overig	78

31H-132-03	4	2036	1970	66	3x3	Overig	78
31H-132-04	4	2036	1970	66	3x3	Overig	78
31H-556-01	4	2036	1984	52	2x3	Kokerligger	60
31H-556-02	4	2036	1984	52	2x3	Kokerligger	60
31H-556-03	4	2036	1984	52	2x3	Kokerligger	60
31H-556-04	4	2036	1984	52	2x3	Kokerligger	60
31H-557-01	4	2036	1984	52	2x3	Kokerligger	48
31H-557-02	4	2036	1984	52	2x3	Kokerligger	48
31H-557-03	4	2036	1984	52	2x3	Kokerligger	48
31H-557-04	4	2036	1984	52	2x3	Kokerligger	60
32C-306-01	4	2036	1973	63	6x3	Omgekeerde T-ligger	42
32C-306-02	4	2036	1973	63	6x3	Omgekeerde T-ligger	42
33E-106-01	31	2025	1970	55	4x3	Volstortligger	108
33E-107-01	31	2025	1970	55	4x3	Volstortligger	108
38G-121-01	24	2031	1962	69	4x3	Volstortligger	44
38G-129-01	24	2031	1962	69	4x3	Volstortligger	44
40C-002-02	34	2024	1976	48	2x4	Kokerligger	14
40C-110-02	34	2024	1976	48	2x4	Volstortligger	46
40E-102-01	34	2024	1960	64	4x2	Overig	80
40E-102-02	34	2024	1960	64	4x2	Overig	80
40G-102-01	34	2024	1973	51	4x2	Volstortligger	52
60C-302-01	23	2027	1962	65	4x2	Volstortligger	40
60C-303-01	23	2027	1962	65	4x3	Volstortligger	32
60C-303-02	23	2027	1962	65	4x3	Volstortligger	32
							2776

Appendix G: Measurement of circularity

G.1 Circular strategies

Circularity is a broad concept and can be interpreted on different ways. On one hand this makes it easier to label an approach as circular, but on the other hand it easily creates a contradiction. The R-principles, as summarized in Figure 84 on page 93, show the different ways of thinking circular. However, these principles do not state anything about the actions that must be done. These actions can be referred to as circular strategies and are different kind of approaches with an aim to reach for circularity. These approaches can then again be subdivided into the pre-mentioned principles. The strategies that are taken into account in this research are applicable to the reuse of existing girders and are based on multiple sources, shown in Table 37.

Table 37 Selection of circular strategies (CB'23, 2020 - b; Iperen, 2021; Gijsbers R. , 2011; Rijkswaterstaat, n.d.-e)

Circular strategy	Definition
Accessibility	Determining on how to get easy access to a particular element
Adjustability	Determining on how to change a function, without changing the technical aspects
Availability	Determining to what extent elements/materials are available and released
Demount ability	Determining on how to detach/disconnect certain elements
Downgrade ability	Determining to what extent an element can be used with lower demands to prevent demolition
Durability	Determining to what extent the element can achieve a certain period of time
Modularity	Determining to what extent multiple (smaller) elements can be combined into one system
Movability	Determining to what extent an element can be relocated
Removability	Determining to what extent an element can be removed from a structure, without negative effects to other elements
Reusability	Determining to what extent an element can be reused without any adjustments
Scalability	Determining to what extent the element is applicable to more structures (within and out of the current scope)
Split ability	Determining to what extent an element can be split into multiple parts
Upgradeability	Determining to what extent an element can be upgraded to improve its performance

G.2 Life cycle assessment and Environmental cost indicator

G.2.1 Life cycle assessment

With the upcoming focus on circularity, the measurement becomes not only more important in the consideration process, but also in monitoring the circularity performances. A tool (or methodology) that is widely used for inventorying the environmental impacts is the life cycle assessment (LCA) and defined in the standard ISO 14040. With this tool it is possible to determine these impacts through the stages of the life cycle of a product/element. However, there are multiple life cycles that can be taken into account: *cradle to grave* (raw material extraction up to waste processing); *cradle to gate* (raw material extraction to manufacturing product) and *cradle to cradle* (Closed loop recycling) (Ecochain, n.d.-a). Depended on the goal of the assessment, the life cycle is determined. The three main life cycles are visualized in Figure 87. In this model the different lifecycles are displayed, together with the phases (from the top, going clockwise): raw material extraction; processing; transportation; use phase and waste disposal. By determining the environmental impacts on a product/element, the best performing product can be determined for internal use (The Ellen MacArthur Foundation, n.d.).

Moreover, a LCA has a fixed structure and consists of 4 different stages, visualized in the Figure 88. The first one is the goal and scope definition in which at first the product and up next the lifecycle is determined (as mentioned before). The questions are answered on 'What to assess and how to assess'. The second phase is the inventory analysis. In this phase all the data is gathered to describe the environmental- inflows as well as the outflows of the product. The third phase is the impact assessment phase in which the inflows and outflows are assessed, with the use of multiple impact categories (such as global warming and toxicity). However, there are a lot of categories and thus must be chosen which ones will be taken into account. When these impacts are chosen, multiple criteria can be compared to each other. Global warming for example is expressed in CO_2 emission to be able to compare. The final phase of an LCA is the interpretation. In this phase the gathered data is assessed to be able to draw a conclusion and/or recommendation (Ecochain, n.d.-a; Muralikrishna & Manickam, 2017; CB'23, 2020 - b).

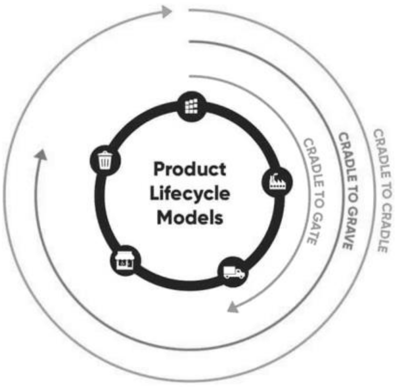


Figure 87 Product lifecycle models (Ecochain, n.d.-a)

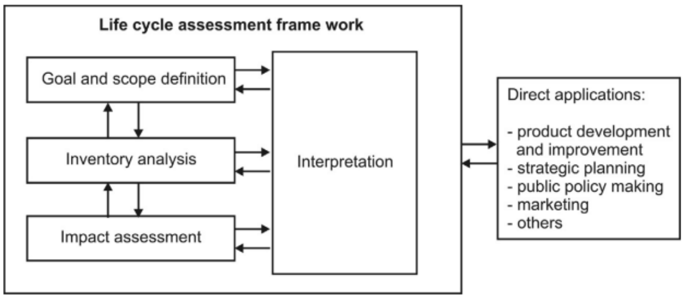


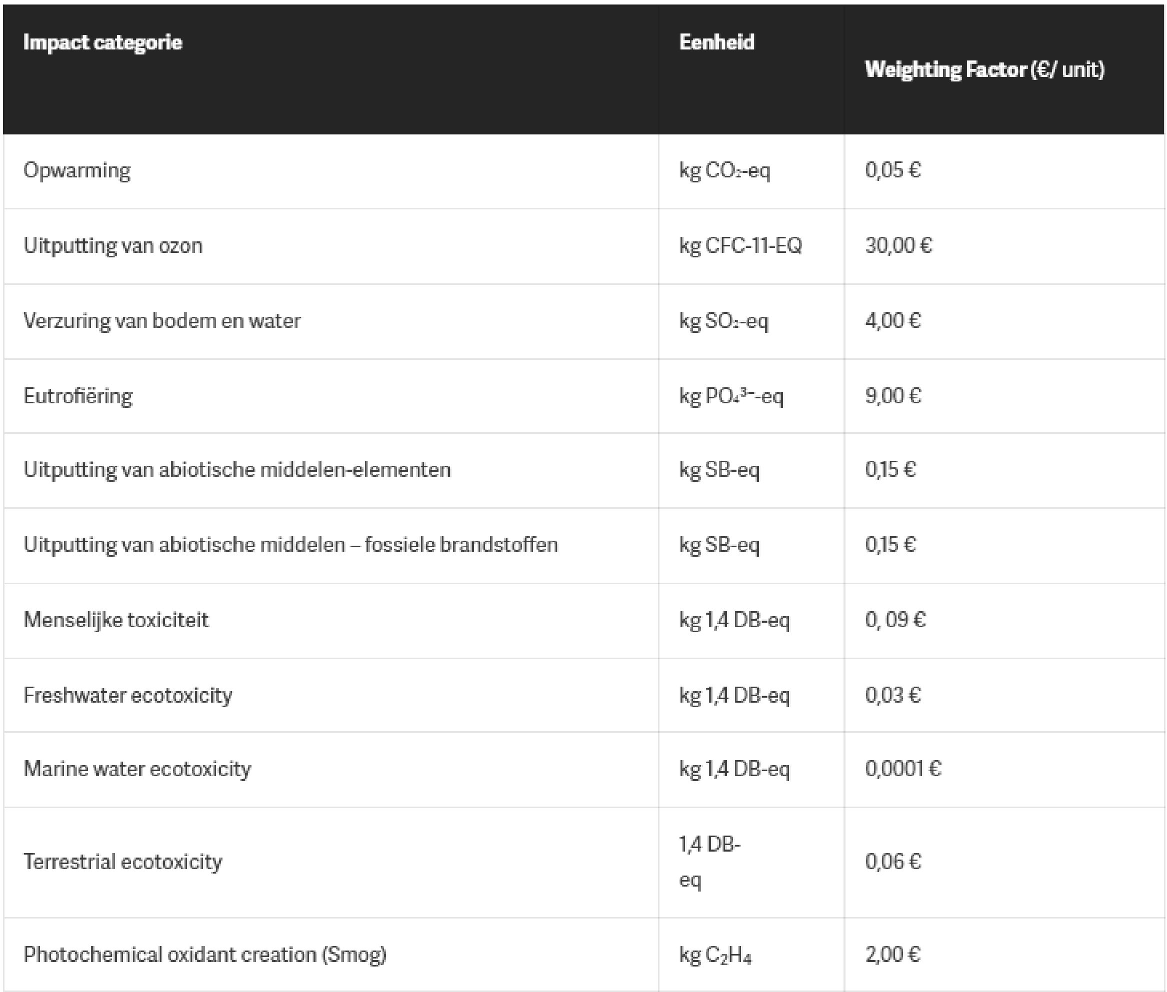
Figure 88 LCA Stages according to ISO 14040 (Muralikrishna & Manickam, 2017)

Unfortunately, this worldwide popular method also has some limitations. The first one considers the fact that the LCA only focusses on protecting the environment (CB'23, 2020 - b). Of course, this is an important aspect, but there are more categories for sustainability. The next limitation is the flexibility of the method. The LCA method assesses only the aspects that you want it to assess (The Ellen MacArthur Foundation, n.d.).

G.2.2 Environmental cost indicator

As mentioned in the previous paragraph, the environmental impact of a product can be expressed by using a LCA method. This method models different impacts in different units. For example, global warming is expressed in kilogram CO_2-equivalents, electricity in Joules and water usage in cubic meters. A popular tool which combines all the environmental impacts is the environmental cost indicator (ECI). It expresses all the environmental aspects in one unit: euros. This way different impacts can be summed up and give a total amount of euros of a specific product. This total sum is called shadow costs. These shadow costs can be seen as the money that needs to be spent to restore the negative environmental impact that has been made. With this shadow costs, which differs per product in a defined life cycle, can be easily compared to others. This way the beneficial product can be chosen (Ecochain, n.d.-b).

Currently, sustainable material use is not yet a legislation in the infrastructure sector (Peschier, 2021). However, the demand for sustainability is improving by the different clients. In contradiction to the (non)-residential industry in which a legal boundary is set to the ECI. This was introduced in the year 2018. This is called the EPB (Environmental performance of building, or in Dutch MPG; *Milieu prestatie gebouwen*) and contains the sum of the shadow costs of one whole building. Or in units: the ECI per year per square feet (m^2). With the use of reused materials, it is achievable to lower this score. This information combined means that the ECI score is an important criterium in Dutch tenders regarding the whole construction industry. The better your ECI score, the more fictitious discount you get on your final sum. An example of different environmental impacts, including costs, is seen in Figure 89.



Impact categorie	**Eenheid**	**Weighting Factor** (€/ unit)
Opwarming	kg CO_2-eq	0,05 €
Uitputting van ozon	kg CFC-11-EQ	30,00 €
Verzuring van bodem en water	kg SO_2-eq	4,00 €
Eutrofiëring	kg PO_4^{3-}-eq	9,00 €
Uitputting van abiotische middelen-elementen	kg SB-eq	0,15 €
Uitputting van abiotische middelen – fossiele brandstoffen	kg SB-eq	0,15 €
Menselijke toxiciteit	kg 1,4 DB-eq	0, 09 €
Freshwater ecotoxicity	kg 1,4 DB-eq	0,03 €
Marine water ecotoxicity	kg 1,4 DB-eq	0,0001 €
Terrestrial ecotoxicity	1,4 DB-eq	0,06 €
Photochemical oxidant creation (Smog)	kg C_2H_4	2,00 €

Figure 89 A selection of environmental impacts, including costs (Ecochain, n.d.-b)

G.3 Improved measuring method

G.3.1 Core measuring method

Building on the basis of the LCA, CB’23 created another method for the measurement of circularity to provide a uniform measuring method. This LCA method has overlaps based on the data obtaining and the framework of life cycles and inflow versus outflow. With this uniform method it is possible to be able to make big steps in the transition into a CE. From research with stakeholders and parties from the building constructions it turned out that the desired circular construction section can be divided in three main goals for protection. Protecting the material supply, the environment and the current value (CB'23, 2020 - b). The three main goals are divided in a total of seven indicators to measure circularity per main goal. An overview is visualized in Table 38. Each indicator then has another subdivision which leads to a total of 34 aspects.

Table 38 Overview of main goals of core measuring method (CB'23, 2020 - b)

Core goals	Core indicators	Subdivision of core indicators
A. Protection of material supply	1. Amount of used material	Distinction made in primary and secondary material (reuse and recycling) Scarcity of the material Socio-economic scarcity of raw-materials[20]
	2. Amount of available material for the upcoming cycle	Amount of material for reuse Amount of material for recycling
	3. Amount of lost material	Amount of material into energy production Amount of material into dumping
B. Protection of Environment	4. Influence on Environment	Based on 19 different environmental aspects (Table 39)
C. Protection of current value	5. Amount of initial value	Technical-functional value Economic value
	6. Amount of available value for the following cycle	Technical-functional value Economic value
	7. Amount of lost current value	Technical-functional value Economic value

This type of measurement for circularity is called the core measuring method and was created by platform CB’23. The R-principles, as summarized in Figure 84 on page 93, suggest that a higher grading principle is better dan a lower one. However, in practice it turns out that it is not necessarily the case for each case/application (CB'23, 2020 - b). Where the 10R-model gives an idea of an applied method, this core method measures the impact based on three circular goals. Within these three goals the different circular strategies are assessed in total. It must be noted that this method does not provide a total summarized score due to the unknown underlying factors between the core goals. Per company it differs which goals is regarded as most important and thus contains a higher value. The circular impact can only be determined by taking into account the total lifecycle of a structure, since each main goal can have another impact per moment of this lifecycle (CB'23, 2020 - b). For the measurement of the circularity the input and output flows are taken into account. Input flows are the materials (primary or secondary) to construct, repair and adapt structures. Output flows are the materials that are taken out of the structure, divided in reuse, recycle or waste materials. These flows are visualized in Figure 90.

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[20] Socio-economic scarcity is based on economic interests and supply security (CB'23, 2020 - a)

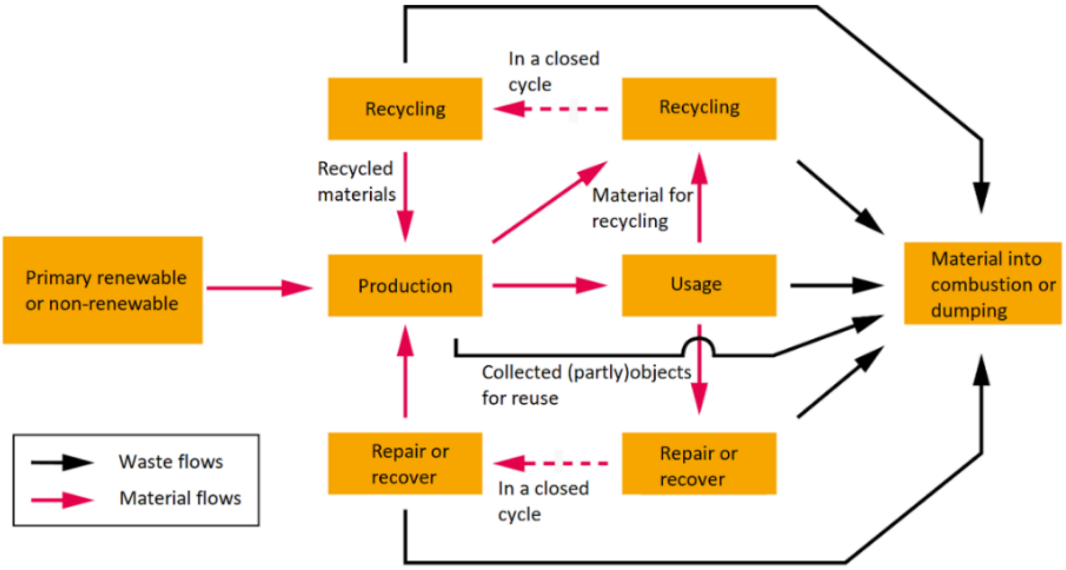

Figure 90 In- and output flows of a structure, adapted from (CB'23, 2020 - b)

To be able to quantify the circularity measures, each core goal has its own determination procedure.

- For core goal A (Protection of material supply) calculations are based on the principle of determining the defined material as a percentage of the total. This is shown in Equation (15). The defined material will differ in multiple aspects (e.g. primary/secondary/renewable), as mentioned in the most right column in the Table 38[21]. A part of the indicators is corresponding to the LCA methods as mentioned in the previous chapter.

$$V = \frac{\sum(m_i \cdot m_j)}{\sum m_j} \qquad (15)$$

Where:
V = Percentage ‘defined’ input material of a total structure [%]
m_i = Mass of total structure [kg]
m_j = Mass percentage of ‘defined’ materials in structure [%]

From this formula it can be seen that specific input data is required for applying this method into the reviewed system.

- For main goal B (Protection of the Environment) indicator 4 is divided into 19 different environmental aspects. These categories are based on the LCA methods for the building industry and shown in Table 39. These indicators have certain, pretty complex calculation rules, which can be found in the determination method of the environmental performance (Bepalingsmethode Milieuprestatie - Milieudatabase.nl). In the Netherlands an open source national environmental database is available, which contains the (in the previous paragraph mentioned) shadow costs to express the environmental impact in euros. For different products these shadow costs are determined per unit and can be used easily in further calculations. This environmental database can be found in the following link: viewer.database.nl/producten. This database contains only 11 categories (see Figure 89) into account to calculate the ECI score.

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[21] For specified elaboration of the formulas per subdivision of the core indicator, see Platform CB'23 - Meten van Circulariteit (page 39) (CB'23, 2020 - b)

Table 39 Subdivision of core indicator for core goal protection of the environment (CB'23, 2020 - b)

Environmental aspects of core indicator 4. Influence on Environment	
Climate change – total	Depletion of abiotic raw materials – Minerals and metals
Climate change – Fossil	Depletion of abiotic raw materials – Fossil energy carrier
Climate change – Biogen	Water usage
Climate change – Land usage and change in land usage	Particulate matter emission
Ozone layer deterioration	Ionizing radiation
Acidification	Ecotoxicity
Eutrophication fresh water	Human toxicity – Carcinogenic
Eutrophication sea water	Human toxicity – Non-carcinogenic
Eutrophication land	Land use related impact/ soil quality
Smog	

- The indicators for main goal C. Protection of the current value, are still under development as well as the measurement methods. However, they do apply to the main goals and the scope of this research and will therefore be taken into account on a superficial level.

G.3.2 Circular strategies on core indicators

Platform CB’23 states that a circular strategy must lead to an effect which is measurable on the core indicators (CB'23, 2020 - b). The selection of the multiple strategies from Table 40 is expanded with an elaboration based on the core goals, since this differs per strategy. Where for example one strategy focusses on limiting the *use* of material supplies, the other one focusses on limiting the *loss* of material supplies (CB'23, 2020 - b). These strategies have been graded from 1-5, where 1 means little to no effect on the core goal and 5 the highest effect. In the second to last column the total score is shown to see which strategy makes the most impact and is used as a critical part of the assessment of the design applications

Table 40 Assessment of circular strategies

Circular strategy	Impact on usage of new materials	Environmental impact	Current value impact	Sum	Explanation
Accessibility	1	4	5	10	Easy access means no harm to other elements and no extra measurements to reach an element
Adjustability	5	1	5	11	Higher chance of function change means less demolishing and higher reuse possibility
Availability	5	3	3	11	More elements available, means less new production
Demount ability	3	3	5	11	Better demount ability results in better usage of element and less material reuse for new connections
Degradability	4	3	3	10	Higher chance of reusing means less new production
Durability	5	5	5	15	A higher durability and thus longer residual lifetime means less new production
Modularity	1	4	1	6	More uniformity means easier tasks and therefore less construction time
Movability	1	5	1	7	Better relocating, and thus transport, has a big influence on the environment
Removability	5	1	5	11	Better removability results in higher reuse and less new production
Reusability	5	5	5	15	Reusability affects all the core goals
Scalability	1	4	5	10	Higher scalability means higher chance of reuse
Split ability	4	1	3	8	Being able to split an element improves the chance of reuse and therefore prevents new production
Upgradeability	5	3	2	10	Upgrading requires the addition of new materials

Appendix H: Comparing girder BAU with reuse

H.1 Graph ZIP girders

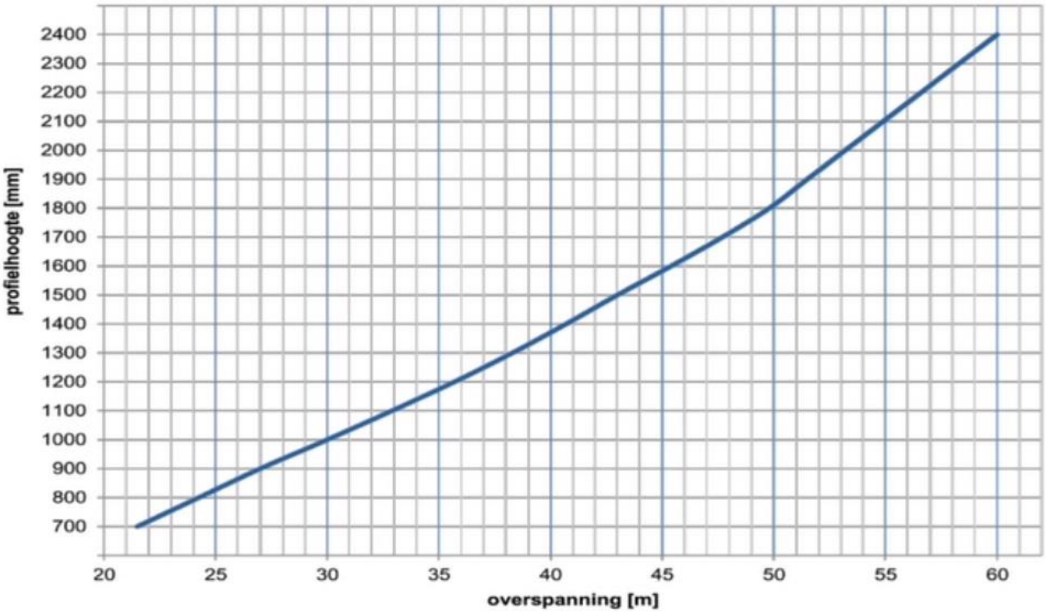


Figure 91 Graph of span vs. profile height of ZIP girders (Spanbeton, n.d.-b)

H.2 Maple sheet comparison BAU and Reuse

```
restart;
#All expressed in Euros, except the CO2 contribution
#Girder dimensions: ZIP 700
L := 20; b := 1.180 : A := evalf(389000/10^6); V := L·A;
 Weight_C := 2400; #kg/m^3
 W := V·Weight_C/1000; #[tons]
                                        L := 20
                                   A := 0.3890000000
                                    V := 7.780000000
                                   Weight_C := 2400
                                    W := 18.67200000                                     (1)

lanes := 4 : width_viaduct := lanes·3.5 : length_viaduct := L : spans_viaduct := 3 :
x_span := ceil(width_viaduct/b);
 Amount_of_girders := spans_viaduct·x_span;
 x := Amount_of_girders :
                                      x_span := 12
                                 Amount_of_girders := 36                                 (2)

#BAU
#Economic
Constr_B := 1000·V·x;
 Dem_B := 37.51·0;
 Top_B := 208.73·(x·b·L);
                                 Constr_B := 280080.0000
                                      Dem_B := 0.
                                  Top_B := 177337.0080                                   (3)

#Environment
MKI_reversedT25_B := 45.55·L·x;
 MKI_top_B := 17.33·(x·b·L);
 CO2_Manu_B := 300·L;
 CO2_transport_B := 28·L;
 CO2_building_B := 10·L;
 CO2_totalB := CO2_building_B + CO2_transport_B + CO2_Manu_B;
                               MKI_reversedT25_B := 32796.00
                                MKI_top_B := 14723.56800
                                    CO2_Manu_B := 6000
                                  CO2_transport_B := 560
                                   CO2_building_B := 200
                                    CO2_totalB := 6760                                   (4)
 Costtotal_BAU := Constr_B + Dem_B + Top_B + MKI_reversedT25_B + MKI_top_B;
                                Costtotal_BAU := 504936.5760                             (5)

#Reuse
#Economic
SawingC_R := 120·(spans_viaduct + 1)·width_viaduct; SawingD_R := 70·L·x;
 Demolishing := SawingC_R + SawingD_R;
 Repairing_R := 37.51·0 : #Assumed perfect state
 Top_R := Top_B;
 Research_R := 1000·x;
 Applying_R := 1100·x;
 Transport_R := 0 : #Assumed same location
                                   SawingC_R := 6720.0
                                   SawingD_R := 50400
                                  Demolishing := 57120.0
                                  Top_R := 177337.0080
                                   Research_R := 36000
                                   Applying_R := 39600                                   (6)
 #Environment
 MKI_reversedT25_R := 0.2·MKI_reversedT25_B;
 MKI_top_R := MKI_top_B;
 CO2_Manu_R := 0;
 CO2_transport_R := CO2_transport_B;
 CO2_building_R := CO2_building_B;
 CO2_totalR := CO2_building_R + CO2_transport_R + CO2_Manu_R;
                               MKI_reversedT25_R := 6559.200
                                MKI_top_R := 14723.56800
                                     CO2_Manu_R := 0
                                  CO2_transport_R := 560
                                   CO2_building_R := 200
                                    CO2_totalR := 760                                    (7)
 Costtotal_Reuse := SawingC_R + SawingD_R + Repairing_R + Top_R + Research_R + Applying_R + Transport_R + MKI_reversedT25_B + MKI_top_B;
                               Costtotal_Reuse := 357576.5760                            (8)
 #Comparison
 CO2difference := CO2_totalB − CO2_totalR;
 Costdifference := Costtotal_BAU-Costtotal_Reuse;
                                   CO2difference := 6000
                               Costdifference := 147360.0000                             (9)
```

Appendix I: Score sheet design applications

The score sheet (in Dutch) which is used for the classifying of different design applications

Score toepassing

Impact

1. Manier van hergebruik

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Laagwaardig
Hoogwaardig

2. Mate van impact (Schaalbaarheid)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Geen vraag naar
Veel vraag naar

3. Toevoeging benodigd van (primaire) materialen

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Veel
Geen

4. Afwijking van oorspronkelijke functie

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Hoge afwijking
Lage afwijking

5. Levensduur

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Kort
Lang

Technische haalbaarheid

6. Constructieve uitdaging (Veiligheid)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Hoog (Diep/nader onderzoek)
Laag (vuistregels)

7. Schade afhankelijkheid

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Wel afhankelijk
Niet afhankelijk

8. Extra invloed op manier van oogsten

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Veel
Weinig tot geen

9. Losmaakbaarheid nieuwe cyclus

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Niet losmaakbaar
Goed losmaakbaar

10. Restlevensduur

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Laag
Hoog

Economisch perspectief

11. Mogelijkheid tot extra levenscyclus (Opnieuw slopen)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Moeilijk, extra handelingen benodigd
Makkelijk

12. Mate van aanpassing

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Moeilijk, extra handelingen benodigd
Makkelijk

13. Bereikbaarheid (Logistiek)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Moeilijk, extra handelingen benodigd
Makkelijk

14. Potentie tot afzetmarkt

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Laag
Hoog

Appendix J: Expert judgement design applications

J.1 Summarized grading of the applications

Score Constructief	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
Constructieve uitdaging (Hoog - Laag)	4,25	4	1,75	3,25	4,25	3,5	1,5	4,5	4,5	1,5	2,75	1,75	1,25	3,5	4	3,5	3,5	3,75
Invloed op manier van oogsten (Veel - Weinig)	4,5	4	3	4	4	4,5	2	4,75	4,5	4	4,5	3	3	4,5	3,75	4	3,5	3,75
Losmaakbaarheid nieuwe cyclus (Niet - Wel)	4,25	3,5	1,75	3,25	4	3,25	2	4,75	4,25	2,75	3,75	3,75	2,5	4,25	3	3,75	3,75	4,5
Restlevensduur (Laag - Hoog)	5	3,75	3	3,25	5	3	3,25	3,5	4,75	3,5	4,25	4,25	3,5	4,75	4	3,75	3,75	4,5
Schade afhankelijkheid (Wel - Niet)	4,5	3,25	2,75	3,25	3,25	2,75	3	4,5	5	3,25	4,5	2,75	3	4,5	4,75	3,5	3,75	3,25
Eindtotaal	**22,5**	**18,5**	**12,25**	**17**	**20,5**	**17**	**11,75**	**22**	**23**	**15**	**19,75**	**15,5**	**13,25**	**21,5**	**19,5**	**18,5**	**18,25**	**19,75**

Score Milieu	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
Afwijking oorspronkelijke functie (hoog - laag)	3,25	2,5	3,75	2,5	3	3	3	2,5	2	2	2,25	2,5	3,25	2,75	3,5	1,5	3,25	2,25
Levensduur (Kort - lang)	4,25	4	3,75	4,25	4	4,5	3,5	3,75	3,5	2,25	3,75	3,5	4,25	3	4	3,5	3,25	3
Manier van hergebruik (Laagwaardig - Hoogwaardig)	3,5	3	3,5	2,75	4,5	3	2,5	2,75	1,75	3	3,25	3,5	3,25	2	4,25	1,5	3,25	2,25
Mate van impact, schaalbaarheid (Geen vraag - veel vraag)	3,75	4	3,25	3,25	4	2,25	3,75	3	2,75	3,25	3,25	3,25	2,5	2,25	3	1,25	2,75	2,25
Toevoeging benodigd (primaire) materialen (Veel - Geen)	3,75	4,25	3	3	3,25	3,75	3,75	4,5	3,25	3,25	3,5	3	3,75	4	2,75	3,25	3,25	2,75
Eindtotaal	**18,5**	**17,75**	**17,25**	**15,75**	**18,75**	**16,5**	**16,5**	**16,5**	**13,25**	**13,75**	**16**	**15,75**	**17**	**14**	**17,5**	**11**	**15,75**	**12,5**

Som van Score	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
Bereikbaarheid (Logistiek)	2,25	3	3	3	3	3	3	0,75	3	1,5	3	3	3	3	3	3	2,25	3
Mate van aanpassing	0,75	2,25	2,25	3	3	0,75	0,75	0,75	3,75	0,75	3	0,75	1,5	2,25	0,75	3	2,25	0,75
Mogelijkheid tot extra levenscyclus (Opnieuw slopen)	3	3	0,75	3	3	3	0,75	1,5	3,75	3	3	3	0,75	3	3	3	2,25	1,5
Potentie tot afzetmarkt (Laag - Hoog)	3	3	0,75	1,5	2,25	1,5	1,5	2,25		0,75	2,25	2,25	1,5	1,5	1,5	0,75	1,5	0,75
Eindtotaal	**9**	**11,25**	**6,75**	**10,5**	**11,25**	**8,25**	**6**	**5,25**	**10,5**	**6**	**11,25**	**9**	**6,75**	**9,75**	**8,25**	**9,75**	**8,25**	**6**

	B&U	Duiker	Dwarsdrager	Faunatunnel	Fietsbrug	Fundering	Funderingspaal	Geleidebarrier	Geluidswand	Kademuur	Keerwand	Kolom	Landhoofd	Overkapping	Parkeergarage	Skatepark	Steiger	Tribune
TOTAAL	3,73	3,6667	2,716666667	3,35	3,866667	3,15	2,55	3,15	3,583333333	2,5833333	3,6333333	3,0833	2,7666667	3,45	3,383333333	3,05	3,1833	2,816666667

J.2 Example calculation total score

Since the written text in the paragraph 6.4.2 can be a bit confusing, an elaborated example is shown below on how to come up with the final score of all the design applications. The application of (non)residential buildings (*B*&U) is used as an example.

For the structural part, the application is graded based on five criteria. Each criterion is filled in by 4 different experts. As an example, the first criteria *Structural challenge* has given 3 times a 4 and 1 time a 5. This mean the average grade on this criterion is

$$s_{avarage}^{Crit1} = \frac{4+4+4+5}{4} = 4.25$$

This is then also done for the other criteria. These average grades are added, which gives a total of

$$s_{total}^{Crit1} = 4.25 + 4.5 + 4.5 + 4.25 + 5 = 22.5$$

Therefore, the average grade of this application is

$$s_{avarage}^{B\&U} = \frac{22.5}{Number\ of\ criteria} = 4.5$$

If this is also done for the two other main categories, the application will have three different average grades (4.5; 3.7; 3). Since no specific benefit will be achieved for a specific category (For example when economic aspects are most important), all the average grades of the criteria are weighed with the same factor $\frac{1}{3}$. This then gives the following total average score for this specific application:

$$s_{total}^{B\&U} = 4.5 * \frac{1}{3} + 3.7 * \frac{1}{3} + 3.0 * \frac{1}{3} = 3.73$$

J.3 Design applications (dis)advantages

Toepassing	Design application	Advantage	Disadvantage	Examples/ Possibilities
B&U	(non)-residential	Low loads thus long lifespan Technical installations in between the girders Used of loads in the original design direction	Fire-resistance Heavy, big bulky elements, bad for foundation Low-quality reuse	
Duiker	Culvert	Good for use, especially for 'older' girder High demand	Soil settling Lost formwork needs to be removed by box girders System required in longitudinal direction to combine multiple elements Some box girders do not have continuous polystyrene body but transverse bulkheads to prevent kip Change of environmental class	Ability for flexibility by small cuts in the top?
Dwarsdrager	Transverse girder		Lots of connections, top and bottom Certain width required for the horizontal forces Force distribution, needs to carry load of 2 times half span Hard to apply with intersection angle	
Faunatunnel	Wildlife tunnels	Easier to connect then culvert since no water-resistant layer is required Less risk on animals	Amount of flexibility is limited Unequal Soil settling Extra Ecological facilities required?	
Fietsbrug	Bicycle bridge	Lower loads, easier applicable (for example when damage is done)	Over dimensioned thus heavier foundation	
Fundering	Foundation		Connection to wall or columns requires extra attention Condition: Foundation footing Instead of pulverizing and using it as foundation, directly use of foundation	Maybe usable when it's a monolith deck
Funderingspaal	Foundation pile		Hard to get them into the soil Very big competition (A-symmetrical) reinforcement Once in the ground, cannot be touched	
Geleidebarrier	Traffic barrier		Obstacle fear Hard demands Big competition Hard to connect to each other	Maybe temporary, for road works
Geluidswand	Sound barrier	Lots of demand, new renovation project RWS	Sound permeability of concrete? Low-quality reuse Unnecessary steel present Different camber per girders Dead weight instead of load carrying	
Kademuur	Quay wall		Water permeability Stability hard to realize Implementation hard when water already there Very specific and mostly done in steel	Maybe vertical as a diaphragm wall
Keerwand	Retaining wall		Connection between different girders Pure weight instead of withstanding loads Steel present isn't needed and Reinforcement steel required is not present Is it possible to stack girders with a compressive layer?	Maybe temporary
Kolom	Column	Possible for low loads	Current present reinforcement is not enough Camber has bad influence on the strength Not esthetical	Indoor pool or elevator shaft?

Landhoofd	Abutment		Force distribution to foundation Abutments are very unique	Maybe possible with reinforced soil
Overkapping	Roof/ Canopy	Due to low demanded loads it can last long (even if damaged)	Esthetics Very bulky Connection when collision Foundation is hard	Maybe as storage of salts or concrete factories
Parkeergarage	Parking garage		Over dimensioned thus heavier foundation TT-girders optimized for this use Very light and easy to design Settlements, salts, collisions	Maybe underground use for a canal
Skatepark	Skate park		Only maybe as a final option since very low-quality reuse What about the demand?	
Steiger	Pier		Over dimensioned for small port but to light for seaport	Maybe at a car terminal
Tribune	Stand	Same load direction used	esthetics Already squeezed to the max A lot of girders needed	

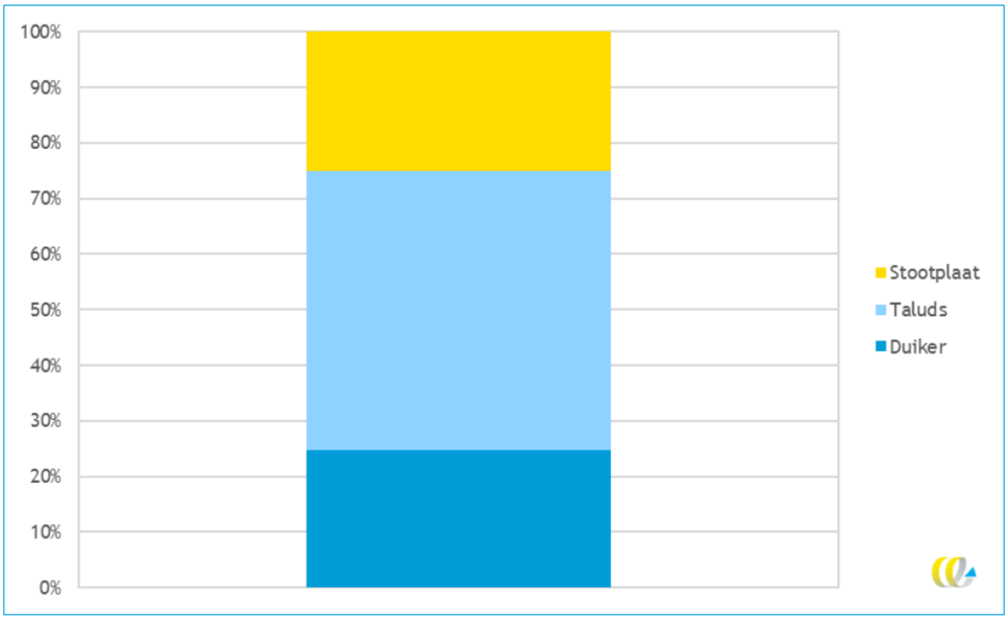
J.4 Vertical variable loads on floors and roofs

Category	Distributed p_k [kN/m²]	Concentrated Q_k [kN]	Remarks
Category A: residential areas			
A - floors	1,75	3	
A - stairs	2	3	
A - balconies	2,5	3	
A - acces routes	2	3	d
Category B: office areas			
B - floors	2,5	3	
B - acces routes	3	3	
Category C: congregation areas			
C1 - floors	4	7	
C2 - floors	4	7	
C3 - floors	5	7	
C4 - floors	5	7	
C5 - floors	5	7	
C - acces routes	5	7	
Category D: shopping areas			
D1 - floors	4	7	
D2 - floors	4	7	
D - acces routes	4	4	
Category E: storage areas			
E1 - floors - shops	≥5	≥7	e
E1 - floors - libraries	≥2,5	≥3	a,e
E1 - floors - other	≥5	≥10	e
E2 - floors	depends on use, but ≥3	depends on use, but ≥7	
E1 - acces routes - libraries	3	3	
E1 - acces routes - other	4	4	
E2 - acces routes	4	4	
Category F: traffic area (light)			
F - floors	2	10	e
Category G: traffic area (heavy)			
G - floors	5	40	e
Category H: roofs			
dependend of roof angle α:			
- $0 \leq \alpha \leq 15$	1	1,5	b,c,f
- $15 \leq \alpha \leq 20$	$4 - 0{,}2\ \alpha$	1,5	b,c,f
- $20 \leq \alpha$	0	1,5	b,c,f

Figure 92 Vertical variable loads on floors and roofs (Wagemans, Soons, Raaij, Pasterkamp, & Es, 2014)

Appendix K: Culvert design with raw materials

K.1 Environmental influences



Type materiaal/ onderdeel	Type duiker	Hoeveelheid per FU	Eenheid	Toelichting
Beton (C55/67)	Duiker; beton, rechthoekig (1.250 x 750 mm inw), incl. console t.b.v. stootplaat	2.621	kg	Cement: CEM III/A
	Duiker; beton, rechthoekig (1.500 x 750 mm inw), duikerelement incl. console t.b.v. stootplaat	2.856		
	Duiker; beton, rechthoekig (1.500 x 1.000 mm inw), duikerelement incl. console t.b.v. stootplaat	3.092		
	Duiker; beton, vierkant (1.000 x 1.000 mm inw), duikerelement incl. console t.b.v. stootplaat	3.271		
	Duiker; beton, rechthoekig (1.250 x 750 mm inw), duikerelement excl. console t.b.v. stootplaat	2.378		
	Duiker; beton, rechthoekig (1.500 x 750 mm inw), duikerelement excl. console t.b.v. stootplaat	2.577		
	Duiker; beton, rechthoekig (1.500 x 1.000 mm inw), duikerelement excl. console t.b.v. stootplaat	2.854		
	Duiker; beton, rechthoekig (2.000 x 1.500 mm inw), duikerelement excl. console t.b.v. stootplaat	3.793		
	Duiker; beton, vierkant (1.000 x 1.000 mm inw), duikerelement excl. console t.b.v. stootplaat	2.968		

K.2 Economic database

bouwkostenkompas
calcsoft bv

Rechthoekig

Duiker, watervoorzieningen, grond-, weg- en waterbouw

Provincie: Noord-Brabant
Gemeente: Eindhoven
Stadsdeel: Eindhoven

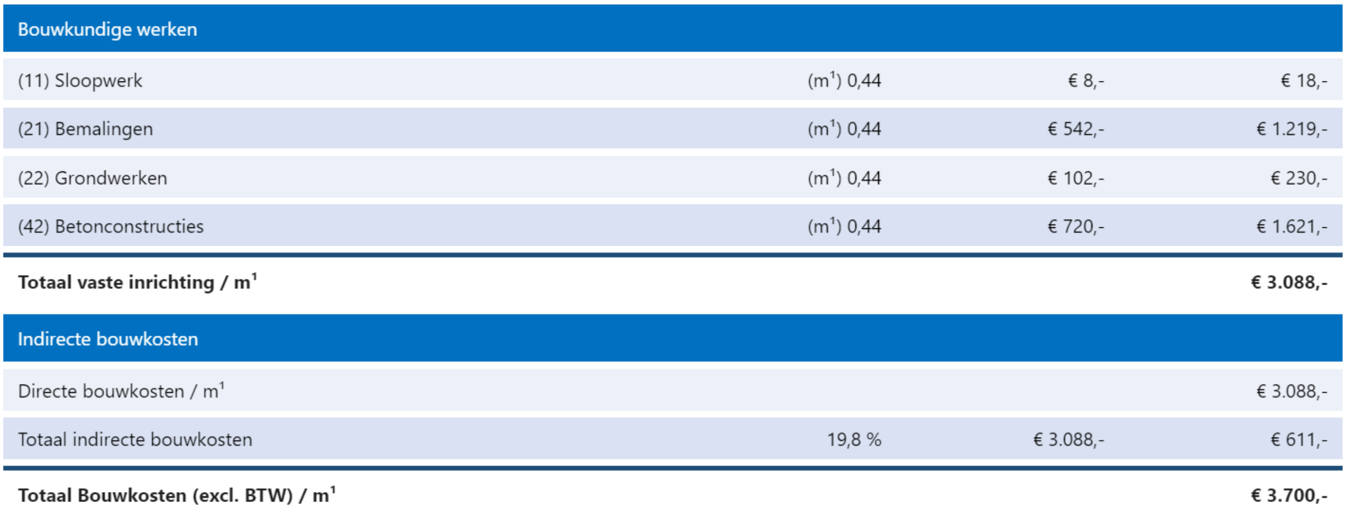
Rechthoekige prefab betonnen duiker. Grond voor de duiker wordt onder talud ontgraven. De duiker wordt gesteld op een betonvloer. Opbreken van de weg of andere bijzonderheden zijn niet meegerekend in de kosten.

Details

Bouwkosten	basis	laag	hoog
Bouwkosten / m^2	€ 1.644,-	€ 1.536,-	€ 1.840,-
Bouwkosten / m^1	€ 3.700,-	€ 3.456,-	€ 4.140,-

Vormfactoren	basis	laag	hoog
Horizontale oppervlakte duiker	2025	m^2	
Lengte duiker	30	m^1	
Oppervlakte duiker	67,5	m^2	
Breedte duiker	2,25	m^1	
Hoogte duiker	2,2	m^1	

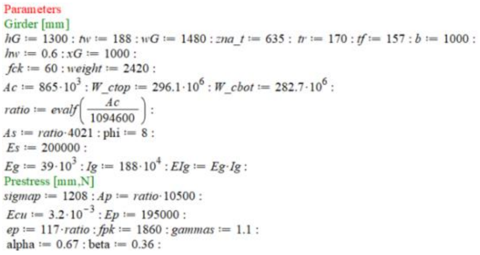
Prijsinvloeden			



Bouwkundige werken			
(11) Sloopwerk	(m^1) 0,44	€ 8,-	€ 18,-
(21) Bemalingen	(m^1) 0,44	€ 542,-	€ 1.219,-
(22) Grondwerken	(m^1) 0,44	€ 102,-	€ 230,-
(42) Betonconstructies	(m^1) 0,44	€ 720,-	€ 1.621,-
Totaal vaste inrichting / m^1			**€ 3.088,-**
Indirecte bouwkosten			
Directe bouwkosten / m^1			€ 3.088,-
Totaal indirecte bouwkosten	19,8 %	€ 3.088,-	€ 611,-
Totaal Bouwkosten (excl. BTW) / m^1			**€ 3.700,-**

Appendix L: Assessment reused girders

L.1 Parameters



Parameters

Girder [mm]

$hG := 1300 : tw := 188 : wG := 1480 : zna\_t := 635 : tr := 170 : tf := 157 : b := 1000 :$

$hw := 0.6 : xG := 1000 :$

$fck := 60 : weight := 2420 :$

$Ac := 865 \cdot 10^3 : W\_ctop := 296.1 \cdot 10^6 : W\_cbot := 282.7 \cdot 10^6 :$

$ratio := evalf\left(\frac{Ac}{1094600}\right) :$

$As := ratio \cdot 4021 : \mathrm{phi} := 8 :$

$Es := 200000 :$

$Eg := 39 \cdot 10^3 : Ig := 188 \cdot 10^4 : EIg := Eg \cdot Ig :$

Prestress [mm,N]

$sigmap := 1208 : Ap := ratio \cdot 10500 :$

$Ecu := 3.2 \cdot 10^{-3} : Ep := 195000 :$

$ep := 117 \cdot ratio : fpk := 1860 : gammas := 1.1 :$

$\mathrm{alpha} := 0.67 : \mathrm{beta} := 0.36 :$

L.1.1 *Determining bulk head lengths*

Bulk heads

$v := 0.2 : b1 := \frac{hG}{2} : b2 := \frac{wG}{2} : t1 := tw : t2 := tf :$

$alpha0 := evalf\left(\mathrm{sqrt}\left(0.5 \cdot \mathrm{sqrt}\left(\frac{3}{1-v^2}\right) \cdot \mathrm{sqrt}\left(\frac{(t1^3 \cdot t2^3)}{b1^2 \cdot b2^2 \cdot (b1 \cdot t1 + b2 \cdot t2) \cdot (b1 \cdot t2^3 + b2 \cdot t1^3)}\right)\right)\right);$

$\alpha 0 := 0.0004705080861$ (12)

$l0 := \frac{\mathrm{Pi}}{alpha0};$

$l0 := 6677.021599$ (13)

$Length := \frac{0.5 \cdot l0}{1000};$

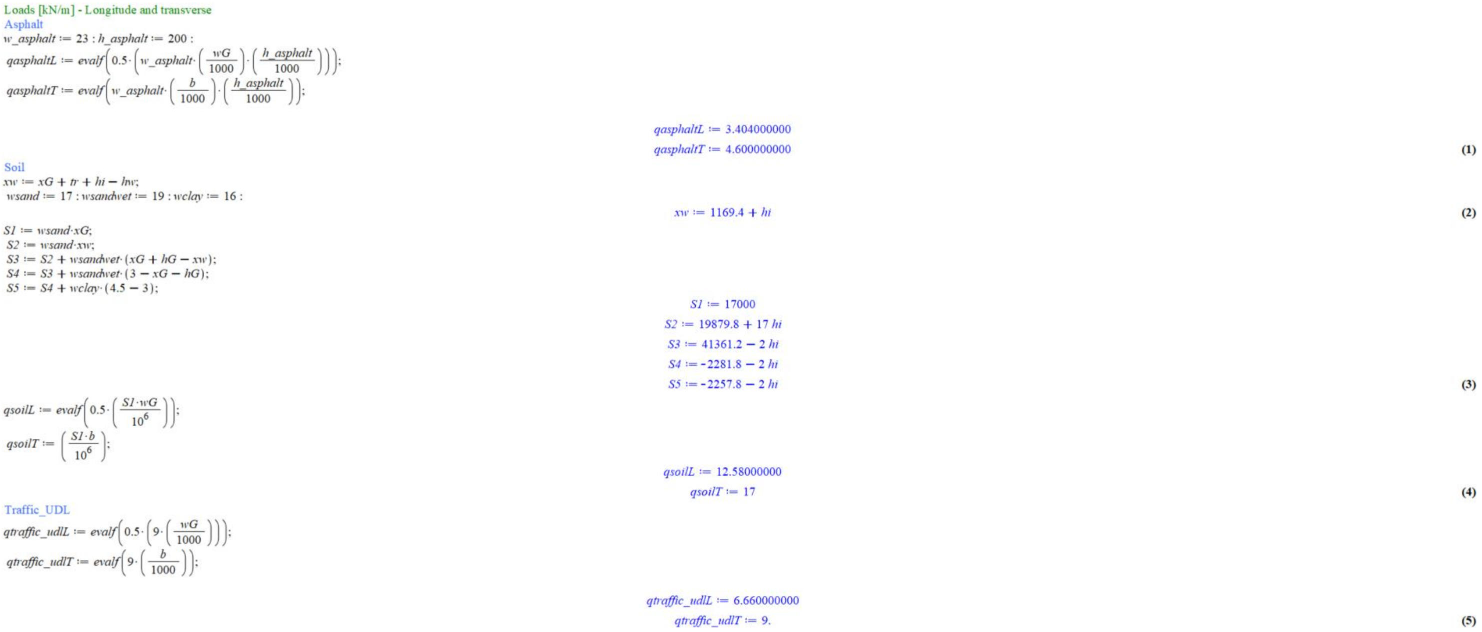
$Length := 3.338510800$ (14)

$Lelement := \mathrm{round}(Length + 1);$

$Lelement := 4$ (15)

$L := Lelement \cdot 1000 : l := evalf\left(\frac{L}{1000}\right) :$

L.2 Loads



Loads [kN/m] - Longitude and transverse

Asphalt

$w\_asphalt := 23 : h\_asphalt := 200 :$

$qasphaltL := evalf\left(0.5 \cdot \left(w\_asphalt \cdot \left(\frac{wG}{1000}\right) \cdot \left(\frac{h\_asphalt}{1000}\right)\right)\right);$

$qasphaltT := evalf\left(w\_asphalt \cdot \left(\frac{b}{1000}\right) \cdot \left(\frac{h\_asphalt}{1000}\right)\right);$

$qasphaltL := 3.404000000$

$qasphaltT := 4.600000000$ (1)

Soil

$xw := xG + tr + hi - hw;$

$wsand := 17 : wsandwet := 19 : wclay := 16 :$

$xw := 1169.4 + hi$ (2)

$S1 := wsand \cdot xG;$

$S2 := wsand \cdot xw;$

$S3 := S2 + wsandwet \cdot (xG + hG - xw);$

$S4 := S3 + wsandwet \cdot (3 - xG - hG);$

$S5 := S4 + wclay \cdot (4.5 - 3);$

$S1 := 17000$

$S2 := 19879.8 + 17\, hi$

$S3 := 41361.2 - 2\, hi$

$S4 := -2281.8 - 2\, hi$

$S5 := -2257.8 - 2\, hi$ (3)

$qsoilL := evalf\left(0.5 \cdot \left(\frac{S1 \cdot wG}{10^6}\right)\right);$

$qsoilT := \left(\frac{S1 \cdot b}{10^6}\right);$

$qsoilL := 12.58000000$

$qsoilT := 17$ (4)

Traffic_UDL

$qtraffic\_udlL := evalf\left(0.5 \cdot \left(9 \cdot \left(\frac{wG}{1000}\right)\right)\right);$

$qtraffic\_udlT := evalf\left(9 \cdot \left(\frac{b}{1000}\right)\right);$

$qtraffic\_udlL := 6.660000000$

$qtraffic\_udlT := 9.$ (5)

Traffic_TS

$$Q1 := 150:$$
$$x1 := \frac{(h\_asphalt + xG)}{1000}:$$
$$sbL := 2 + 2\cdot\left(\frac{0.4}{2} + \frac{x1}{2} + \frac{\left(\frac{hG}{1000}\right)}{2}\right);$$
$$sbT := 1.2 + 2\cdot\left(\frac{0.4}{2} + \frac{x1}{2} + \frac{\left(\frac{tr}{1000}\right)}{2}\right);$$
$$xt := wG - 1200 - tw;$$

$$sbL := 4.900000000$$
$$sbT := 2.970000000$$
$$xt := 92 \tag{6}$$

Lontigudinal:

$$F1 := 150; F2 := F1 : F3 := evalf\left(\frac{F1\cdot xt}{wG}\right); F4 := F3;$$
$$QtotalL := F1 + F2 + F3 + F4;$$
$$Q1m := \frac{QtotalL}{sbL}; Q2m := \frac{2}{3}\cdot Q1m : Q3m := \frac{1}{3}\cdot Q1m :$$
$$qtrafficTSL := Q1m + Q2m + Q3m;$$

$$F1 := 150$$
$$F3 := 9.324324324$$
$$F4 := 9.324324324$$
$$QtotalL := 318.6486486$$
$$Q1m := 65.03033645$$
$$qtrafficTSL := 130.0606729 \tag{7}$$

Transverse:

$$F1 := 150; F3 := evalf\left(\frac{F1\cdot xt}{wG}\right):$$
$$QtotalT := F1 + F3;$$
$$Q1m := \frac{QtotalT}{sbT}\cdot\frac{\left(\frac{wG}{1000}\right)}{sbT}; Q2m := \frac{2}{3}\cdot Q1m : Q3m := \frac{1}{3}\cdot Q1m :$$
$$qtrafficTST := Q1m + Q2m + Q3m;$$

$$F1 := 150$$
$$QtotalT := 159.3243243$$
$$Q1m := 26.73196612$$
$$qtrafficTST := 53.46393224 \tag{8}$$

$$qtrafficL := qtrafficTSL + qtraffic\_udlL;$$
$$qtrafficL := 136.7206729 \tag{9}$$

$$qtrafficT := qtrafficTST + qtraffic\_udlT;$$
$$qtrafficT := 62.46393224 \tag{10}$$

TOTAL

$$qtotalL := qasphaltL + qsoilL + qtrafficL;$$
$$qtotalT := qasphaltT + qsoilT + qtrafficT$$

$$qtotalL := 152.7046729$$
$$qtotalT := 84.06393224 \tag{11}$$

L.3 Shear force

Shear force check

$$d := 0.9\cdot hG : \mathrm{rho} := evalf\left(\frac{As}{Ac}\right):$$
$$k := \min\left(1 + \mathrm{sqrt}\left(\frac{200}{d}\right), 2\right);$$
$$k := 1.413449115 \tag{16}$$

$$vmin := evalf\left(0.035\cdot k^{\left(\frac{3}{2}\right)}\cdot\mathrm{sqrt}(fck)\right);$$
$$vedc := 0.12\cdot k\cdot(\mathrm{rho}\cdot fck\cdot 100)^{\frac{1}{3}};$$

$$vmin := 0.4555792518$$
$$vedc := 0.4755593419 \tag{17}$$

$$vRdc := \max(\{vmin, vedc\}):$$
$$beff := 2\cdot tw:$$
$$VRdc := \frac{vRdc\cdot beff\cdot d}{1000};$$
$$VRdc := 209.2080657 \tag{18}$$

$$VEd := \frac{qtotalT\cdot l}{2};$$
$$VEd := 168.1278645 \tag{19}$$

$$UC\_V := \frac{VEd}{VRdc};$$
$$UC\_V := 0.8036394961 \tag{20}$$

L.4 Bending moment capacity

Bending moment capacity check

$$\mathit{Pinf} := \mathit{sigmap}\cdot \mathit{Ap} : \mathit{fcd} := \frac{\mathit{fck}}{1.5} :$$

$$\mathit{sigmaPass} := \frac{0.95\cdot \mathit{fpk}}{\mathit{gammas}};$$

$$\mathit{sigmaPass} := 1606.363636 \tag{21}$$

$$\mathit{xu} := \frac{(\mathit{Ap}\cdot(\mathit{sigmaPass}))}{\mathrm{alpha}\cdot \mathit{wG}\cdot \mathit{fcd}};$$

$$\mathit{xu} := 336.0449070 \tag{22}$$

$$\begin{gathered}a := d - \mathit{xu};\\ \mathit{deltaEps\_P} := \frac{\mathit{Ecu}}{\mathit{xu}}\cdot a;\ \mathit{Eps\_Pinf} := \mathit{evalf}\left(\frac{\mathit{sigmap}}{\mathit{Ep}}\right);\\ \mathit{Eps\_Ptotal} := \mathit{deltaEps\_P} + \mathit{Eps\_Pinf};\end{gathered}$$

$$\begin{gathered}a := 833.9550930\\ \mathit{deltaEps\_P} := 0.007941368079\\ \mathit{Eps\_Pinf} := 0.006194871795\\ \mathit{Eps\_Ptotal} := 0.01413623987\end{gathered} \tag{23}$$

$$\mathit{sigmaPtotal} := 1522 + ((\mathit{Eps\_Ptotal}\cdot 1000) - 7.8)\cdot 6.21;$$

$$\mathit{sigmaPtotal} := 1561.348050 \tag{24}$$

$$\mathit{sigmadiff} := \mathit{sigmaPtotal} - \mathit{sigmaPass};$$

$$\mathit{sigmadiff} := -45.015586 \tag{25}$$

Again, with new sigma (Not really necessary since first guess was quite accurate)

$$\mathit{xu} := \frac{(\mathit{Ap}\cdot(\mathit{sigmaPtotal}))}{\mathrm{alpha}\cdot \mathit{wG}\cdot \mathit{fcd}};$$

$$\mathit{xu} := 326.6278248 \tag{26}$$

$$\begin{gathered}a := d - \mathit{xu};\\ \mathit{deltaEps\_P} := \frac{\mathit{Ecu}}{\mathit{xu}}\cdot a;\ \mathit{Eps\_Pinf} := \mathit{evalf}\left(\frac{\mathit{sigmap}}{\mathit{Ep}}\right);\\ \mathit{Eps\_Ptotal} := \mathit{deltaEps\_P} + \mathit{Eps\_Pinf};\end{gathered}$$

$$\begin{gathered}a := 843.3721752\\ \mathit{deltaEps\_P} := 0.008262587434\\ \mathit{Eps\_Pinf} := 0.006194871795\\ \mathit{Eps\_Ptotal} := 0.01445745923\end{gathered} \tag{27}$$

$$\mathit{sigmaPtotal} := 1522 + ((\mathit{Eps\_Ptotal}\cdot 1000) - 7.8)\cdot 6.21;$$

$$\mathit{sigmaPtotal} := 1563.342822 \tag{28}$$

$$\mathit{sigmadiff} := \mathit{sigmaPtotal} - \mathit{sigmaPass};$$

$$\mathit{sigmadiff} := -43.020814 \tag{29}$$

$$\mathit{z1} := \mathit{zna\_t} - 0.39\cdot \mathit{xu};\ \mathit{z2} := \mathit{hG} - \mathrm{beta}\cdot \mathit{xu} - \mathit{ep};$$

$$\begin{gathered}\mathit{z1} := 507.6151483\\ \mathit{z2} := 1089.955551\end{gathered} \tag{30}$$

$$\mathit{Mrd} := \frac{(\mathit{Pinf}\cdot \mathit{z1} + \mathit{Ap}\cdot(\mathit{sigmaPtotal} - \mathit{sigmap})\cdot \mathit{z2})}{10^6};$$

$$\mathit{Mrd} := 8301.758312 \tag{31}$$

$$\mathit{Med} := \frac{1}{8}\cdot \mathit{qtotalT}\cdot l^2;$$

$$\mathit{Med} := 168.1278645 \tag{32}$$

$$\mathit{UC\_M} := \frac{\mathit{Med}}{\mathit{Mrd}};$$

$$\mathit{UC\_M} := 0.02025207892 \tag{33}$$

L.5 Tension

Tension check

$$\begin{gathered}\mathit{Mp} := \mathit{Pinf}\cdot \mathit{ep} :\\ \mathit{qself} := \left(\frac{\mathit{weight}\cdot 10}{1000}\right) :\\ \mathit{fcm} := 8 + \mathit{fck} :\quad \mathit{fctm} := \mathit{evalf}\left(2.12\cdot \ln\left(1 + \frac{\mathit{fcm}}{10}\right)\right) :\end{gathered}$$

Situation 1:

$$\begin{gathered}a := \frac{L}{2} :\\ \mathit{Msoil\_1} := \mathit{qsoilL}\cdot\left(\frac{L-a}{2}\right)\cdot\left(\frac{L-a}{4}\right) :\\ \mathit{Mgself\_1} := \mathit{qself}\cdot\left(\frac{L-a}{2}\right)\cdot\left(\frac{L-a}{4}\right) :\end{gathered}$$

$$\mathit{sigma\_ctop\_1} := -\frac{\mathit{Pinf}}{\mathit{Ac}} + \frac{\mathit{Mp}}{\mathit{W\_ctop}} + \frac{\mathit{Mgself\_1}}{\mathit{W\_ctop}} + \frac{\mathit{Msoil\_1}}{\mathit{W\_ctop}};$$

$$\mathit{sigma\_ctop\_1} := -8.395826481 \tag{34}$$

$$\mathit{sigma\_cbot\_1} := -\frac{\mathit{Pinf}}{\mathit{Ac}} - \frac{\mathit{Mp}}{\mathit{W\_cbot}} - \frac{\mathit{Mgself\_1}}{\mathit{W\_cbot}} - \frac{\mathit{Msoil\_1}}{\mathit{W\_cbot}};$$

$$\mathit{sigma\_cbot\_1} := -14.93106227 \tag{35}$$

if *sigma_ctop_1* ≤ 0 **then** "Sigma_ctop < 0 thus OK" **else** "Sigma_ctop >0 thus fctm check needed" **end if**;

"Sigma_ctop < 0 thus OK" (36)

if *sigma_ctop_1* $\leq$ *fctm* **then** "Sigma_ctop is OK for situation 1" **else** "Sigma_ctop is NOT OK for situation 1" **end if**;

"Sigma_ctop is OK for situation 1" (37)

if *sigma_cbot_1* $\geq -0.6\cdot \mathit{fck}$ **then** "Sigma_cbot is OK for situation 1" **else** "Sigma_cbot is NOT OK for situation 1" **end if**;

"Sigma_cbot is OK for situation 1" (38)

Situation 2:

$$\begin{gathered}x := 1000 :\\ \mathit{Msoil\_2} := 2\cdot\left(\mathit{qsoilL}\cdot\left(\frac{L-x}{2}\right)\cdot\left(\frac{L-x}{4}\right)\right) :\\ \mathit{Mgself\_2} := 2\cdot\left(\mathit{qself}\cdot\left(\frac{L-x}{2}\right)\cdot\left(\frac{L-x}{4}\right)\right) :\end{gathered}$$

$$\mathit{sigma\_ctop\_2} := -\frac{\mathit{Pinf}}{\mathit{Ac}} + \frac{\mathit{Mp}}{\mathit{W\_ctop}} + \frac{\mathit{Mgself\_2}}{\mathit{W\_ctop}} + \frac{\mathit{Msoil\_2}}{\mathit{W\_ctop}};$$

$$\mathit{sigma\_ctop\_2} := -8.178450595 \tag{39}$$

$$\mathit{sigma\_cbot\_2} := -\frac{\mathit{Pinf}}{\mathit{Ac}} - \frac{\mathit{Mp}}{\mathit{W\_cbot}} - \frac{\mathit{Mgself\_2}}{\mathit{W\_cbot}} - \frac{\mathit{Msoil\_2}}{\mathit{W\_cbot}};$$

$$\mathit{sigma\_cbot\_2} := -15.15874179 \tag{40}$$

if *sigma_ctop_2* ≤ 0 **then** "Sigma_ctop < 0 thus OK" **else** "Sigma_ctop >0 thus fctm check needed" **end if**;

"Sigma_ctop < 0 thus OK" (41)

if *sigma_ctop_2* ≤ *fctm* **then** "Sigma_ctop is OK for situation 2" **else** "Sigma_ctop is NOT OK for situation 2" **end if**;

"Sigma_ctop is OK for situation 2" (42)

if *sigma_cbot_2* ≥ −0.6·*fck* **then** "Sigma_cbot is OK for situation 2" **else** "Sigma_cbot is NOT OK for situation 2" **end if**;

"Sigma_cbot is OK for situation 2" (43)

PLOT

Situation 1

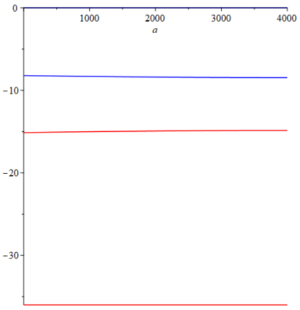
$a := 'a':$

$$Msoil\_pa := \left(qsoilL \cdot \left(\frac{L-a}{2}\right) \cdot \left(\frac{L-a}{4}\right) \right) : \; Mgself\_pa := \left(qself \cdot \left(\frac{L-a}{2}\right) \cdot \left(\frac{L-a}{4}\right) \right) :$$

$$sigma\_ctop\_pa := -\frac{Pinf}{Ac} + \frac{Mp}{W\_ctop} + \frac{Mgself\_pa}{W\_ctop} + \frac{Msoil\_pa}{W\_ctop} :$$

$$sigma\_cbot\_pa := -\frac{Pinf}{Ac} - \frac{Mp}{W\_cbot} - \frac{Mgself\_pa}{W\_cbot} - \frac{Msoil\_pa}{W\_cbot} :$$

```
AA := plot(sigma_ctop_pa, a = 0 ..L, color ='blue') :
BB := plot(0, a = 0 ..L, color ='blue') :
CC := plot(sigma_cbot_pa, a = 0 ..L, color ='red') :
DD := plot( -0.6 fck, a = 0 ..L, color ='red') :
display( {AA, BB, CC, DD} );
```



Situation 2

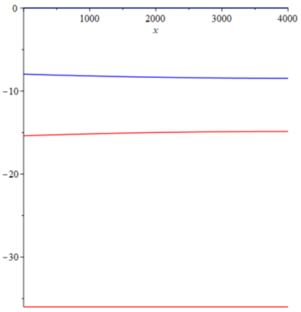
$x := 'x':$

$$Msoil\_p := 2 \cdot \left(qsoilL \cdot \left(\frac{L-x}{2}\right) \cdot \left(\frac{L-x}{4}\right) \right) : \; Mgself\_p := 2 \cdot \left(qself \cdot \left(\frac{L-x}{2}\right) \cdot \left(\frac{L-x}{4}\right) \right) :$$

$$sigma\_ctop\_p := -\frac{Pinf}{Ac} + \frac{Mp}{W\_ctop} + \frac{Mgself\_p}{W\_ctop} + \frac{Msoil\_p}{W\_ctop} :$$

$$sigma\_cbot\_p := -\frac{Pinf}{Ac} - \frac{Mp}{W\_cbot} - \frac{Mgself\_p}{W\_cbot} - \frac{Msoil\_p}{W\_cbot} :$$

```
EE := plot(sigma_ctop_p, x = 0 ..L, color ='blue') :
FF := plot(0, x = 0 ..L, color ='blue') :
GG := plot(sigma_cbot_p, x = 0 ..L, color ='red') :
HH := plot( -0.6 fck, x = 0 ..L, color ='red') :
display( {EE, FF, GG, HH} );
```



L.6 Crack width

Crack width

$$alphasr := 0.5 : \text{beta} := 0 : taub := 1.6 \cdot fctm : z := 0.9 \cdot d : qe := 1.3 \cdot (qasphaltL + qsoilL) + 1.35 \cdot (qtrafficL) :$$

$$Mmax := \frac{1}{8} \cdot qe \cdot l^2; \; Mcr := \frac{W\_ctop \cdot fctm}{10^6};$$

$$Mmax := 410.7042168$$

$$Mcr := 1289.439200 \tag{44}$$

$$sigmas := \frac{\frac{Mmax}{z \cdot As}}{10^6}; \; simgasr := \frac{\frac{Mcr}{z \cdot As}}{10^6};$$

$$sigmas := 122.7456341$$

$$simgasr := 385.3698739 \tag{45}$$

$$wmax := \left(\frac{1}{2} \cdot \frac{fctm}{taub} \cdot \frac{\text{phi}}{\text{rho}} \cdot \frac{1}{Es} \cdot (sigmas \cdot alphasr + \text{beta} \cdot Eps\_cs \cdot Es) \right);$$

$$wmax := 0.1827323734 \tag{46}$$

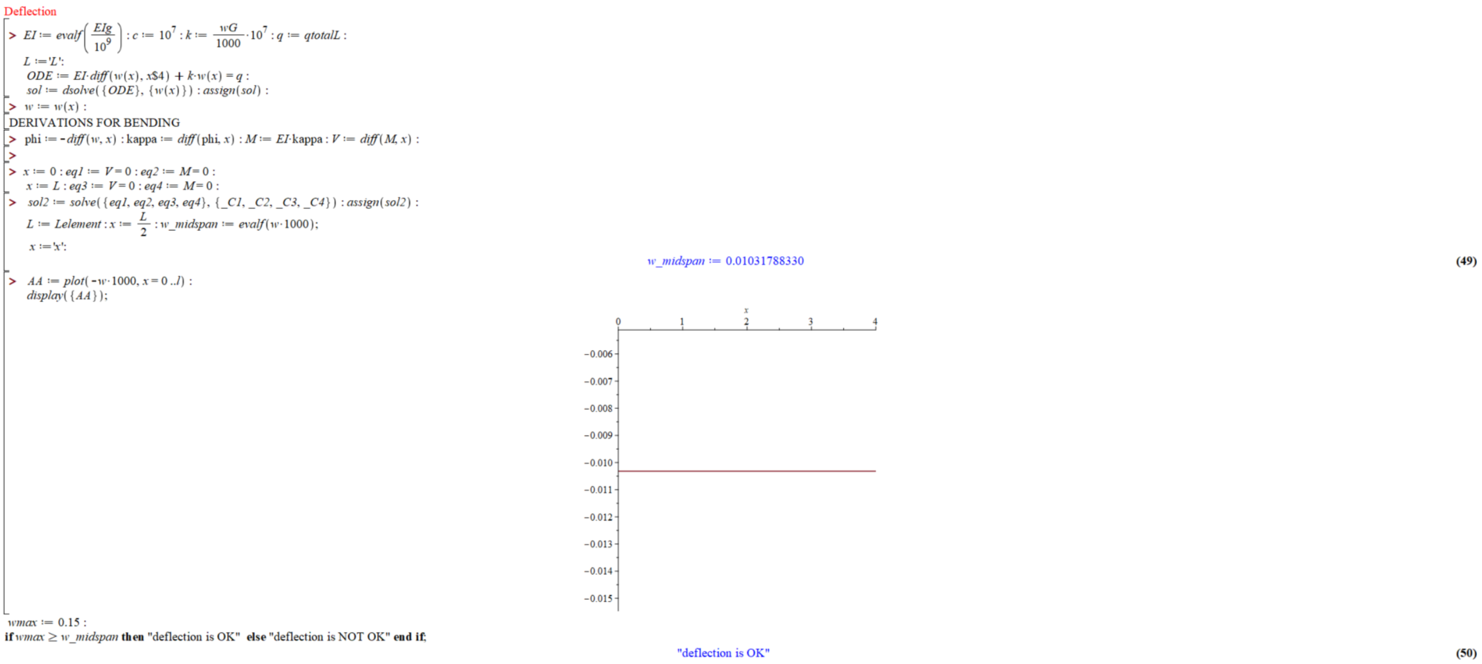
$wallowed := 0.2;$

$$wallowed := 0.2 \tag{47}$$

if *wmax* ≤ *wallowed* **then** "crack width is OK" **else** "crack width is NOT OK" **end if**;

"crack width is OK" (48)

L.7 Deflection



```
Deflection
> EI := evalf(EIg/10^9) : c := 10^7 : k := wG/1000·10^7 : q := qtotalL :
  L :='L':
  ODE := EI·diff(w(x), x$4) + k·w(x) = q :
  sol := dsolve({ODE}, {w(x)}) : assign(sol) :
> w := w(x) :
DERIVATIONS FOR BENDING
> phi := -diff(w, x) : kappa := diff(phi, x) : M := EI·kappa : V := diff(M, x) :
>
> x := 0 : eq1 := V=0 : eq2 := M=0 :
  x := L : eq3 := V=0 : eq4 := M=0 :
> sol2 := solve({eq1, eq2, eq3, eq4}, {_C1, _C2, _C3, _C4}) : assign(sol2) :
  L := Lelement : x := L/2 : w_midspan := evalf(w·1000);
  x :='x':
                                   w_midspan := 0.01031788330          (49)
> AA := plot(-w·1000, x = 0 ..l) :
  display({AA});
 wmax := 0.15 :
if wmax ≥ w_midspan then "deflection is OK"  else "deflection is NOT OK" end if;
                                   "deflection is OK"                  (50)
```

Transversal cross section deflection

#The length of a unit is assumed to be 1 meter. This also affects the moment of inertia

$L := 1 :$

$E := Eg : wG := \frac{wG}{1000} : tr := \frac{tr}{1000} : tf := \frac{tf}{1000} : tw := \frac{tw}{1000} : hG := \frac{hG}{1000} :$

$qS1 := 17 \cdot L; qS3 := 40.6; qwater := hw \cdot 10;$

$$\begin{gathered} qS1 := 17 \\ qS3 := 40.6 \\ qwater := 6.0 \end{gathered} \tag{51}$$

Roof

$EIroof := evalf\left(E \cdot \left(\frac{1 \cdot (tr)^3}{12}\right)\right);$

$$EIroof := 15.96725000 \tag{52}$$

$MA\_roof := evalf\left(\frac{qS1 \cdot wG^2}{12}\right); MB\_roof := MA\_roof; M1\_roof := evalf\left(\frac{qS1 \cdot wG^2}{24}\right);$

$wroof := \frac{qS1 \cdot wG^4}{384 \cdot EIroof};$

$$\begin{gathered} MA\_roof := 3.103066667 \\ MB\_roof := 3.103066667 \\ M1\_roof := 1.551533333 \\ wroof := 0.01330253571 \end{gathered} \tag{53}$$

Floor

$EIfloor := E \cdot \left(\frac{1 \cdot tf^3}{12}\right);$

$$EIfloor := \frac{50308609}{4000000} \tag{54}$$

$MA\_floor := evalf\left(\frac{qwater \cdot wG^2}{12}\right); MB\_floor := MA\_floor; M1\_floor := evalf\left(\frac{qwater \cdot wG^2}{24}\right);$

$wfloor := evalf\left(\frac{qS1 \cdot wG^4}{384 \cdot EIfloor}\right);$

$$\begin{gathered} MA\_floor := 1.095200000 \\ MB\_floor := 1.095200000 \\ M1\_floor := 0.5476000000 \\ wfloor := 0.01688815633 \end{gathered} \tag{55}$$

Walls

$EIwall := E \cdot \left(\frac{1 \cdot tw^3}{12}\right);$

$$EIwall := \frac{1349699}{62500} \tag{56}$$

$MA1\_wall := \frac{qS1 \cdot hG^2}{12} :$

$MA2\_wall := \frac{(qS3 - qS1) \cdot hG^2}{20} :$

$MA\_wall := MA1\_wall + MA2\_wall;$

$MB1\_wall := \frac{qS1 \cdot hG^2}{12} :$

$MB2\_wall := \frac{(qS3 - qS1) \cdot hG^2}{30} :$

$MB\_wall := MB1\_wall + MB2\_wall;$

$M1\_wall := \frac{qS1 \cdot hG^2}{24} + \frac{(qS3 - qS1) \cdot hG^2}{46.6};$

$xL := 0.475 \cdot hG;$

$wwall1 := \frac{qS1 \cdot hG^4}{384 \cdot EIwall} \cdot \frac{0.5\ hG}{xL} :$

$wwall2 := \frac{(qS3 - qS1) \cdot hG^4}{764 \cdot EIwall} :$

$w\_walltotal := wwall1 + wwall2;$

$$\begin{gathered} MA\_wall := 4.388366667 \\ MB\_wall := 3.723633334 \\ M1\_wall := 2.052963161 \\ xL := 0.6175000000 \\ w\_walltotal := 0.01024866674 \end{gathered} \tag{57}$$

if $wallowed \geq wroof$ **then** "deflection is OK" **else** "deflection is NOT OK" **end if**;

$$\text{"deflection is OK"} \tag{58}$$

if $wallowed \geq wfloor$ **then** "deflection is OK" **else** "deflection is NOT OK" **end if**;

$$\text{"deflection is OK"} \tag{59}$$

if $wallowed \geq w\_walltotal$ **then** "deflection is OK" **else** "deflection is NOT OK" **end if**;

$$\text{"deflection is OK"} \tag{60}$$

L.8 Economic calculations

#Girder dimensions: SKK 1300

$L := 40;\ b := 1.48 : A := evalf\left(\frac{865000}{10^6}\right);\ V := L \cdot A;$

$Weight\_C := 2400;\ \#\frac{kg}{m^3}$

$W := \frac{V \cdot Weight\_C}{1000};\ \#[tons]$

$L := 40$
$A := 0.8650000000$
$V := 34.60000000$
$Weight\_C := 2400$
$W := 83.04000000$ (1)

$Amount\_of\_girders := \frac{L}{40};$

$x := Amount\_of\_girders + 1 :$

$Amount\_of\_girders := 1$ (2)

#Reuse
#Economic
$SawingC\_R := 120 \cdot (2 \cdot b);\ SawingD\_R := 70 \cdot L \cdot x;$
$Demolishing := SawingC\_R + SawingD\_R;$
$Repairing\_R := 37.51 \cdot 0 :$ #Assumed perfect state
$Top\_R := 0;$
$Research\_R := 1000 \cdot x;$
$Applying\_R := 1100 \cdot x;$
$Transport\_R := 0 :$ #Assumed same location

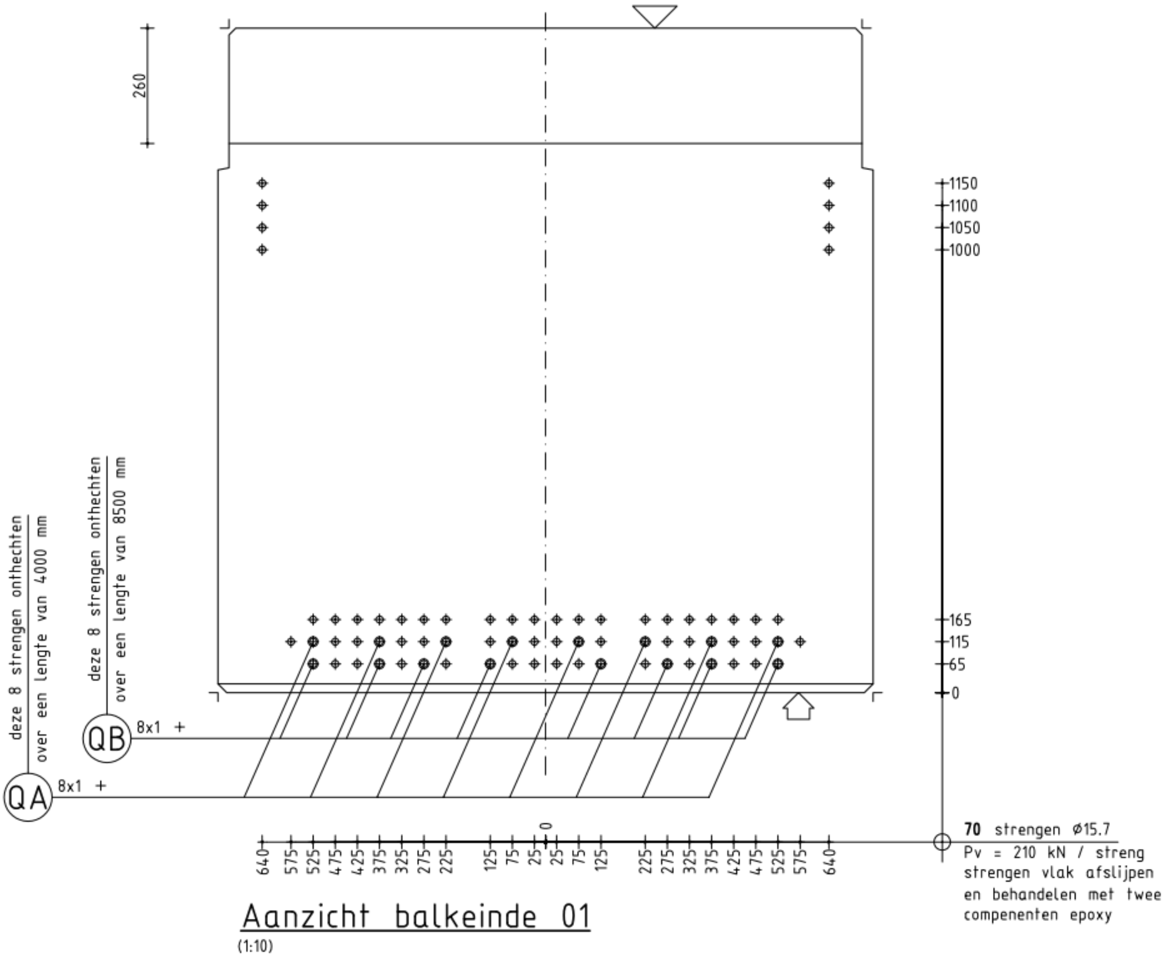
$SawingC\_R := 355.20$
$SawingD\_R := 5600$
$Demolishing := 5955.20$
$Top\_R := 0$
$Research\_R := 2000$
$Applying\_R := 2200$ (3)

$Costtotal\_Reuse := SawingC\_R + SawingD\_R + Repairing\_R + Research\_R + Applying\_R;$

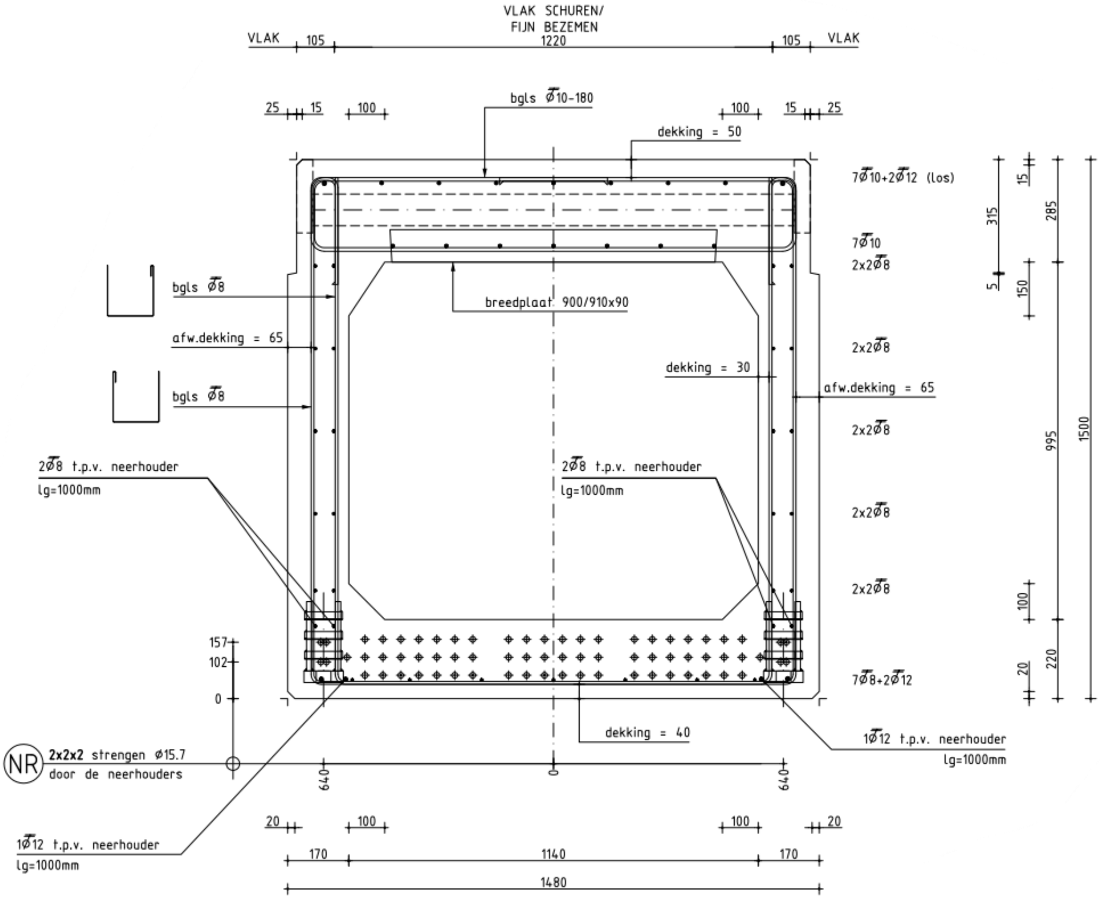
$Costtotal\_Reuse := 10155.20$ (4)

Appendix M: Technical drawings HKP 1500

M.1 End cross section



M.2 Mid-span cross section



Doorsnede D1

(1:10)