An approach to integrating the environmental costs into the decision-making process of cost-benefit analysis for Circular viaducts

An environmental cost analysis of the construction of circular viaducts in the Netherlands

Puneeth Krishna 27/09/23 Master Thesis

Graduation Committee

Committee Chair:	**Dr. D.F.J. (Daan) Schraven** Chairman graduation committee Delft University of Technology Faculty of Civil Engineering and Geosciences Department 3MD – Section Integral Design & Management
First Supervisor:	**Prof. Dr. H.M. (Henk) Jonkers** Supervisor from Delft University of Technology Faculty of Civil Engineering and Geosciences Department 3MD – Section Materials & Environment
Second Supervisor:	**Dr. Ir. Y. (Yuguang) Yang** Supervisor from Delft University of Technology Faculty of Civil Engineering and Geosciences Department Engineering Structures
Company Supervisor:	**P.A.H.M. (Paul) Schraven BBE** Ontwerpleider, ABT B.V., Delft Specialist LCC - Consortium ViCi ViCi consortium (Boskalis Netherland BV, Integraaljagers B.V., ABT B.V., Martens Beton B.V.)

Graduate student

Puneeth Krishna
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Master Construction Management and Engineering
Design and Integration specialisation
Student number: 5396107

Preface

With great pleasure and enthusiasm, I present the report titled “An Approach to Integrating the Environmental Costs into the Decision-making Process of Cost-benefit Analysis for Circular Viaducts.” The research focussed on a new perspective of viewing the environmental costs and the economic benefits of circular viaducts to boost the adoption rate. This thesis report was presented as a part of my study at Delft University of Technology to obtain a master’s degree in construction management and engineering with a specialisation in design and integration. The past two years have been a transformative journey filled with memorable experiences and invaluable knowledge.

I am immensely grateful for my committee's unwavering support and guidance throughout this endeavour to complete the master thesis in the last six months. Firstly, I would like to thank Daan, who served as the chair of my thesis committee and the coordinator of my specialisation. Daan’s early support and confidence in approving my study planning set the foundation for my successful completion of this study. I am grateful for your instrumental role in connecting me with suitable supervisors for the thesis topic.

I also owe a debt of gratitude to Henk, who graciously accepted the role of my first supervisor. It has been an honour and privilege to learn from you. Henk’s positivity, boundless enthusiasm, and unwavering dedication throughout my thesis journey have been truly inspiring. I thoroughly enjoyed our conversations in the meetings and admired your approach towards guiding me through this research in the humblest way with much patience.

Next, I would like to express my appreciation for Yuguang, my second supervisor, whose diligence and profound knowledge in the field of bridge construction have enriched this research. Your expertise in this sector provided me with a guiding light on the elements of the viaduct for the focus of my research.

I am eternally grateful to Paul, my company supervisor at ABT B.V., for his guidance throughout this thesis. Thank you for being vigilant and patient in our meetings and providing valuable information. I appreciate your pragmatic approach to problem-solving and your calls to check on me to offer your help; I learnt many lessons from how you work. Progressing into the future, I will incorporate your advice about communication and perception given by you for working in this corporate world.

Furthermore, I would like to thank my family, who had all the confidence and provided support when I moved to the Netherlands to pursue my academic journey. Their perseverance, among numerous past instances, is one of the motivating factors for my achievements. I am grateful for all my friends, without whom this journey would not have been completed. I was lucky to have the right set of friends to help me through the most challenging times.

I extend my sincere gratitude to my past/present colleagues, from whom I was inspired and learnt a lot of life lessons, including leading through kindness, learning from past challenges, overcoming my fear, organisational skills, positive and happy attitude, optimisation skills, etc. These traits also bolstered my way of working academically.

Hope you enjoy reading!

Puneeth Krishna

Disclaimer

This study is founded upon a set of hypothetical expressions regarding the potential applicability of the methods employed and the projection of economic trends in the future. It is crucial to note that a part of the evaluation procedure utilised within this study is speculative in nature and does not constitute financial or investment advice. The predictions and analyses herein are based on the information available at the time of this study, and they were conducted to offer a new perception of the current methods. The data and the information utilised in the study are subject to change due to evolving economic, political, and social conditions.

Readers are encouraged to exercise caution and conduct their independent research and analysis before making any financial or strategic decisions based on the information contained in this study. The author involved in this study assumes no liability for any direct or indirect consequences that may arise from the use or interpretation of the findings in this study.

Furthermore, it should be understood that economic trends and market dynamics are inherently unpredictable; for instance, a new war situation may shift the market conditions dramatically or political decisions arising from a trade war can also stipulate the economic conditions of the products in the market. This study does not guarantee the accuracy or reliability of the analysis. The information presented here is an academic exploration and should not be considered a substitute for professional financial or economic advice.

The author of this study would like to emphasise that the purpose of this study is educational purpose and analytical evaluation. It is intended to stimulate further discussion and research in economic forecasting and methodology. The conclusion and recommendations should be interpreted within the context of their speculative nature.

By accessing and utilising this study, readers acknowledge and accept the conditions and limitations outlined in this disclaimer.

Executive summary

The construction industry is one of the most significant contributors to carbon emissions, impacting climate change in the long run. Over 130 countries and territories have embraced “Zero carbon” objectives. In the past, infrastructure development led to excessive, unsustainable material usage and enormous carbon footprints; recent efforts have curbed emissions and other environmental impacts. Among many sustainable solutions, implementing circular economy construction techniques to tackle the linear functioning of the construction market has been at the forefront in recent times.

To achieve the goal of becoming completely circular by 2050, the Dutch government has initiated a program called SBIR (Small Business Innovation Research) to develop technologies to attain circular goals. Rijkswaterstaat has undertaken the SBIR approach to imbibe circularity in viaducts and is currently developing three circular viaduct prototypes. Despite many environmental advantages, implementing circular construction has been challenging due to its high initial construction costs. The decision to implement the circular construction on a larger scale has been challenging.

Generally, before implementing an infrastructure project such as a viaduct, the most common practice at the governmental level is to draft the cost-benefit analysis of the potential project to see if the benefits outweigh the project's costs. In the decision-making framework, environmental costs were neglected and focussed on the total economic costs of the bridge and the economic impacts it generated in the surroundings. To improve the decision-making framework to incorporate the environmental costs in the cost-benefit analysis to make informed decisions, the main research question was drafted to reach the objective of finding another perspective of incorporating the environmental costs and checking the economic benefits of circular viaducts.

What is the approach to integrate environmental costs into the decision-making process and balance environmental and economic outcomes in the cost-benefit analysis framework for constructing circular viaducts?

The primary strategy to obtain the objective of the research question was in three main parts: analysis, monetisation, and integration. The research started with a literature study to understand the concept of circular economy and the relevant strategies implemented by the government for circular transitions. The current state and the most common type of bridge built in the Netherlands were studied to set a baseline to which the circular viaduct will compete. Next, cost-benefit analysis procedures were studied, and the importance of environmental cost-benefit analysis was looked at specifically to find the gaps to improve the framework for this research; also, the assessment techniques, such as Life Cycle Assessment (LCA), were studied to find the existing environmental impact factors over the entire life cycle of the materials used in the project, while also looking at the concept of Environmental Product Declaration(EPD), a concept of declaring the quantities of all the relevant environmental impact factors of the materials used in the construction. The four main life stages were the Production and construction phase, the Use phase, the End-of-life stage, and the Recovery stage. Through the literature, the challenges in the environmental CBA were understood to draft the methodology to find an approach to convert the environmental costs into values that can be used in CBA.

The methodology for this research was based on a new proposition for academic studies, considering the world economy functions in a different way. To boost the adoption of circular construction, a bonus was provided if the contractor were to build the viaduct with a specified limit by the client. There were numerous assumptions through which the analysis and monetisation were conducted. A circular viaduct and a traditional viaduct (inverted T-beam girder) were selected to analyse the environmental costs. For the feasibility of the research, four main elements with the most impact on the structure were carefully selected to extract the quantities to focus on the analysis. The focus elements included piles, arch/girder elements, sand, and road. An EPD was extracted for all four elements in both the bridge types to determine the quantities of the environmental impact factors based on the code EN 15804:2015 A1. Based on these quantities, the impact factors were monetised through monetisation values agreed upon by various stakeholders.

The environmental impact cost data determined is incompatible with what is included in the CBA; hence, with slight modification of the data in the procedure of life cycle stages, cash inflows and cash outflows were set for the monetised values in the entire life stage. A negative value was given at the recovery stage if the element could be reused; if the element could not be reused, it was provided with a positive value (See Appendix C, D, E, F, G and H). The monetised environmental impact costs at various stages served as inputs for determining the net present value (NPV), which can be used to integrate the environmental costs in the CBA.

The findings were conducted for both cases for Scenario 1 – 200 years, Scenario 2 – 100 years and Scenario 3 – 50 years. It was done to check the conditions of the environmental costs on a what-if basis. The results provided a rather fascinating insight into the environmental impact cost for the elements. The overall environmental costs of the viaducts provide a more comprehensive visualisation of where and in which scenario the implementation of the circular viaduct is most viable. Upon analysis, it was observed that the least environmental costs were observed for scenario 1 (200 years) for the circular viaduct. This was mainly due to the fact that the traditional viaduct was completely replaced after a period of 100 years, which increased the environmental costs by a large margin. Scenarios two and three did not yield the best results in confiding the best-case scenarios to implement the circular viaduct as the circular viaduct had 18 to 25 per cent higher environmental costs than the traditional viaduct.

The overall net present value provided somewhat different insight; it showed that the present value of the environmental costs for the traditional viaduct was the least in all three scenarios. However, importance should be noted to the reuse probability for scenarios two and three, which generate higher economic benefits of material reuse. Even with inflation into account, it is challenging to determine the future price of the same elements in 50 or 100 years, but it could be argued that the prices in the future are much higher than today’s price; this new element price can be considered as a benefit in the CBA after that period. Through determining the NPV and analysing the CBA, scenarios two and three provide the best results to be implemented for circular viaducts.

Progressing into the future, more funding and grants need to be provided for research into circular viaducts to find new materials and techniques to decrease the initial environmental costs and economic costs, which can be a challenge at this moment to adopt circular viaducts at a swift rate and achieve the ambitious circularity goals set by the government.

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List of abbreviations

BCR – Benefit Cost Ratio

CBA – Cost Benefit Analysis

CE – Circular Economy

ECI – Environmental Cost Indicator

EPD – Environmental Product Declaration

IRR – Internal Rate of Return

LCA – Life Cycle Assessment

LCC – Life Cycle Costs

LCCA – Life Cycle Costing Assessment

MKI – Milieu Kosten Indicator

MPG – Milieu Prestatie Gebowen

NMD – National Milieu Database

NPV – Net Present Value

PV – Present Value

RWS - Rijkswaterstaat

SBIR – Small Business Innovation Research

1. Introduction

1.1 Background Information

The preservation of the world is a job shared by all human beings, and no nation can successfully accomplish its objectives on its own. Currently, "zero carbon" or "carbon neutral" climate objectives have been suggested by more than 130 countries and territories (Zhao, Su, Li, & Zhang, 2022). In the past few decades, in the name of infrastructure development for the country, various unsustainable use of raw materials generated a very high carbon footprint; In recent times there have been several curbs on carbon emissions (Ming, et al., 2021). However, CO2 emissions within the Rijkswaterstaat public infrastructure department in the Netherlands account for 8% of total carbon emissions used in building materials through concrete in the country for bridges (Diemel & Fennis, 2018).

The Dutch construction sector incorporates resource-intensive activities in terms of both energy and raw materials (Ministerie van Infrastructuur en Waterstaat, 2022). With the Dutch government's goals of moving completely circular by 2050 and reducing the consumption of primary raw materials, and operating without wastage by 2030 (Ministerie van Infrastructuur en Waterstaat, 2022), there is a need to focus on building a more sustainable future with growing trends for circular economic construction in the country.

Circular economic construction is an approach that seeks to reduce waste and promote sustainable resource use throughout the entire construction process (Kirchherr, Reike, & Hekkert, 2017). It involves designing, constructing, and operating buildings and infrastructure, focusing on maximising the use of resources and minimising waste. The benefits of circular economic construction are numerous, ranging from reducing carbon emissions and preserving natural resources to creating new business opportunities and improving the resilience of the built environment (Ghisellini, Ripa, & Ulgiati, 2018). Given the country's pressing environmental challenges, circular economic construction is becoming increasingly important to build a more sustainable future.

Following the Netherlands' ambition to be fully circular by 2050, RWS, as the executive agency of the Ministry of Infrastructure and Water Management, aims to be circular in the construction, replacement, and renovation of viaducts and bridges by 2030 (Rijkswaterstaat, 2022a). Therefore, a program called SBIR (Small Business Innovation Research) was initiated to focus on developing technologies to achieve this ambition. The Circular Viaducts programme is part of the SBIR and aims to stimulate the development of circular infrastructure through close cooperation with market parties (Rijkswaterstaat, 2022b). The innovative market seeks both a challenge and certainty to cooperate across disciplines to provide the best result for the client.

The current practice of building girder viaducts does not include modular design and significantly contributes to CO_2 emissions and life cycle costs (LCC). In addition, 40% of the viaducts in the Netherlands are owned by RWS; 15 viaducts will be replaced yearly (ViCi, 2020, p. 30). Moreover, due to the SBIR programme, innovative circular viaducts may be introduced in the market; Because of this, an opportunity arises in the Dutch construction sector to respond with a low-cost solution to the government's sustainable narrative, contributing to reducing emissions for future generations.

Nevertheless, even if the circular viaduct SBIR programme successfully provided proof of concept and stimulated construction companies to develop a circular innovative product, the implementation of it in an actual scenario is very complicated currently. Rijkswaterstaat, a part of the Ministry of Infrastructure and Water Management in the Netherlands, generally makes final decisions about constructing new national bridges. Of the many parameters, one of the main factors in making a decision is the cost of the project and the budget allocated to it. This is because before funding is given to a particular project, the financial effects of decisions must be shown.

When considering the construction of large-scale infrastructure projects such as viaducts or bridges, it is crucial to meticulously evaluate all available options before deciding to build, check alternatives or avoid the project. Although there are many tools for decision-making, cost-benefit analysis is one of the most commonly used tools for making informed decisions about such projects (Koopmans & Mouter, 2020). The fundamental principle of cost-benefit analysis is to ensure that a proposed project results in an overall increase in societal welfare, with the benefits outweighing the costs (Jonkman, Brinkhuis-Jak, & Kok, 2004).

Cost-Benefit Analysis (CBA) is a comprehensive assessment of a project's positive and negative impacts, quantified and valued in monetary terms based on peoples' willingness to pay. Costs and benefits may occur at different points in time, so they are represented as present values, adjusted for inflation and discount rate (Mouter, 2014). In simple terms, the method utilises the greater value of euro now compared to the future for any project or item, accounting for inflation. To measure the project's net impact on social welfare, present values are often combined into indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR) (Pulmanis & Bruna, 2011). This process systematically estimates and assigns a monetary value to each investment project's outcome to assess the impact on the economy, environment, and society.

Utilising the cost-benefit analysis tool to evaluate infrastructure projects, decision-makers can make more informed choices about whether to proceed with construction or seek alternative solutions, ultimately leading to more sustainable and beneficial outcomes for both the organisation and society.

1.2 Problem Analysis

Despite the environmental benefits of a circular economy model, many organisations are reluctant to adopt it due to the high costs associated with its implementation. At the inception of the design phase, circular constructions seem lucrative because they consume fewer raw materials and may need less maintenance. However, the hidden costs arising from the tedious labour work and meticulous time-consuming demolishing and reconstruction activities make the CE in construction less practical to implement. In the master thesis by (Kanters, 2022), an extensive analysis was made of the costs for the reuse of viaduct girders; the study concluded that the direct construction costs of the circular construction project are more expensive than a regular traditional construction project. Lower costs always seem advantageous for a governmental organisation such as Rijkswaterstaat, which relies on the tender process to award the project.

Nevertheless, in recent times the focus has shifted to not only the project’s cost but also the environmental costs (Ahn, et al., 2013), environmental impacts (del Mar Casanovas-Rubio & Ramos, 2017) and the Milieu Kosten indicator (Environmental cost indicator) to award the contract (Coenen, 2019). The dilemma in this process arises when there is an imbalance in the construction and environmental costs for different designs from the contractors. The decision-making authority then needs to go through a tedious process to evaluate the construction and environmental costs separately to rank the best competitor to award the project. This is a big problem for the decision makers as an optimised process to integrate both the environmental and the construction costs has not been utilised yet. Generally, to evaluate sustainability, the decision-making authorities undergo a tedious process to compute the Life Cycle Assessment (LCA) and Life Cycle Costing Analysis (LCCA) to rank the project. LCA and LCCA are comprehensive methods for measuring environmental profiles, but it needs simplification to be practical during design/development (Anastasiades, et al., 2020).

The range of available instruments to reduce CO_2 emissions is expanding, including options such as MKIs, DuboCalc, Ambition Web, the CO_2 Performance Ladder, and innovation labs (Klimaatverbond, 2021). For these instruments to be most effective, they should be implemented across all relevant areas. However, this is currently not feasible, as there are still issues with the coordination and communication between different departments and project stakeholders. With so many available options, the complication of selecting and using the criteria for the construction project may also increase. For example, introducing CO2 pricing in Drenthe initially caused confusion on how to implement the price for construction projects (Klimaatverbond, 2021).

Furthermore, looking at the context of the SBIR programme to develop circular viaducts; for stepping into a more sustainable environment and achieving the national goals for climate change, CE can be used as a strategy at the forefront to reach the targets for the construction industries. Moreover, circular viaducts are a promising solution for sustainable infrastructure development. But, before it is implemented, the authorities chart up a cost-benefit analysis and use the computed results of benefit to cost ratio for the bridge to make informed decisions based on the region. Currently, as explained, the construction costs are high for circular viaducts; the benefit-to-cost ratio still favours traditional bridges. Circular bridges still need to improve their benefits or reduce the costs to have a better ratio for swift implementation in the country.

While circular economic viaducts offer several benefits, such as reducing carbon emissions and promoting sustainable resource use, they also have environmental costs that are often overlooked in cost-benefit analysis (Atkinson & Mourato, 2008). In today's world, it is crucial to consider the environmental impact of infrastructure projects, and to integrate these costs into cost-benefit analyses for circular economic viaducts for making essential informed decisions. The environmental cost data does not have cash inflow or outflow, making it a challenge to convert it to net present value (NPV), which can be integrated and viewed in the CBA.

2. Research Design

2.1 Research Gap

Circular economy (CE) measurement tools are available for the construction sector; however, the implementation of CE continues to face delays. According to (Kirchherr, et al., 2018), four barriers hinder CE implementation: cultural, technological, market, and regulatory.

The cultural barrier relates to a lack of awareness or willingness to engage with the CE. The technological barrier is due to the unavailability of appropriate CE implementation technologies. The lack of economic viability of CE business models causes the market barrier. The regulatory barrier is due to the absence of policies supporting a CE transition. Overcoming these barriers requires a comprehensive approach addressing these four categories, including raising awareness.

Focussing further on the market barriers, there are many studies and programmes, such as (Coenen, 2019) (González, et al., 2021) (Rijkswaterstaat, 2022a) researching on assessing and improving the economic viability of circular constructions, while mentioning the benefits on the side-lines. As mentioned in section 1.2, the Life Cycle Costing Analysis (LCCA) and Environmental Cost Indicator (ECI) are popularly used by decision-making authorities to weigh the environmental costs. Still, decision-making tools such as the CBA do not see these cost savings and environmental indicators integrated into them. The research is currently very limited in integrating environmental costs into the decision-making framework.

In the research by (Hauck, et al., 2016), the authors combined the Life Cycle Cost Assessment (LCC), environmental Life Cycle Assessment (LCA) and assessment of traffic hindrance costs for steel bridges to enable the decision-makers to choose the better maintenance alternatives. In the cost-benefit analysis drafted in the research, the approach to the integration part of the environmental costs was still limited. Moreover, the research was done mainly to select the maintenance option and not the bridge’s design before construction. The environmental savings due to the carbon savings, monetisation of carbon, time savings in the construction duration and the integration procedure for the environmental costs and benefits needs to be explored further.

In the latest advancement, (Provincie Utrecht, 2022) has monetised and published the latest CO_2 pricing per ton; this price, as suggested by the report, would be used in the social cost-benefit analysis (SCBA) for future construction projects. However, the authorities are still working on the methods and approaches to use the cost in the CBA while also assessing the implementation methods for levying carbon taxes for future construction projects.

Additionally, by applying internal CO_2 pricing, governments can factor in the social costs of climate change when they make decisions, report results, communicate with stakeholders and procure goods and services; this was seen as a piece of critical advice from a report of the Netherlands environmental assessment agency (PBL, 2021). This helps the government to lower its CO_2 emissions in a way that minimises economic disruption. A study still needs to be done on how the government can use the pricing for social costs or environmental benefits in deciding crucial infrastructure projects.

2.2 Research Objective

It is essential to propose the research objective to address the research problem and bridge the gap. The main objective of this research is to promote the use and need for circular viaducts in the country by showing their long-term benefits in terms of monetary value for the organisations to justify their high initial investments statistically. This can be done by depicting the cost-benefit analysis (CBA) from another perspective and a new approach towards integrating the environmental benefits into the CBA.

The new approach tends to help decision-makers and contractors to recognise the value of environmental services and justify the investments in circular economic projects that are high-priced yet valuable to society in the long run. This goal is anticipated to be accomplished by comparing savings from environmental factors between a circular and a regular bridge to add them to the benefits column of the CBA to improve the benefit-to-cost ratio.

2.3 Research Question

The primary research goal of this topic can be translated into the main research question:

> *What is the approach to integrate environmental costs into the decision-making process and balance environmental and economic outcomes in the cost-benefit analysis framework for constructing circular viaducts?*

Sub-questions

The thesis is broken down into a series of 4 sub-questions to develop the final results and provide a solution to the primary research issue. These sub-questions would assist the process of obtaining data and aid in gaining relevant knowledge for developing an approach to monetise and integrate the environmental benefits into the cost-benefit analysis for the circular viaducts. The sub-questions are either exploratory analysis or refer to the methodology that has been suggested, the findings that have been made, or the research implications. The four main questions are listed as follows:

1. What are the challenges in the decision-making process of environmental cost-benefit analysis during the design phase for constructing circular viaducts?

2. Which factors can be used to engage the decision-making tool to balance the economic and environmental costs?

3. How can the environmental costs be monetised to assess the circularity in viaducts?

4. How can environmental impact costs integrate and aid in optimising the decision-making framework of the cost-benefit analysis tool?

2.4 Research Scope

Implementing the circular economy in the construction sector is a complex topic that requires focused research. To ensure a comprehensive study for this research, a scope needs to be established to ensure clear boundaries will enable the study to concentrate on the most relevant components of the circular bridge. Collaborating with the ViCi consortium provides access to details of specific projects, not just the circular bridge but also the traditional bridge constructed previously.

The study focuses on the infrastructure side of the construction sector and specifically addresses the emergence of circular bridges/viaducts. The research will not focus on the measurement of circularity of the bridges, but on the benefit side of the bridge components. While assessing the research question, there is a need to focus on the economic and environmental costs. Diving deeper, the costs may be divided into two types: Construction and Transactional costs. The Transactional costs in construction refer to the expenses incurred in legal, financial, and administrative activities such as contract negotiation, dispute resolution, and permit acquisition (Li, Arditi, & Wang, 2013). The essence of this study will be focussed only on the construction costs of the project and essentially the direct costs that arise due to the factors such as labour costs, material costs, environmental costs, logistics and machinery costs, etc. The indirect costs pertaining to the risks, overheads, or contingency will not be addressed in the scope of this thesis.

The crucial environmental factors and the elements of direct construction costs falling under the scope of this research need to be analysed according to the available data. Similar factors for traditional bridge types and circular bridge types will be assessed. The environmental benefits evaluated in the research will be mainly carbon savings and nitrogen savings. LCC and LCA will also be checked to lay the monetary value to evaluate the savings that can be seen as benefits under the umbrella of cost-benefit analyses.

2.5 Research Strategy

To perform a systematic and structured approach for conducting the research for this thesis, it is essential to chart out the strategy for this research. Following a well-set, logical, and organised approach for the research can address the research question and ensures that the data collected is valid, reliable, and relevant to the research objectives.

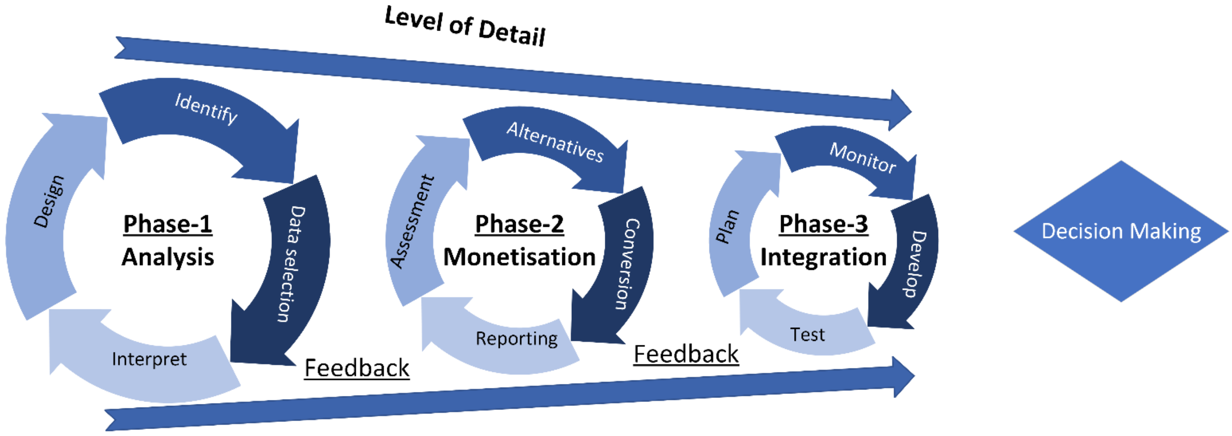
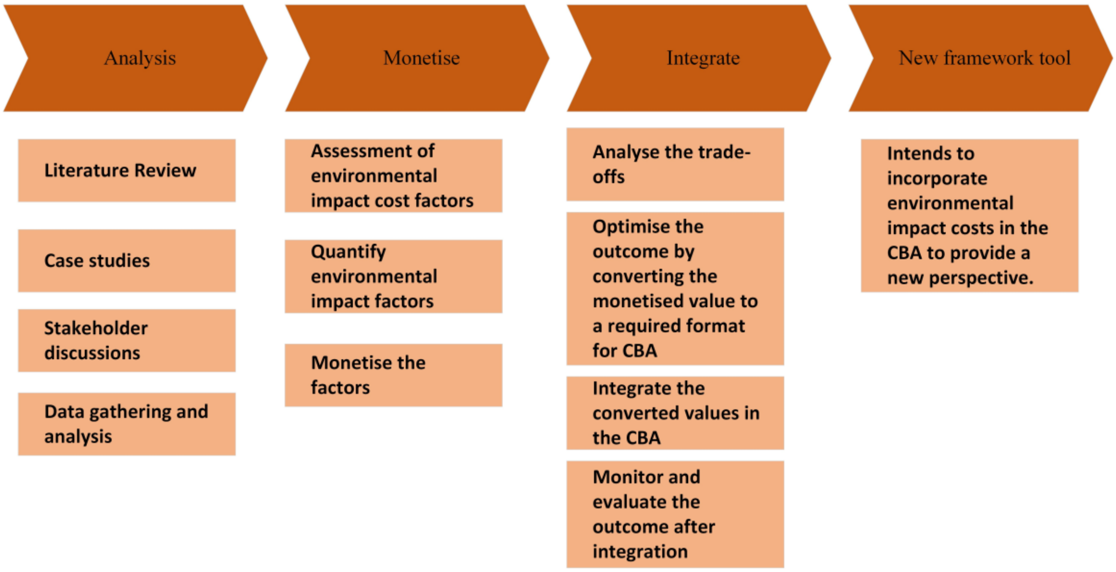


Figure 1: Strategy to answer the research questions (Source: own image)



Analysis	Monetise	Integrate	New framework tool
Literature Review	**Assessment of environmental impact cost factors**	**Analyse the trade-offs**	**Intends to incorporate environmental impact costs in the CBA to provide a new perspective.**
Case studies	**Quantify environmental impact factors**	**Optimise the outcome by converting the monetised value to a required format for CBA**	
Stakeholder discussions	**Monetise the factors**	**Integrate the converted values in the CBA**	
Data gathering and analysis		**Monitor and evaluate the outcome after integration**	

Figure 2: Phases in the research strategy (Source: own image)

2.5.1 Analysis

Literature review: The first step is to conduct a comprehensive literature review of existing studies and articles on integrating environmental costs into the decision-making process for infrastructure projects, specifically circular viaducts. This will provide a strong foundation for the research and help identify the current gaps and limitations in the existing frameworks.

Case studies: The second step is to analyse the case study of circular viaduct construction projects (ViCi viaduct design) and the traditional girder bridge construction. This will provide a baseline that helps to specify the project for data collection and evaluation.

Stakeholder discussions: The third step is to discuss with relevant stakeholders such as government officials (Rijkswaterstaat), project managers (ViCi), and environmental experts (Klimaatverbond). It can help to set the scope to relevant criteria based on the inputs. This will also provide insights into their perspectives on the best approach to integrate environmental costs into the decision-making process.

Data gathering and analysis: The fourth step is to gather the data. With collaboration with the ViCi consortium, relevant data regarding the construction costs, Life Cycle Costs (LCC), Life Cycle Assessment (LCA) data, Milieu Kosten Indicator (MKI) data, environmental saving data such as carbon savings, nitrogen savings, material savings in comparison to the traditional bridge will be collected.
Following this, relevant data for carbon pricing from (Provincie Utrecht, 2022) and (Klimaatverbond, 2021) will be collected. Also, working closely with Rijkswaterstaat, data will be collected on the organisation’s perspective on environmental costs. This will help identify patterns, trends, and relationships between different variables and draw conclusions about the best approach to integrate environmental costs into the CBA.
The key parameters contributing to the environmental benefits will be evaluated and meticulously selected to monetise in the next phase.

2.5.2 Monetisation

Assessment of the environmental cost factors: The first step is identifying the environmental costs of constructing circular viaducts. This may include materials and energy consumption costs, emissions, waste generation, and biodiversity and ecosystem services impacts. However, alternative environmental data, Life Cycle Costing (LCC) or the most relevant and contributing factors to the benefit scale of adopting circular viaducts will be considered based on the extent of the data.

Quantify the environmental factors: The second step is to quantify the environmental factors identified in step one. This may involve using existing data sources, such as environmental impact assessments, environmental cost data, and Life Cycle Costing (LCC) or conducting new studies to monetise factors of importance that can be used in the cost-benefit analysis.

Monetise the environmental factors: The third step is to monetise the environmental costs by assigning a monetary value to them. This can be done using a variety of approaches, such as market prices or replacement costs. There are also approaches to assess and monetise environmental costs and social benefits, as presented by (Hoogmartens, et al., 2014), (CE Delft, 2023) and (Provincie Utrecht, 2022). In this step, selecting an appropriate price for monetising the benefits is essential, as each research paper evaluates various ways to attain the results. For this thesis, the carbon pricing used the methodology from (Klimaatverbond, 2021), where they incorporated the German pricing index to compute the current CO_2 price. The (CE Delft, 2023) method was used for the other emission savings. The authors set up a valuation framework to determine the environmental impacts and the price by allocating specific data on the emission to the model using LCA.

The monetised data will be taken into the next phase to check for the best approach to integrate the costs into CBA.

2.5.3 Integration

Plan to analyse the trade-offs: The first step is to analyse the trade-offs between the environmental and economic outcomes of the circular viaduct construction projects. This may involve performing sensitivity analyses to explore how changes in the monetised environmental costs or other variables affect the overall outcomes.

Optimise the outcomes: The second step is to optimise the outcomes by adjusting and selecting the monetised environmental saving factors. The most contributing factors of the environmental benefits will be designated with higher priority to be added to the benefits under the CBA. This may ensure that the data is filtered and sorted for further steps.

Monitor and evaluate the outcomes: The third step is to monitor and evaluate the outcomes of the circular viaduct construction projects using indicators that measure both environmental and economic performance. This will show where the cost factors act predominantly in the CBA. The data for circular viaducts can be monitored through the LCC and be compared for traditional bridges to evaluate the additional saving benefit costs. This will help identify areas for improvement and inform future decision-making processes.

Develop a new approach to decision-making framework: The last step is to develop a decision-making framework that integrates the environmental saving costs identified and quantified into the decision-making process as benefits for constructing circular viaducts. This may involve assigning a monetary value to the environmental costs to make them comparable with the economic costs of the construction. Thereby improving the benefit-cost ratio for the circular bridges; the decision-makers can adopt this approach to justify their investment in the project's construction. This will guide future circular construction projects in other sectors and help promote sustainable development.

2.6 Research Relevance

The significance of this research can be classified into three distinct categories: scientific relevance, practical relevance, and societal relevance.

2.6.1 Academic Relevance

- There are four barriers to implementing circular economic constructions, according to (Kirchherr, et al., 2018); as mentioned in section 1.2, this research focuses on the market barriers by linking the theoretical knowledge to the practical approach of comparing the circular economic bridges with traditional bridges to identify the environmental benefits. This research can offer insights into the high construction costs of CE and justify the costs by monetising and statistically offering the benefit costs to justify the high investments.
- Global circularity gap is over 90%, while extraction of and consumption of over 100 billion tonnes of resources (Circle Economy, 2022, p. 8); It is of utmost importance to decrease this gap by scaling up the adoption of circular construction. This can happen

with continuous research on the challenges to adopting CE and finding ways to optimise the solutions for the prevailing market situations.
- The research question addresses a gap in the existing literature on integrating environmental costs into the decision-making process for infrastructure projects. The research results can contribute to developing best practices and guidelines for sustainable infrastructure development.
- Understanding the proper integration of environmental costs into Cost-Benefit Analysis (CBA) in the decision-making process is important in making policy discussions as objective as possible.
- Identify problems for stakeholder approvals and find possible solutions to ensure the decision-making process benefits from the new approach to the CBA.

2.6.2 Practical Relevance

- The integration of environmental costs into the decision-making process can also lead to economic benefits, such as reduced operational costs, increased efficiency, and enhanced reputation. This can attract investors, customers, and stakeholders who are increasingly concerned about sustainability for the ViCi consortium.
- Providing policy changes to the government for approach or guidelines to use CBA, can help organisations such as Rijkswaterstaat adopt circular constructions in more infrastructural projects within their portfolio.
- This research can also provide an advantage for the companies intending to enter CE practices, as they can statistically depict the long-term benefits over the higher capital costs.
- This approach for this study can help companies seeking to develop circular business models for their products, as provided by (The Circular Business Model, 2021); they can choose one or more of the three main strategies – product life extension (PLE), retain product ownership (RPO), and design for recycling (DFR).

2.6.3 Societal Relevance

- Public health can be significantly impacted by infrastructure development, including air and water quality, noise pollution, and safety. The research can help create infrastructure that is safer and healthier for society by factoring environmental costs into the decision-making process.
- The study can support stakeholder collaboration and involvement by taking into account both environmental and economic outcomes, resulting in better-informed decisions and more socially equitable outcomes.
- The study can aid in the transition to a more circular, sustainable, and resilient society as well as efforts to mitigate climate change to improve the well-being of the people by adoption of CE.

3. Literature Review

3.1 Circular Economy

3.1.1 Circular Economy: General Concept

Circular Economy was seen as a solution to the depleting resources in the world (D'Amato, Veijonaho, & Toppinen, 2020). The primary aim of CE is to decouple the economic growth from resource consumption and waste generation (Ellen MacArthur Foundation, 2013). In simple terms CE deals with continuous circulation of materials and resources within the system. CE ensures that products, parts, and materials are used for as long as feasible by designing the system in to improve their lifespan, reuse, and recycling capabilities.

The concept of CE is gaining popularity worldwide, with various definitions and perceptions in different sectors. With the emergence of new innovations in the field of CE, there is a pressing need for greater clarity and understanding of CE across all levels; the academic findings are expanding rapidly as it is evident from recent studies ((Granta Design and EMF, 2015), (Castro, et al., 2022), (Korhonen, et al., 2018), (Aarikka-Stenroos, Ritala, & Thomas, 2021)). An article by (Kirchherr, Reike, & Hekkert, 2017) analysed more than a hundred definitions for the CE concept to develop and define CE as “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes”. Perception of CE changes from one author to another, and from one organisation to another. The concept of Circular Economy (CE) goes beyond any definition and can be better viewed as a mindset or philosophy.

3.1.2 An approach towards CE design principles by Rijkswaterstaat

After the circularity goals had been set by the Dutch government, Rijkswaterstaat which is responsible for infrastructure in the country along with Witteveen&Bos, an engineering firm, developed circular design principles on an object level for the future construction projects (W+B & Rijkswaterstaat, 2017). The initial principal scheme is represented in the figure 3. From early pre-design phases (prevention of wastage) to design solution for concrete and functions these guidelines were applicable.

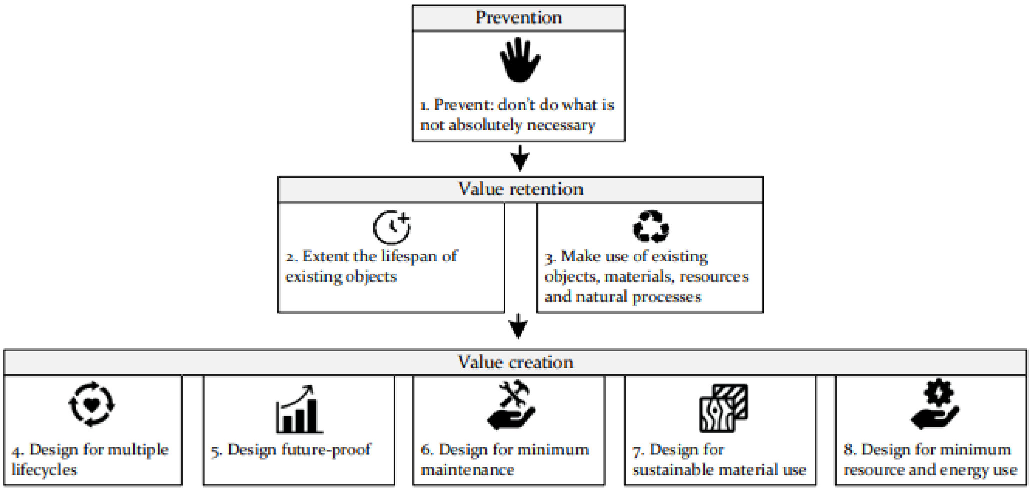


Figure 3: Design principles for circular construction for RWS (source: (W+B & Rijkswaterstaat, 2017))

Rijkswaterstaat has already used these principles to realise the first circular bridge in the Netherlands in 2018 (Ministry of Infrastructure and Water Management, 2022), with proof of concept been provided, RWS has partnered with several companies to develop more such circular innovative projects under its carefully designed circular principles. As time progressed, there have been very few circular design projects undertaken as pilot projects under the influence of Rijkswaterstaat (e.g., Circular viaduct programme under SBIR, pilot project for reusing bridge girders, etc.).

Moreover, at this moment, it is yet to be seen how the design principles have panned out in the following years. There are several areas in which these circular design schemes could play as a major influence, such as material toxicity, regenerative systems, and circular business models. Nonetheless, at a later stage, most of these aspects may potentially be integrated within one or more principles and may not be applicable to bridge or a viaduct anymore (Coenen, 2019). From a pragmatic view, to validate the circular designs of the projects after their completion will take time and it will happen over the years to come.

3.1.3 The cycles of an asset

In an asset lifecycle there are mainly two phases namely the acquisition phase and the Utilisation phase; each phase can be further classified into different stages as depicted in the figure 5.

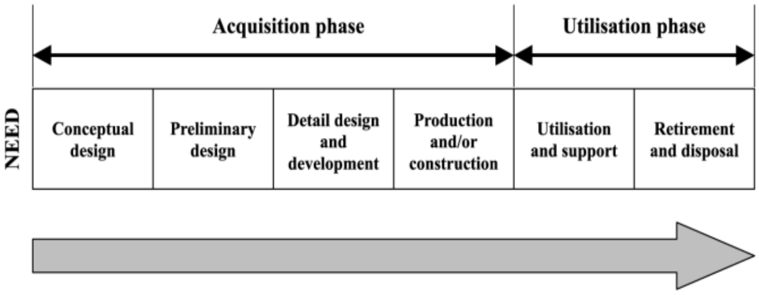


Figure 4: Physical asset lifecycle phases (Blanchard & Fabrycky, 1998)

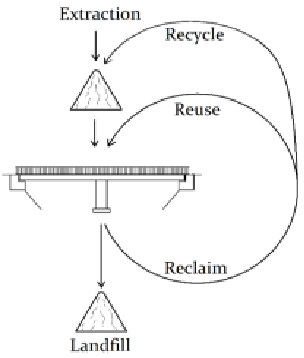


Figure 5: Reuse vs Recycling

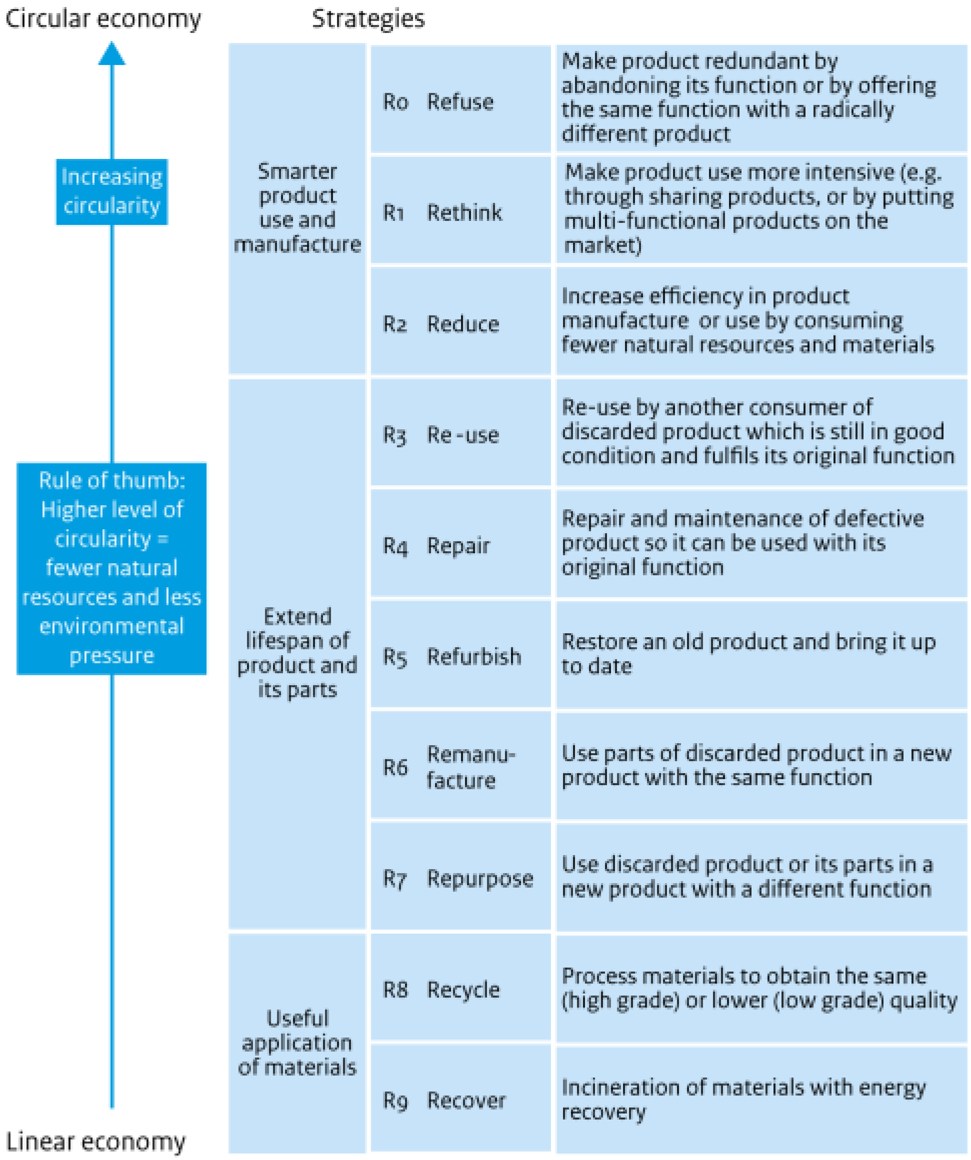
The primary focus of concern is regarding the usage of the terms recycling and reusing towards the end of the lifecycle of the asset. The process of recovery at the end phase, including incineration of the products is not considered recycling, despite some viewpoints according to some literature articles. The reason is that recovery may not involve reusing of materials in a new cycle of the same asset, so it lacks a circular approach to the material utilisation. Instead, it can be seen as a form of energy recycling; In this form more energy is consumed to transform the materials into a usable form for another product or asset (for e.g., the recovered steel beams from the bridge can be melted and casted to form steel containers or guard rails on the bridge).

The clear distinction between reuse and recycling can be visualised in figure 6. Recycling becomes the next option after an item has been reused extensively and cannot be used again in its current form. When recycling is no longer possible, the remaining material becomes waste. However, renewable materials can lead to closing the biological loop instead of creating waste. Reusing materials generally requires lesser energy than recycling of materials, which usually has very high consumption of energy (Coelho, et al., 2020).

3.1.4 Implementation and measurement of CE in construction projects

In the construction sector, the objective of implementing CE revolves around optimising the utilisation of materials, products, and components in the construction project through extensive reuse and recycling practices, this process actively contributes to the promotion of enhanced, sustainable and production cycles (Sparrevik, et al., 2021). Numerous strategies, referred to as R-strategies, have been devised to reduce resource and material consumption in product chains to foster and improve the circular economic chain.

The Netherlands Environmental Assessment Agency (PBL) in its report (Potting, et al., 2017) corroborated the most diverse 10R model to transition to CE. The various R-lists mentioned in the figure 7, may have a similar structure, but they typically differ in the quantity of circular strategy. These lists have a wide range ranging from high circularity (low R-number) to low circularity (high R-number). Strategies labelled R0 and R1 aims to minimise resource and material consumption by achieving the same functionality of the product.



Strategies			
Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3	Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recover	Incineration of materials with energy recovery

Figure 6: R-strategies implemented by Netherlands Environmental Agency (source: (PBL, 2021))

There has been a recent surge in the literature focussed on measuring resource efficiency and circularity. Various studies ((Linder, Sarasini, & van Loon, 2017), (Elia, Gnoni, & Tornese, 2017), (Figge et al., 2018), (Pauliuk, 2018), (Parchomenko et al., 2019)) explored diverse approaches to measure circularity at both product and asset levels. (Saidani et al., 2019) developed a "circularity indicator tool" which systematically organises existing indicators from the literature into a structured taxonomy. (Moraga, et al., 2019) aimed to capture and classify circular economy (CE) indicators within a framework.

Considering the lengthy lifespan of bridges and the unpredictable nature of the management of bridges, it may not be practical to adopt these indicators as a means to promote circular design, construction, and management of bridges without making uncertain assumptions about lifecycle stages of the asset. To address this, design strategies that account for future uncertainties have gained significance over the past two decades. Design-for-Disassembly and transformable designs have emerged as an effective means of waste reduction in the construction industry. However, the measurements for disassembly, transformability index, and adaptability index through metrics and indicators should be considered in the aforementioned circular indicators studies.

Nevertheless, principles of CE in construction projects, which have a more consolidated literature base ((Addis & Schouten, 2004), (Durmisevic, 2006), (Crowther, 2018), (Kibert, 2016), (Schmidt, 2014)). Can broadly apply to civil engineering structures due to similarities in techniques, materials, and conditions. The key takeaway from these studies is that by making assets transformable or disassembling, the potential for adaptation or reuse increases.

3.1.5 Conceptual limitations

In a linear economy, products are designed to be used and then discarded. However, in a Circular Economy (CE), products are designed to be reused, repaired, or recycled. This requires a fundamental shift in the way we design, manufacture, and consume products. Nevertheless, CE cannot be seen as the only solution to every problem pertaining to resource depletion. In the article by (Korhonen, Honkasalo, & Seppälä, 2018), aspects of both economic and social elements were considered to point out limitations to the concept of CE.

- **Thermodynamic limitation**: this group looks at how the amount of matter and energy of the CE product is used in an economic system that is related to the amount of money generated. It also lays down the fact that in the practical world, any material cannot be reused forever, as there maybe wear and tear or other factors that limits the product's lifecycle in the long run. For example, some materials such as plastics, can only be recycled a limited number of times before they become too degraded to be used.
- **Spatial and temporal system boundaries**: It can be difficult to assess and apply CE to different regions, countries, and industries, and it can also be difficult to implement over a long period of time. In some cases, it the project may also result in lower sustainability on the long run due to unknown future impacts.
- **Economic growth limitations**: CE can be more expensive than the linear economy, at least in the short term, as CE requires investment in new technologies and business models. There is also a rebound effect in question, wherein CE activities, which have a lower impact per product, also cause increased levels of production, reducing their benefit. For example, if a person buys an electric car that is more efficient than the previous one, they may drive more as they feel that they are saving more on fuel.

- **Path dependencies and lock-in limitations**: This group prioritises the survival of early entrants in the market rather than favouring the most adaptable solutions. Consequently, the most intricate and comprehensive CE initiative can be overpowered by a simpler and financially advantageous solution.
- **Organisational strategy and management limitations**: CE innovations or products need to undergo multiple levels of administrative processes, necessitating the establishment of extensive network structures. The policies, financial management, risk management, responsibilities can lead to complexities with implementing CE.
- **Physical flow definitional limitations**: The concept of waste itself has a wide variety of inferences, it has a strong influence on its handling, utilisation, and waste management. As mentioned in 3.1.1 the definition of CE and it's meaning also has a deeper impact on the project.

3.1.6 CE innovation and transition

In order to realise CE goals in the Netherlands, the government has embraced a collaborative public-private approach. This approach acknowledges the essential role of governments, businesses, and citizens in facilitating the transition towards a circular economy (Hanemaaijer, et al., 2023). Five key transition themes have been identified by the government which includes Biomass and Food, Construction, Consumer Goods, Plastics, and Manufacturing. To drive these transitions, dedicated teams consisting of representatives from government authorities and businesses have been established; for example, the SBIR programme as explained in section 1.1 by Rijkswaterstaat to implement CE in bridge construction, which will be the main focus point of this report.

Figure 7: Circular economy transition elements (Source: adapted from (Hanemaaijer, et al., 2023))

The CE transition efforts and resources invested by companies, citizens, and government authorities in the Netherlands have shown a modest increase. As of early 2022, the country witnessed notable growth with approximately 130,000 circular companies, indicating an increase of around 30,000 compared to two years ago (Royal Haskoning DHV, 2022). In terms of employment, a selected number of industries involved in circular activities experienced an increase from 254,000 full-time jobs in 2001 to 327,000 in 2020 (Hanemaaijer, et al., 2023), (CBS, 2023). Additionally, the number of circular innovations monitored by the Netherlands Enterprise Agency (RVO) rose from 373 in 2018 to 475 in 2020 (RVO, 2022). However, in the absence of proper valuing and pricing for wasteful, polluting practices, circular products and services face a disadvantage in comparison to non-circular alternatives, leading to an unfair and uneven competitive playing field. Nevertheless, these developments demonstrate the growing momentum and commitment towards circular initiatives in the Netherlands.

3.1.7 Connecting CE with Viaducts or Bridges

Circular Economy (CE) is a promising approach for improving sustainability in bridge construction. (Anastasiades, et al., 2020) translated the CE principles exclusively for bridge construction. The authors argue that CE can help to reduce waste, conserve resources, and improve the environmental performance of bridges. The discussion points also included the challenges of implementing CE in bridge construction, such as the need for new materials, design methods and economic costs. The critical analysis of the research included an action plan for achieving circular bridge construction. This strategy primarily included four main aspects.

- **Technical solutions**: This strategy emphasises the design of a bridge that can be easily dismantled, allowing for the reuse or recycling of components. The design for Deconstruction and Adaptability approach ensures that materials can be effectively recovered at the end of the lifecycle of the bridges (Minunno et al., 2018). The action plan also mentioned the need to develop a standardisation technique for bridges without any compromises to the architectural design.
- **Ownership and behaviour of users**: Due to the higher economic costs for CE bridge constructions government as owners of the bridge assets needs to be incentivised to implement the Design for Deconstruction and Adaptability approach strategy along with Construction and Demolishing waste management practices.
- **Bio-based construction**: On one hand, bio-based materials improve the sustainability and reduce the carbon impact of the bridge, such as including treated wood in the design of the bridge, on the other hand, it is difficult to integrate into the system as these materials may deteriorate over time and requires continuous maintenance to protect these elements.
- **Circularity assessment**: It is a valuable tool that can be used to make bridge construction more sustainable, cost-effective, and resilient. Dedicated circularity indicators need to be developed for the meso-scale of bridge construction; parameters and baseline are also required to be set up to assess the circularity of the bridges.

3.1.8 Current state and condition of the bridges

To prevent any major economic disruptions and bridge collapse, it is imperative to study the current state of the bridges to predict how they will deteriorate in the future. It is crucial to understand the current state of the bridges and the number of bridges expected to be repaired or replaced. Currently, the bridges across the Netherlands, vary with respect to the size, conditions, and technical specifications. Connecting their lifecycles to enable reuse is a challenging process. A critical evaluation is carried out to prepare the prognosis report called the Vervangingen en Renovatie (V&R) by Rijkswaterstaat for the bridges in the Netherlands.

The report (Rijkswaterstaat, 2022d) estimates the future projects based on the qualitative research, periodic inspection report, planned initiatives, and statistical analysis. From the circularity standpoint, this information is essential as it clarifies the need for reusable and adaptable design measures and the extent of technical and functional demolition.

From the prognosis report, it can be inferred that the majority of the bridges and viaducts were constructed between 1960 to 1980; within the next 20 years, approximately 140 concrete bridges will require renovation, and about 40 will need replacement (Coenen, 2019). The report also mentioned an internal memo from Rijkswaterstaat highlighting that out of 271 removed bridges, 215 were demolished due to functional reasons rather than technical issues. Although the designed technical norms specify a lifespan of 100 years for bridges, practically the average lifespan of viaducts is 80 years, and fixed water-crossing bridges are 92 years (Rijkswaterstaat, 2022d). Furthermore, bridges located within large intersections tend to have a lifespan of approximately 10 years shorter than standalone structures, emphasising the need for adaptability and reusability in such scenarios to complete the renovation or replacement works at a swift pace to reduce any inconvenience to the public.

3.2 Appraisal method

In this research, the primary focus lies on Cost-Benefit Analysis (CBA). While it is worth noting that some of these tools were not originally developed for sustainability assessment, we include them in our analysis due to their widespread usage in decision-making processes for evaluating transport projects. Furthermore, these techniques are progressively adapting to incorporate sustainability parameters, making them relevant to this research.

Cost-benefit analysis (CBA): CBA is a highly prevalent method used to assist decision-makers in evaluating transport projects. It is a well-established and commonly utilised technique that facilitates the comparison of alternatives with the goal of maximising the social welfare. Typically employed as an ex-ante evaluation tool, CBA relies on the ability to quantify and monetise both positive aspects such as user benefits (e.g., travel time savings), and the negative aspects, such as investment costs and various detrimental effects (e.g., CO_2 emissions, resource utilisation).

In the academic literature, there has been extensive discussion regarding the role of CBA. Some scholars advocate for the suitability of CBA in evaluating public projects, examining its influence and implications ((Grant-Muller, et al., 2001), (Pearce & Nash, 1981)). Conversely, others raise concerns about its effectiveness as a decision-making support tool, particularly when appraising large-scale infrastructure projects. These critiques highlight the challenges associated with utilising CBA in such contexts ((Vickerman, 2007), (Jones, Moura, & Domingos, 2014)). It is important to note that this research does not aim to provide an exhaustive critique of the well-established CBA method. Instead, the focus is on assessing its performance within the context of incorporating environmental cost impact factors in the view of sustainability considerations.

3.3 Assessment technique

The assessment of environmental impact factors of different transport project options involves the consideration of Life Cycle Assessment (LCA). Environmental factors and the costs pertaining to their respective criteria is an essential factor to combine with the tools for a comprehensive sustainability assessment.

Life Cycle Assessment (LCA): LCA is a methodology to evaluate the environmental impacts of a product, activity, or process. This analysis enables a comprehensive assessment of the environmental performance throughout their life cycle, encompassing stages such as material extraction, manufacturing, transportation, distribution, product use, service, and maintenance, as well as end-of-life considerations such as reuse, recycling, waste management and energy recovery. While LCA has been utilised to assess the environmental efficiency of certain transport infrastructure projects, most studies have focused on road infrastructure projects (Stripple & Erlandsson, 2004).

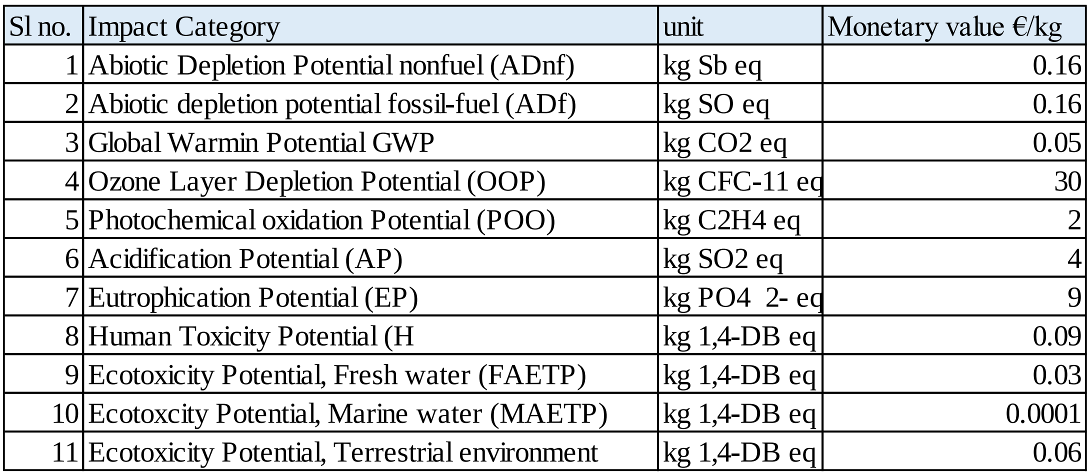
Companies can benefit from utilising LCA as it enables them to identify, evaluate, consolidate, interpret, and disseminate data regarding the environmental impacts associated with their operations. This empowers them to make informed decisions, implement sustainability measures, and communicate their environmental performance to stakeholders effectively. Ultimately, LCA serves as a valuable tool for organisations which tend to minimise their environmental footprint and enhance their overall sustainability efforts.

LCA has become widely adopted for evaluating the environmental performance of construction projects (Baker & Lepech, 2009). However, despite its usefulness, the LCA does not without limitations. (Reap, Roman, Duncan, & Bras, 2008) highlighted several issues that affect the accuracy and increase uncertainty in assessment results. These challenges include selecting appropriate impact categories, indicators, and models, accounting for spatial variation, incorporating subjective values, and addressing problems in monetisation methods.

Furthermore, in the sustainability context, the drawbacks of the LCA require improvements to enhance its accuracy. While LCA primarily focuses on assessing the environmental consequences of an activity, it does not fully incorporate all sustainability criteria (Bueno, Vassallo, & Cheung, 2015). Therefore, integrating LCA with other appraisal tools is necessary to assess all the dimensions of sustainability. Consequently, LCA can be viewed as a crucial step in the development of a complete sustainability assessment tool.

Environmnetal Impact Category	
Factors from set 1 in EN 15804:2015 A1	
1	Depletion of abiotic raw materials, excl. fossil energy carriers
2	Depletion of fossil energy carriers
3	Global warming
4	Ozone layer depletion
5	Photochemical oxidant-formation (smog)
6	Acidification
7	Eutrophication
8	Human toxicity potential
9	Ecotoxicological effects, aquatic (freshwater)
10	Ecotoxicological effects, aquatic (marine)
11	Ecotoxicological effects, terrestrial

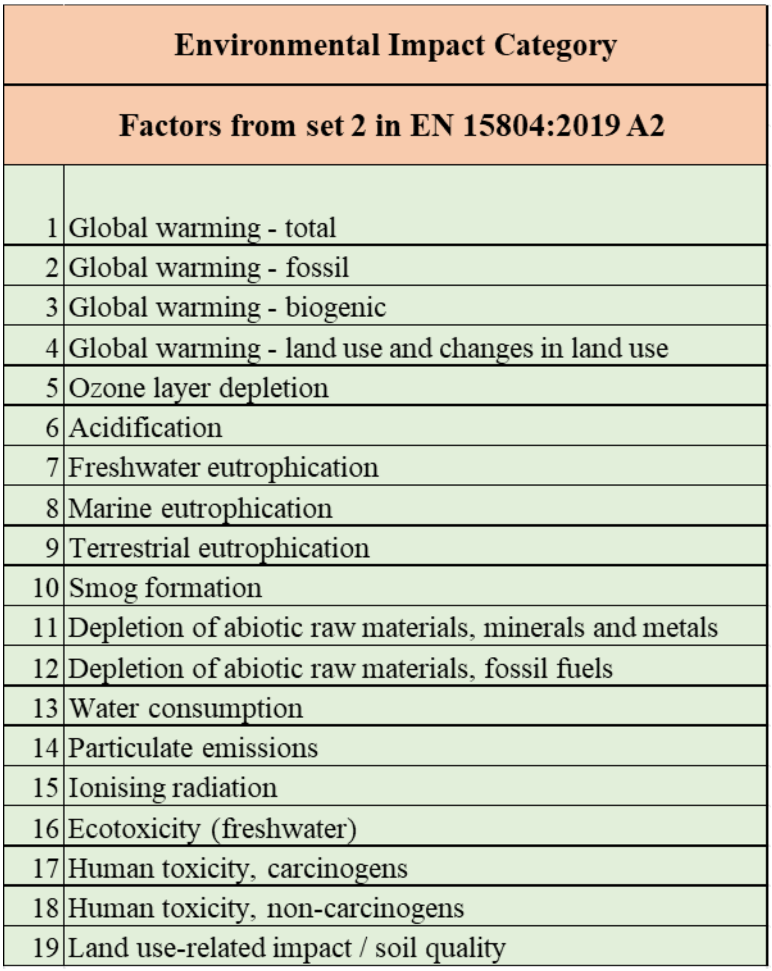
Table 1: Environmental impact categories (Set 1)



Sl no.	Impact Category	unit	Monetary value €/kg
1	Abiotic Depletion Potential nonfuel (ADnf)	kg Sb eq	0.16
2	Abiotic depletion potential fossil-fuel (ADf)	kg SO eq	0.16
3	Global Warmin Potential GWP	kg CO2 eq	0.05
4	Ozone Layer Depletion Potential (OOP)	kg CFC-11 eq	30
5	Photochemical oxidation Potential (POO)	kg C2H4 eq	2
6	Acidification Potential (AP)	kg SO2 eq	4
7	Eutrophication Potential (EP)	kg PO4 2- eq	9
8	Human Toxicity Potential (H	kg 1,4-DB eq	0.09
9	Ecotoxicity Potential, Fresh water (FAETP)	kg 1,4-DB eq	0.03
10	Ecotoxcity Potential, Marine water (MAETP)	kg 1,4-DB eq	0.0001
11	Ecotoxicity Potential, Terrestrial environment	kg 1,4-DB eq	0.06

Table 2: Monetary values of set 1 factor from EN 15804:2015 A1

In this research, the computation of environmental impact scores was performed based on EN 15804:2013 A1 'set 1' with 11 factors, following the assessment method in anticipation of the complete implementation of EN 15804:2019 A2 'set 2' with 19 environmental impact factors. Although the environmental impact scores were already determined according to 'set 2', which adheres to the updated standard EN 15804:2019 A2, it was decided not to conduct a full analysis of this set.



	Environmental Impact Category
	Factors from set 2 in EN 15804:2019 A2
1	Global warming - total
2	Global warming - fossil
3	Global warming - biogenic
4	Global warming - land use and changes in land use
5	Ozone layer depletion
6	Acidification
7	Freshwater eutrophication
8	Marine eutrophication
9	Terrestrial eutrophication
10	Smog formation
11	Depletion of abiotic raw materials, minerals and metals
12	Depletion of abiotic raw materials, fossil fuels
13	Water consumption
14	Particulate emissions
15	Ionising radiation
16	Ecotoxicity (freshwater)
17	Human toxicity, carcinogens
18	Human toxicity, non-carcinogens
19	Land use-related impact / soil quality

Table 3: Environmental impact categories (Set 2)

The new set of factors, with 19 factors, is an enhancement over the set 1 factors. It introduces new factors that not only built upon prior factors but also introduce distinguishing factors over the factors from EN 15804:2015 A1. Factors such as ozone layer depletion, smog formation and acidification were similar in both the sets, but factors such as global warming, eutrophication, human toxicity were separated and distinguished into separate factors for consideration, other factors such as water consumption, ionising radiation, and land use impacts were newly added to the new set of factors.

The primary reason for this decision is that the prices for the factors incorporated in ‘set 2’ have not been finalised yet. As the cost data plays a crucial role in the assessment of the impact categories, the unavailability of accurate and finalised prices of the various elements within the EN 15804:2019 A2 standard necessitated the reliance on ‘set 1’ for this research. However, the consideration of ‘set 2’ remains important as it aligns with the updated standard and lays the groundwork for future comprehensive analyses once the prices for these factors are available and finalised.

As depicted in figure 8, it briefly comprehends the literature review, currently, for project decision among various parameters and factors the CBA yields a specific value while the environmental impact costs yield another value which are evaluated separately, and design decisions are taken accordingly.

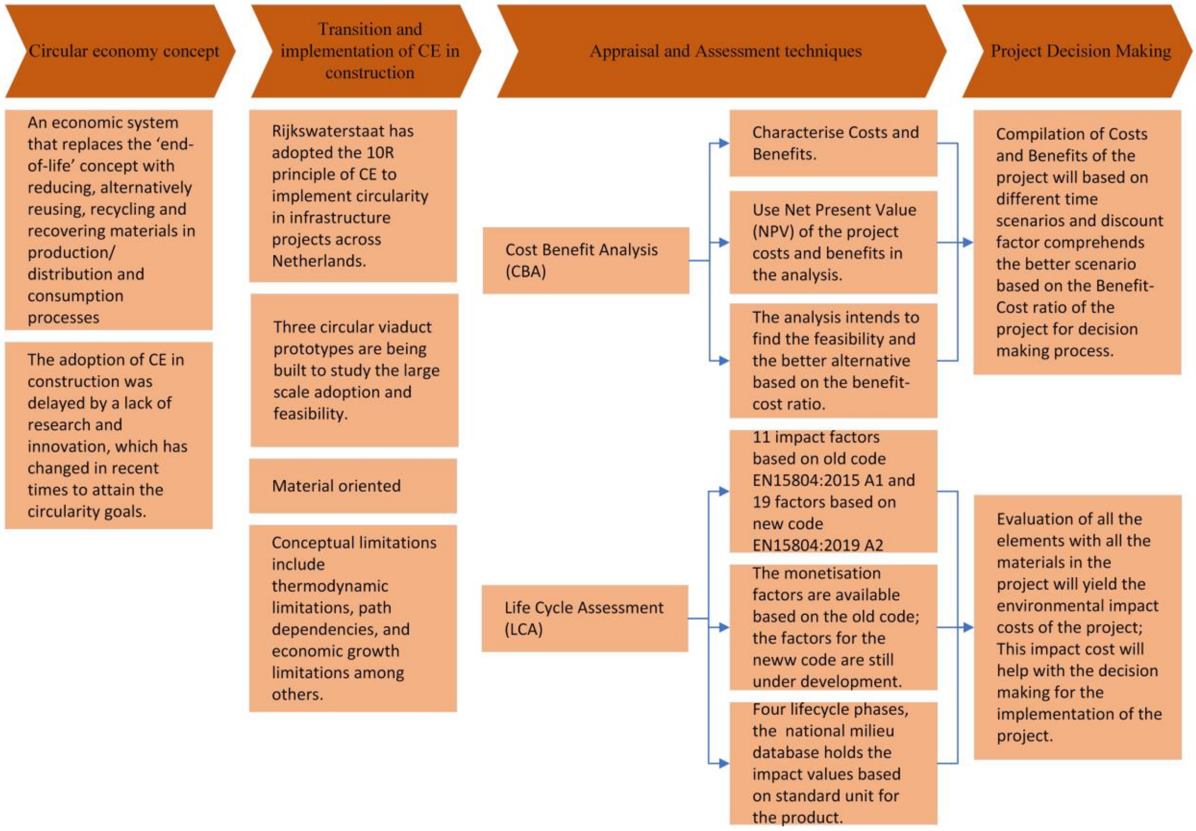


Figure 8: Framework for literature study (Source: Own image)

4. Methodology

4.1 Case selection

The research focuses on two distinct cases in the Netherlands to compare the environmental impact. The first case involves a circular viaduct design (ViCi design), which represents an innovative and sustainable bridge model. The second case revolves around the most common traditional viaduct design, specifically the inverted T-beam girder bridge, which is widely used in the Netherlands.

4.1.1 Circular bridge construction case

The concept of circularity and circular constructions have been prominent in the past few years, but circular infrastructure projects are yet to be implemented widely in the Netherlands. The government is pushing towards building a prototype to verify and validate the viability of implementing the circular viaducts on a larger scale. The selected case circular viaduct type (Arch bridge) is a newly constructed that can be reused in the future. But, in recent times, there are many projects that focus on reusing the existing traditional viaduct models. After extensive testing, all the viable parts such as girders, guard rails, etc, are planned to be reused without complete demolition. As mentioned in section 1.1, through the SBIR program, a ray of opportunity was shown to three circular viaduct prototypes.

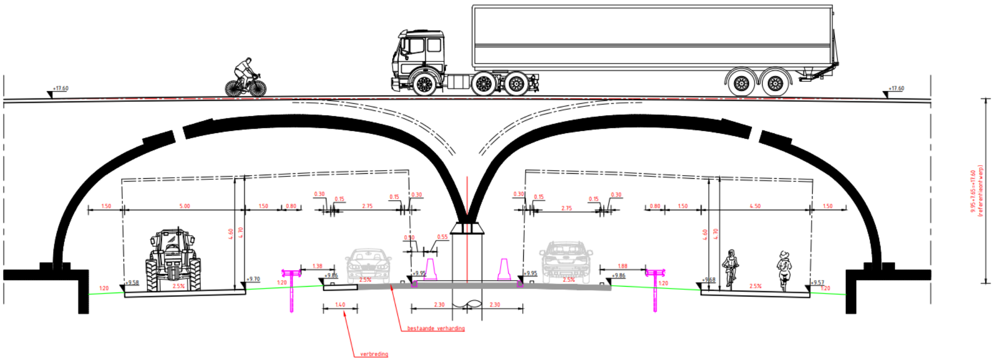


Figure 8: Concept of a circular viaduct (Source: ABT B.V.)

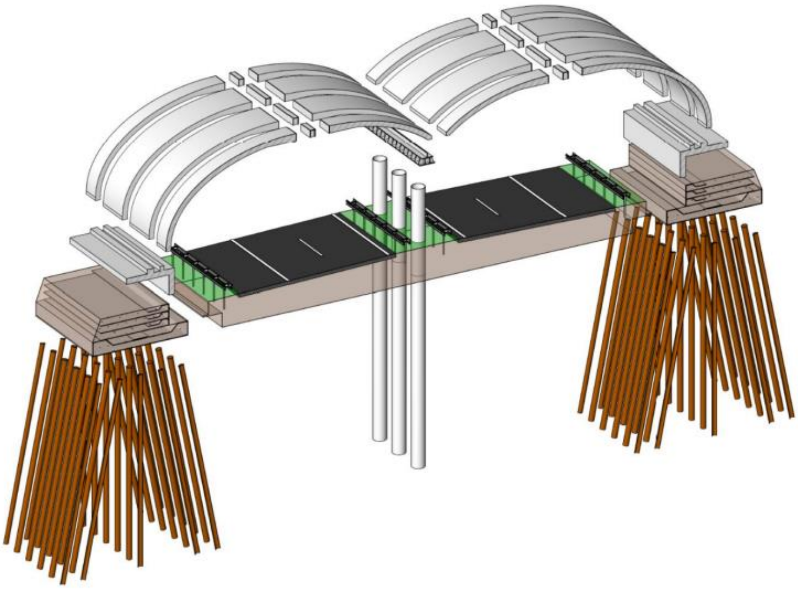


Figure 9: Modular design concept of the circular viaduct (Source: ABT B.V.)

One of the prototypes is selected for the case, for the purpose of this research. It comprises an arch bridge consisting of reclaimable modular concrete arch structure. The innovative components, which enable the circular construction system are demountable connections of the structure. The material circularity index and detachability index rated to be 0.94 and 0.78, which means 94 percent of the materials/components can be reused and 78 percent of the component easily detachable, thereby reducing the lad to be recycled using higher energy or be sent to the landfills (ViCi, 2020).

The planning and designing phase of the concept shown in figure 9 and 10, has commenced and the construction of the project will be continued. The project has been handled by the ViCi consortium consisting of Boskalis B.V., ABT B.V., Maartens Beton B.V., Integraaljagers B.V. The construction case details, which is in the concept and tendering stage, at the time of this research, will be built on Stationsweg, Gemeente Hellendorn on the highway N35.

CBA is usually conducted at the design phase to contemplate the viability of the project (European Commission, 2014), for the integration of environmental costs into the CBA, this project made it ideal to check the economic costs and the environmental benefits, while also comparing with a traditional viaduct as the concept was still in the design and detailing phase going on for tendering.

4.1.2 Traditional bridge construction case

The traditional bridge project can be picked from a wide range of available projects, in contrast to the selection of a circular case project. Traditional bridge construction projects are generally not designed to be reused, at the end of the service life the bridge is generally demolished, and the elements are usually recycled or sent to landfills. The traditional bridge referred hereon refers to the inverted T-beam girder bridge in the Netherlands. Inverted T-beam girder bridge is the most common type of bridge found in the country.

Figure 10: Example of the inverted T-beam girder viaduct (source: (Pircher, 2006))

To ensure a comprehensive analysis for this research, the study will focus on the same location where the circular viaduct is proposed to be built with comparison to a hypothetical traditional viaduct. The primary motive of comparing the circular viaduct to the hypothetical traditional viaduct, is to identify the unique benefits and difficulties of each design. Comparing the circular viaduct with the traditional viaduct built at two different places can arise two main issues which leads to discussion, firstly, the environmental factors can be compromised when comparing to two different locations; secondly, there can be cost variations due to site location, logistical issues, and maintenance. As it was a newly built circular viaduct, which is reusable in the future it was decided to use a hypothetical traditional bridge at the same location for reference.

This approach will enable to evaluate and compare the economic feasibility of the circular viaduct with respect to the traditional viaduct required for CBA. The hypothetical traditional bridge used for evaluation was considered at the same location with the dimensions similar to the circular viaduct ensuring it fulfils the functional and technical requirements of the viaduct the same location on Stationsweg, Gemeente Hellendorn on the highway N35.

4.2 Selection metrics

Project size

The size of the project can be view in two aspects, namely, the length and width of the viaduct to be constructed, as well as the ratio between the length and width. These dimensions can significantly impact various aspects of the projects. It is important to note that finding a project with the exact same dimensions is unlikely, which is why the length-to-width ratio is included as a metric.

Materials

Materials used in the construction project can significantly impact the construction process, design, and costs. It differs from one project to the other based on the requirements, location, and various other factors to establish a completely identical comparison between the two viaduct construction cases. As a result, it is crucial for the materials used in both projects to be comparable, ensuring that they have similar properties. All the materials that will be analysed for the projects will be based on their functional requirement. By employing functional based materials in both the projects, the projects become more comparable, thereby enhancing the scientific basis of the case study.

Project duration

This criterion encompasses three crucial aspects: the duration of bridge design, bridge construction, and bridge decommissioning. Each of these factors impacts the project’s start date, the timeline for the bridge to become operational for public use, and the eventual decommissioning of the bridge at the end of its service life. Furthermore, the costs associated with the project significantly affected by the timing of specific sections of the bridge construction, as material and labour prices tend to fluctuate over time.

Construction costs

The project’s features include the construction costs, which serve as a valuable source of information for comparing two bridges and making an informed decision between them. However, it is crucial to understand the key factors considered during this study’s analysis. Examining construction costs leading to lifecycle costs associated with the various components of the bridge is vital for conducting this research effectively to weigh in the monetised benefits in the framework.

Location

The project’s location plays a vital role in determining its accessibility, which, in turn, can have an impact on the project’s cost and environmental costs. However, in the context of this report as explained in section 4.2.2, both type of viaduct designs, circular viaduct and traditional viaduct, were analysed for the same location considering the traditional viaduct design to be in a hypothetical situation.

4.3 Identification of elements

For this research, considering the selection metrics, four main elements of the bridge were selected to analyse further. Although it is possible to analyse all the elements of the bridge to check their environmental impact, it is not practical to complete the compilation of everything practically within the timeline; With the explained procedure and the approach used for the technique, it is possible to analyse all the elements in further research. Furthermore, a comparison chart was prepared to check the different types of elements or parameters in both type of bridges.

Traditional viaduct (inverted T-Beam girder)	**Circular viaduct (Arch bridge)**
Concrete piles	Tubular steel piles (Expensive)
Girder beams are cheaper	Arch elements are expensive (incl. anchor joints)
Limited use of sand	More quantity of sand
Self-weight is less	Self-weight is more
Less embankment quantity	More embankments or steeper ramps
Lesser material at cross-section	More material at the cross-section (due to self-weight)
Flexible applications	Limited flexible options

Table 4: Comparison of Traditional viaduct (inverted T-beam girder) with Circular viaduct (arch bridge)

When comparing the environmental impact of a circular bridge with a traditional bridge, careful consideration was given to the select the four elements with the most significant environmental implications. The four main elements with most environmental impact included in this analysis are:

- **Piles**
    - Pile elements were identified due to their potential impact on soil and the wastage it generates at the end-of-life cycle of the bridge. The traditional bridges incorporate the concrete piles while the circular bridge uses the tubular steel piles, which are more expensive, but they are reusable unlike the concrete piles that are demolished and recycled in the end to extract the byproducts.
- **Arch elements**
    - Arches in case of circular bridge and girder elements in the case of traditional bridge were chosen as they contribute to the overall structural integrity of the bridge and have implications for resource consumption and emissions during manufacturing.
- **Sand**
    - Sand was considered due to concerns related to its extraction, which can lead to ecosystem disruption and habitat loss. A larger quantity of sand required for the circular bridge construction poses another challenge as to the cost to procure and the environmental costs, although sand filing has one of the highest reusability rates.

- **Asphalt and expansion joints**
    - Asphalt and expansion joints were identified due to their impacts on air quality and carbon emissions during production. An important note here is that there are no expansion joints in the circular bridge, so there is lesser maintenance that reduces the road closure time.

4.4 Assumptions

Proposition: The research study was based on the proposition in which, for academic purposes, the world economy functions in a different manner than the existing one. The new proposition study was done to evaluate the circumstances and check the implications if new policies were implemented in the future; It was done to also check on a what if analysis.

The new economy in the construction works on the principle that at the inception of the project the client prepares the baseline for the environmental costs; in the contract, it will be specified that if the contractor does not exceed the baseline of the environmental costs the contractor receives a bonus specified according to the project, while if the actual environmental costs were to exceed then the contractor pays a penalty price to the client. This motivates the contractor to find solutions to not only reduce their environmental costs but also move to be more circular, which tends to lower the environmental costs and may also reduce the economic costs of the project in the future.

Assumptions play a crucial role in research, providing a framework for designing the study, collecting data, and analysing results. In comparing the circular viaduct and the traditional viaduct, several assumptions were made:

- **Design lifespan of the bridge**: The ViCi design was assumed to have a lifespan of 200 years, while the inverted T-beam girder bridge was assumed to have a design lifespan of 100 years according to the current design standards in the Netherlands. These assumptions were based on typical expectations for the longevity of each bridge type and also it was assumed that the bridge was of similar dimensions to have a fair comparable scale.
- **Materials used**: It was assumed that performance-based materials would be used in the construction of both the bridge types. Important to note that the assumption was made on the material type and not the elements used, for example, in case of piles, the traditional viaduct uses the concrete piles while the circular viaduct uses tubular steel with concrete filling, while it was assumed that the materials were similar but not the entire element itself.
- **Availability of recycled materials**: The research assumed that recycled materials would be available for use in both bridge types. This assumption considers the environmental benefits associated with using recycled materials and their potential availability in the construction industry.
- **Cost of disposal of non-recycled materials**: The assumption was made that the cost of disposing non-recycled materials would be consistent for both bridge types. This assumption acknowledges the potential environmental impact of disposing of waste materials and its associated costs.
- **Time consumed for demolition/deconstruction:** The research assumed that the time required for the demolition or deconstruction of circular bridge is longer than the traditional bridge. On one hand, as in case of traditional bridge it can all be demolished and sent to industries for recycling of materials, on the other hand, the element needs to be meticulously deconstructed or removed in case of a circular bridge without any damage, hence accounting for longer time period for deconstruction of circular bridge. This

assumption accounts for the potential environmental impact during the end-of-life phase of the bridges.

- **No storage of materials:** It was assumed that there would be no need for long-term storage of materials during the construction or maintenance of either bridge type. This assumption considers the potential environmental implications associated with material storage and its impact on project timelines. In the discussion, section 6, a brief analysis on the impacts of storage on costs, space and time were discussed.
- **Ideal case of maintenance:** The viaducts were considered to be ideal case, where the viaducts do not require any major maintenance or replacements, other than the planned maintenance factors at the planning stage of the project.
- **Environmental cost quantification:** The environmental costs data are quantified using a standard procedure from the LCA, but as there are no actual cash inflows or outflows, the data is incompatible for use in CBA. Hence, it was assumed that the cash inflows were from the module D, due to the reusable application, and the cash outflow were from the module A, B and C from the LCA data of the elements analysed.

4.5 Economic Analysis

The costs for LCC are also dependent on material costs, inflation rates and unforeseen fluctuations. The costs incurred due to diversions, road closures, design cots and storage costs are not considered for the analysis as these specific costs are completely dependent on the place of construction based on the closest diversion place or alternate route. The CBA (cost-benefit analysis) relies on the findings of the LCA (life cycle assessment), which systematically evaluates and quantifies the environmental impact of a product throughout its lifespan, encompassing everything from raw material extraction to end-of-life management, including all intermediate stages. To compare the two types of bridges, scenario analysis has been formulated to give a better view of the situation where the circular bridge is practically the most viable.

4.5.1 Life cycle assessment

An LCA is a quantitative approach that assesses the comprehensive environmental impact of a product throughout its entire life cycle, encompassing raw material extraction, production, use, and end-of-life disposal. This method empowers companies to gain insights into the environmental effects of their products and raw materials across the entire value chain. The product's life cycle in a structure is divided into four stages from modules (A to D) which categorise the system boundary. These modules are further classified as shown in table 4.

LCA methodology according to the code EN 15804:2019 A2, investigates 19 environmental impact categories, which encompass aspects concerning resource depletion (such as raw materials, energy, water, and land usage) and the release of harmful substances (such as greenhouse gases, nitrogen, and toxic compounds). LCA evaluates both the resources taken from the environment and the pollutants released into it. The analysis covers the entire lifecycle of the product, starting from raw material extraction through production, use, and potential reuse, up to waste disposal – in other words, from inception to disposal.

As explained earlier in section 3.3, due to discrepancies in the pricing index for the 19 environmental impact categories, an older version of the code EN 15804:2015 A1, with 11 impact categories is incorporated for this research. For each impact category of the product all the four modules (A to D) are evaluated. Additionally, in the NMD, B6 and B7 indicators were excluded for the declaration.

Product stage			Construction process stage		Use stage							End of life stage				Resource recovery stage
Raw Materials	**Transport**	**Production**	**Transport**	**Construction installation**	**Use**	**Maintenance**	**Repairs**	**Replacements**	**Renewal**	**Operational Energy Use**	**Operational Water use**	**Demolition**	**Transport**	**Waste Processing**	**Disposal**	**Reuse-Recovery-Recycling Potential**
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 5: Environmental performance declaration (source: own image)

To conduct LCA, specialised software such as SimaPro, Dubocalc is used, which relies on databases such as NMD (Nationale Milieu Database) and Ecoinvent. These databases provide detailed environmental data on production processes, energy generation, and transportation at national and international levels. The assessment method for environmental performance of construction works, along with the European standard EN 15804 and related ISO standards, establishes the guidelines for preparing an LCA using the environmental data in the NMD.

The result of conducting an LCA is an environmental impact score matrix, known as the 'environmental profile', which assesses each indicator at every stage. From this profile, a single score is derived, termed the Milieu Kosten Indicator (MKI) also known as Environmental Cost Indicator (ECI). In the construction sector, the environmental profile of a structure like a viaduct is expressed using MKI. Similarly, in the building sector, Milieu Prestatie Gebowen (MPG), calculates the MKI per year of the building's life and per square meter of gross floor area.

4.5.2 Cost-Benefit Analysis: methodology

CBA is used to assess and quantify the project's impacts by comparing the costs and the benefits of the entire project in its entire service-life. Costs and benefits are measured in monetary terms to enable a meaningful comparison by utilising the present value of both the factors. The CBA utilises an incremental approach, which involves comparing scenarios with project's implementation to a baseline scenario. This helps isolate the project's specific contributions and assess its true value.

To conduct CBA, initial methodology decisions were made as follows:

- The Analysis considered a reference period of 30 years. This duration allows for the assessment of both the environmental and economic effects during the implementation of the project and its outcomes afterward. This choice also aligns with the recommendations of the European Commission for conducting CBA (European Commission, 2014). It must be noted that the reference is just a baseline to consider at least 30 years, which was analysed for preliminary understanding, but in the scenarios considered for this research a minimum of 50 years is used for a practical approach.
- The costs from module A, C and D were considered to be cash inflow only once as these activities doesn't recur but the mode B, the use phase, of the project recurs, due

to all the maintenance activities that needs to take place. The environmental costs for the use phase will be discounted.

- Although the recommendation from European commission utilises a zero residual value (European Commission, 2014), in this research a residual value has also been considered from the environmental impact factor costs through the national milieu database pertaining to the elements chosen to be studied. This decision was based on the assumption that by the end of service life, the elements in the bridge can still be salvaged, recycled, or reused, which has a considerable monetary value, while also reducing the impact on the environment.
- Based on the scenario, for the analysis, in case of the circular viaduct, the residual costs or the reusable component costs of the bridge were added back to the CBA as benefit, while there is no residual value assumed in case of the traditional viaduct.
- A discount rate of 4% was implemented in this research based on the regulation guidelines from the European Commission.
- There are concerns regarding continuous discounting by the experts, wherein environmental damage occurring far in the future is undervalued compared to current damages, due to which a time-declining discount rate was in development. In this study, a time-declining discount rate was not employed for two main reasons:
  - The European Commission guidelines do not recommend the use if this type of discount rate (Gigli, Landi, & Germani, 2019).
  - The monetisation of costs and benefits was carried out to consider an increase in value per year for emissions based on the code form EN15804 and its assessment method.

In this research, the approach to discounting was based on the considerations mentioned above, considering the European Commission’s guidelines and the specific nature of the analysed costs and benefits related to environmental factors. Another important note in this research is that the primary objective is to portray the benefits and have a different view of the considered benefits and not entirely based on the economic cost in the CBA.

4.5.3 Scenario analysis

The Scenario analysis helps the decision-makers make informed choices about the structure and ensure its continued safety and functionality over time. This kind of analysis provides and perceives a situation on the basis of what if something were to happen in a way imagined. It allows them to be prepared for any potential challenges that may arise as the bridge ages and assists in implementing a proactive approach to bridge management and infrastructure planning. Scenario analysis for the lifetime of a bridge involves assessing the potential outcomes of the longevity of the bridge under three scenarios. To conduct the analysis, the performance of the bridge needs to be stimulated under each scenario and analyse the implications of each case.

In this case, the three major scenarios considered are as follows:

Scenario 1: Technical lifetime (200 years)

In this scenario, assume that the bridge has been designed and constructed to have a technical lifetime of 200 years. The technical lifetime refers to the duration for which the bridge structure can remain stable and safe from a structural standpoint. In this case, the bridge is expected to remain fully functional and safe for a very long period.

Scenario 2: Functional lifetime (100 years)

The functional lifetime refers the period during which the bridge can perform its designed function efficiently and safely. In this instance, assumption has been drawn such that the bridge has a lifetime of 100 years. After this period, it may require extensive maintenance, repairs, or even replacement to continue functioning adequately. Although the average age of traditional bridges varies and many bridges are in dire need of replacement before their intended service life of 100 years, it is assumed in this scenario that the bridge serves the entire 100 years for the analysis.

Scenario 3: Functional lifetime (50 years)

In the last scenario, the bridge was assumed to have a shorter functional lifetime of 50 years. This suggests that the bridge will have a relatively limited period during which it can operate effectively before requiring substantial intervention, such as major repairs or replacement. This can be seen in areas where substantial transition occurs in the city planning or in instances where the bridge is not able to facilitate the vehicle load anymore and in need of a new plan.

4.6 Integration of environmental benefits

Integrating the environmental benefits in CBA remains a crucial aspect of assessing the true value and impact of the project on the society. As explained in earlier sections, the true focus of this research is to not mainly on the construction costs but more leaning towards the environmental impact costs that can be portrayed as benefit factor in CBA. To integrate the environmental costs the following steps were incorporated for this study:

4.6.1 Identify and quantify environmental impacts.

First step in this process was to analyse the identified elements of focus to extract the quantity of the materials. After the quantity of the materials were determined, these materials were looked up in the National Milieu Database (NMD) through Dubocalc to extract the Environmental Product Declaration (EPD) of all the four modules in their entire life cycle. The analysis will be conducted based on the standard code EN 15804:2015 A1 of set 1 with 11 environmental factors. Each environmental impact factor was checked for all the four modules (A to D) to determine the total quantity based on the unit of each factor.

4.6.2 Monetisation process of environmental factors

The methodology for the monetisation process of environmental factors involves a systematic approach to assigning monetary values to various environmental benefits. After the data from LCA is utilised to determine the extent of the impacts. Next, relevant economic valuation methods, such as market-based valuation, assessment method of statutory body directed by the government, or economic valuation are applied to convert these environmental factors into monetary terms. Sensitivity analysis and expert consultations are often incorporated to ensure the monetisation results are robust and accurate.

Many factors, during the monetisation process, are based on a lot of assumption provided in the assessment methodology. For the ‘set 1’ with 11 environmental impact factors from EN 15804:2015 A1, the monetisation analysis concluded with a weighting factor for each impact category to convert the impact factor unit to a monetary sum. The organisation ‘CE Delft’ was responsible to draft the monetisation factor for Netherlands. It was done through careful consultation and agreements with the stakeholders, who included the market parties, organisation within the government and academic researchers. The monetisation factors for each of the 11 impact factors were converted from a variable unit to a monetary value in euros (for example: the global warming impact factor with a unit of kg CO_2 was given a weighting factor of 0.05 to convert the carbon di oxide to euros). As mentioned earlier, since the monetisation factors, at this point in time during the research, has not been agreed upon for the 'set 2' factors of the 19 impact factors of EN 15804:2019 A2; hence, for this research only set one has been considered for the monetisation and analysis of 'set 1' factors.

The monetisation process provides decision-makers with a clearer understanding of the economic implications of environmental impacts to make informed decisions about the project. However, it is essential to acknowledge the challenges and limitations in quantifying certain environmental factors and to use these monetary values cautiously in decision-making, some environmental values may be inherently non-market based and difficult to quantify precisely.

4.6.3 Discounting environmental costs

Discounting is used to convert future environmental costs and benefits into their present value equivalents, portraying the idea that society tends to value benefits and costs more highly in the present compared to the future. The process involves selecting an appropriate discount rate, which represents the rate at which future values are discounted over time. The choice of discount rate can significantly influence the outcome of the analysis and is often subject to debate. On one hand, a higher discount rate leads to greater weight on immediate benefits and costs, potentially undervaluing long term environmental impacts. On the other hand, a lower discount rate prioritizes future benefits and costs. In the recent past, especially after the start of the war between Russia and Ukraine, debates have intensified over the discount rates as many material and labour costs have skyrocketed and has been difficult to determine a fixed discount rate.

To ensure transparency and consistency, discounting rate of 4% was considered as mentioned in section 4.5.1 as it aligns with the established guidelines and standards, taking into account both economic and ethical considerations. The discount rate was utilised in all the three scenarios for both cases of circular viaduct and traditional viaduct for comparison based on the environmental costs. After the discount rate was set, the net present value (NPV) of each of the element of focus, for this research, in the viaduct is determined for the environmental impact factors followed by other economic cost or benefit factors of the element. The present value of the environmental impact factors for the three scenarios are evaluated for the comparison between the traditional and circular viaduct to determine best scenario to implement the circular viaduct.

$$Net\ Present\ Value(NPV) = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} + C_0 \qquad (1)$$

Where,

C_t = Cash flow at time period t
r = discount rate
n = number of periods
t = time period

4.6.4 Integration of environmental factors in CBA

The process to integrate the environmental factors in cost-benefit analysis started with quantifying and evaluating the elements of focus utilising the LCA method. As mentioned, the LCA data for each environmental impact were retrieved from the national milieu database through dubocalc. The values provided were for only module A, as the values for use phase, end of life and recovery phase (modules B to D) will vary immensely based on the structure.

Additionally, with reference to infrastructure projects, the recovery phase value is completely neglected as it is assumed that there is no value for the recovered items, but in case of circular construction projects, there is generally a higher value for the elements that are recovered as they may be reused in another projects. Hence, it is essential to drive use-based value division among the modules, this means that the values, based on the scenarios considered for the evaluation, it was divided and the values at the recovery stage were added back to module D for circular case projects. The negative value in EPD for module D was assumed that the materials were reused resulting in decrement to the environmental cost and a positive value indicated the materials were recycled or sent to landfill incurring an increment to the environmental costs. In case of the traditional viaducts, the project is completely demolished at end of life, so the values to module D were not considered as there is little/no value after recovery.

Furthermore, the values divided across the modules were based on scenarios considered in the evaluation. For example: in case of scenario 2, where both types of bridges are evaluated for a functional life of 100 years, based on the element, in case of material steel in girder elements the recovered value was not considered in traditional viaduct, while the recovered value was half of the original value from module A as the circular bridge was assumed to serve the entire 200 year design life and it can be reused for building another viaduct, thereby reducing the environmental impact and increasing the environmental benefits that can be viewed in the CBA. The environmental impact factors were then monetised as explained in section 4.6.2 through their weighting factors to arrive at the final value for each product.

Followed by this, the factors discounted to check their present value. In the CBA framework, either the economic costs (C) or the benefits (B) are seen in terms of present value (PV), which makes it a better approach to integrate the environmental costs into CBA.

The results section comprehends the analysis of LCA for each of the elements considered for the study to determine the environmental costs and benefits based on the scenarios and selected impact category. Figure 11 depicts the overview of the methodology.

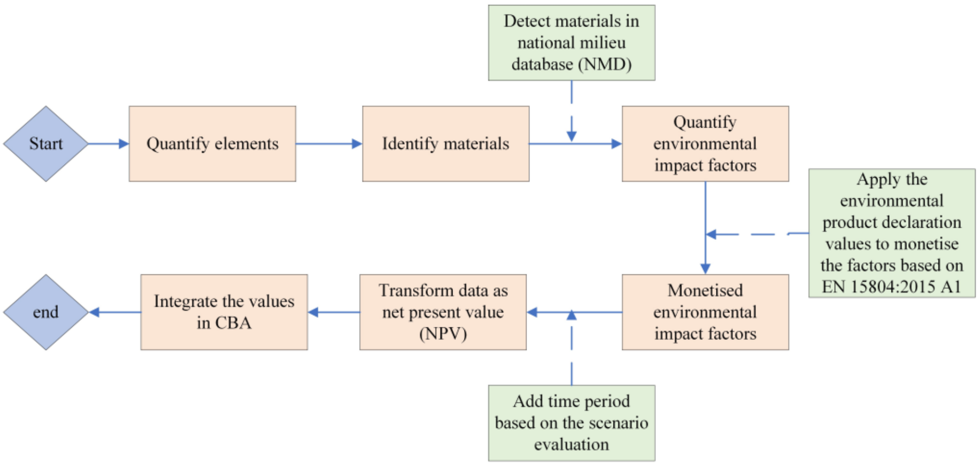


Figure 11: Methodology overview (source: own image)

5. Results

The results from the life cycle assessment provided a thorough understanding of the environmental effects of the circular viaduct and the traditional viaduct. The analysis made it possible to quantify multiple environmental effect categories across different life cycle stages (from module A to D), including greenhouse gas emissions, energy use, resource depletion, etc. The findings were analysed for the elements of focus identified in section 4.3, for both circular and traditional viaduct designs.

Each element in the viaduct were further analysed for all the materials involved in the element, for each element the environmental product declaration was used to quantify the environmental impact factors and the template shown in appendix B, was used to monetise each material in the element while comprehending the total impact cost of each element. Based on the scenarios considered the impact costs were evaluated as shown from appendix C to H for circular and traditional viaduct.

5.1 Life cycle interpretation for elements of focus

The different elements of focus for both types of bridges were considered for the assessment. Each of the elements were checked for all the different scenarios, under circular viaducts and traditional viaducts. Environmental costs were analysed across various scenarios across different life cycle stages.

5.1.1 Piles

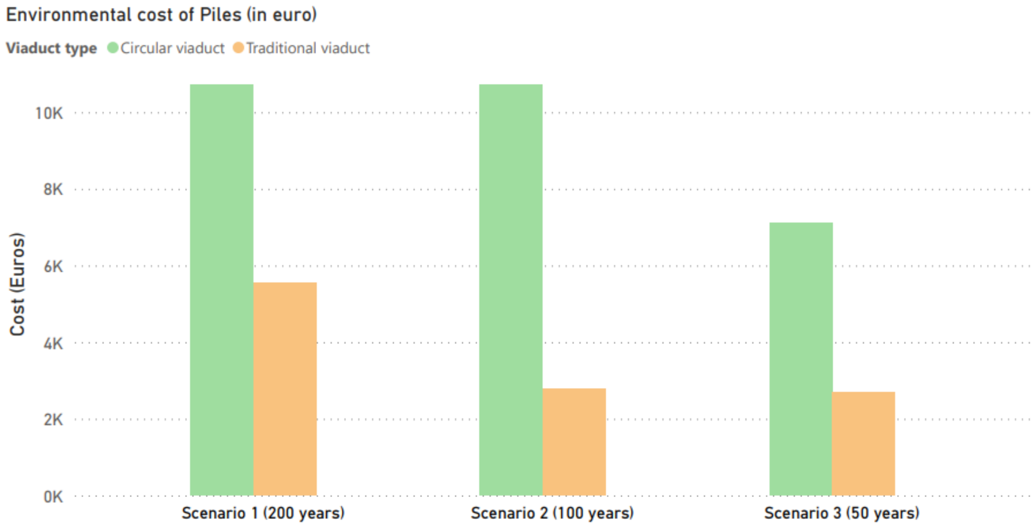
Circular viaducts: In the circular viaduct case selected, the primary support system comprises of open-ended steel tubular piles. These piles possess an external diameter of 1220mm and a wall thickness of 18mm. The piles are positioned at a distance of 3m from each other. These piles are inserted into the load-bearing layer and are responsible to transfer the vertical and horizontal loads from the viaduct to the sub-soil. Notably, the tubular piles remain unfilled with concrete. An advantageous aspect is that during the dismantling of the viaduct, the tubular piles can be extracted from the ground without incurring any (irreparable) damage, rendering them reusable after inspection and any necessary refurbishment. Furthermore, these piles can be readily adjusted in length to optimise their reuse potential.

The environmental costs have been calculated for all the three scenarios, in scenario 3, after 50 years, all the piles are considered to have a reuse potential, therefore the module D was assumed to be a negative value. While evaluating Scenario 1 and 2, it was considered that the steel piles cannot be reused as the corrosion process would have damaged the original material properties and cannot be reused once it has been excavated out after 100 years, but if the piles were allowed to be in the same place, they would satisfy the technical requirement and serve 200 years.

Obj.Code	Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
	Circular Viaduct			
	Onderbouw - Landhoofd (2x)			
	Paalfundering			
	Stalen buispaal 5st 356x12,5 hoh1,5m L15m 108kg/m1	10,555	10,555	7,041
	Stalen paaldeksel r400 20kg/st	171	171	78
	Total	10,725	10,725	7,119

Traditional viaducts: The traditional viaducts are designed to have precast concrete piles. It is the most common type of piles used for these kinds of viaducts. It was considered that these piles cannot be deconstructed or removed out of the ground without any damage. Hence there was no reuse potential at any of these scenarios. Nevertheless, a part of the steel used after 50 years, had reuse potential, so the module D had a negative value while scenarios 1 and 2 had no reuse potential. As mentioned earlier, the traditional viaduct is designed for only 100 years, hence, in case of scenario 1, the viaduct was considered to be built twice with all the components been replaced, this explains the drastic increase in environmental costs of scenario 1 when compared with the other two scenarios.

Obj.Code	Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
	Traditional Viaduct			
	Onderbouw - Landhoofd (2x)			
	Paalfundering			
	Prefab betonpaal hoh1,50m vk400mm L22m =3,52m3/st	3,558	1,779	1,779
	Voorspanstaal ca 35kg/m3	700	350	263
	Wapening ca 100 kg/m3	1,285	643	643
	Total	**5,543**	**2,772**	**2,684**



5.1.2 Girder/Arch elements

Circular viaducts: The arch elements are designed to be modular with interconnections and a crown piece in the entire frame of each complete arch. In the design there are two arch segments which can be extended to three to four arches. The arch elements are provided with steel anchor plate, through which the anchors pass, this connection holds the arch elements in place. The elements are precast with required properties and attached in place while construction. These elements are designed for a service life of 200 years, after their service life the arch elements are viable for reuse. But within this time frame, the arch elements can be reused multiple times.

While viewing the environmental costs, as scenario 1, after 200 years, the elements had no reuse applications, the impact at module D was considered to be positive, while at scenarios 2 and 3, the arch elements could be reused thereby reducing the environmental impact thereby it had a negative value for module D.

Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
Circular Viaduct			
Bovenbouw			
Verbinding boog-LH			
Fixatie met staalklossen 3st/m1 46kg/st	883	404	404
Boogdeel LH-Knoop (2x) (b=2,4m/st)			
Beton C45/55 (per m1 element)	1,690	1,690	1,690
Wapening ca 175 kg/m3	1,029	682	682
Boogdeel Knoop-TSP (2x) (b=2,4m/st)			
Beton C45/55 (per m1 element)	2,529	2,529	2,529
Wapening ca 175 kg/m3	2,103	1,392	1,392
Kroonknoop boogdelen (boxligger) (2x)			
Staalconstructie 834kg/m1	5,336	2,439	2,439
Total	**13,571**	**9,135**	**9,135**

Traditional viaducts: In traditional viaducts, precast inverted T-beam girders have been used along with the deck slab upon which the pavement will be laid. With immense research and optimisation of the girder type and casting procedure, inverted T-beam girders are currently more economical than other type of viaducts. It was assumed that there is no reuse potential after any of the scenarios. While looking at scenario 1, the inverted T-beam girders are replaced with a new set of girders, which also drives up the environmental costs.

Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
Traditional Viaduct			
Dekconstructie			
ZIPXL 800 T-liggers C60/75 (L=22m)	13,026	6,513	6,513
Wapening ca 80kg/m3	1,894	947	947
Voorspanstaal ca 100kg/m3	2,617	1,309	1,309
Druklaag C35/45 (250mm)	5,090	2,545	2,545
Wapening ca 200 kg/m3	2,870	1,435	1,435
Total	**25,496**	**12,748**	**12,748**

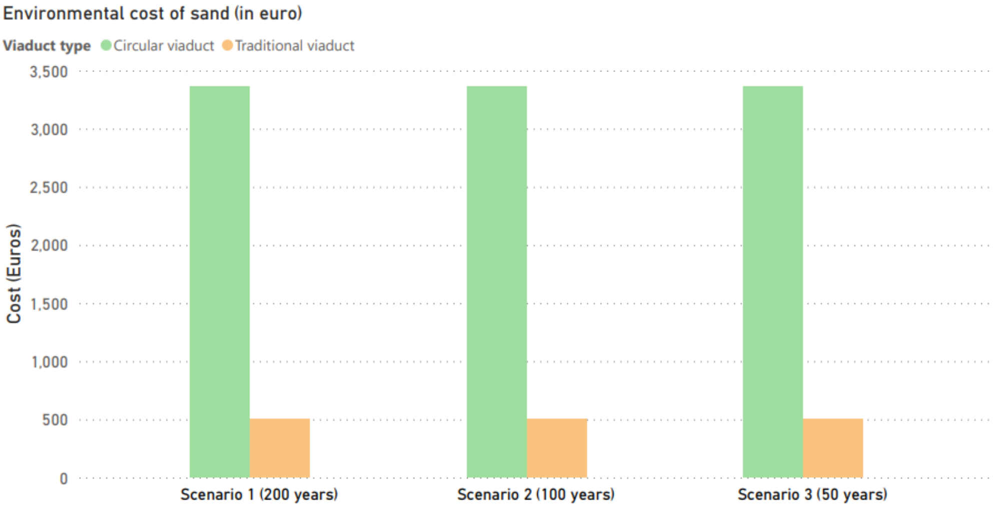
5.1.3 Sand

Circular viaduct: In this design, sand is required in huge quantities for filling on top of the arches, upon which the road layer will be laid. Sand is used for ramps as well as for filling on top of the arches. Although, sand is essential, but its extraction can have environmental implications, nevertheless, the reusability index is very high for sand. As the stated lifespan according to databases 1000 years, the reusability at any stage of the scenario is considered similar.

Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
Circular Viaduct			
Grond- en taludafwerking			
Zandaanvulling totaal	3,364	3,364	3,364
Total	**3,364**	**3,364**	**3,364**

Traditional viaduct: In this case, apart from concrete mixes, sand is used in its original state only for filling of ramps or the approach to the viaducts. At the stage of deconstruction or demolition in this case the sand can be recovered and reused in another project, therefore the environmental costs are similar at all the scenarios.

Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
Traditional Viaduct			
Grond- en taludafwerking			
Grond (talud landhoofden)	504	504	504
Total	**504**	**504**	**504**



5.1.4 Pavement

Circular viaduct: In circular viaduct, the pavement layer is laid on top of the compacted sand filling on top of the arches. In this design there are no expansion joints which require rubber. The road construction typically involves asphalt that provides a smooth and durable surface for transportation. In this case there is no major maintenance or replacing the expansion joints or replacing the rubber in the joints. This reduces the closure time of the viaduct while also improving the traffic flow. The only maintenance in this case is laying a new road once the service life of the previous one is completed. At each scenario for the circular viaduct the environmental costs remain unchanged.

Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
Circular Viaduct			
Afbouw			
Verhardingsconstructie			
Verhardingsconstructie toplaag 50mm	6,742	6,742	6,742
Verhardingsconstructie onderlaag 100mm	2,103	2,103	2,103
Fundatielaag verharding 200mm	2,742	2,742	2,742
Total	**11,588**	**11,588**	**11,588**

Traditional viaduct: In this case, the pavement is laid on top of the deck slab and on the approaches to the viaduct. On top of the viaduct, there are expansion joints with rubber. In case of scenario 3, when the viaduct is demolished a part of the steel used is considered to be reused that reduces the environmental costs with a slight margin when compared to scenario 2, in which the entire road will be demolished and none of the parts is reusable. Lastly, in scenario 1, as entire viaduct is built twice it can be observed that the environmental costs are also twice the amount compared to scenario 2.

Obj.Element	Scenario 1 (200 years) MKI [Euro]	Scenario 2 (100 years) MKI [Euro]	Scenario 3 (50 years) MKI [Euro]
Traditional Viaduct			
Afbouw			
Verhardingsconstructie			
Verhardingsconstructie toplaag 50mm	13,484	6,742	6,742
Verhardingsconstructie onderlaag 100mm	1,266	633	633
Waterdicht membraam (SAMI)	18	9	9
Voegovergangen			
Aandeel rubber 10%	482	241	241
Aandeel staal 80%	4,249	2,125	1,699
Aandeel bitumen 10%	146	73	73
Total	**19,646**	**9,823**	**9,398**

5.2 Evaluation of CBA

The evaluation of cost-benefit analysis provided a comprehensive understanding of the environmental costs that could be integrated into the decision-making process for viaduct construction. Through the application of net present value (NPV) calculations, the environmental costs associated with different scenarios were quantified for their respective life cycle.

In this research, as mentioned, the main focus was not to conduct the entire cost-benefit analysis of the projects, rather find ways and approach to integrate the environmental costs into the framework. Currently, the main problem can be viewed at the environmental impact data; this data does not pertain to direct cash inflow or outflow for its inclusion to convert to net present value (NPV) format to integrate into CBA.

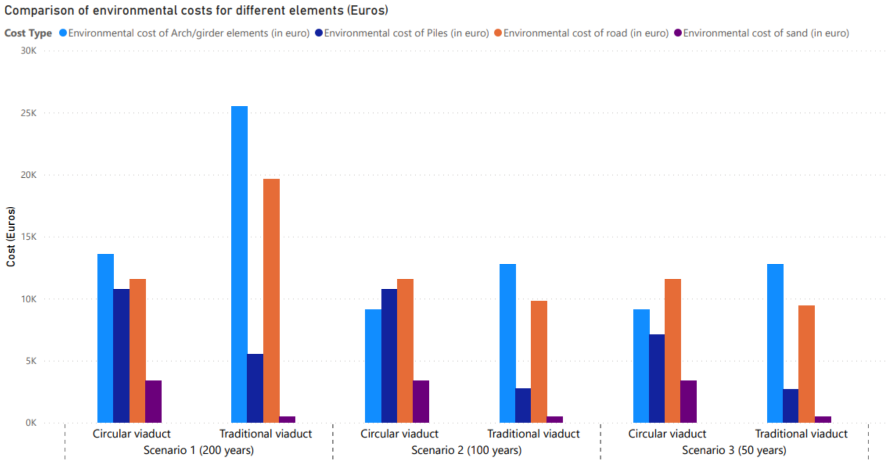
Hence, as explained in the Methodology, the cash inflows were considered for module D in the Environmental product declaration table after the monetisation; if there were a reuse potential for any element of the bridge it was considered with a negative value in module D. While, cash outflows, were for modules A, B and C as these activities cause environmental damage so their impacts were monetised and regarded as environmental costs. Determining the net present value of the environmental cost of the items paved way towards the final step to integrate the environmental costs into the CBA.

Elements	Scenario 1 (200 years) NPV [Euro]	Scenario 2 (100 years) NPV [Euro]	Scenario 3 (50 years) NPV [Euro]
Circular Viaduct			
Piles	8,003	8,058	7,871
Arch elements	9,536	9,525	9,473
Sand	3,217	3,220	3,239
Pavement	12,070	12,058	11,985
Total	**32,826**	**32,861**	**32,568**

Elements	Scenario 1 (200 years) NPV [Euro]	Scenario 2 (100 years) NPV [Euro]	Scenario 3 (50 years) NPV [Euro]
Traditional Viaduct			
Piles	2,781	2,731	2,722
Girders	11,389	11,197	11,394
Sand	493	483	486
Pavement	14,144	13,876	13,267
Total	**28,807**	**28,287**	**27,869**

5.3 Findings

The life cycle interpretation of the viaducts offered insights into the environmental cost implications. Table 6 gives the main factors influencing the environmental cost for each element upon comparison. In the findings, it was noticed that steel piles, in circular viaduct, carry a higher environmental cost compared to concrete piles in traditional viaduct. Based on the scenario the difference was as low as 50 percent in scenario 1 and 75 percent scenario 2 when compared against the circular viaduct values. For the arch/girder elements, due to complete replacement of the girders after 100 years in traditional viaduct, a huge difference in environmental costs can be noticed in scenario 1 with a negative 87 percent, while the other two scenarios yielded a negative 40 percent. The higher environmental costs in traditional viaducts in case of girders was noticed due to larger material usage arising from girders and deck slab.

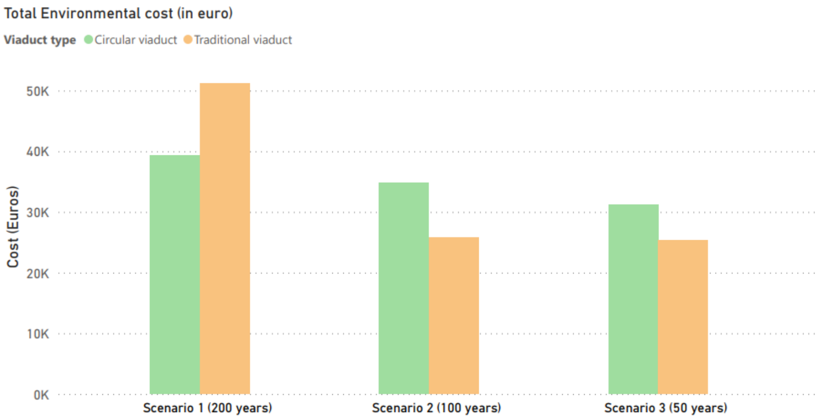


The circular viaduct was based on the concept of arch structure with sand filling on top of the arch elements. This concept had its own merits and demerits; on one hand, the merits included that the reusability index of the material was very high, which aided in improving the circularity of the structure. On the other hand, due to higher height to length ratio of the arch design when compared to traditional viaduct, there was a larger quantity of sand filling that gave rise to higher environmental costs, 6 times more than the traditional viaduct. The impact costs for the road were comparable, with a small difference, on comparison of circular with traditional viaduct, except in the case of scenario 1, when the entire road surface was laid twice which had higher implications of environmental costs. A summary of the environmental costs for each element for all the scenarios along with the factors influencing the cost and their assumptions are provided in table 6.

Element	Scenario	Environmental costs (Euro)		Main factor influencing the cost	Assumptions
		Circular viaduct	Traditional viaduct		
Piles	200 years	10,725	5,543	The reusable property of steel piling in a circular viaduct comes with very high environmental costs compared to the traditional one with concrete piles.	Concrete piles were replaced in traditional viaducts after 100 years. Steel piles were not available for reuse after 100 years.
	100 years	10,725	2,772		
	50 years	7,119	2,684		
Arch/girder elements	200 years	13,571	25,496	Higher material usage in traditional viaduct through girders and deck slab drives up the environmetnal costs considerably when compared to arch elements of circular viaduct.	Girders in the case of traditional viaduct cannot be reused after it is demolished in any scenario, while the arch elements cannot be reused after 200 years.
	100 years	9,135	12,748		
	50 years	9,135	12,748		
Sand	200 years	3,364	504	The exorbitant difference is due to the presence of large quantities of sand in the circular viaduct used for filling, but it also comes with one of the best reusable property with highest circularity index.	It was assumed that the entire sand, used for filling can, be extracted and reused when necessary.
	100 years	3,364	504		
	50 years	3,364	504		
Pavement	200 years	11,588	19,646	Petroleum by-products (Asphalt), used in roads, carry one of the highest environmental costs, it can be seen that the costs are almost similar in both cases except when the traditional one needs to be built twice in scenario 1.	A part of the steel used in traditional viaducts was reusable in traditional viaduct, in scenario 3.
	100 years	11,588	9,823		
	50 years	11,588	9,398		

Table 6: Factors influencing the environmental costs of the elements in viaducts.

The overall environmental costs of the viaducts, provides a more comprehensive visualisation of where and in which scenario the implementation of the circular viaduct is most viable. Upon, analysis, it was observed that the least environmental costs were observed for scenario 1 (200 years) for circular viaduct. This was mainly due to the fact that the traditional viaduct was completely replaced after a period of 100 years, which increased the environmental costs by a large margin. While the scenario 2 and scenario 3, did not yield the best results in confiding the best-case scenarios to implement the circular viaduct as the circular viaduct had 18 to 25 percent higher environmental costs as compared to traditional viaduct. Table 7 gives the overview of the difference in environmental costs of both types of viaducts for each scenario.



Scenario	Environmental cost (in euro)		% difference
	Circular viaduct	Traditional viaduct	
Scenario 1 (200 years)	39,248	51,189	-30.43
Scenario 2 (100 years)	34,812	25,846	25.75
Scenario 3 (50 years)	31,206	25,334	18.82

Table 7: Comparison of environmental costs for each scenario.

Integration of environmental costs required the values to be converted to NPV based on the timeline of activities in the scenarios. Monetising and converting the environmental impact values yielded interesting results not benefiting the circular viaduct case at first glance. The NPV of the environmental costs for traditional viaducts are much lower than circular viaduct, making the traditional viaduct case more favourable initially.

Perceiving the values in another sight, when looked at the values a little deeper, it can also be inferred that the reuse values of the economic and environmental costs are neglected. On the hindsight, when we include the economic cost of the elements after 50 or 100 years for circular viaduct due to its reuse potential, the benefit outweighs the environmental cost impacts. Table 8 depicts the NPV value for the scenarios considered with the difference in values compared to the circular viaduct.

Scenario	Net Present Value (in euro)		% difference
	Circular viaduct	Traditional viaduct	
Scenario 1 (200 years)	32,826	28,807	12.24
Scenario 2 (100 years)	32,861	28,287	13.92
Scenario 3 (50 years)	32,568	27,869	14.43

Table 8: Comparison of net present value (NPV) of the environmental impact costs for each scenario.

6. Discussion

This research offers a new perspective for integrating environmental costs into CBA, for the case of viaducts considered in the study. The synthesis of life cycle interpretations, CBA, and scenario evaluations provide new insights into economic benefits of reuse in monetary value while also looking at the environmental costs.

Economic and Environmental cost implications

Economic costs, as explained in Appendix 1, of the project is estimated based on the design and submitted by the contractor to the client. As for the environmental costs of the project, in this case the viaducts, is just a factor for representation and not actual costs borne by any party. The contractor with the lower economic costs and environmental costs is generally awarded with the project. In this research proposition, while integrating the environmental costs it was discussed that the total environmental costs, would be a mere baseline set by the client at the inception of the project, and if the contractor were to not exceed the baseline, based on the contract, the contractor is set to receive a bonus. This bonus acts as an incentive for the contractors to achieve the goals of reducing the environmental costs and move to a more circular construction process, which generally has lesser environmental costs at the time of reuse.

This proposition for research purposes, has larger implications to push circular activities, as reuse of elements consume lesser environmental costs than constructing new elements. The contractors to maximise their profits may tend to reduce their environmental costs. On another note, a point of concern is when the contractors tend to increase their economic costs to maximise their profits instead of reducing the environmental costs. Policies need to be drafted with utmost caution to prevent any misuse of the policies.

There are certain factors that can increase or decrease the economic costs of the circular viaduct while reconstruction. The factors that could increase the costs include, harvesting of materials, cleaning of materials, careful disassembly, repairs, preparation for procurement, testing and certification of elements for reuse, labour, and equipment costs; the factors that potentially decreases the economic costs include lower purchasing costs of materials in the future and time saving costs of rebuilding.

At this moment in time, among many uncertainties there are also many negative factors that may hinder the development of circular viaduct leading to a more optimised model of recyclable bridge, which minuses wastage, but at the end of the day there are still a lot of emissions, environmental impacts that cannot be avoided. Nevertheless, progressing into the future, more funding and grants needs to be provided for research into circular viaducts to find new materials and techniques to decrease the initial environmental costs and economic costs, which can be challenge at this moment to adopt the circular viaducts at a swift rate and achieve the ambitious circularity goals set by the government.

Interpretation of results

The scenario analysis enabled the identification of critical variables during the timeline for the project that were based on a what if situation. It was mainly done to find the scenario or timeline at which, the project has the largest impact on the environmental cost while comparing the circular viaduct to the traditional viaduct.

Comparison of circular and traditional viaduct was done mainly to check the viability of implementing the circular viaduct while checking with a baseline of the most commonly constructed viaduct. Although the main purpose of the research is to find the approach to integrating the environmental costs, it was essentially important to find out the implications of the circular viaduct and check if there were any benefits that could boost the adoption rate.

Analysing the cases based on the scenarios, the most favourable scenario when considering the NPV values with the benefits of economic costs due to the reuse potential, scenarios 2 and 3 seems to provide better results. On the contradicting sight, when looking at the just the total environmental costs the most favourable scene is scenario 1. Choosing the right scenario to implement the circular viaduct may rather be challenging looking at just the environmental costs. Although, it was recommended to improve the research funding to reduce the environmental costs, it was also important, through this research, to recommend the need to look at the actual economic benefits of reuse as the prices of elements can significantly rise in the next 50 to 100 years, which could be beneficial to implement circular viaduct, but it is also equally essential to look at the labour and equipment costs for demounting and reuse procedure in future research.

Storage of materials

A brief analysis of storing of the elements of the circular viaduct after the deconstruction procedure revealed intriguing considerations. Although there is no data source for the numbers provided in this analysis, but discussions with industry experts gave rise to this small gist of the calculation. With the size and quantity of the elements an area of 10,000 m^2 was assumed to place the demounted elements. A large area was required to store and for the lifting vehicles to move the elements around. The lease for this kind of area is approximately 300,000 euro per year. It can change from which area in the country one wants to lease, areas closer to the cities are more expensive. The rate assumed based on a more ballpark range on the rural side with less traffic disruptions for easy movement of vehicles to store the elements.

Additionally, materials cannot be just placed on the field, proper maintenance and treatment needs to be conducted for all the elements Maintenance expenses, ranging from 50,000 to 100,000 euros, introduce an additional variable in the equation. Initial projections stand at around 400,000 euros annually for storage. These figures are alarming as it is not viable at this moment to spend an exorbitant amount for storing. This can impact the economic benefits of reusing of viaducts and create excessive costs to cover for just storing the materials. Hence, it is recommended to find a place which needs a viaduct to be constructed and plan the procurement or find a place with no lease rents required to store the materials.

7. Conclusion

7.1 Answering research questions

SQ 1: “What are the challenges in the decision-making process of environmental CBA during the design phase?” can be answered.

The primary challenges can be seen in four main points, as summarised below.

- Integrating environmental considerations: While CBA has been used for major infrastructure decisions for a long time, its extensive use as a practical tool for environmental decision-making is relatively recent. Integrating environmental impacts into the analysis poses challenges, and there have been debates about the methods used to uncover the monetary value of these impacts.
- Dealing with uncertainties: The uncertainties associated with environmental losses have led to a search for ways to combine the cost-benefit approach with environmental impact factors. Finding a suitable method to address and account for uncertainty is an ongoing challenge.
- Addressing Equity Concerns: There is a growing interest in integrating equity or distributional concerns with CBA, especially regarding the distribution of environmental burdens and benefits. Guidelines for minimum standards of practice are emerging, but convincing practitioners of their significance in appraisals remain a challenge.
- Influencing Policy Decisions: Environmental factors in CBA has seen an upsurge in influence, but the modest aim of making cost-benefit thinking an input to public policy decisions is often not fully realised. Understanding why and how CBA informs some environmental decisions while neglecting others is to be seen.

Looking to the future, additional challenges in environmental CBA include further developments in valuation methods, particularly in valuing ecosystem services and establishing empirical values that can be applied across various policy contexts. The integration of CBA with concerns for precaution, sustainable development, and the inclusion of equity weights for different groups across space and time are also areas that require attention and progress. Additionally, bridging the gap between official CBA practices and advancements in academic literature is an ongoing challenge.

SQ 2: “Which factors can be used to engage the decision-making tool to balance the economic and environmental costs?”

The case study encompasses a circular viaduct and a traditional viaduct, that have a predetermined set of metrics. Through an analysis of both the projects based on their economic and environmental costs over their project processes a comprehensive overview of each case can be determined. In the context of constructing circular viaducts, various factors need to be considered to engage the decision-making tool to view the environmental and economic costs in another perspective. These factors play a crucial role in ensuring that the cost-benefit analysis accounts for both the environmental and economic outcomes. The main factors that can be used to engage in the CBA are:

- Life Cycle Assessment (LCA) data: Integrating comprehensive LCA data is vital in assessing the environmental impact of circular viaducts across their entire life cycle. LCA provides insights into resource consumption, emissions, and waste generation, and LCC provides insights into an estimate of the project's total costs in its entire lifetime, enabling decision-makers to make informed choices that minimise negative environmental effects.

- Environmental Impact Factors: Incorporating the environmental impact factors from the code EN15804 A2 provides information on factors such as carbon emissions, energy usage for raw materials, climate impact factors, that help the decision-making tool to evaluate the environmental costs quantitatively for different viaducts or bridges under several scenarios of the lifecycle.

SQ 3: "How can the environmental costs be monetised to assess the circularity in viaducts?"

Monetising the environmental costs in the viaducts first involves quantifying the environmental impacts caused by the elements used for construction and translating them into monetary values. This approach involved methods such as Environmental Product Declaration (EPD) and Life Cycle Assessment (LCA). Each material used in the element constructed in the viaduct was separated to determine the EPD of each product within the element. In this process, the environmental impact categories were distinguished and the quantity per standard unit was represented for each product.

Additionally, looking at the LCA, the quantity at each stage in the product life cycle including the service life was noted. The volume or quantity of the elements for each product were determined from the viaduct designs. Based on the design quantities the factors from the environmental impact categories were scaled up to determine the total amount of each product pertaining to the element. Lastly, the total amount was multiplied with the standard available monetary value, accepted by the Dutch government, from the code EN 15804:2015 A1. If and when the new monetary value is established for the new code EN 15804:2019 A2, the same procedure can be used to monetise the environmental cost.

SQ 4: "How can environmental impact costs integrate and aid in optimising the decision-making framework of the cost-benefit analysis tool?"

The data obtained for environmental costs in its form is incompatible to use in the cost-benefit analysis as the raw data does not indicate the cash inflows or outflows to convert the data to net present value (NPV). From the LCA data, the modules A, B and C stages were considered to be cash outflow as the environmental impacts are cased due to the products used at those stages while the module D, recovery stage, provided the reuse potential that could reduce the environmental impacts again, hence it was assumed to be cash inflow for the project. Module C and D are attained only during the stage at which the viaduct is deconstructed or demounted, hence the values were used appropriately in the NPV calculations.

Once the parameters were set, the NPV calculations were completed to determine the comprehensive environmental impact costs based on the scenario in terms of NPV in euros. This data is compatible to be used in the CBA calculation. The impact costs can be integrated into the costs of the project to provide a comprehensive and accurate tool for evaluating the overall value including the environmental impacts of the viaducts in CBA.

Main research question: What is the approach to integrate environmental costs into the decision-making process and balance environmental and economic outcomes in the cost-benefit analysis framework for constructing circular viaducts?

The answers to the sub-questions gave the basis to respond and explain the main research question. The optimal approach to integrating the environmental costs to balance environmental and economic costs in CBA revolves around a multi-step strategy. The case selected and analysed indicated the various effects based on the scenarios for the circular and traditional viaducts. In this research, only four major elements that considerably impacted the environmental costs were considered for the analysis. The quantities of the elements for both traditional and circular viaducts were calculated.

The first step started with conducting the Life Cycle Assessment (LCA) and utilising the Environmental Product Declaration (EPD) to find each element's impact categories. This involved scrutinising the environmental impacts of viaducts across their entire lifecycle and identifying and quantifying the impacts based on the code EN 15804:2015 A1. The extracted data, through the Dubocalc tool, was also used to monetise further the impacts based on the quantities of each element and the products involved in them.

Additionally, the environmental cost was converted to NPV as answered in sub question 4, this methodology provided the best parameters and situation to integrate the values in the CBA. Upon comparison of monetised environmental costs data, it revealed that the impact cost of circular viaduct is higher than the traditional viaduct in scenario 2 and 3 but lower in case of the first scenario. Suggesting that for circular viaducts the initial environmental impacts are higher but as time progresses it tends to decrease due to its reuse potential.

Furthermore, recognising the dynamic interaction between short-term costs and long-term benefits is essential. While circular viaducts may entail to higher investments and higher environmental costs initially, their potential long term cost reductions by reusing the materials or elements of the viaduct to build a new one is significant. By reusing the entire elements of the viaducts, after 50 or 100 years, the economic as well as environmental costs is reduced by a large margin as there may be no/less requirement of new materials contributing to both economic and environmental cost.

In conclusion, this approach of integrating the environmental costs and comparing circular viaducts to traditional viaducts gave rise to a new perception to view the benefits in both economic and environmental factors of circular viaduct in monetary terms, which helps to understand and balance the high initial economic and environmental costs of the circular viaduct to promote the adoption rate.

7.2 Limitations

The limitation for this research is given under three main categories, limitations for methodology, case studies and results.

7.2.1 Limitations of methodology

Firstly, the assumptions made regarding the practicality of the lifespan (100 years for traditional viaduct and 200 years for circular viaducts) of the viaducts may or may not be met in practical conditions. While viaducts are designed with durability in mind, it is uncertain if the viaducts can meet the entire design life, predicting the variable functional life of the viaducts in the everchanging conditions of the real world is a challenging task.

Secondly, although, the circular viaducts are designed for reuse, but predicting the conditions under which the viaducts might be reused is a challenge at this point in time. The viaducts are considered to be ideal with no major issues till the end-of-life, but in reality, effects due to corrosion, structural cracks, etc. during the demountable time may be an issue. For instance, the National Milieu Database (NMD) refers to steel with 1000 years of lifespan, but with corrosive action, the reuse of tubular steel piles in circular viaducts can be a big challenge after it is demounted.

Additionally, the NMD has a list of construction products for which the Environmental Product Declaration (EPD) analysis was done, but there are several products for which the analysis has not been conducted yet. While updating the library has been a recommendation for the future, but the present unavailable materials used in the design of the viaducts had to be interpolated to the closest available materials in the database library.

7.2.2 Limitations of case studies

The case of the circular viaduct analysed in this analysis has not been constructed yet. Hence, the construction costs considered for the analysis is based on the estimates during the planning stage and not the actual costs that occurred after the construction.

The hypothetical case of studying the traditional viaduct at the same location, leads to unexpected design management issues arising due to the fact that the circular viaduct selected has a higher height to length ratio than the traditional viaduct, which leads to a longer ramp approach to the circular viaduct than the traditional viaduct. It may not be an ideal scene for comparison, nevertheless, on a larger view comparing the circular viaduct to the most popular and commonly viewed inverted T-beam girder bridge in this country to have a base for comparison.

The circular viaduct is assumed not to be demounted and stored, instead be reused after the deconstruction procedure. This process raises a few procurement issues, as the location of the new viaduct needs to be fixed and all the testing procedures need to be finished on the elements that are going to be reused in another location.

7.2.3 Limitations of results

Firstly, the results obtained for the environmental costs were based on the prices from 2015 as deduced from the code EN 15804:2015 A1. The prices were not accounted for any inflation or price fluctuations in the recent past which was not accounted for the environmental prices. Although the monetised factors were based on the standard code, but in this research for the calculation purposes, a discount rate of 4 percent was considered, the validity of this approach has been updated for the recommendation for the future.

Secondly, analysing the materials in the two cases revealed that there were many distinctions between the two cases in this research. There were scenarios considered to understand the environmental cost implications of the cases in the future, but the estimate considered for the construction costs in the future and the circular practices can vary with the conditions presumed for this research.

Lastly, the results considered only the environmental costs based on the values from the Environmental Product Declaration (EPD) values of all the materials used in the construction and ignored the costs that arise due to the damage to the surroundings during construction.

7.3 Recommendation

The recommendations were categorised and formulated for practitioners who are currently focussing on the circular construction sector and for future research.

7.3.1 Recommendations for practitioners

Progressing into the future, achieving circularity in the construction sector may be challenging but necessary to combat the world's modern problems of waste management. This research contributes to the environmental and financial implications of viaducts/bridges. For practitioners, the following recommendations have been identified:

- Address the limited number of circular infrastructural projects by swifter adoption and construction of more projects may enhance the understanding of circular constructions to improve the knowledge and increase research opportunities. Ensure comprehensive data collection for the project for improvements from previous circular construction projects.
- To accommodate potential challenges, uncertainties, and risks in the early years of circular construction projects, it is necessary to allocate a larger budget when commencing the construction.
- Although, governmental organisations such as RWS is trying to implement circular projects, it is crucial to recognise the need for collaboration and coordination among all the stakeholders when initiating a circular infrastructural project to make it a success.
- Look beyond the initial construction costs and evaluate the long-term economic and environmental benefits of the project in monetary values. This encompasses to reduce maintenance costs, enhance resilience to environmental challenges, and potential benefits to the environment through eco-friendly features.
- Incorporate end-of-life strategies at the design stage of the project, to have comprehensive view of the plan to facilitate the material recovery and recycling.
- Actively utilise material passports across the circular construction sector to manage reusable elements effectively. For instance, at end-of-life during the demounting if any element is damaged and rendered not of use, it is necessary to have the material passport of the element to build a new part minimising delays while also having to recycle or repurpose the damaged element.
- Once the circular viaducts are built, it remains crucial to continue monitoring their environmental performance. Actively update the database for registering the environmental data of the products to keep a track of new or changing materials in the future.

7.3.2 Recommendations for future research

Among numerous studies on circularity and economics of circular constructions, there were a limited number of investigations intending to integrate environmental costs with construction costs. The insights gained through this research have contributed to inputs for potential future research into the topic. The following research recommendations are suggested:

- The current research methods for valuing environmental costs are often based on estimates that are subjective with various assumptions, which can lead to significant uncertainty in the evaluation process. Future research should focus on developing more accurate and objective methods for valuing environmental costs, such as contingent valuation.
- Explore the possibilities of utilising multi-criteria decision analysis (MCDA) in the cost-benefit analysis; MCDA can be used to consider multiple objectives, such as economic efficiency and environmental benefit prediction under various scales. Future research can focus on those implications to better understand the trade-offs between different objects for decision-making.
- While this research concentrated on viaducts/bridges, it could be insightful to extend the investigation to other types of infrastructure projects.
- Further research on environmental valuation techniques must continue incorporating uncertainties such as inflation rate, cost factors, or environmental imparts in a particular area. Establishing empirical values that can be effectively utilised or adapted for various policy scenarios is also important.
- Research on the actual economic benefits of reuse needs to be studied. On the one hand, there are benefits of just reusing materials of the viaduct; on the other hand, cost bleeding factors such as labour, equipment and preparation charges may impact those benefits.

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Appendices

Appendix A: Project lifecycle process for bridge assets from Rijkswaterstaat

There are several stages to the lifecycle process when it comes to a new bridge or viaduct from the perspective of Rijkswaterstaat, the typical stages can be outlined as follows:

1) When initiating a new infrastructure development or plan, the initial step is the pre-project phase where the responsible minister for infrastructure decides on establishing a new connection between two locations, often as a part of a route decision. This route decision is then translated into one or more projects in which Rijkswaterstaat assumes the lead in execution. As a result, the construction of a new bridge or viaduct becomes an integral part of a new construction project.
2) Following that, the project progresses into the planning and design phase. Rijkswaterstaat formulates objectives and requirements for the new bridge or viaduct. Simultaneously, a feasibility study is conducted to develop a project brief. These requirements encompass various aspects, including safety, aesthetics, environmental impact, and traffic flow. Rijkswaterstaat often creates a preliminary design to estimate costs and establish a reference point.
3) Subsequently, the procurement phase begins with a tender process to carry out the construction project. The best bid is selected for executing the design and construction activities based on several criteria aligned with the requirements, such as environmental impact or circularity. This selection process usually results in a single contract, sometimes encompassing financing and asset maintenance in the contract.
4) Using the set of requirements and contractor’s preliminary design, different design stages are undertaken to reach a final design. This design process often involves collaboration between one or more consultancy and architectural firms alongside the contractor. All parties involved must adhere to the agreements and requirements specified in the contract.
5) Once the design phase is completed, the actual construction phase commences. The main contractor seeks subcontractors and suppliers to carry out various aspects of the construction process, although this may also occur in earlier stages. For instance, one subcontractor may handle excavation while another provides pre-stressed girders. During this executional phase, Rijkswaterstaat primarily ensures that the contractor adheres to the contract and agreements, and in some cases, assumes additional project management responsibilities.
6) After the completion of the construction work, the bridge enters its service life. In most cases, the regional departments of Rijkswaterstaat assume ownership of the asset and are responsible for monitoring its structural integrity and maintenance. Often, the monitoring and maintenance practices are outsourced through contracts. If there are indications of structural safety concerns or other contextual factors that jeopardize the functionality of the bridge, decisions need to be made regarding the necessary follow-up steps. These steps can range from preventive maintenance like painting to the renovation or complete replacement of the entire structure. For significant interventions, new projects with distinct procurement procedures and contracts are initiated.
7) The aforementioned process is repeated until certain factors prompt the regional department of Rijkswaterstaat to consider end-of-life steps, including renovation, replacement, or removal. This is also the stage where an asset becomes eligible for the V&R program (as explained in section 3.1.8). In practice, maintenance costs tend to increase as structures age, reaching a point where extending the lifetime is no longer economically viable. In many cases, a new demolition project is initiated, focusing

primarily on removing the current structure. The materials obtained from the demolished structure generally revert back to the demolition contractor, who often lacks direct involvement in the reuse or recycling of these materials or components.

8) In several instances, the existing route remains in place, necessitating the development of a new asset that meets updated functional requirements. The entire process begins again, although step 1 in the process may be skipped depending on the specific infrastructure plan.

The entire process outlined above provides a simplified overview and should be understood that it can vary significantly for each project. In reality, the critical decision points for Rijkswaterstaat occur primarily in step 2, during the design and project initiation phase, as well as in step 6, which pertains to asset management. Step 7 also significantly impacts the structure's material flow, while the most effective choices for achieving circular economy (CE) objectives are typically made in Step 2. Additionally, the timing of these decisions influences the feasibility of implementing CE practices. The earlier the decision is made, the greater the potential for incorporating circularity principles. Achieving the most economically advantageous tender (EMVI) comes into play in steps 3 and 4 after the decision to prioritise it has been made in step 2.

Appendix B: Template for Life Cycle Assessment for environmental impact costs

Environmnetal Impact Category	Unit	Product stage			Construction process stage		Use stage					End of life stage				Resource recovery stage	Total	Weighting Factor	Total*Weighting factor
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D			
Depletion of abiotic raw materials, excl. fossil energy carriers	kg antimony	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		0.16	
Depletion of fossil energy carriers	kg antimony																	0.16	
Global warming	kg CO_2																	0.05	
Ozone layer depletion	kg CFC 11																	30	
Photochemical oxidant-formation (smog)	kg ethylene																	2	
Acidification	kg SO_2																	4	
Eutrophication	kg $(PO_4)^{3-}$																	9	
Human toxicity potential	kg 1.4 dichlorobenzene																	0.09	
Ecotoxicological effects, aquatic (freshwater)	kg 1.4 dichlorobenzene																	0.03	
Ecotoxicological effects, aquatic (marine)	kg 1.4 dichlorobenzene																	0.00	
Ecotoxicological effects, terrestrial	kg 1.4 dichlorobenzene																	0.06	

Appendix C: Environmental cost calculation of circular viaduct for scenario 1

Obj.Code	Obj.Element	Levensduur element (jaar)	Materiaal	Hoeveelheid		A1-A3	A4-A5	B	C	D	MKI [Euro]
	Onderbouw - Landhoofd (2x)										
	Paalfundering										
	Stalen buispaal 5st 356x12,5 hoh1,5m L15m 108kg/m1	200	Heipaal (staal)	108,0	ton	7293.21	374.11	-	1130.63	1756.71	10554.66
	Stalen paaldeksel r400 20kg/st	200	Profielstaal (verzinkt)	0,5	ton	78.98	5.65	-	39.69	46.32	170.64
	Bovenbouw										
	Verbinding boog-LH										
	Fixatie met staalklossen 3st/m1 46kg/st	200	Profielstaal (verzinkt)	2,8	ton	408.73	29.22	-	205.38	239.75	883.08
	Boogdeel LH-Knoop (2x) (b=2,4m/st)										
	Beton C45/55 (per m1 element)	200	Betonmortel C55/67 (CEMIII)	59,8	m3	1110.79	127.53	-	380.18	71.72	1690.22
	Wapening ca 175 kg/m3	200	Betonstaal	10,5	ton	720.83	37.06	-	97.32	173.63	1028.84
	Boogdeel Knoop-TSP (2x) (b=2,4m/st)										
	Beton C45/55 (per m1 element)	200	Betonmortel C55/67 (CEMIII)	122,2	m3	2268.86	260.61	-	776,90	146,55	2529.47
	Wapening ca 175 kg/m3	200	Betonstaal	21,4	ton	1473.01	75.74	-	198.87	355.8	2103.42
	Kroonknoop boogdelen (boxligger) (2x)										
	Staalconstructie 834kg/m1	200	Profielstaal (verzinkt)	16,7	ton	2470.16	176.16	-	1241.19	1448.7	5336.21
	Grond- en taludafwerking										
	Zandaanvulling totaal	200	Werk met werk maken: zand (wege n	2.025,0	m3	-	3216.9	-	1431.92	-1285.32	3363.5
	Afbouw										
	Verhardingsconstructie										
	Verhardingsconstructie toplaag 50mm	14	Asfalt, AC surf zonder PR	55,0	ton	6372.42	89.33	-	280.48	-	6742.23
	Verhardingsconstructie onderlaag 100mm	60	Asfalt (STAB) 0 % PR	110,0	ton	1291.27	468.52	-	337.02	6.68	2103.49
	Fundatielaag verharding 200mm	60	Betongranulaat (200mm)	430,0	m2	598.42	748.6	-	690.34	704.76	2742.12
											39248

Appendix D: Environmental cost calculation of circular viaduct for scenario 2

Obj.Code	Obj.Element	Levensduur element (jaar)	Materiaal	Hoeveelheid		A1-A3	A4-A5	B	C	D	MKI [Euro]
	Onderbouw - Landhoofd (2x)										
	Paalfundering										
	Stalen buispaal 5st 356x12,5 hoh1,5m L15m 108kg/m1	200	Heipaal (staal)	108,0	ton	7293.21	374.11	-	1130.63	1756.71	10554.66
	Stalen paaldeksel r400 20kg/st	200	Profielstaal (verzinkt)	0,5	ton	78.98	5.65	-	39.69	46.32	170.64
	Bovenbouw										
	Verbinding boog-LH										
	Fixatie met staalklossen 3st/m1 46kg/st	200	Profielstaal (verzinkt)	2,8	ton	408.73	29.22	-	205.38	-239.75	403.58
	Boogdeel LH-Knoop (2x) (b=2,4m/st)										
	Beton C45/55 (per m1 element)	200	Betonmortel C55/67 (CEMIII)	59,8	m3	1110.79	127.53	-	380.18	71.72	1690.22
	Wapening ca 175 kg/m3	200	Betonstaal	10,5	ton	720.83	37.06	-	97.32	-173.63	681.58
	Boogdeel Knoop-TSP (2x) (b=2,4m/st)										
	Beton C45/55 (per m1 element)	200	Betonmortel C55/67 (CEMIII)	122,2	m3	2268.86	260.61	-	776,90	146,55	2529.47
	Wapening ca 175 kg/m3	200	Betonstaal	21,4	ton	1473.01	75.74	-	198.87	-355.8	1391.82
	Kroonknoop boogdelen (boxligger) (2x)										
	Staalconstructie 834kg/m1	200	Profielstaal (verzinkt)	16,7	ton	2470.16	176.16	-	1241.19	-1448.7	2438.81
	Grond- en taludafwerking										
	Zandaanvulling totaal	200	Werk met werk maken: zand (wege	2.025,0	m3	-	3216.9	-	1431.92	-1285.32	3363.5
	Afbouw										
	Verhardingsconstructie										
	Verhardingsconstructie toplaag 50mm	14	Asfalt, AC surf zonder PR	55,0	ton	6372.42	89.33	-	280.48	-	6742.23
	Verhardingsconstructie onderlaag 100mm	60	Asfalt (STAB) 0 % PR	110,0	ton	1291.27	468.52	-	337.02	6.68	2103.49
	Fundatielaag verharding 200mm	60	Betongranulaat (200mm)	430,0	m2	598.42	748.6	-	690.34	704.76	2742.12
											34812.12

Appendix E: Environmental cost calculation of circular viaduct for scenario 3

Obj.Code	Obj.Element	Levensduur element (jaar)	Materiaal	Hoeveelheid		A1-A3	A4-A5	B	C	D	MKI [Euro]
	Onderbouw - Landhoofd (2x)										
	Paalfundering										
	Stalen buispaal 5st 356x12,5 hoh1,5m L15m 108kg/m1	200	Heipaal (staal)	108,0	ton	7293.21	374.11	-	1130.63	-1756.71	7041.24
	Stalen paaldeksel r400 20kg/st	200	Profielstaal (verzinkt)	0,5	ton	78.98	5.65	-	39.69	-46.32	78
	Bovenbouw										
	Verbinding boog-LH										
	Fixatie met staalklossen 3st/m1 46kg/st	200	Profielstaal (verzinkt)	2,8	ton	408.73	29.22	-	205.38	-239.75	403.58
	Boogdeel LH-Knoop (2x) (b=2,4m/st)										
	Beton C45/55 (per m1 element)	200	Betonmortel C55/67 (CEMIII)	59,8	m3	1110.79	127.53	-	380.18	71.72	1690.22
	Wapening ca 175 kg/m3	200	Betonstaal	10,5	ton	720.83	37.06	-	97.32	-173.63	681.58
	Boogdeel Knoop-TSP (2x) (b=2,4m/st)										
	Beton C45/55 (per m1 element)	200	Betonmortel C55/67 (CEMIII)	122,2	m3	2268.86	260.61	-	776,90	146,55	2529.47
	Wapening ca 175 kg/m3	200	Betonstaal	21,4	ton	1473.01	75.74	-	198.87	-355.8	1391.82
	Kroonknoop boogdelen (boxligger) (2x)										
	Staalconstructie 834kg/m1	200	Profielstaal (verzinkt)	16,7	ton	2470.16	176.16	-	1241.19	-1448.7	2438.81
	Grond- en taludafwerking										
	Zandaanvulling totaal	200	Werk met werk maken: zand (wege	2.025,0	m3	-	3216.9	-	1431.92	-1285.32	3363.5
	Afbouw										
	Verhardingsconstructie										
	Verhardingsconstructie toplaag 50mm	14	Asfalt, AC surf zonder PR	55,0	ton	6372.42	89.33	-	280.48	-	6742.23
	Verhardingsconstructie onderlaag 100mm	60	Asfalt (STAB) 0 % PR	110,0	ton	1291.27	468.52	-	337.02	6.68	2103.49
	Fundatielaag verharding 200mm	60	Betongranulaat (200mm)	430,0	m2	598.42	748.6	-	690.34	704.76	2742.12
											31206.06

Appendix F: Environmental cost calculation of traditional viaduct for scenario 1

Obj.Code	Obj.Element	Levensduur element (jaar)	Materiaal	Hoeveelheid		A1-A3	A4-A5	B	C	D	MKI [Euro]
	Onderbouw - Landhoofd (2x)										
	Paalfundering										
	Prefab betonpaal hoh1,50m vk400mm L22m =3,52m3/st	100	Betonmortel C35/45 (CEMIII)	98,6	m3	2644.94	384.78	-	292.42	236.22	3558.36
	Voorspanstaal ca 35kg/m3	100	Voorspanstaal	3,4	ton	476.26	24.04	-	112.14	87.32	699.76
	Wapening ca 100 kg/m3	100	Betonstaal	9,9	ton	1359.12	70.38	-	185.1	-329.3	1285.3
	Dekconstructie										
	ZIPXL 800 T-liggers C60/75 (L=22m)	100	Betonmortel C70/85 (CEMI-CEMIII)	181,7	m3	9488.64	781.76	-	2314.48	440.94	13025.82
	Wapening ca 80kg/m3	100	Betonstaal	14,5	ton	2003.36	102.5	-	270.64	-482.96	1893.54
	Voorspanstaal ca 100kg/m3	100	Voorspanstaal	18,2	ton	2504.02	128.42	-	587.36	-602.7	2617.1
	Druklaag C35/45 (250mm)	100	Betonmortel C35/45 (CEMIII)	110,0	m3	2953.18	431.08	-	1440.22	265.66	5090.14
	Wapening ca 200 kg/m3	100	Betonstaal	22,0	ton	3031.42	157.96	-	411.34	-730.88	2869.84
	Grond- en taludafwerking										
	Grond (talud landhoofden)	1000	Werk met werk maken: zand (wegenbou	303,8	m3	-	482.11	-	215.37	-193.85	503.63
	Afbouw										
	Verhardingsconstructie										
	Verhardingsconstructie toplaag 50mm	14	Asfalt, AC surf zonder PR	55,0	ton	12744.84	178.66	-	560.96	-	13484.46
	Verhardingsconstructie onderlaag 100mm	60	Asfalt (STAB) 0 % PR	110,0	ton	775.1	283.02	-	202.12	6.04	1266.28
	Waterdicht membraam (SAMI)	1000	Bitumen emulsie kleeflaag (0,4 kg/m2)	0,2	ton	15.7	2.12	-	-	-	17.82
	Voegovergangen										
	Aandeel rubber 10%	20	--Rubber (1500kg/m3, 7,../22kg)	0,3	m3	441.22	30.24	-	10.66	-	482.12
	Aandeel staal 80%	20	--Profielstaal (verzinkt)	2,0	m3	2508.76	823.96	-	491.34	425.18	4249.24
	Aandeel bitumen 10%	20	--Bitumen emulsie kleeflaag (0,4 kg/m2)	0,3	m3	109.54	19	-	17.38	-	145.92
											51189.33

Appendix G: Environmental cost calculation of traditional viaduct for scenario 2

Obj.Code	Obj.Element	Levensduur element (jaar)	Materiaal	Hoeveelheid		A1-A3	A4-A5	B	C	D	MKI [Euro]
	Onderbouw - Landhoofd (2x)										
	Paalfundering										
	Prefab betonpaal hoh1,50m vk400mm L22m =3,52m3/st	100	Betonmortel C35/45 (CEMIII)	98,6	m3	1322.47	192.39	-	146.21	118.11	1779.18
	Voorspanstaal ca 35kg/m3	100	Voorspanstaal	3,4	ton	238.13	12.02	-	56.07	43.66	349.88
	Wapening ca 100 kg/m3	100	Betonstaal	9,9	ton	679.56	35.19	-	92.55	-164.65	642.65
	Dekconstructie										
	ZIPXL 800 T-liggers C60/75 (L=22m)	100	Betonmortel C70/85 (CEMI-CEMII	181,7	m3	4744.32	390.88	-	1157.24	220.47	6512.91
	Wapening ca 80kg/m3	100	Betonstaal	14,5	ton	1001.68	51.25	-	135.32	-241.48	946.77
	Voorspanstaal ca 100kg/m3	100	Voorspanstaal	18,2	ton	1252.01	64.21	-	293.68	-301.35	1308.55
	Druklaag C35/45 (250mm)	100	Betonmortel C35/45 (CEMIII)	110,0	m3	1476.59	215.54	-	720.11	132.83	2545.07
	Wapening ca 200 kg/m3	100	Betonstaal	22,0	ton	1515.71	78.98	-	205.67	-365.44	1434.92
	Grond- en taludafwerking										
	Grond (talud landhoofden)	1000	Werk met werk maken: zand (wegen	303,8	m3	-	482.11	-	215.37	-193.85	503.63
	Afbouw										
	Verhardingsconstructie										
	Verhardingsconstructie toplaag 50mm	14	Asfalt, AC surf zonder PR	55,0	ton	6372.42	89.33	-	280.48	-	6742.23
	Verhardingsconstructie onderlaag 100mm	60	Asfalt (STAB) 0 % PR	110,0	ton	387.55	141.51	-	101.06	3.02	633.14
	Waterdicht membraam (SAMI)	1000	Bitumen emulsie kleeflaag (0,4 kg/m	0,2	ton	7.85	1.06	-	-	-	8.91
	Voegovergangen										
	Aandeel rubber 10%	20	--Rubber (1500kg/m3, 7,../22kg)	0,3	m3	220.61	15.12	-	5.33	-	241.06
	Aandeel staal 80%	20	--Profielstaal (verzinkt)	2,0	m3	1254.38	411.98	-	245.67	212.59	2124.62
	Aandeel bitumen 10%	20	--Bitumen emulsie kleeflaag (0,4 kg/	0,3	m3	54.77	9.5	-	8.69	-	72.96
											25846.48

Appendix H: Environmental cost calculation of traditional viaduct for scenario 3

Obj.Code	Obj.Element	Levensduur element (jaar)	Materiaal	Hoeveelheid		A1-A3	A4-A5	B	C	D	MKI [Euro]
	Onderbouw - Landhoofd (2x)										
	Paalfundering										
	Prefab betonpaal hoh1,50m vk400mm L22m =3,52m3/st	100	Betonmortel C35/45 (CEMIII)	98,6	m3	1322.47	192.39	-	146.21	118.11	1779.18
	Voorspanstaal ca 35kg/m3	100	Voorspanstaal	3,4	ton	238.13	12.02	-	56.07	-43.66	262.56
	Wapening ca 100 kg/m3	100	Betonstaal	9,9	ton	679.56	35.19	-	92.55	-164.65	642.65
	Dekconstructie										
	ZIPXL 800 T-liggers C60/75 (L=22m)	100	Betonmortel C70/85 (CEMI-CEMII	181,7	m3	4744.32	390.88	-	1157.24	220.47	6512.91
	Wapening ca 80kg/m3	100	Betonstaal	14,5	ton	1001.68	51.25	-	135.32	-241.48	946.77
	Voorspanstaal ca 100kg/m3	100	Voorspanstaal	18,2	ton	1252.01	64.21	-	293.68	-301.35	1308.55
	Druklaag C35/45 (250mm)	100	Betonmortel C35/45 (CEMIII)	110,0	m3	1476.59	215.54	-	720.11	132.83	2545.07
	Wapening ca 200 kg/m3	100	Betonstaal	22,0	ton	1515.71	78.98	-	205.67	-365.44	1434.92
	Grond- en taludafwerking										
	Grond (talud landhoofden)	1000	Werk met werk maken: zand (wegen	303,8	m3	-	482.11	-	215.37	-193.85	503.63
	Afbouw										
	Verhardingsconstructie										
	Verhardingsconstructie toplaag 50mm	14	Asfalt, AC surf zonder PR	55,0	ton	6372.42	89.33	-	280.48	-	6742.23
	Verhardingsconstructie onderlaag 100mm	60	Asfalt (STAB) 0 % PR	110,0	ton	387.55	141.51	-	101.06	3.02	633.14
	Waterdicht membraam (SAMI)	1000	Bitumen emulsie kleeflaag (0,4 kg/m	0,2	ton	7.85	1.06	-	-	-	8.91
	Voegovergangen										
	Aandeel rubber 10%	20	--Rubber (1500kg/m3, 7,../22kg)	0,3	m3	220.61	15.12	-	5.33	-	241.06
	Aandeel staal 80%	20	--Profielstaal (verzinkt)	2,0	m3	1254.38	411.98	-	245.67	-212.59	1699.44
	Aandeel bitumen 10%	20	--Bitumen emulsie kleeflaag (0,4 kg/	0,3	m3	54.77	9.5	-	8.69	-	72.96
											25333.98

Appendix I: Net Present Value (NPV) calculation of environmental cost for circular viaduct

CBA of environmental cost for circular viaducts

Time horizon	50, 100 & 200	year
Discount rate	4.00%	

50 years

		Discount Factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44
Present Value		Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
7,871	Piles		7,752	10	9	9	9	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	4
9,473	Arch Elements		9,159	14	14	13	13	12	12	11	11	11	10	10	9	9	9	8	8	8	7	7	7	7
3,239	Sand		3,217	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11,985	Road		9,570	96	92	89	85	82	79	76	73	70	68	65	62	60	58	56	53	51	49	47	46	44
Net Present Value **32,569**																								

100 years

		Discount Factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44
Present Value		Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
8,058	Piles		7,752	10	9	9	9	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	4
9,525	Arch Elements		9,159	14	14	13	13	12	12	11	11	11	10	10	9	9	9	8	8	8	7	7	7	7
3,220	Sand		3,217	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12,058	Road		9,570	96	92	89	85	82	79	76	73	70	68	65	62	60	58	56	53	51	49	47	46	44
Net Present Value **32,861**																								

200 years

		Discount Factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44
Present Value		Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
8,003	Piles		7,752	10	9	9	9	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	4
9,536	Arch Elements		9,159	14	14	13	13	12	12	11	11	11	10	10	9	9	9	8	8	8	7	7	7	7
3,217	Sand		3,217	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12,070	Road		9,570	96	92	89	85	82	79	76	73	70	68	65	62	60	58	56	53	51	49	47	46	44
Net Present Value **32,826**																								

Appendix J: Net Present Value (NPV) calculation of environmental cost for traditional viaduct

		CBA of environmental cost for traditional viaducts
Time horizon	50, 100 & 200	Year
Discount rate	4.00%	

50 years

			Discount Factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44	0.42
	Present Value		Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	2,722	Piles		2,480	10	9	9	9	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	4	4
	11,394	Girder		10,790	14	14	13	13	12	12	11	11	11	10	10	9	9	9	8	8	8	7	7	7	7	6
	486	Sand		483	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	13,267	Road		8,965	192	185	178	171	164	158	152	146	141	135	130	125	120	115	111	107	103	99	95	91	88	84
Net Present Value	**27,870**																									

100 years

			Discount Factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44	0.42
	Present Value		Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	2,731	Piles		2,480	10	9	9	9	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	4	4
	11,197	Girder		10,790	14	14	13	13	12	12	11	11	11	10	10	9	9	9	8	8	8	7	7	7	7	6
	483	Sand		483	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	13,876	Road		8,965	192	185	178	171	164	158	152	146	141	135	130	125	120	115	111	107	103	99	95	91	88	84
Net Present Value	**28,287**																									

200 years

			Discount Factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44	0.42
	Present Value		Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	2,781	Piles		2,480	10	9	9	9	8	8	8	7	7	7	6	6	6	6	6	5	5	5	5	5	4	4
	11,389	Girder		10,790	14	14	13	13	12	12	11	11	11	10	10	9	9	9	8	8	8	7	7	7	7	6
	493	Sand		483	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14,144	Road		8,965	192	185	178	171	164	158	152	146	141	135	130	125	120	115	111	107	103	99	95	91	88	84
Net Present Value	**28,807**																									