FRP ROAD BRIDGES AS A CONCRETE ALTERNATIVE

Determining life cycle costs of all-FRP and concrete road bridges using a parametric calculation tool

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SUMMARY

Transport infrastructure is of great economic value because it allows trade, which is essential to the development of societies. Infrastructure owners have the responsibility to ensure the correct functioning of infrastructure. They self-evidently search for a way to ensure this correct functioning of infrastructure while simultaneously aspiring to have the lowest costs that accompany this responsibility. Increasingly infrastructure owners turn to infrastructure asset management to cope with this problem. Infrastructure asset management is a systematic approach to manage infrastructure assets cost-effectively. One aspect of infrastructure asset management is life cycle cost (LCC) analysis. With life cycle cost analysis investment decisions can be made based on the total cost incurred during the complete life cycle of an asset.

This research focuses on the life cycle costs of bridges. Alternative bridge designs offer alternative investment possibilities. Currently bridge decks are often build with reinforced concrete, but fiber reinforced polymer (FRP) is emerging as an alternative construction material for bridge decks. Claims are made that FRP bridges can offer financial and environmental benefits as a construction material. However, in practice it is unclear in what situations and to what extent FRP offers these benefits. This causes engineers to be reluctant with choosing FRP as a bridge deck construction material.

The objective of this research has been to aid engineers in making a more informed decision when choosing a bridge deck construction material by offering a parametric LCC calculation tool. This tool allows the user to enter a certain bridge design and maintenance scenario which the tool then uses to calculate the total LCC.

First, based on literature on LCC an LCC model was developed which describes the input parameters, necessary calculations and resulting outputs. This led to dividing the total LCC into three cost categories: 1) Agency costs, costs incurred by the agency (construction, maintenance, end of life); 2) User costs, costs incurred by the user of the road (delay, vehicle operation, accidents); 3) Society costs, costs incurred by society as a whole (environmental). Next this model was translated into a calculation tool developed in spreadsheet software. To test the workings of the tool and to get an idea of the competitiveness of FRP bridge decks for beam road bridges, a specific case analysis has been performed. Based on the results the following conclusions have been drawn.

Total LCC values are largely determined by the initial investment costs. This is because the user costs and maintenance costs - which occur in the future – are discounted and the environmental costs are very small compared to the other cost categories.

The investment costs of bridge decks make up a large part of the initial investment costs (especially at larger spans) and therefore make up a large part of the total LCC. The premium price of FRP bridge decks compared to concrete bridge decks (about twice as high) is therefore hard to negate with lower maintenance costs and user costs. This becomes even harder as spans increase.

The discount factor used has the largest influence on LCC results, followed by extra travel time caused by work zones. If maintenance scenarios are different enough between the two design alternatives these two variables can be decisive for what the preferred design alternative will be at smaller spans.

Overall bridges with FRP bridge decks for beam road bridges have a hard time competing with concrete bridge decks. At smaller spans (10 to 15 meters) user costs might contribute enough in certain cases to total LCC to cancel out the premium price of FRP bridge decks. At larger bridge spans this seems unlikely with current production costs.

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LIST OF ABBREVIATIONS

AC	Agency costs
ADT	Average daily traffic
Aq	Quantity of units for activities
AUC	Activity unit cost
CBS	Centraal Bureau voor de Statistiek
CFRP	Carbon fiber reinforce polymers
CUC	Construction unit cost
Cq	Construction element quantity
DTT	Detour travel time
EAV	Extra accidents per vehicle
EI	Environmental impact
EoLC	End of life costs
EPS	Expanded polystyrene
ETT	Extra travel time
FRP	Fiber reinforced polymers
GFRP	Glass fiber reinforced polymers
ICC	Initial construction costs
I_y	Area moment of inertia
LCA	Life cycle assessment
LCC	Life cycle costs
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LM1	Load model 1 from the Eurocode
MC	Maintenance costs
PCE	Passenger car equivalent
PUR/PU	Polyurethane
PVC	Polyvinyl chloride
SC	Society costs
SLS	Serviceability limit state
SP	Shadow price
SSK	Standard systematiek voor kostenraming
TAC	Traffic accidents costs
TDC	Traffic delay costs
UC	User costs
VARTM	Vacuum assisted resin transfer moulding
VOC	Vehicle operating costs

1. PROBLEM AND ITS SETTING

This chapter will introduce the topic of the research project. The research problem is the driver of the entire research project and therefore also the starting point of this proposal. From there the rest of the research proposal will follow. This chapter starts with some background information in Paragraph 1.1 that will introduce some general concepts and ideas that are relevant for this research project. Following in Paragraph 1.2 the problem that provides the reason for executing this research will be described. Next the research objective (in Paragraph 1.3) and the research questions (in Paragraph 1.4) will be presented. These are directly derived from the research problem. An explanation of the scope and the relevance of the research can be found in Paragraph 1.5 and Paragraph 1.6. This chapter will end with a description of the research design that was used for this research in Paragraph 1.7.

1.1. BACKGROUND

This Paragraph will start with a general background description which explains the importance of bridges as building objects and why they are worth researching. After that the focus lies on the design of bridges and the different design variables that define different types of bridges. Following, the construction material FRP will be described. Lastly there will be a description of the focus of this research.

1.1.1. GENERAL

Bridges are key structures of a transport infrastructure system. If a bridge fails, the system fails. What is a bridge? A bridge can be defined as follows: "A bridge is […] a crossing of two very different types of flow on different levels and, […] is a support for one of these flows when it rises from the ground" (Troyano, 2003). The function of a bridge can be extracted from this definition. The function is to provide a pathway across an obstacle without disrupting the flow beneath it. The obstacle can be a body of water, a valley, another pathway or something else. When a bridge fails to provide this function it means the pathway across this obstacle is no longer available and thus the function of a transport infrastructure system (to provide a pathway from point A to point B) is interrupted and the flow beneath the bridge might be interrupted as well.

From an economic viewpoint it is crucial that bridges provide their designed function. Infrastructure systems and the bridges that are part of these systems are crucial to the successful functioning of an economy. Not only are they expected to provide the required function, but in general the bridge must be designed in such a way that it can provide this function in an efficient manner. That means it should not cost more than it is necessary.

Besides the initial investment costs of the bridge construction there are other costs associated with the life cycle of the bridge. When construction is finished it enters the operation stage, during which the maintenance and repair costs will normally occur. After a certain amount of time the bridge will be demolished/removed. This is called the life cycle of the bridge. During all stages of this life cycle different kind of costs arise. The sum of all these costs are called the life cycle costs (LCC) and the method of obtaining the LCC of an object is called life cycle cost analysis (LCCA). LCCA and its function will be discussed in more detail later in Paragraph 2.2.

1.1.2. BRIDGE DESIGN

The life cycle costs of a bridge are directly related to the design of a bridge. Different bridge design alternatives will have different LCC. There are different ways to classify bridge designs, for example: type of traffic (footbridge, road bridge or railway bridge), construction material and bridge span. Besides these, another often used classification is by structural type (the way the bridge transfers the forces acting on it to the supports and, from these supports, to the ground). To become more familiar with bridge design options these bridge design variables will be discussed in more detail.

Structural type

Generally four main types of bridges can be distinguished this way: arch bridges, girder or beam bridges, frame or truss bridges and cable sustained bridges (see Figure 1). The cable-sustained bridge group is divided into two large groups, suspension bridges and cable stayed bridges (Troyano, 2003). Beam and girder bridges can be considered the simplest kind of bridges. This is because with these bridges only the horizontal structure needed to provide crossing is materialized. Its main load bearing structure is solely based on the cross-sections resistance to bending. The relatively simple structural design makes this type of bridge the most predominant bridge type but also limits its maximum span.

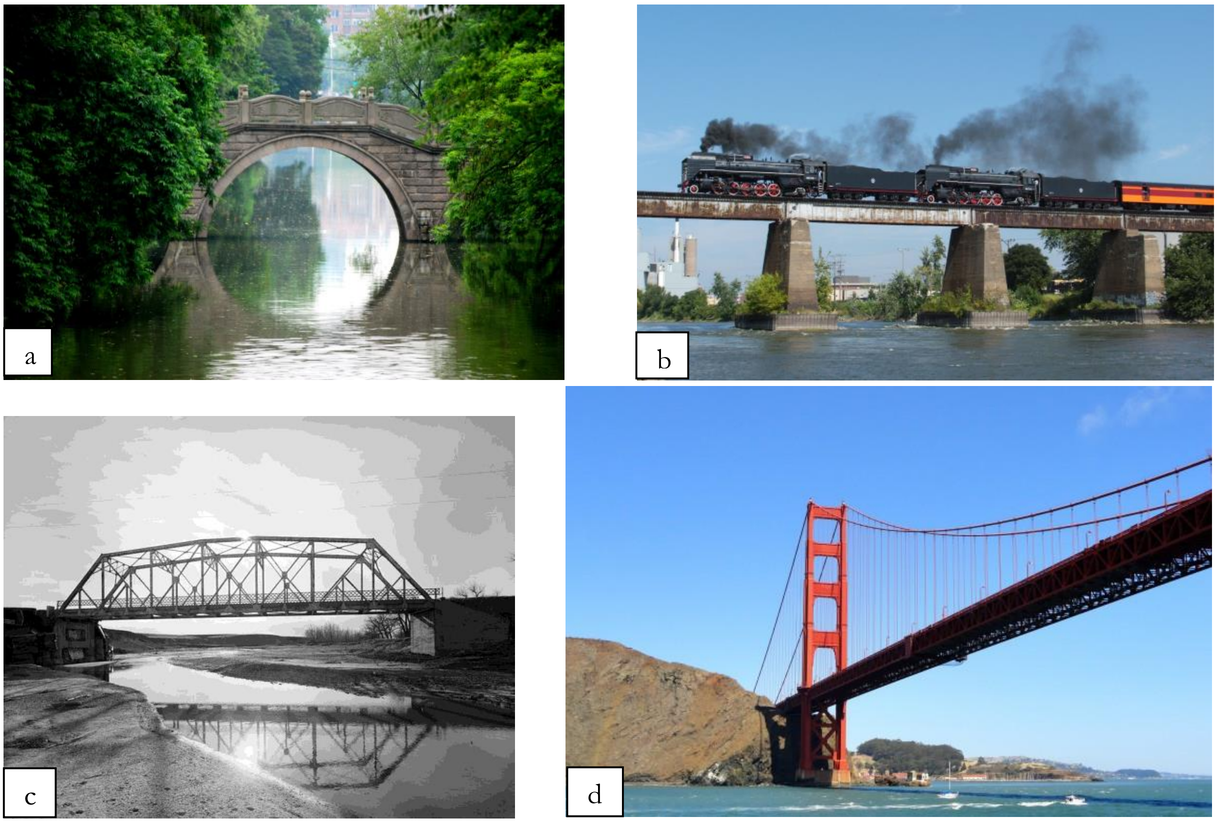


Figure 1: Examples of the four different structural types of bridges (a, arch bridge; b, beam bridge; c, truss bridge; d, suspension bridge)

Bridge span

The span of a bridge is the length between two supports from where the forces are further transferred to the ground. Das, Frangopol, & Nowak (1999) define short span bridges as bridges with a span of less than 50 meters. The way the forces are transferred to the supports depends on the type of structural bridge. As mentioned above, for beam bridges this happens through resistance to bending. The bending moment in a beam is a function of the forces acting on it and the distance between the supports i.e. its span (Troyano, 2003). This means that when the span increases the moment increases as well. This relation between span and moment is quadratic. The bigger the bending moment, the bigger the area moment of inertia has to be to withstand this moment. This can be done by increasing the cross-sectional dimensions of the bridge. Thus the longer the span, the bigger the cross-sectional dimensions. This direct relation limits the maximum span of beam and girder bridges (Figure 2). This can be because of constructability limitations or financial considerations. It might be that certain dimensions are just not structurally producible by manufacturers or made by constructors. It might also be the case that at a certain point, while possible to produce or make, when the span increases the costs rise to a point that shorter spans – if possible – are financially more beneficial or other bridge structures than beam or girder bridges become more financially beneficial.

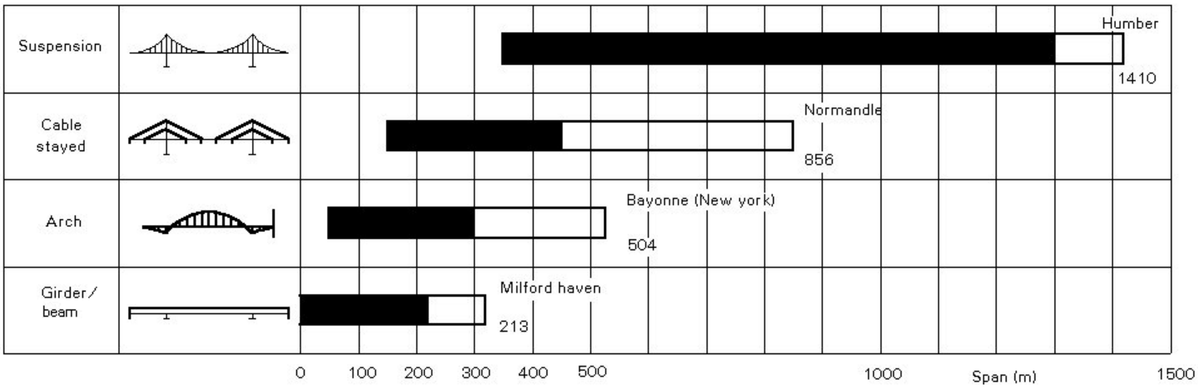


Figure 2: Typical and record spans for different types of bridges (www.fgg.uni-lj.si)

Traffic type

The type of traffic a bridge is required to support also greatly influences the design of a bridge. This is because the loads that are generated by the traffic differ greatly between the different traffic types. A footbridge endures much lower loads than a vehicular road bridge and a road bridge endures lower loads than a railway bridge. Of course a bridge should be able to withstand the loads that act upon it and thus loads influence its design.

Construction material

As mentioned above, the construction material used to build the bridge can also be used to define what type of bridge it is. Different materials have different mechanical properties. This is why, in parallel with the appearance of new materials, new structures have been appearing throughout history (Troyano, 2003). As Troyano (2003) explains: "*When a new material appears, the same structure used as the previous ones are initially build, but as their technology is developed structures more matched to the new material are achieved. This does not mean to say that the material defines the structure nor vice versa, although there is a close relationship between them*." Today most bridges are made from pre-stressed concrete since concrete offers an economical benefit to steel. But large bridges are built from steel because steel offers higher specific strength than concrete which is needed because of the bigger stresses that work on larger structures (Troyano, 2003). Other materials that are or have been used for bridge building are timber, stone, masonry and iron. A relatively new material that is used to build bridges, and the focus of this research, is fibre reinforced polymer (FRP). FRP is a composite material that consists of a thermoset plastic which has been reinforced with usually - in the case of bridge construction - glass fibre material. FRP seems to be an interesting alternative construction material for bridges. It offers high strength, low weight and little to no maintenance compared to steel and concrete. In spite of some disadvantages such as less stiffness and higher initial investment, FRP might at least in some cases be more beneficial – in terms of LCC - than traditional construction materials. In the next section FRP will be explored in more depth.

1.1.3. Fibre reinforced polymers (FRP)

FRP is a composite material. A composite material is a combination of two or more distinct materials into one with the intent of suppressing undesirable properties of the constituent materials in favour of desirable properties (Astrom, 1997). FRP consists of a matrix of thermoset polymers which is reinforced with fibre material. The polymers often used for FRP are epoxy, vinylester or polyester. For the reinforcement fibres often carbon, glass or aramid fibres are used. In the case of using FRP for bridge construction the mostly used polymer is polyester and the mostly used fibre is glass fibre. The reason for this is that these options are the most economical (Kim, 2014). A combination of carbon fibres and epoxy is also possible. This offers higher strength but is also much more expensive.

Because of the one dimensional nature of fibres they will only reinforce in the direction of the fibres. Therefore different fibre orientations should be used to reinforce the material in more than one dimension if necessary. One way of doing this is by using woven lamella of fibre roofing (a combination of fibre strands) to create a so called laminate (Figure 3).

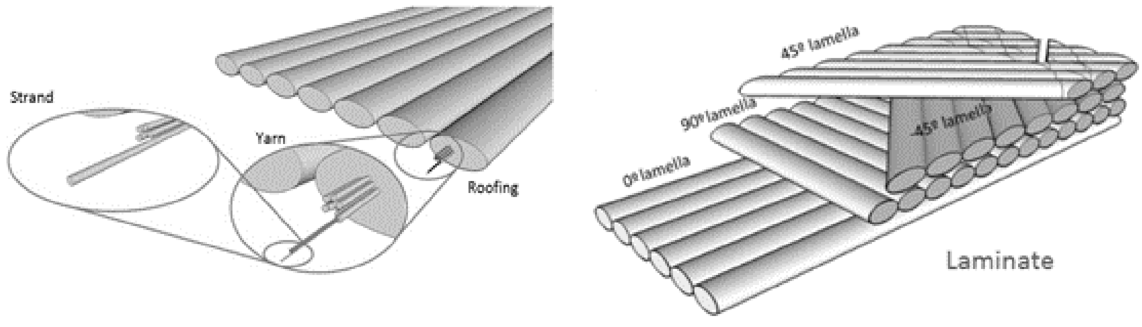


Figure 3: Laminate construction of fibre strands (Nijssen, 2013)

There are many production methods available for FRP products. For the use in bridge construction there are two mayor methods used. One of these methods is pultrusion with which standard profile elements can be produced with minimal labour involved. A number of fibres (roofing) are pulled off coils through a polymer resin bath after which they pass through a heated die which forms the required profile and hardens the resin. The profile is then cut to the required length (Figure 4). These profile can then be joined together to create bridge decks.

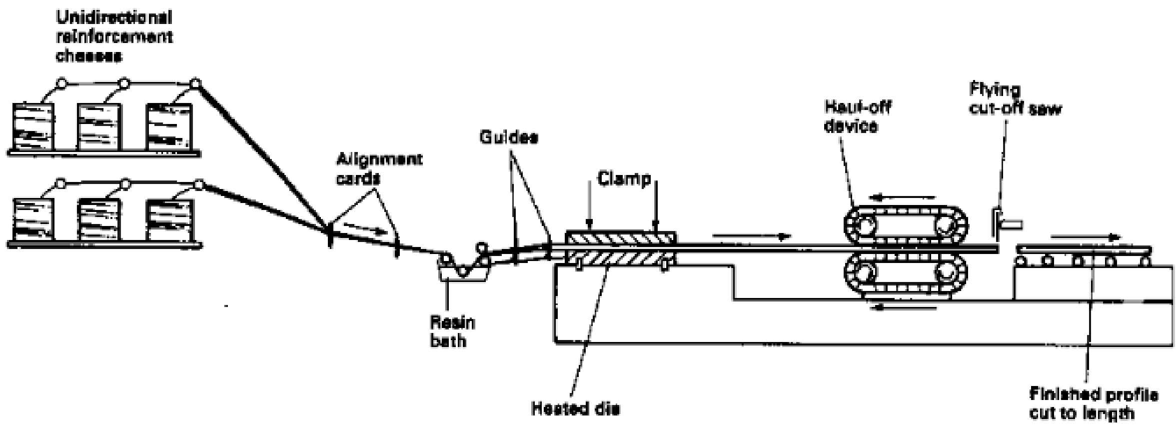


Figure 4: Pultrusion method (Chlosta, 2012)

The other often used method is vacuum assisted resin transfer moulding (VARTM) in which the reinforcement fibres are applied around a mould by hand in the form of different layers (woven fabric laminates). Next an airtight film is applied and a vacuum pump is used to consolidate the reinforcement fibres and transfer the polymer resin around the reinforcements and in the shape of the mould (Figure 5). This process allows for a large freedom in form and size but is rather labour intensive.

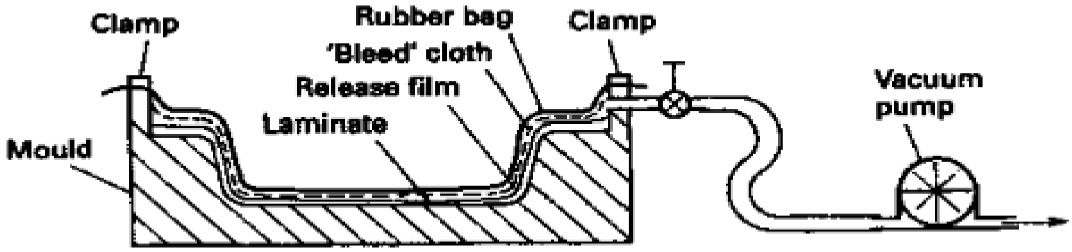


Figure 5: VARTM (Chlosta, 2012)

Using the VARTM method FiberCore Europe - the leading FRP bridge manufacturer in the Netherlands - creates sandwich constructions among which sluice doors and bridges. Sandwich constructions utilize the same principle as steel H construction profiles. The construction allows for increasing profile height (increasing its area moment of inertia and thus its resistance to bending) with minimal weight increase. This is done by creating a upper and lower laminate of FRP material between which a lightweight core material has been placed such as expanded polystyrene (EPS), Polyvinyl chloride (PVC) or Polyurethane (PU/PUR). FiberCore Europe uses this system very successfully for manufacturing all-FRP footbridges and have made some short span road bridges using this system.

1.1.4. Focus of this research

This research will focus on the influence of certain design considerations of short-span road beam bridges and their financial consequences. More specifically it will focus on the influence of material selection (concrete vs FRP) for bridge superstructure on the life cycle costs. Choosing a design is influenced a lot by the financial consequences of the design choices. As mentioned above one of these design choices is material choice. In the next section the problem of choosing FRP as a bridge construction material will be described.

1.2. Problem description

While several road bridges have been build using FRP, these days most of the bridges are still being build using more traditional materials such as timber, steel and concrete. Most of the bridges that are being build using FRP are pedestrian/bicycle bridges. There are some examples of FRP road bridges that are designed to withstand heavy traffic, such as the in 2002 built West Mill Bridge in Oxfordshire, UK (Figure 6), suited for vehicles up to 46 ton (Fiberline Composites, n.d.). Also the in 2010 completed Hoofdbrug Oosterwolde in the Netherlands (Figure 6), suited for vehicles up to 60 ton (FiberCore Europe, n.d.). In this category there are even less bridges that fit the so called all-FRP label. All-FRP means the complete superstructure has been built using FRP. The promising properties that are prescribed to FRP as a building material raise the question why the development of all-FRP road bridges has not taken off more.

Figure 6: Left: West Mill bridge (fiberline.com) Right: Hoofdbrug Oosterwolde (fibercore-europe.com)

Claims of low life cycle costs (LCC) and low environmental impact (EI) are often used to promote the use of FRP as a construction material. While the construction industry is not particularly known for its innovative character, ways to lower expenditures have always been of interest to infrastructure owners. This factor, and the growing focus on environmental impact of construction activities during tender procedures should spur the construction industry to at least consider FRP as a construction material.

When reading literature on FRP road bridges such as (Hastak, Halpin, & Hong, 2004; Shah, Walsh, & Ross, 2013; Tuakta, 2005) and talking to people in the industry several factors are mentioned that could explain the lack of FRP usage in bridge construction. First, there is the general ignorance concerning the design possibilities of FRP. This can be attributed to the fact that there are very few practical examples that show the possibilities of FRP in bridge construction and the simple fact that it is a relatively new material. Secondly, there is a lack of design codes concerning FRP as a building material. Slowly these design codes are being developed such as the CUR Recommendation 96 "Fibre-reinforced polymers in civil load bearing structures" (CUR 96) as an often cited document in the Dutch industry when designing civil structures in FRP. Lastly, there are no long term performance data on FRP as a bridge construction material. The first time FRP was used in bridge construction was in 1982 in the Ginzi Highway Bridge in Bulgaria (Hollaway, 2012) and in the Miyun Traffic Bridge in Beijing, China (Ye, Feng, & Yue, 2012). That means that to this day there is 33 years of worldwide experience with FRP in bridge construction. Compared to an often designed lifespan of a 100 years for road bridges, this is not a lot.

The consulting and engineering company Grontmij also faces these challenges. At Grontmij they do see the possible opportunities of using FRP for bridge construction. However, the unfamiliarity with the material is said to be the leading cause of the fact that all-FRP bridges are not (yet) fully taken into consideration as a serious candidate during the design process of road bridges. The claims of low life cycle costs and low environmental impact are interesting but one has to take a critical look at these claims. Often it is the manufacturers of FRP products that provide these claims and they, of course, are not completely unbiased. Consequently, to what extent and in what conditions all-FRP outperforms concrete road bridges remains unclear.

To make a good comparison between different construction materials for short span road bridges, one has to know in which cases all-FRP can outperform concrete bridges. As long as the performance - and thus the benefits - of all-FRP bridges are unclear, they will not be fully taken into account by bridge engineers.

Together with engineers at Grontmij it was decided to investigate bridges with spans between 10 and 30 meters. All-FRP road bridges have been executed in spans up to 10 meters. It is therefore interesting to see how all-FRP bridges with bigger spans will perform. With spans up to 30 meters most of the single span concrete bridges can be covered.

The problem definition for this research is therefore determined to be:

> While there might exist financial and environmental advantages, engineers in general - including at Grontmij - often do not consider all-FRP bridges as an alternative for concrete bridges partly because the extent and situations in which these advantages exist are unknown.

1.3. RESEARCH OBJECTIVE

Following from the research problem the research objective has been determined to be twofold:

First, the aim is to develop an LCC calculation tool in order to support short-span beam road bridge design considerations.

Second, application of this developed LCC calculation tool to a specific case will demonstrate the applicability of the tool. An analysis of the results will provide a general sense of the competitiveness of FRP as a superstructure construction material compared to concrete.

1.4. RESEARCH QUESTIONS

By answering the following research questions the research objective should be met:

1. What are the considerations of the LCC calculation tool that should be taken into account?
   1.1. What outputs should the tool generate?
   1.2. What input variables and calculations are needed to generate these outputs?
2. Using the developed LCC calculation tool, what LCC values can be attributed to the specific case?
   2.1. What are the input values for the specific case (based on the bridge designs)?
   2.2. What output values (LCC scores) does the tool generate?
3. Based on the results, what are the main applications for and what are the main limitations of the developed LCC calculation tool?
   3.1. How much are the results influenced by uncertainty of input values?
   3.2. What factors influence the results the most?
   3.3. What limitations have to be taken into account when using the tool?
4. What can be said about the economic performance of all-FRP bridges compared to concrete in general?

1.5. SCOPE

This research will be investigating the relationship between the design variables of bridges and LCC. Specifically the relation between construction material choice (concrete vs FRP) of short-span beam road bridge superstructure and LCC. Also the influence of bridge span on this relationship will be investigated. This research will be limited by making a selection of the design variables and LCC cost elements to make sure the research can be completed in the appropriate timespan.

It is not feasible to research the relation of the complete set of aspects of bridge design to LCC. The sheer number of aspects, their interconnectedness and their relations to LCC would take too much time to consider integrally. Therefore a selection will be made.

First a selection of bridge types based on type of traffic will be made. This research focusses on vehicular road bridges or road bridges for short. The reason is that Grontmij - the company where and in collaboration with this research is executed – is especially interested in these bridges. Road bridges are very common and although FRP footbridges have seen quite some real world examples, all-FRP road bridges are very rare. There might lie great opportunities in all-FRP road bridges. Limiting the research to one type of bridge will make this research fit better in the appropriate time span attributed to the research.

Concerning structural bridge types, this research will be looking at beam bridges. The reason for this is that the technology of all-FRP road bridges is still young and experience in all-FRP road bridges is low. This means practical application of all-FRP beam bridges is most logical concerning the small amount of experience with all-FRP road bridges. All current FRP road bridges are executed as beam/girder bridges that are, as mentioned, the simplest structural type of bridges. It therefore seems logical to stay close to practical experience and research the possibilities of all-FRP beam bridges.

Looking at bridge materials the research will, besides FRP, explore concrete bridges. As mentioned, most bridges today are made from pre-stressed and reinforced concrete which is technically a combination of concrete and steel, but in this research they will be called concrete bridges for short. Steel bridges are relatively expensive compared to concrete bridges and thus, when looking at the most economically beneficial construction material, concrete generally outperforms steel (Troyano, 2003). To limit the research efforts to a more manageable scale the researcher decides to compare only FRP bridges and concrete bridges.

This research will not provide a definitive answer to the question whether and when all-FRP will outperform concrete bridges in terms of LCC. It will provide a calculation tool that can calculate LCC of bridge designs of specific cases. The case that will be used to test the calculation tool is expected to give a general sense of the feasibility of all-FRP bridges to compete with concrete bridges. But it must be stressed that the results of the LCC calculation are expected to be heavily influenced by the assumptions and demands that are specific to the cases. The case has been carefully selected to represent an average road bridge as much as possible. This is done to make the conclusions of the case calculations as generally applicable as possible.

The results of the tool are per definition dependant of the input variables. The input variables are largely based on assumptions and estimations. Data collection is the main challenge of LCCA. During the research the researcher will aim to gather the most accurate data that can be gathered in the available time span and using a Monte Carlo-analysis the effect of uncertainty of the input values on the output values will be investigated. Fact remains that the results of the calculation tool are only as accurate as the input data used. During the research it will become clear whether the available time span will offer accurate enough data to draw trustworthy conclusions about whether all-FRP bridges can outperform concrete bridges in terms of LCC.

1.6. RELEVANCE

The tool will provide a simple assessment method to determine the advantages or disadvantages of an all-FRP bridge in a specific case scenario. Current tools/software (such as BridgeLCC developed by NIST US Department of Commerce (2011) or the Bridge WebLCC tool developed by the KTH Royal Institute of Technology (2009)) are less specific and more complex and therefore more complicated to use. For the goal of feasibility evaluation of alternatives - as required from Grontmij - the point is to assess things on a high abstraction level for quick evaluation at the early design stage. This tool will be developed following that need.

Based on the results of the specific case, the research will also provide Grontmij with an idea of whether all-FRP road bridges are an interesting development to further investigate. It will show whether it can be reasonably expected that all-FRP road bridges will offer benefits over concrete bridges or not. A sensitivity analysis will offer information on what factors mostly influence the outcome and thereby are of most importance for determining the competitiveness of FRP in bridge building. This will then give an idea for where the focus should be put to collect more accurate data for more accurate results.

1.7. RESEARCH DESIGN

1.7.1. RESEARCH METHODOLOGY

The research will be conducted using a quantitative research design. Specifically design based research mainly conducted via desk research. The focus will be on a quantitative research because the aim is to specifically provide insight into the situations and extent of the performance difference in term of LCC between the two construction materials concrete and FRP. For this purpose figures will be needed of construction dimensions (based on mechanical calculations). The researcher will also need figures on construction costs. These figures will be based on the expertise of Grontmij.

1.7.2. DATA COLLECTION AND DATA ANALYSIS METHODS

During the course of the research project different types of data collection and -analysis methods will be used. Here the general outline of the research will be described by walking through the research questions and their accompanying methods.

1. What are the considerations of the LCC calculation tool that should be taken into account?

The main data collection method for this question will be literature study. Based on the available literature and the specific wishes of Grontmij that were determined by oral communication the needed output variables will be determined. Based on the available literature and the availability of relevant data, the needed input variables and the accompanying calculations will be described. This way a model that describes the needed input, outputs and their relationship will be developed. This model will then be used to generate a spreadsheet calculation tool using Microsoft Excel software.

2. Using the developed LCC calculation tool, what LCC values can be attributed to the specific case design alternatives?

To calculate the LCC values the specific input values for the specific cases will be needed. Together with engineers at Grontmij an existing specific concrete bridge design was chosen to function as a base case. This base case will provide all the project demands that influence the input variables of both the concrete as well as the all-FRP bridge. This means things like traffic loads, foundation properties, dimensional preconditions, et cetera will be known. Since there is no existing all-FRP bridge design that can be used to calculate material costs and environmental impacts, a preliminary FRP design alternative will have to be developed during the research. It will be based on mechanical calculations which are based on the design codes (CUR 96 and Eurocode). To gather the input values needed to execute the calculation I will have to analyse relevant documents present at Grontmij that can provide the price indicators and structural dimensions for the concrete structure and the foundations. For pricing figures concerning the FRP structure I will have to look for figures present in literature and if possible the results of interviews with people at FiberCore.

3. Based on the results, what are the main applications for and what are the main limitations of the newly developed LCC calculation tool?

The influence of uncertainty of the input values on the results are analysed by using a Monte Carlo-simulation using the Excel add-in @Risk. This will provide a range of statistic LCC values for both design alternative. A comparison of the results then allows to make conclusions about the accuracy of the calculation tool. A sensitivity analysis will also be executed to determine the most influential variables of the calculation tool. This will provide insight into what variables are most important to determine accurately and might say something about the general applicability of FRP as a bridge construction material.

4. What can be said about the economic performance of all-FRP bridges compared to concrete in general?

A comparison between the results of the different design alternatives will shed light on how FRP bridge decks compare to concrete bridge decks in terms of LCC in the specific case under investigation. However, the nature of the results will determine whether more general statements can be made about the overall competitiveness of FRP bridge decks compared to concrete bridge decks.

1.7.3. Validity

Due to the nature of the research most values that are put into the calculation will be approximations. This means that numerical ranges for these approximations will be used. A sensitivity analysis will therefore be performed to give an idea of how much the results are influenced by the approximations.

Validity will also be governed by making sure to provide the source of the input variables and to describe whether they are based on assumptions or approximations. Input values will also be checked by the appropriate experts as much as possible.

2. CONCEPTUAL FRAMEWORK

In this chapter the conceptual framework is set out. The conceptual framework describes the research variables and their relationship in more detail. It allows to pinpoint the exact topic for the research. Paragraph 2.1 starts with a basic description of the theory of infrastructure asset management and the role that LCCA plays therein. Next follows a further investigation of the elements of LCCA in infrastructure management in Paragraph 2.2. In Paragraph 2.3 a description will be given on how the different design variables and their requirements will be determined. Finally the relationship between the variables that will be researched and the precise elements of those variables that are relevant to the research project will be described and shown in Paragraph 2.4.

2.1. INFRASTRUCTURE ASSET MANAGEMENT

Infrastructure asset management is getting increasing attention throughout the world. According to Van der Velde, Klatter, & Bakker (2013) budget restraints and increased public demand in terms of service and quality put pressure on government bodies that have to manage these infrastructure systems while dealing with these dynamics. Looking for ways to cope with this issue the attention from infrastructure operators is increasingly turned to asset management.

There are a lot of different definitions of asset management but just to get an idea of what asset management entails the definition of the Federal Highway Administration (1999) is provided:

> "*Asset Management is a systematic approach of maintaining, upgrading, and operating physical assets cost effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision making. Thus, asset management provides a framework for handling both short- and long-range planning.*" (http://www.fhwa.dot.gov)

Applying this approach to infrastructure is seen as a way to deal with the pressures that are present on the management of public transportation infrastructure which were discussed above.

(Moon, Aktan, Furuta, & Dogaki, 2009) describe the different concepts that are involved with infrastructure asset management. According to them, integrating these concepts should lead to a better infrastructure management. The following concepts are described: 1, Performance based engineering and management leads to the definition of performance objectives and correlated metrics; 2, Structural identification, health monitoring and intelligent infrastructures are used to monitor and forecast metrics; 3, Life cycle costs and decision making are used to identify trade-offs. These concepts and their interplay is depicted in Figure 7. For this research the focus will be on one of these concepts: life cycle cost analysis. In the next section this concept will be further explored.

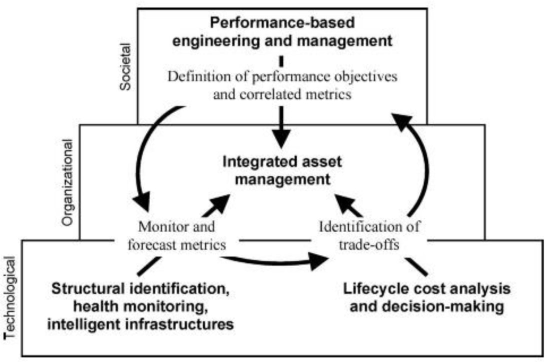


Figure 7, Integration of the different aspects of integrated asset management (Moon et al., 2009)

2.2. Life-cycle cost analysis (LCCA)

As discussed above, optimal use of financial resources has become an essential part of managing infrastructure. Life cycle cost analysis is a method that enables optimal investment decision making. LCCA enables one to compare different investment alternatives based on the total costs that are associated with that alternative. Not only initial investment costs but also all costs that develop throughout the objects life cycle are taken into account. This entails costs made during operation as well as end of life costs.

2.2.1. LCC cost categories

Although by definition LCCA seeks to include all costs that arise during the lifetime of an object, not everyone agrees on the precise identification of these costs (Woodward, 1997). Based on literature on LCCA of infrastructure, the general cost elements of interest to the research will be described below:

Agency costs

As mentioned above LCC generally refers to all costs associated with the life cycle of an object. For infrastructure objects a traditional view of LCC would be the costs incurred by government bodies for realisation, maintenance and disposal of the object in question. So called agency costs. (Chandler, 2004).

User costs

A more holistic approach as for example used by the U.S. Department of Transportation (2002) includes the costs incurred by the users of the object, so called user costs. As can be seen by this definition.

> *"Life-cycle cost analysis (LCCA) is an evaluation technique applicable for the consideration of certain transportation investment decisions. […] All of the relevant costs that occur throughout the life of an alternative, not simply the original expenditures, are included. Also, the effects of the agency's construction and maintenance activities <u>on users</u>, as well as the direct costs to the agency, are accounted for."* (U.S. Department of Transportation, 2002)

Thus, user costs are the financial effects of construction and maintenance activities that are incurred by the user of the infrastructure object in question. This includes costs generated by the fact that during construction and maintenance users are spending more time on the road (traffic delay and vehicle operation costs). But this can also include costs based on the fact that during road work activities traffic accident rates increase (accident costs).

Social costs

An even broader interpretation of LCC can be made by also including social costs. For example: (Ehlen, 1997) mentions the importance of including 'third party costs', such as costs incurred by surrounding businesses and environmental costs. Murphy (2013) also distinguishes social costs as a third cost element that has to be accounted for. He includes aesthetic and cultural value and environmental costs in this category. He does not however describe a method to monetize these social costs. Keoleian et al. (2005) also include some environmental costs for LCC calculation but the methods and data used are not clearly explained. The MAINLINE-project (Boniou, 2013) also incorporates environmental effects of maintenance activities into the LCC of steel railway bridges.

There are different ways to monetize environmental effects. One of these is the so called 'revealed collective preference method' (Davidson & Wit, 2003). Environmental life cycle assessment research on bridge designs of different materials done by BECO (2013) using this method revealed that all-FRP bridges have a hard time competing with steel and concrete regarding environmental aspects. Results were seen to be largely dependent on assumptions that were made regarding, among others, production and disposal methods. It will be interesting to see to what extent the environmental effects influence the total LCC by integrating this method into the LCC calculations.

As mentioned above, viewpoints on what cost elements to include differ. In the next section it will be determined what cost elements will be included in this research.

2.2.2. Determining the relevant LCC cost elements

Concerning the agency costs this research will take into account the construction costs (this includes material as well as labour costs), inspection and maintenance costs and end of life costs (remove, disposal and residual value). Depending on the availability of the data the level of detail in which these costs will be accounted for will have to be determined.

Unlike most private assets, transport infrastructure systems - and the bridges that are part of those systems - provide a public function and thus are often owned by public bodies. These governmental bodies are paid by the public to provide services that benefit the public. It therefore seems logical that costs that are directly incurred by the public, in this case the users of the infrastructure, are taken into account when assessing the LCC of an object designed to serve the public. Therefore the researcher will strive to include the most commonly included user costs of which can be expected that the researcher will to be able to determine them, and are expected to have a significant influence on the total LCC. These are the so called user delay costs, vehicle operating costs and traffic accident costs (Ehlen, 1999).

As social costs are concerned this research will consider the environmental costs for the following reasons. A growing interest in general and also in the building industry is the effects of business activities on the environment. Grontmij also requested to research the environmental effects of FRP as a bridge construction material. To be able to compare the environmental effects in terms of relative benefit of one construction material over another the researcher is of the opinion that these effects should be monetized and thus included in the LCCA. Based on the resources available this research will strive to determine the environmental costs using environmental life cycle assessment (LCA) software (GaBi). This software allows to estimate the relevant environmental indicators (based on the CML-2001 method (see Thinkstep, 2015)). Using the 'revealed collective preference method' the environmental costs can then be determined (this will be explained later in the research). Other social or third party costs such as costs incurred by local businesses and aesthetic values are not considered relevant enough for this research project.

2.3. Design of optimal deck dimensions

This paragraph will describe the calculations and assumptions used to determine the optimal bridge deck dimensions based on the bridge material and the span of the bridge. The calculations will be used in the LCC tool to allow the user to quickly select the appropriate bridge deck and the accompanying input variables such as unit cost and material quantities.

2.3.1. Concrete bridge deck design

In this research it is decided - when looking at concrete bridges - to only investigate pre-stressed concrete bridges. When designing pre-stressed concrete bridges there is a choice of several different systems. The three mainly used systems in The Netherlands are: 1, volstortliggers (SJP/HKO); 2, railbalkliggers (ZIP/HRP); 3, kokerliggers (SKK/HKP). These systems are depicted in Figure 8.

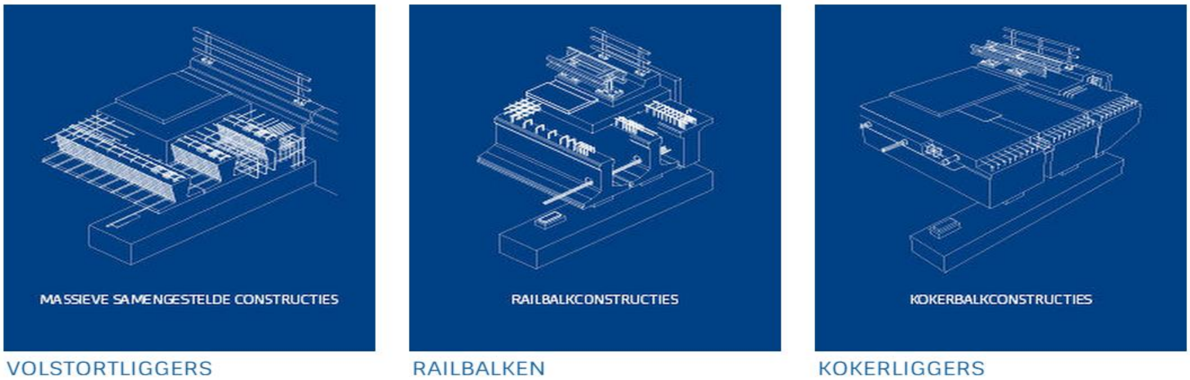


Figure 8, Different pre-cast concrete systems (source: www.spanbeton.nl)

Depending on the span of the bridge one system has an economical advantage over another. Based on cost figures supplied by Grontmij the relation as depicted in Figure 9 has been estimated. The abbreviation SJP, ZIP or SKK represent the type of system used. The number behind the abbreviation describe the dimensions (height) of the beams. Which beam height is necessary for a certain span is determined by information provided by the manufacturer (Spanbeton, 2015). This relation will be used to determine the most economical (and therefore most appropriate) system based on the span of the bridge.

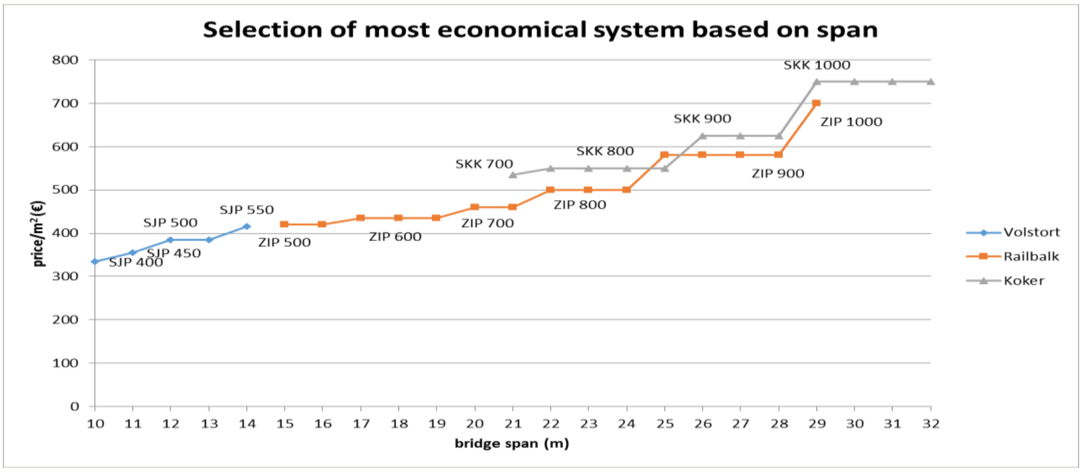


Figure 9, Different pre-cast concrete systems and their prices (Grontmij, 2015)

2.3.2. FRP BRIDGE DECK DESIGN

As explained in Chapter 1 there are different methods of constructing an FRP bridge deck. In this research a sandwich panel as produced by FiberCore (see Paragraph 1.1.3) is chosen. This system is chosen because this is currently the most used system in the Netherlands and has proven to work for several road bridges already.

The system uses different laminates of reinforcement fibers to construct a sandwich panel. This panel consists of an upper FRP-skin and a lower FRP-skin. These skins are connected with each other by FRP-webs in vertical orientation. The area between the FRP-skins is filled with a certain lightweight core material (EPS/PVC/PU). This system is depicted in Figure 10.

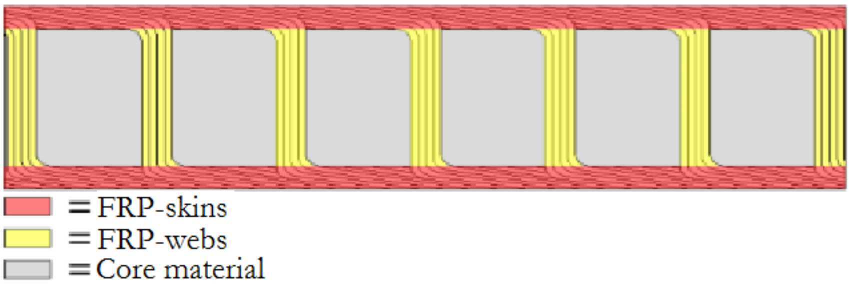


Figure 10, Example sandwich FRP deck system

When designing with FRP there is one big difference compared to steel or concrete. Because of the low stiffness and high strength of FRP compared to steel and concrete, global dimensions of FRP structures are generally driven by the serviceability limit state (SLS) which means the maximum deflection of the bridge deck under load (Tromp & De Boer, 2014).

According to the EN 1990 – Eurocode there are no strict requirements for the maximum deflection of bridge decks (see EN 1990 national Appendix B2.4.1 (2)). However the Dutch directive Richtlijnen Ontwerp Kunstwerken (ROK) 1.2 - which is issued by Rijkswaterstaat and often assigned as part of the contract by principals in the Netherlands – does mention a SLS requirement of $1/300^{th}$ of the span of the bridge (1/300L). The CUR 96 also mentions this as an often used requirement. This will be the requirement that will be used.

Resistance to bending

The resistance to bending of a structural element is determined by two factors: the elasticity modulus or E-modulus (E) and the area moment of inertia (I_y). There are several elements which can be varied for a FRP sandwich system that will determine the properties relating to the resistance to bending. For the determination of the E-modulus the type of fiber, type of resin (polymer), the amount of reinforcement (expressed in fiber volume fraction) and the fiber orientation all contribute to the outcome. For the determination of the area moment of inertia there are two contributing factors: the total height of the bridge deck and the thickness of the FRP-skins of the sandwich panel. How these two factors are determined will be explained in the next section.

E-modulus

To determine the E-modulus of the FRP the author used the work of (Pieters & Pol, 2014). Using the classical laminate theory - of which a discussion falls outside the scope of this research – they created a spreadsheet which calculates the E-modulus of a certain FRP based on the contributing factors mentioned above.

Based on the advice of FiberCore in the work of (Pieters & Pol, 2014) two types of FRP have been selected with the properties as described below.

1. Glass fiber reinforced polymers:
   Type of fiber: E-glass with a modulus of 92 GPa
   Type of resin: polyester E=3.8 GPa
   Fiber volume fraction: 52%
   Fiber orientation: 80%/10%/10%/0% for 0°/45°/-45°/90°

   Using the spreadsheet of (Pieters & Pol, 2014) this type of FRP gives a resulting E-modulus of 35189 MPa.

2. Carbon fiber reinforced polymers:
   Type of fiber: HT-carbon with a modulus of 240 GPa
   Type of resin: epoxy E=5.0 GPa
   Fiber volume fraction: 52%
   Fiber orientation: 80%/10%/10%/0% for 0°/45°/-45°/90°

   Using the spreadsheet of (Pieters & Pol, 2014) this type of FRP gives a resulting E-modulus of 109917 MPa.

According to the CUR 96 a conversion factor (γ_c) has to be applied to the E-modulus. This convention factor takes into account influences of temperature, moisture and fatigue on the material. The conversion factor is in this case - according to the CUR 96 - determined to be: $y_c = 1.331$. The E-modulus has to be divided by this conversion factor to obtain the calculation value of the E-modulus.

There is also a material factor (γ_m) that is used when designing with FRP but this factor is not taken into account when looking only at the SLS (CUR commissie C 124, 2013).

Area moment of inertia

The area moment of inertia is determined by the structural profile (cross-sectional dimensions) of the deck. To determine the I_y the following assumption has been made according to the advice of FiberCore: the core material and the FRP-webs in between the FRP-skins do not contribute to the structures capacity to resist bending. This means only the thickness of the FRP-skins and the distance between these skins will determine the I_y of the FRP bridge deck.

The value of the I_y of a rectangular cross-section can be calculated using Equation (2-1).

$$I_y = \frac{1}{12} \times b \times h^3 \tag{2-1}$$

Wherein:

I_y = area moment of inertia (mm^4)
b = the width of the cross-section (mm)
h = the height of the cross-section (mm)

For a cross-section that represents the sandwich construction as shown in Figure 11 the I_y of the sandwich panel can be calculated by subtracting the I_y of the core from the I_y of the total cross-sectional profile. This can be done using Equation (2-2).

$$I_y = I_{tot} - I_{core} = \left(\frac{1}{12} \times b \times h^3\right) - \left(\frac{1}{12} \times b \times (h - 2t)^3\right) \tag{2-2}$$

Wherein:

I_y = area moment of inertia (mm^4)
b = the width of the cross-section (mm)
h = the height of the cross-section (mm)
t = the thickness of the FRP-skins (mm)

This equation can be rewritten in such a way that the thickness of the FRP-skins becomes a function of the total height of the cross-section. This way the necessary thickness of the FRP-skins at a certain selected total height of the cross-section can be calculated. This is shown in Equation (2-3).

$$t = \frac{1}{2}h - \frac{\sqrt[3]{b^3 \times h^3 - 12 \times b^2 \times I_y}}{b} \tag{2-3}$$

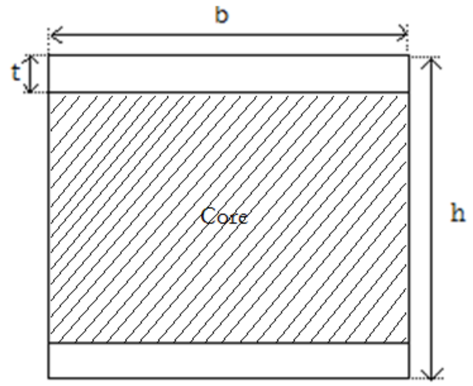


Figure 11, Cross-section sandwich construction

In this equation the relation between the thickness of the FRP-skins and the total height of the cross-section is still dependant on the width of the cross-section and the required I_y. By making the width of the cross-section a constant this variable can be taken out of the equation. This can be done by considering a meter-width (1000 mm) of the deck as representative for the entire deck and schematizing this meter of the deck as a simply supported beam. This is shown in Figure 12.

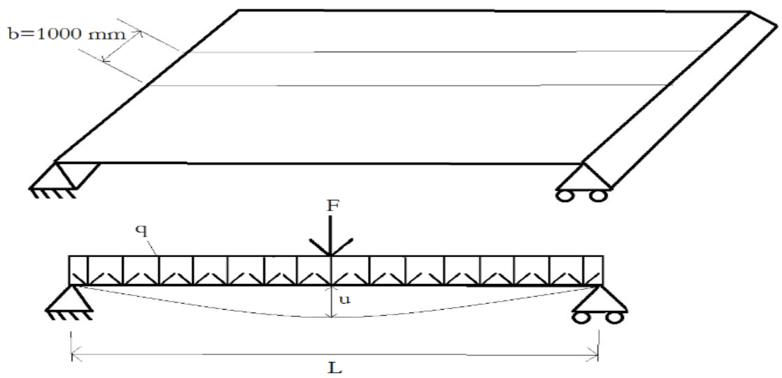


Figure 12, Schematisation bridge deck

The required I_y can also be made constant depending on the span of the bridge (L). This can be done as follows. The maximum deflection for the system shown in Figure 12 can be determined using Equation (2-4).

$$u = \frac{F \times l^3}{48E \times I} + \frac{5q \times l^4}{384E \times I} \tag{2-4}$$

Wherein:

u = maximum deflection (mm)
F = point load (N)
l = span of the bridge (mm)
I = area moment of inertia (mm^4)
E = E-modulus (N/mm^2)
q = distributed load (N/mm)

This can be rewritten so that I_y is dependent on the loads, the span of the bridge, the E-modulus and the maximum allowed deflection. This is done in Equation (2-5).

$$I_y = \frac{F \times l^3}{48E \times u} + \frac{5q \times l^4}{384E \times u} \tag{2-5}$$

Since the E-modulus and the maximum deflection are both known and the span will be kept variable, the only variables left to determine are the loads F and q. This will be done in the next section.

Calculation of the loads

The load that the bridge needs to be able to withstand are determined according to the EN 1991 - Eurocode. There are several different types of loads such as self-weight and imposed loads, snow, wind, thermal, horizontal traffic loads (brake forces, etc.) and vertical traffic loads. In this research the only loads under investigation will be the vertical traffic loads. This is because these loads are responsible for the maximum deflection. The self-weight and imposed loads do contribute to deflection but these deflections are permanent and can be cancelled out during the production of the deck using an arc. Therefore these loads will not be taken into account for determination if the design stands the test for the SLS.

The EN 1991 - Eurocode differentiates four different load models for road bridges. For the determination of the maximum deflection SLS the main model - Load Model 1 (LM1) - is the most appropriate. This model consists of a concentrated load in the form of a tandem system (TS) and a uniformly distributed load (UDL). LM1 accounts for most of the effects of the traffic of lorries and cars.

LM1 differentiates traffic induced loads between different lanes. The width of the bridge is divided into theoretical traffic lanes of 3 meters wide. Depending on the most unfavourable situation the lanes are assigned a number from 1 to 3 (see Figure 13).

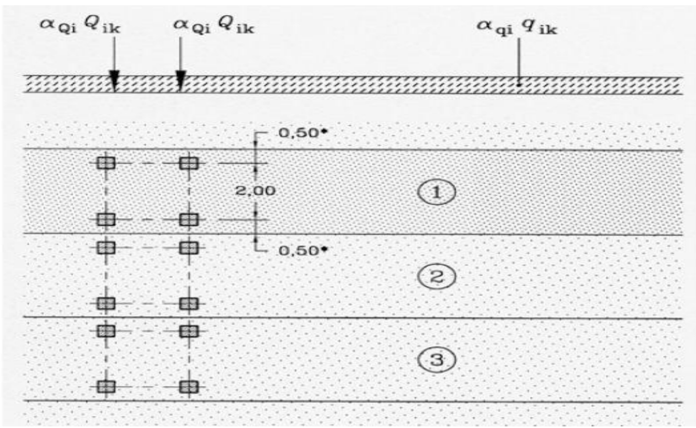


Figure 13, Loads according to EC 1991

Depending on the lane number values are assigned to the axle loads Q and the uniform distributed load (q) (see Figure 14).

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

Figure 14, Values for loads according to EC 1991

It is decided to simplify the calculation by combining the two axle loads into one point load in the middle of the span of the bridge (F). This is allowed according to EN 1991 - Eurocode 4.3.2 (6b).

The maximum deflection occurs at the place where the loads are the heaviest, therefore a meter width deck from the lane with the heaviest loads is picked. This is lane number one. The value for F will therefore be: 2 x 300 kN / 3 meter lane width = 200 kN. The value for q is: 9 kN/m^2 x 1 meter wide = 9 kN/m.

Factors

Correction factor traffic class: α

EN 1991 – Eurocode allows for an α-factor which can account for the type of traffic ("international heavy", "medium" or "light"). The EN 1991 – Eurocode recommends to use the value α = 1.0 if there is no further specification of the traffic type available (which is the case in this research). α = 1.0 is equal to heavy international traffic and should suffice for this case. This is the value that is taken for α in this research.

"Frequent value" factor: Ψ

When testing for the SLS the EN 1991 – Eurocode prescribes a Ψ-factor to be used on the loads. This factor accounts for the amount of which the effects (deflection) may exceed the maximum allowed value (if applicable). In case of the vertical traffic induced loads (frequent value) the factor Ψ_1 is used. In the Dutch national annex $\Psi_1 = 0.8$ is prescribed.

Dispersion factor: f_s

The schematization of the bridge deck into a meter wide simply supported beam suggests that the loads are only distributed in the longitudinal direction. In practice this is not the case. Because LM1 from the EN 1991 – Eurocode models different loads for different lanes some of the load of the heaviest loaded lane will be distributed transversally along the entire width of the bridge. This dispersion of the load has a significant effect on the maximum occurring moment and thus the maximum deflection of the bridge deck.

During the research it became clear that determining the effect of the spreading of the load on the maximum occurring deflection by manual analytic calculations is rather complicated and not appropriate for the scope of this research. It was therefore determined to calculate the maximum occurring moment with the aid of finite element method (FEM) software called SCIA (for the SCIA report see Appendix F). The maximum occurring moment calculated by SCIA could then be compared to the maximum occurring moment that would coincide with the simply supported beam schematization. This analytically calculated maximum occurring moment was calculated using Equation (2-6).

$$M_{max} = \frac{1}{4}F \times l + \frac{1}{8}q \times l^2 \tag{2-6}$$

Wherein:

M_{max} = maximum occurring moment (kNm)
F = point load in middle of span (kN)
q = distributed load along bridge span (kN/m)
l = span of bridge (m)

The factor difference between the two calculated maximum occurring moments would then be used as a correction factor (dispersion factor: f_s) on the determined loads F and q in the model.

The amount of transversally distributed load – and therefore the dispersion factor – is dependent on the length and width of the bridge deck. Using SCIA the dispersion factors for different bridge deck spans and widths were determined. For bridge decks with spans from 10 to 32 meters and widths from 10 to 30 meters the factors range between 0.65 and 0.4. These dispersion factors are shown in Appendix C.

FRP-deck design

Now that the loads are determined, the E-modulus is known and the maximum deflection is determined, the relation between the span of the bridge (L) and the required area moment of inertia (I_y) can be calculated using Equation (2-5). By using this calculated required I_y a combination of total height and FRP-skin thickness can be calculated for every bridge span using Equation (2-3).

Of all the possible combinations of total height and skin thickness an optimal combination can be selected based on the material costs. Per square meter the amount of material can be calculated based on the determined skin thickness and total height of the sandwich FRP bridge deck. The costs and volumetric mass densities used for the materials are taken form (Pieters & Pol, 2014) and are shown in Table 1.

Table 1, Material costs and densities (Pieters & Pol, 2014)

Material	Material costs (€/kg)	Density (kg/m3)
E-Glass	2.50	2600
Carbon	27.50	1800
Polyester	2.25	1178
PVC	11.11	46

In conversation with FiberCore it was mentioned that the possible skin thickness that can be produced lies between 20 and 40 mm. The maximum height of the total sandwich is currently about 1 meter. Figure 15 displays possible combinations of skin thickness and total height for different bridge spans (results in Figure 15 slightly deviate from actual values used by the calculation tool because the spread factor (f_s) is not optimized for each span in this overview). An optimal combination is chosen if the combination lies between the production limits that are mentioned by FiberCore. If the optimum combination lies outside the limits an as-close-as-possible combination to the optimum is chosen. In Figure 15 it can be seen that the maximum bridge span for Glass-FRP is about 24 meters.

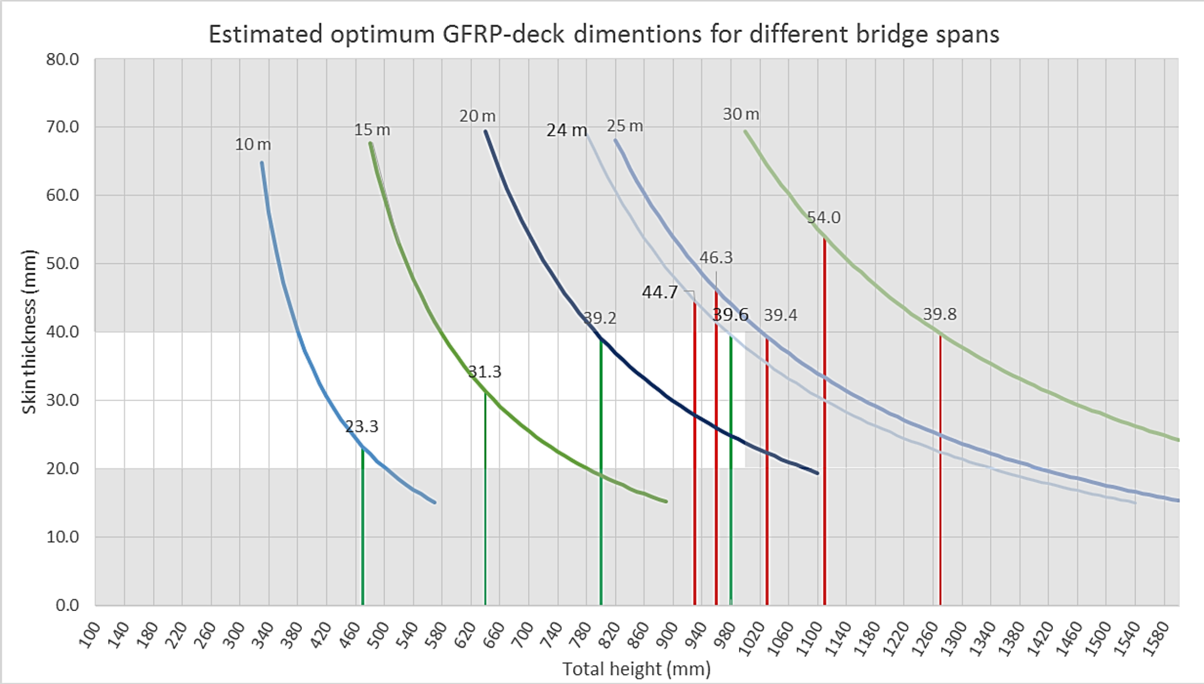


Figure 15, Possible dimensions for GFRP deck depending on span

The same has be done for Carbon-FRP. The results of this is shown in Figure 16. For a complete overview of the input and output of the calculations see Appendix B.

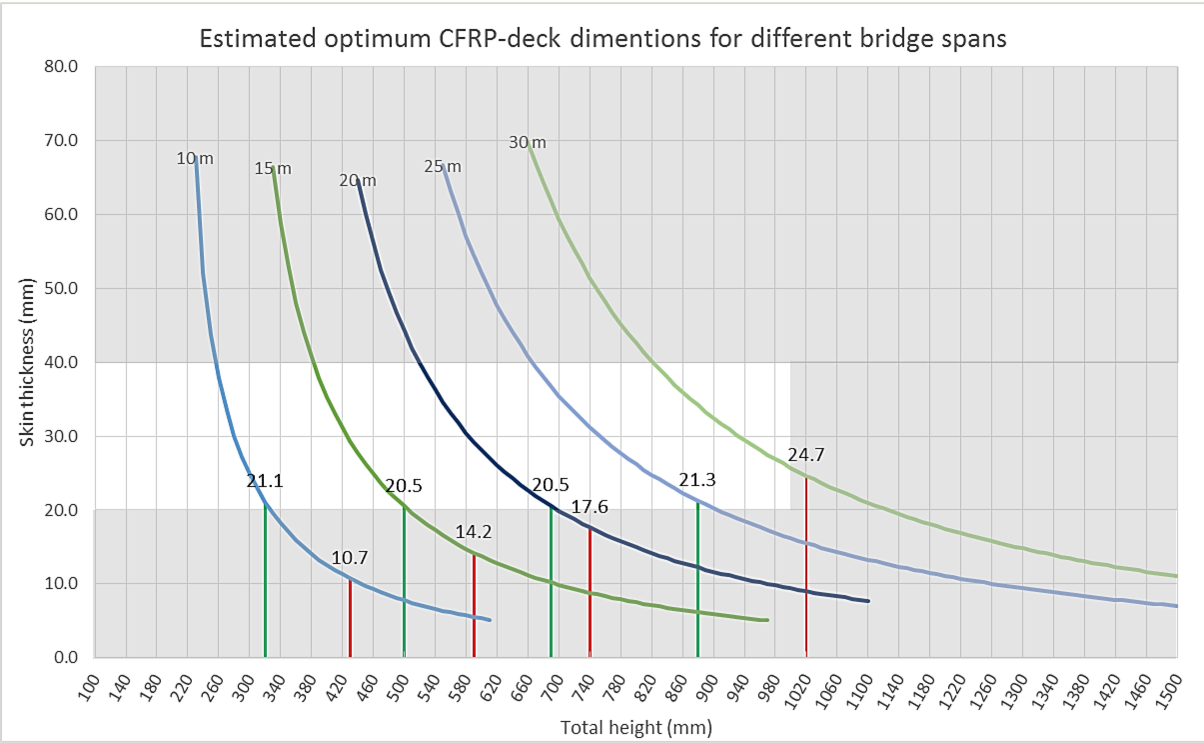


Figure 16, Possible dimensions for CFRP bridge deck depending on span

2.4. Overview conceptual framework

To summarise the conceptual framework: during this research it will be investigated how the choice between concrete and all-FRP as the type of construction material of short span, beam, road bridges influences LCC. Furthermore it will be investigated how the span and lifespan of the bridge influences this relation. The conceptual framework described above is visually represented in Figure 17.

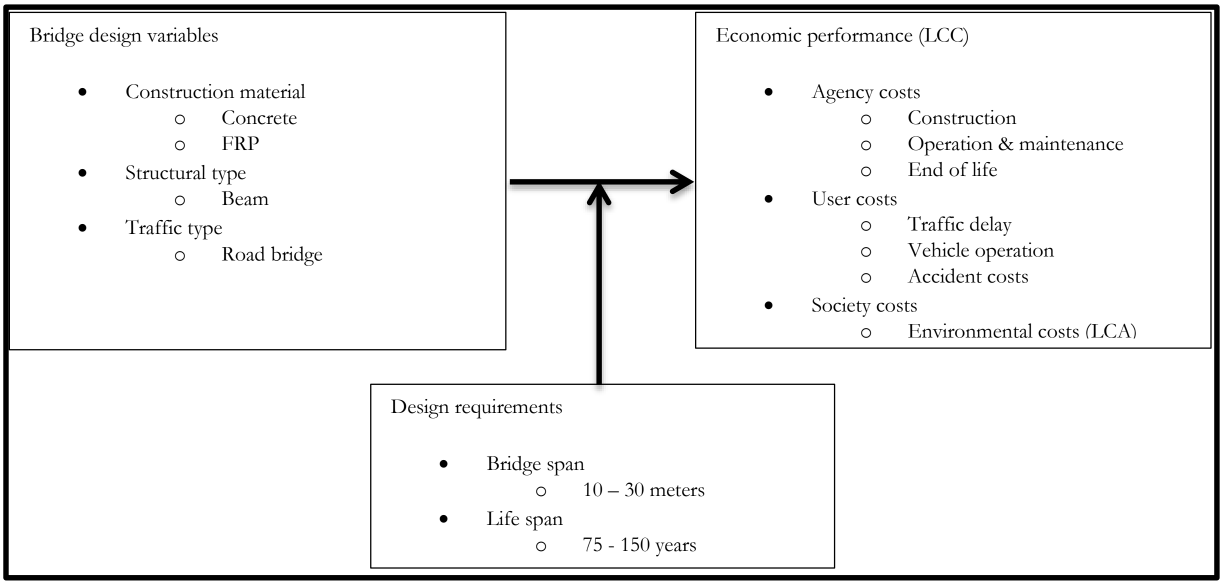


Figure 17, Conceptual framework

3. LCC MODEL

This chapter describes the LCC model that has been developed. The three cost categories that make up the total LCC – agency costs, user costs and society costs – and how they are to be determined will be discussed. This chapter describes the needed input variables and the necessary calculations (equations) that will be used in Chapter 4 to develop the LCC calculation tool. The determination of the total LCC is described in Paragraph 3.1. In Paragraph 3.2 the agency costs will be discussed. The determination of the user costs will be explained in Paragraph 3.3 and in Paragraph 3.4 the method for determining the society costs will be given. An overview of the complete model can be found in Appendix A.

3.1. TOTAL LCC

The total LCC are calculated by summarizing the different cost categories which have been discussed in the previous chapter. These cost categories are: Agency costs (AC), User costs (UC) and Society costs (SC). This can be done using Equation (3-1).

$$LCC = AC_{disc} + UC_{tot,disc} + SC \tag{3-1}$$

Wherein:

LCC = total life cycle costs incurred over the entire life cycle of the object (€)
AC_{disc} = discounted agency costs (€)
$UC_{tot,disc}$ = total discounted user costs (€)
SC = society costs (€)

In the next paragraphs the determination of the individual costs categories will be explained further

3.2. AGENCY COSTS

The most obvious cost category included in the LCC model is the category agency costs. Agency costs are the costs that are directly borne by the agency. These agency costs can further be divided into three subcategories, namely: Initial construction costs, maintenance costs, and end of life costs. These three types of costs are described in more detail below. The method of calculating the Agency costs is based on the works of Chandler (2004). Basically this means breaking down the total structure into different elements and multiplying these elements with an estimated unit cost per element. This method has been applied in such a way that it fits the method described in CROW's Standaardsystematiek voor Kostenramingen (SSK) (CROW, 2010). This methodology is used throughout the Dutch civil construction sector for estimating construction costs. Because this is the way it is done in the Dutch civil sector and because Grontmij had this information available in this manner this methodology will be applied during this research.

3.2.1. TOTAL DISCOUNTED AGENCY COSTS

The total discounted agency costs are the sum of the three sub cost categories and therefore calculated by Equation (3-2).

$$AC_{disc} = ICC + \left(\sum_{t=0}^{T} \frac{MC_{t,nom}}{(1+r)^t} \right) + \frac{EoLC_{T,nom}}{(1+r)^T} \tag{3-2}$$

Wherein:

ICC = Initial construction costs (€)
$MC_{t,\,nom}$ = nominal maintenance costs for year t (€)
$EoLC_{nom}$ = nominal end-of-life costs (€)
t = year in life cycle from 0 until end of life cycle T
T = year in which life cycle ends
r = discount factor (%)

3.2.2. Initial construction cost

The initial construction costs are the costs that the agency will have to make for realising the construction of the object. These costs include *direct construction costs*: costs of material, labour and equipment. *Indirect construction costs*: such as risks, profit, general costs, execution costs and one-off construction costs. Besides direct and indirect construction costs there are also *unassigned object risks*, *engineering costs* and *other additional costs*. This way of dividing and assessing the initial construction costs is based on the Dutch standardised cost estimation system SSK.

The direct construction costs are calculated by first dividing the designed object into separate construction elements. The next step is determining the unit cost of a particular construction element and multiplying it by the amount that that element occurs in the design. This results in the total costs of that particular element in the total object. Doing this for every construction element and summarising these costs will yield the total *assigned construction costs*. Adding 15% of *unassigned construction costs* finally gives the total *direct construction costs* (percentage used by Grontmij in the SSK documentation of the case: Trekvlietbrug).

The rest of the initial construction costs are calculated by taking a percentage of the direct construction costs (plus if applicable the one-off, execution and general costs). The percentage and the value with respect to which that percentage is taken is shown in Table 2. The percentages are based on the percentages used by Grontmij in the SSK documentation of the case: Trekvlietbrug.

Table 2, Additional percentages over the assigned construction costs (Grontmij, 2015)

Cost category				**Additional percentage**	**With respect to**
Total investment costs	Foreseen construction costs (FCC)	Direct construction costs (DCC)	Assigned construction costs (ACC)		
			Unassigned construction costs	15.00%	ACC
		Indirect construction costs	One-off construction costs (OOCC)	4.00%	DCC
			Construction execution costs (CEC)	7.00%	DCC
			General costs (GC)	8.00%	DCC+OOCC+CEC
			Profit	3.00%	DCC+OOCC+CEC+GC
			Risk	2.00%	DCC+OOCC+CEC+GC
	Unassigned object risks			10.00%	FCC
	Engineering Costs			8.00%	FCC
	Other additional costs			3.00%	FCC
Total additional percentage (χ)				**75%**	**ACC**

All these costs are made at the beginning of the life cycle of the object. Therefore there is no need for any discounting. The needed calculation for the initial construction costs are given by Equation (3-3).

$$ICC = \sum_{i=n}^{m} CUC_i \times Cq_i \times (1+\chi) \tag{3-3}$$

Wherein:

ICC = initial construction costs (€)
i = construction element n until element m
CUC_i = construction unit cost of element *i* (€/unit)
Cq_i = the quantity of construction element *i* present in the design (unit)
x = an additional percentage to cover unassigned, indirect, engineering and other costs

3.2.3. MAINTENANCE COSTS

The maintenance costs is another cost category that can contribute significantly to the total life cycle costs. The maintenance costs will be calculated in a similar manner to the initial construction costs. First the maintenance scenario that most accurately describes the estimated required maintenance over the life cycle of the object has to be determined. This means determining the different necessary maintenance activities, their accompanying frequencies and their estimated unit costs. Next, the unit cost of a certain maintenance activity (AUC_i) is multiplied by the quantity of units related to that activity (Aq_i). The resulting yearly maintenance cost for that activity is attributed to all the years in the life cycle of the object in which that maintenance activity takes place (based on the frequency attributed to that activity (t=?). This creates a maintenance schedule with which the total maintenance costs of every year in the life cycle can be calculated.

The maintenance costs for one specific year is therefore calculated by Equation (3-4).

$$MC_{t,nom} = \sum_{i=n}^{m} AUC_i \times Aq_i \tag{3-4}$$

Wherein:

$MC_{t,\,nom}$ = nominal maintenance costs for year t (€)
i = activity n until m
AUC = activity unit cost of activity I (€/unit)
Aq_i = quantity of units for activity i in year t (unit)

Summarizing the maintenance costs of every year in the life cycle of the object gives the total nominal maintenance costs of the object. Because the maintenance costs are made in the year the maintenance takes place, the future cash flows have to be discounted to create a present value.

The total discounted maintenance costs are also increased by a certain percentage that cover the *unassigned costs*, *indirect costs* and *unassigned object risks* (but not *engineering costs* and *other additional costs*). This is done with similar percentages as seen with the initial construction costs (see Table 2). This is in accordance with the SSK-method and current practice at Grontmij.

The total maintenance costs for the object during its life cycle is therefore calculated by Equation (3-5).

$$MC_{tot,disc} = \sum_{t=0}^{T} \frac{MC_{t,nom}}{(1+r)^t} \times (1+\chi) \tag{3-5}$$

Wherein:

MC_{tot} = the total maintenance costs during the life cycle of the object (€)
$MC_{t,\,nom}$ = maintenance costs for year t (€)
t = year in life cycle from 0 until end of life cycle T
r = the discount factor (%)
x = an additional percentage to cover unassigned, indirect, engineering and other costs

3.2.4. End-of-life costs

The third sub category in the category agency costs are the end-of-life costs. These include the costs of demolition and disposal minus the residual value. In this model the end-of-life costs will be calculated the same way that the initial construction costs are calculated. Namely by assigning the construction elements with a unit cost for end-of-life costs and multiplying the amount of a certain building element with the corresponding end-of-life unit cost. In this research it will be assumed residual value is equal to zero. The resulting equation is shown in Equation (3-6).

$$EoLC_{nom} = \sum_{i=n}^{m} DUC_i \times Cq_i \qquad (3\text{-}6)$$

Wherein:

$EoLC_{nom}$ = nominal end-of-life costs (€)
i = construction element n until element m
DUC_i = demolition and disposal unit cost for element I (€/unit)
Cq_i = the quantity of construction element i present in the design (unit)

Because the end-of-life costs take place at the end of the life cycle of the object the costs will have to be discounted. This is done using Equation (3-7).

$$EoLC_{disc} = \frac{EoLC_{T,nom}}{(1+r)^T} \qquad (3\text{-}7)$$

Wherein:

$EoLC_{disc}$ = are the discounted end-of-life costs (€)
$EoLC_{T,nom}$ = are the nominal end-of-life costs at the end of the life cycle (€)
T = year in which life cycle ends
r = discount factor (%)

3.3. User costs

As determined in Chapter 2, the second cost category that is included in the life cycle costs is the category *user costs*. The user costs are the costs that are borne directly by the user of the bridge. These costs can be divided into several sub-categories of which the most common and most significant are taken into account in this study, namely: *vehicle operating costs*, *traffic delay costs*, and crash costs or *traffic accident costs*.

These costs are all a result of the work zones that are associated with the construction and maintenance of the bridge during its life cycle. It is therefore essential for the determination of these costs that the amount of maintenance (frequency and duration) that is needed and the results of this maintenance on the traffic flow and traffic safety is estimated carefully. The maintenance scenario that is used for the determination of the maintenance costs will therefore also have to include information about the effect of the maintenance activity on the traffic flow (i.e. resulting extra travel time per vehicle and the duration of the activity) and the effect on the traffic safety (i.e. the number of extra accidents).

The equations used for determining the vehicle operating costs, traffic delay cost and traffic accident costs are based on the work of Sundquist & Karoumi (2012). There are other methods available for determining the vehicle operating costs such as the National Cooperative Highway Research Program (NCHRP) Report 133 method, the Texas Research and Development Foundation (TRDF) method, and the Federal Highway Administration's (FHWA) HERS-ST Method (FHWA's office of operations, 2015). While these methods are more extensive and thus may yield more accurate results, these methods also require more data for input.

Data of which it is deemed unlikely (and not considered part of the scope of this study) that the researcher was able to determine the needed values. The method of Sundquist & Karoumi (2012) is therefore chosen as the most appropriate method in this case.

3.3.1. The total discounted user costs

The total user costs are a summation of the three sub-categories; vehicle operating costs, traffic delay costs and traffic accident costs. Because the user costs are made during the life cycle of the bridge, future cash flows will have to be discounted to determine a total present value.

The total discounted user costs are determined using Equation (3-8).

$$UC_{tot,disc} = \sum_{t=0}^{T} \frac{VOC_{t,nom}}{(1+r)^t} + \sum_{t=0}^{T} \frac{TDC_{t,nom}}{(1+r)^t} + \sum_{t=0}^{T} \frac{TAC_{t,nom}}{(1+r)^t} \tag{3-8}$$

Wherein:

$UC_{tot, disc}$ = total discounted user costs (€)
t = year in life cycle from 0 until end of life cycle T
r = discount factor (%)
$VOC_{t, nom}$ = nominal vehicle operating costs in year t (€)
$TDC_{t, nom}$ = nominal traffic delay costs in year t (€)
$TAC_{t, nom}$ = nominal traffic accident costs in year t (€)

How the different sub-categories are determined exactly will be discussed below.

3.3.2. Vehicle operating costs

The vehicle operating costs are the costs that are associated with the operation of the vehicles that pass the work zone (e.g. fuel costs, lubricant costs, overall vehicle wear, depreciation, etc.). Because of the extra travel time that is caused by the maintenance work zones – either by a limited allowed driving speed along the work zone or by a (potentially imposed) detour route taken by vehicles - the vehicles passing the work zone road section endure longer operation times and thus more operating costs. These costs will differ for different sizes of passenger cars and different sizes of freight traffic. To avoid the need of having to know the exact traffic composition an average value is taken based on certain amount of freight traffic.

In case of reduced maximum allowed driving speed due to the presence of a work zone the extra travel time can be determined by Equation (3-9).

$$ETT = \frac{L}{S_a} - \frac{L}{S_n} \tag{3-9}$$

Wherein:

ETT = extra travel time (hours)
L = length of the work zone (km)
S_a = adjusted average traffic driving speed during work zones (km/h)
S_n = normal average traffic driving speed outside work zones (km/h)

If the maintenance activity in question requires a detour (so that the above equation is not applicable) the extra travel time can be estimated and entered as a direct time value (DTT). This gives Equation (3-10).

$$ETT = DTT \tag{3-10}$$

Wherein:

ETT = extra travel time (hours)
DTT = detour travel time (hours)

The vehicle operating costs can then be determined using Equation (3-11).

$$VOC_t = ETT \times ADT_t \times V_{OC} \times N_t \tag{3-11}$$

Wherein:

VOC_t = the vehicle operating costs for year t (€)
ETT = extra travel time per vehicle (hours)
ADT_t = the average daily traffic in year t (passenger car equivalent (PCE)/day)
V_{oc} = is a monetary value for operating costs expressed (€/hour)
N_t = the duration of a certain maintenance activity expressed (days)

3.3.3. Traffic delay costs

The traffic delay costs are the costs that represent the valuable time of the road user itself. This economic value of the user's time is dependent on several factors. The type of traffic (passenger vehicle or freight traffic), the amount of persons/cargo per vehicle and the type of cargo/person (business/leisure).

The model should not become too complicated and the necessary data needed to use as input for the model should be obtainable by the user of the model. Therefore a general average user time value is taken. This value is estimated by assigning a certain percentage of the traffic as freight traffic and the rest of the traffic as passenger vehicles. Average time values for these types of traffic are estimated from used values in the literature. The time value for freight traffic and passenger traffic is then proportionally averaged to a general average time value for the road section under investigation.

The traffic delay costs can be determined in a similar fashion as the vehicle operating costs this is done by Equation (3-12).

$$TDC_t = ETT \times ADT_t \times V_{UT} \times N_t \tag{3-12}$$

Wherein:

TDC_t = traffic delay costs for year t (€)
ETT = extra travel time per PCE (hours)
ADT_t = the average daily traffic in year t passing the bridge in question (PCE/day)
V_{ut} = is a monetary value for the users time (€/hour)
N_t = the duration of a certain maintenance activity (days)

3.3.4. Traffic accident costs

According to the FHWA's office of operations (2015) numerous studies indicated that there is an increase (of between 20% to 70%) in crash rates along work zones. The traffic accident costs are the costs that are a result of the death, injury or material damages due to this increase in crash rates. This study differentiates between two types of accidents and their resulting costs; traffic accident costs with resulting deaths and traffic accident costs of accidents with severe injury. In this last category of accident costs the costs of accidents with minor injury and mere material damages are also included by an increase in the value used for crash costs per accident that represents these types of accidents. This is based on the data provided by Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (SWOV, 2014). Both the crash costs of accidents with resulting deaths as the crash costs of accidents with severe injury can be determined using the same equations. The total traffic accident costs are a summation of the two.

The extra accidents per vehicle can be determined by Equation (3-13).

$$EAV = L \times (A_a - A_n) \tag{3-13}$$

Wherein:

EAV = extra accidents per PCE (# of accidents/PCE)
L = the length of the work zone (km)
A_a = the adjusted crash rate during work zones (# of accidents/PCE km)
A_n = the normal crash rate outside of work zones (# of accidents/PCE km)

The traffic accident costs are then determined using Equation (3-14).

$$TAC_t = EAV \times ADT_t \times V_{AC} \times N_t \tag{3-14}$$

Wherein:

TAC_t = traffic accident costs for year t (€)
EAV = extra accidents per PCE (# of accidents/PCE)
ADT_t = average daily traffic (PCE/day)
V_{ac} = average cost value per accident (€/accident)
N_t = the duration of a certain maintenance activity (days)

3.4. SOCIETY COSTS

The third and final costs category included is the category society costs. These are costs borne by society at large. The only type of society costs that are taken in to account are the environmental costs. The environmental costs are the costs that are caused by use of energy and resources during the construction, maintenance and end-of-life phase of the bridge and the accompanying emissions to the environment.

There are a couple of general steps associated with environmental impact or life cycle assessment (LCA) studies. ISO 14040 is an international guideline on how to perform an LCA and suggest the four steps shown in the life cycle framework in Figure 18.

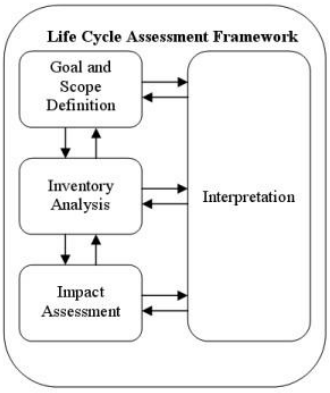


Figure 18, LCA framework of ISO 14040 (ISO 14040)

This study will not extensively perform all the steps described in the ISO 14040. This is because this study is focussing on the development of a calculation tool that allows the user to estimate and compare the environmental effects of different bridge designs. This means that the tool needs to be dynamic while the LCA framework from ISO 14040 is set-up to perform one LCA at a time. However, the framework is used as a basis for the estimation method used in this research. The general method will be describe below.

3.4.1. GOAL AND SCOPE DEFINITION

The goal of the estimation of environmental impact with the calculation tool is to compare the environmental effects of different design alternatives for a bridge with a certain functional unit (i.e. a bridge of a certain specified span and a certain specified width, capable of withstanding a certain specified load). The functional unit is not specifically defined yet because the calculation tool has to be dynamic (i.e. capable of calculating different bridge designs with different dimensions). During the case analysis the functional units will have to be defined to be able to compare different design alternatives.

Because of the dynamic nature of the calculation tool the assessment method and scope will have to be chosen in such a way that it is possible to cope with this dynamic nature. The following scope limitations will allow incorporating the environmental assessment into the dynamic calculation tool.

Based on the results of an environmental study of BECO (2013) it is determined that most of the environmental effects (about 90%) are caused by the use of construction material during initial construction and during maintenance. It is therefore decided that - for the sake of simplicity of the model - only the determination of environmental effects caused by material use is included. This means that environmental effects due to transportation, construction activities and end of life scenarios are not taken into account.

More specifically, only the environmental impacts of the bulk of materials in the design are assessed. These materials are estimated to be:

- Steel;
- Concrete;
- Polyester;
- Glass fiber;
- Epoxy;
- Carbon fiber;
- Asphalt;
- Gravel;
- PVC.

Of these materials the environmental impact per kg of material is determined using LCA-modelling software GaBi. GaBi software comes with a database of elemental flow data - flows of different elements in and out of the environment for basic processes (e.g. production of 1 kg of steel) – and uses this to calculate the resulting effects in different environmental impact categories (e.g. abiotic depletion potential, global warming potential, etc.).

In this research the environmental effect categories of the CML-2001 method will be used since this is an often used method in Europe. Also, for these effect categories the Dutch agency Rijkswaterstaat (part of the Dutch Ministry of Infrastructure and the Environment) published a list of corresponding shadow prices determined by the so called revealed collective preference method (TNO-MEP, 2004). These shadow prices are a way of monetizing environmental effects. For an explanation and in-depth discussion the author refers to the report by CE Delft (2003). The different environmental effect categories and their corresponding shadow prices are presented in Table 3.

Table 3, Environmental effect categories and shadow prices (TNO-MEP, 2004)

Environmental effect category	**Shadow price (€ / kg equivalent)**
Abiotic depletion elements (ADP) (€/Sb eq)	0.16
Abiotic depletion fossil (ADP) (€/Sb eq)	0.16
Global warming potential (GWP) (€/CO2 eq)	0.05
Ozone depletion potential (ODP) (€/CFK-11 eq)	30
Photochemical ozone formation potential (POCP) (€/C2H2 eq)	2
Acidification potential (AP) (€/SO2 eq)	4
Eutrofication potential (EP) (€/PO4 eq)	9
Human toxicity potential (HTP) (€/1,4-DCB eq)	0.09
Freshwater aquatic ecotoxicity potential (FAETP) (€/1,4-DCB eq)	0.03
Marine aquatic ecotoxicity potential (MAETP) (€/1,4-DCB eq)	0.0001
Terrestic ecotoxicity potential (TETP) (€/1,4-DCB eq)	0.06

This is where the method used in this research differs from the framework of the ISO 14040. Instead of first determining the life cycle inventory (LCI) of one complete product life cycle and then determining the resulting impact via life cycle impact assessment (LCIA), this study first determines the environmental impact of one kg of material as a basic parameter of the model and then uses those values to calculate the total environmental impact by multiplying it with the amount of material present in the design (which is determined during the entry of the different bridge elements into the calculation tool).

The total environmental costs (in this case the total society costs) can then be determined using (3-15). Environmental costs incurred during the life cycle of the bridge are not discounted as recommended by (Hellweg, Hofstetter, & Hungerbuhler, 2003).

$$SC = \sum_{i=n}^{m} EE_i \times SP_i \tag{3-15}$$

Wherein:

SC = society costs (€/functional unit)
EE_i = environmental effects for impact category *i* (kg of impact category equivalent (ICeq)/functional unit (one bridge))
SP_i = the shadow price for environmental effect category *i* (€/kg of ICeq)
i = environmental impact category n until m

The environmental effects per impact category can be determined using Equation (3-16).

$$EE_i = \sum_{j=n}^{m} EE_{i,j} \times Mq_j \tag{3-16}$$

Wherein:

EE_i = environmental effects for impact category *i* (kg of impact category equivalent (kg ICeq)/functional unit (one bridge))
$EE_{i,j}$ = environmental effect for impact category *i* per kg of material *j* (kg ICeq/kg material)
Mq_j = material quantity per functional unit for material *j* (kg material/functional unit)
j = the different materials n until m

4. LCC TOOL

The model that has been developed in Chapter 3 has been used to create the LCC calculation tool. This tool has been created in the spreadsheet software MS Excel. A description of the tool and how it should be used will be given in this chapter.

The developed LCC calculation tool consists two database worksheets and three input worksheets and four output worksheets. These worksheets and their function will be described in this chapter. Starting with the database worksheets in Paragraph 4.1. The three input worksheets will be discussed in Paragraph 4.2 and the output worksheets in Paragraph 4.3. The chapter is closed with some concluding remarks is Paragraph 4.4.

4.1. DATABASE WORKSHEETS

There are two database worksheets: the *Construction element database* and the *Activity database*. The reason for using these databases is to increase the usability of the tool. The input worksheets will pull data from these databases. This way the input variables will not have to be re-entered manually every time.

4.1.1. CONSTRUCTION ELEMENT DATABASE

The *Construction element database* stores the different construction elements and their specific information. These construction elements can be used to set up a specific bridge design in the worksheet *Bridge design*.

When entering elements into the *Construction element database* first a description of the construction element in question is needed. This is done by assigning the construction element a *category*, *item* name and a description of the *type* of element. Next the following information is stored about the relevant element:

- Construction unit cost (CUC): the cost of the construction element per unit expressed in euro's
- Unit: type of units the element is measured in (m, m^2, etc.)
- Material quantities per unit: kilograms of material present in the construction element per unit

An example of the *Construction element database* is shown in Table 4. For an example of the worksheet see Appendix B.

Table 4, Construction element database

Construction element database

Category	**Item**	**Type**	**Construction unit costs (CUC)**	**Unit**
Structure element	Pile_foundation	Prefab. Piles 400x400mm, l=18m + add.rebar	€ 997.75	pc

Continuation:

Kg steel	**Kg concrete**	**Kg polyester**	**Kg glass**	**Kg epoxy**	**Kg carbon fibre**	**Kg asphalt**	**Kg gravel**	**Kg pvc**
615	6660	0	0	0	0	0	0	0

4.1.2. Activity database

The activity database contains the different activities that can be used to make a maintenance scenario in the worksheet *Maintenance scenario*.

First an activity name has to be entered. The following information is then stored about that activity.

- Activity unit cost (AUC): The cost of that activity per unit expressed in euro's
- Unit: type of units the activity is measured in (times, m, m^2, etc.)
- Frequency of activity: determines in what years the activity takes place

An example of the *Activity database* is displayed in Table 5. For an example of the worksheet see Appendix B.

Table 5, Activity database

Activity database			
Activity name	**Activity unit cost**	**Unit**	**Frequency default values (t=?) (once every x years)**
Functional_inspection	€ 500.00	times	2

4.2. INPUT WORKSHEETS

There are three input worksheets: *Bridge design*, *Maintenance scenario,* and *Traffic and general input.* The input worksheets requires the user to enter certain input variables that will be used by the tool to make the necessary calculations. Which inputs are to be entered into what worksheet will be described below.

4.2.1. BRIDGE DESIGN

In the worksheet *Bridge design* a specific bridge design can be entered of which the tool will calculate the LCC. Via dropdown menus the user selects construction elements which are pulled from the *Construction element database*.

One important feature of the tool is that the tool automatically provides the user with the appropriate bridge deck (and the corresponding data such as unit cost and material quantities) that corresponds with the span and width which the user should specify in the *Bridge design* worksheet. The tool does this using the calculations provided in Chapter 2.

When all relevant construction elements have been selected, the worksheet requires you to enter the *Construction element quantity (Cq)* for each selected construction element. The *Construction costs per construction element (ICCi)* are then calculated by multiplying the Cq with the CUC from the database. A summation of these construction costs for every element will then give the total *Assigned construction costs* (see Paragraph 4.1).

Multiplying the *Cq* with the *material quantities per unit* from the *Construction element database* will give the *Material quantities per construction element* ($Mq_{i,j}$). Summing these material quantities for all construction elements will give the *Material quantity per functional unit* (Mq_j).

An example of the worksheet *Bridge design* is shown in Table 6. For an example of the worksheet see Appendix B.

Table 6, Construction inventory

Construction inventory						
Category	**Item**	**Type**	**Construction element quantity (Cq) (# of units)**	**Unit**	**Construction unit cost (CUC) (€/unit)**	**Construction costs (ICC) (€)**
Structural_ element	Pile_ foundation	Prefab. Piles 400x400mm, l=18m + add.rebar	90	pc	€ 997.75	€ 89,797.50

Continuation:

Kg steel	**Kg concrete**	**Kg polyester**	**Kg glass**	**Kg epoxy**	**Kg carbon fibre**	**Kg asphalt**	**Kg gravel**	**Kg pvc**
55,350.00	599,400.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

4.2.2. MAINTENANCE SCENARIO

In the worksheet Maintenance scenario the user of the tool can specify a maintenance scenario which the tool will use to calculate the resulting *Maintenance costs (MC)* and *User costs (UC)*.

The worksheet *Maintenance scenario* works in a similar manner as the worksheet *Bridge design*. The user of the tool has to select maintenance activities from a dropdown menu. The tool then pulls the relevant data (*Frequencies*, *Activity unit costs (AUC)* and *Units*) from the *Activity database*.

There are several other input variables that have to be entered by the user of the tool, these are:

- Quantity of units for activities (Aq): quantity of units corresponding to that activity.
- Activity duration (N): estimation of the duration of the activity expressed in number of days
- Length of work zone (L): the estimated length of the work zone relevant for that activity in km

The user should also select whether the activity calls for a work zone or a complete detour. This choice determines whether Equation (3-9) or Equation (3-10) will be used to determine the *Extra travel time (ETT)*.

The worksheet then calculates the Maintenance costs for each activity *i* (MC_i) by multiplying the Activity unit cost (AUC_i) with the Quantity of units for activities (Aq_i) (according to Equation (3-4)).

The worksheet also calculates the different User costs (UC_i) per activity (i.e. VOC_i, TDC_i and TAC_i) (according to Equation (4.8) – (4.13) which result from the maintenance activity; either due to work zone or due to detour.

An example of the maintenance scenario is given in Table 7. For an example of the worksheet see Appendix B.

Table 7, Maintenance scenario

Maintenance Scenario

Activity name	Frequency (every x years)	Quantity of units for activities (Aq)	Type of unit	Activity unit cost (AUC)
Functional_inspection	2	N/A (1)	times	€ 500.00

Continuation:

Maintenance costs (MCi)	Activity duration (N) (# of days)	Length of work zone (L) (km)	Work zone (calculated ETT) or Detour (specified ETT)?
€ 500.00	1	0	Work zone

Continuation:

Extra travel time (h)	VOC_i	TDC_i	TAC_i
0	€ 0.00	€ 0.00	€ 0.00

4.2.3. Traffic and general input

In the worksheet *Traffic and general input* no calculations are made. The worksheet just stores the input variables as listed in Table 8, Table 9 and Table 10 below. For an example of the worksheet see Appendix B.

Table 8, General parameters

Input general parameters
Discount factor (r) (%)
Operation cost value (€/h)
User cost value (€/h)
Accident cost value (deaths) (€/accident)
Accident cost value (severe injury) (€/accident)
Shadow prices (SP) (€)
Abiotic depletion elements (ADP) (€/Sb eq)
Abiotic depletion fossil (ADP) (€/Sb eq)
Global warming potential (GWP) (€/CO2 eq)
Ozone depletion potential (ODP) (€/CFK-11 eq)
Photochemical ozone formation potential (POCP) (€/C2H2 eq)
Acidification potential (AP) (€/SO2 eq)
Eutrofication potential (EP) (€/PO4 eq)
Human toxicity potential (HTP) (€/1,4-DCB eq)
Freshwater aquatic ecotoxicity potential (FAETP) (€/1,4-DCB eq)
Marine aquatic ecotoxicity potential (MAETP) (€/1,4-DCB eq)
Terrestic ecotoxicity potential (TETP) (€/1,4-DCB eq)

Table 9, Traffic parameters

Input traffic parameters
Average daily traffic (ADT) (PCE)
Yearly rise in traffic intensity (PCE/year)
Normal traffic speed (Sn) (km/h)
Adjusted (work zone) traffic speed (Sa) (km/h)
Average extra travel time due to detour (DTT) (h)
Normal accident rate, deaths (An) (#/vehicle km)
Adjusted (work zone) accident rate, deaths (Aa) (#/vehicle km)
Normal accident rate, severe injury (An) (#/vehicle km)
Adjusted (work zone) accident rate, severe injury (Aa) (#/vehicle km)

Table 10, Environmental parameters

Environmental parameters									
Environmental effects / material **Impact categories**	**EE** steel	**EE** concrete	**EE** polyester	**EE** glass fibre	**EE** epoxy	**EE** carbon fibre	**EE** asphalt	**EE** gravel	**EE** pvc
Abiotic depletion elements (ADP)									
Etc.									

4.3. OUTPUT WORKSHEETS

There are four output worksheets: *Overview*, *Agency costs*, *User costs* and *Society costs*. On these worksheets there is no need to enter any values. The sheets calculate and display the different output variables. The different worksheets will be explained below.

4.3.1. AGENCY COSTS

In the worksheet *Agency costs* the total agency costs are determined. First *the Initial investment costs (ICC)* are determined according to Equation (3-3). The *assigned construction costs* (see Paragraph 4.1) are calculated by summing all the ICC_i from the worksheet *Bridge design*. Next the appropriate percentages (see Table 2) are added to cover *unassigned, indirect, engineering* and *other costs*.

The End of life costs (EoLC) are calculated in the same manner, but are discounted according to Equation (3-7).

To determine the maintenance costs a *Maintenance cost schedule* is created in which the MC_i for each activity is scheduled on the years determined by the *Frequency* corresponding with that activity. The tool can then discount the scheduled maintenance cost depending on the year in which the costs are scheduled. This is done according to Equation (3-5).

An example of the Maintenance costs schedule is shown in Table 11.

Table 11, Maintenance cost schedule

Maintenance costs schedule		year	0	1	2	3	4	…
Maintenance activity	MC_i (€)							
Functional_inspection	€ 500.00		€ 0.00	€ 0.00	€ 500.00	€ 0.00	€ 500.00	…
…	…		…	…	…	…	…	…
Total nominal			**€ 0.00**	**€ 0.00**	**€ 500.00**	**€ 0.00**	**€ 500.00**	**…**
Total discounted			**€ 0.00**	**€ 0.00**	**€ 475.91**	**€ 0.00**	**€ 452.98**	**...**

The *Assigned maintenance costs (MC)* are calculated by summing up all the discounted yearly maintenance costs from the *Maintenance schedule* according to Equation (3-5). Next the appropriate percentages (see Paragraph 4.1.2) are added to cover *unassigned and indirect costs*.

The total *Agency costs (AC)* are then calculated by summing up the three sub-cost categories ICC, MC and EoLC as done in Equation (3-2).

For an example of the worksheet see Appendix B.

4.3.2. USER COSTS

In the worksheet *User costs* the different user costs: *Vehicle operation costs (VOC), Traffic delay costs (TDC) and Traffic accident costs (TAC)* are calculated. This is done in a similar manner as with the *Maintenance costs*. A schedule similar to Table 11 is created for all the three types of user costs and the occurring costs in that schedule are then discounted and summed up according to Equation (3-8).

Summing up the VOC, TDC and TAC (Equation (3-8)) finally gives the total *User costs (UC)*.

For an example of the worksheet see Appendix B.

4.3.3. SOCIETY COSTS

In the worksheet *Society costs* the total environmental costs are calculated. First the *Environmental effects per material (EE_i)* are calculated by multiplying the *Environmental effects per kg of material* ($EE_{i,j}$) as stored in the worksheet *Traffic and general input* (Table 10), by the material quantity per functional unit (Mq_i) as calculated in the worksheet *Bridge design* (see Equation (3-16)).

Next these EE_i are multiplied by the *Shadow prices (SP_i)* as stored in the worksheet *Traffic and general input* (Table 8) and summed up for every environmental effect category according to Equation (3-15).

For an example of the worksheet see Appendix B.

4.3.4. OVERVIEW

The worksheet *Overview* finally displays all outputs into an easy to read page. The page shows the general characteristics of the bridge in question: the bridge deck material, the width and the span of the bridge.

It also sums up the *Agency costs (AC), User costs (UC)* and *Society costs (SC)* into one total LCC value and finally graphs all occurring costs along the life cycle of the bridge.

For an example of the worksheet see Appendix B.

4.4. CONCLUDING REMARKS

The tool described in this chapter is meant to allow the user to quickly and easily assess the LCC of different bridge designs. By having developed this tool the first research goal has been met. In the next chapter this tool will be applied to a specific case in order to meet the second objective of this research. The results of the case study in the next chapter will shed light on the general economic competitiveness of bridges with FRP bridge decks compared to bridges with concrete bridge decks.

5. CASE STUDY

The LCC tool - which has been developed in Chapter 3 and Chapter 4 – will now be used to analyse a specific case. In this chapter this case study will be described. The case under investigation in this research is the Trekvlietbrug. This case has been selected together with Grontmij to represent a rather average single span pre-stressed concrete beam bridges as good as possible.

In paragraph 6.1 a description of the case under investigation will be given. Paragraph 6.2 describes the design alternatives that were compared and which input variables have been used for these design alternatives. Paragraph 6.3 describes the traffic and general input variables used for this case.

5.1. DESCRIPTION CASE TREKVLIETBRUG

The Trekvlietbrug is a vehicular traffic bridge situated at the edge of the Dutch city Leiden as part of the non-highway road Europaweg (N206). It crosses the waterway Trekvliet. According to the Provincie Zuid-Holland (2015) about 40,450 cars pass the bridge every day in 2011, rising with about 460 cars per year from 1995 until 2011. Several interventions are planned for infrastructure in the area to accommodate the rising traffic intensities. The Trekvlietbrug is one of the structures that is planned to see an upgrade in the near future. The base case in this research will be the new design for the Trekvlietbrug.

Currently the bridge consists of a draw bridge with 2 x 2 traffic lanes. The new bridge will be a simply supported single span concrete bridge. The bridge will provide for six traffic lanes and two cycle lanes and is designed to have a lifespan of 100 years.

The new bridge consists of a single sub-structure on which two separate bridge decks will be constructed, one of about 14.70 meters and the other 19.75 meter in width. The span of the bridge will be 32.50 meter. For calculation of the surface area of the bridge deck the design is simplified by assuming one single deck with a total width of 34.50 meter and a total span of 30 meters. For calculating the amount of meters of parapets and edge elements two separate bridge decks are still the assumption. Therefore these are assumed to be four times the span of the bridge.

The following information has been obtained from reference design documents and cost estimation data provided by Grontmij:

- Foundation: 90 precast concrete piles (400x400 mm) with a length 18 meters.
- Abutments: In-situ concrete abutments. Floor, 154.4 m^2, 1250 mm thick, rebar 150kg/m^3; wall, 87.24 m2, 600 mm thick, rebar 150kg/m^3.
- Deck: beams, SKK 1000,
- Approach slabs: 5000x1000x350 mm, 67 pieces
- Sheet piles: AZ37-700, length = 12meters, 104+114 meters
- Sheet piles caps: 900x600 mm, 104 meters
- Grouted anchors: 15 meters, 42+46 pieces
- Groundwork: remove ground, 775 m^3; apply ground, 200 m^3
- Asphalt: 120 mm thick, 1260 m^2
- Waterproof expansion joints: 69 meters
- Sloped ground cover: 290 m^2
- Rainwater drainage: 4 pieces
- Parapets: 144.6 meters
- Concrete edge elements: 144.6 meters

5.2. DESIGN ALTERNATIVES

Two main design alternatives will be investigated in this case study. These two are: a bridge with a concrete deck (Figure 19) as also found in the reference design of the Trekvlietbrug provided by Grontmij (see Paragraph 5.1) and a similar bridge with the only difference being that the concrete deck has been replaced by an FRP bridge deck (Figure 20) based on the calculations provided in Chapter 2 (including a different top layer: epoxy vs asphalt). This means it is assumed that the rest of the bridge design (substructure and surrounding elements) stays exactly the same for both bridge design alternatives. In reality the substructure of the FRP design alternative can probably be optimized to fit the lighter FRP bridge deck. In this research this fact is not taken into account because this is determined to fall outside the scope of this research. A quick evaluation determined that the savings that might go along with a lighter substructure are expected to be rather minimal, but more research would be necessary to determine the actual cost saving possibilities.

Of these two main design alternatives this research also investigates the influence that different bridge spans and differing service lives have on the LCC results. Of both main design alternatives span of 10, 15, 20, 25, and 30 meter are analysed. An overview of the different design alternatives is given in Table 12.

Table 12, Different design alternatives investigated in case study

Design alternatives		
Bridge deck material	**Span**	**Service lives**
Concrete	10	100 and 75
Concrete	15	100 and 75
Concrete	20	100 and 75
Concrete	25	100 and 75
Concrete	30	100 and 75
FRP	10	100 and 150
FRP	15	100 and 150
FRP	20	100 and 150
FRP	25	100 and 150
FRP	30	100 and 150

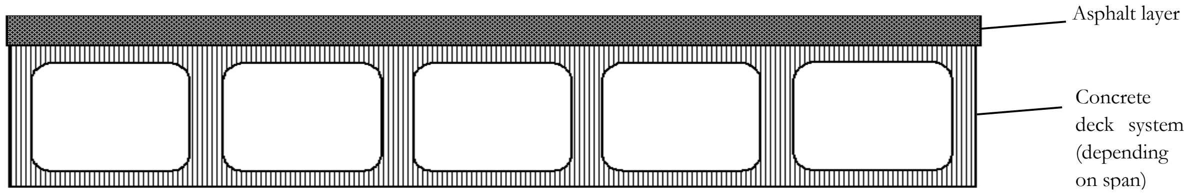


Figure 19, Concrete deck design

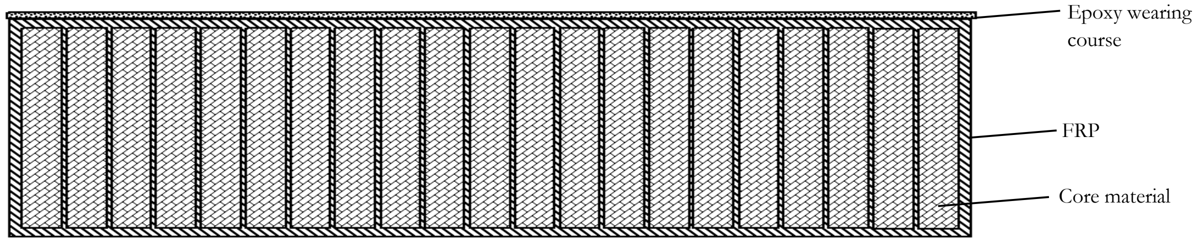


Figure 20, FRP deck design

5.2.1. INPUT WORKSHEET BRIDGE DESIGN

The first worksheet to be entered into the LCC tool is *Bridge design*. Based on the figures found in the reference design and the costs estimation data provided by Grontmij Table 13 shows the bridge design that has been entered into the LCC calculation tool for a 30 meter concrete bridge. The bridge designs of the other design alternatives can be found in Appendix D.

Table 13, Input bridge design for 30 meter concrete bridge

Bridge design	
Bridge deck material	Concrete_deck
Bridge span (m)	30
Bridge width (m)	34.5
Deck surface (m2)	1035
Service life (years)	100

Construction inventory

Category	Item	Type	Construction element quantity (Cq)	Unit	Construction unit cost (CUC) (€/unit)
Structural_element	Pile_foundation	prefab. Piles 400x400mm, l=18m + add.rebar	90	pc	€ 997.75
Structural_element	Abutment	Floor(d=1250mm), wall (d= 600mm)	72.7	m	€ 1,652.13
Structural_element	Concrete_deck	SKK 1000	1035	m²	€ 750.00
Structural_element	Approach_slab	5x1x0,35	67	pc	€ 1,740.00
Structural_element	Sheet_pile_caps	900x600mm	104	m	€ 400.00
Structural_element	Sheet_piles	AZ37-700, lg=12m	104	m	€ 2,148.00
Groundwork	Construction_pit_abutment	Apply ground = 200 m3, remove ground = 775 m3	2	pc	€ 6,336.75
Retaining_wall	Sheet_piles	AZ37-700,lg=12m	114	m	€ 2,148.00
Retaining_wall	Grouted_anchors	lg=15m	46	pc	€ 1,175.00
Pavement	Asfalt	d=12mm	1035	m²	€ 40.00
Pavement	Bridge_expansion_joints	Waterproof	69	m	€ 1,325.00
Pavement	Sloped_ground_cover	Incl. ZC stab.	290	m²	€ 40.00
Pipe_and_cable_work	Rainwater_drainage	Unspecified	4	pc	€ 3,000.00
Pavement	Wearing_course	Epoxy_aggregate	0	m²	€ 65.00
Structural_element	Grouted_anchors	lg=15m	42	pc	€ 1,175.00
Structural_element	Concrete_deck	Parapet	120	m	€ 380.00
Structural_element	Concrete_deck	Edge elements	120	m	€ 176.00

5.2.2. INPUT MAINTENANCE SCENARIO

The second worksheet to be entered in the LCC tool is *Maintenance scenario*. The values for the Frequencies, Activity unit cost (AUC), the number of work days (N) and the length of the work zone (L) are estimations to be made by the user of the calculation tool (preferably based on empirical data). For this case analysis experts at Grontmij helped estimate these numbers. The length of the work zone is based on the Dutch CROW guidelines 96b (CROW, 2014).

The quantities of units for activities (Aq) are – just like the construction element quantities (Cq) – based on the design of the bridge and are expected to be known (or determined) by the user of the calculation tool. Some activities have been given a unit cost (AUC) that is, unlike most, not dependent on any quantities (Aq). For these activities a constant AUC is estimated which reflects the AUC per occurrence. For these activities the Aq not applicable (N/A) and is therefore set to 1 (times). The maintenance scenario for a 30 meter concrete bridge is displayed in Table 14. The maintenance scenarios of the concrete bridges with alternative spans have been altered to match these spans. The *Quantity of units for activities* (Aq) have been altered according to the bridge designs as seen in Appendix D. Also the *Activity duration* (N) of the activities *Asphalt replacement* and *Concrete repair* have been changed proportionately with the span of the bridge (1 day for a span of 10 meters, 1,5 days for a span of 15 meters, etc.) The rest of the maintenance scenario was kept the same for all concrete bridges.

Table 14, Maintenance scenario of 30 meter concrete bridge (source: expert estimations)

Maintenance Scenario

Activity name	Frequency (every x years)	Quantity of units (Aq)	Type of unit	Activity unit cost (AUC)	Activity duration (N) (# of days)	Length of work zone (L) (km)	Workzone or detour?
Construction	100	N/A (1)	times	€3,429,333.80	7	0.5	Workzone
Functional_inspection	2	N/A (1)	times	€500.00	1	0	
Cleaning_parapet_ and_rainwaterdischarge	1	N/A (1)	times	€1,000.00	1	0	
Calamity_maintenance	1	N/A (1)	times	€2,000.00	1	0.5	Workzone
Technical_inspection	10	N/A (1)	times	€5,000.00	2	0	
Repaint_parapets	15	120	m	€150.00	3	0	
Asphalt_maintenance	10	1035	m²	€25.00	0.2	0.5	Workzone
Replace_asphalt	25	1035	m²	€150.00	3	0.5	Workzone
Parapet_replacement	60	120	m	€400.00	1	0.5	Workzone
Guard_rail_ replacement	30	120	m	€300.00	1	0.5	Workzone
Bridge_expantion_ joints_replacement	30	69	m	€2,000.00	2	0.5	Workzone
Concrete_repair	15	1035	m²	€25.00	3	0	
Bridge_bearing_ replacement	50	44	pc	€2,500.00	2		Detour

The maintenance scenario of GFRP bridges is naturally different than of concrete bridges. The activities *Asphalt maintenance, Replace asphalt* and *Concrete repair* are not applicable for GFRP bridges. Therefore these quantities and activity durations have been set to zero. The activity *Replace wearing surface* does come in place for these activities. For the duration of this activity the assumption has been made that it is equal to the duration of the activity *Replace asphalt* of a concrete bridge with the same span.

Another difference is that the duration of the construction of a GFRP bridge has been assumed to be half the duration of a concrete bridge (3.5 days instead of 7 days).

The maintenance scenario of a 30 meter GFRP bridge is shown in Table 15.

Table 15, Maintenance scenario of a 30 meter GFRP bridge (source: expert estimation)

Maintenance Scenario							
Activity name	**Frequency (every x years)**	**Quantity of units (Aq)**	**Type of unit**	**Activity unit cost (AUC)**	**Activity duration (N) (# of days)**	**Length of work zone (L) (km)**	**Workzone or detour?**
Construction	100	N/A (1)	times	€4,890,633.80	3.5	0.5	Workzone
Functional_inspection	2	N/A (1)	times	€500.00	1	0	
Cleaning_parapet_and_ rainwaterdischarge	1	N/A (1)	times	€1,000.00	1	0	
Calamity_maintenance	1	N/A (1)	times	€2,000.00	1	0.5	Workzone
Technical_inspection	10	N/A (1)	times	€5,000.00	2	0	
Repaint_parapets	15	120	m	€150.00	3	0	
Parapet_replacement	60	120	m	€400.00	1	0.5	Workzone
Guard_rail_ replacement	30	120	m	€300.00	1	0.5	Workzone
Bridge_expantion_ joints_replacement	30	69	m	€2,000.00	2	0.5	Workzone
Replace_wearing_ surface	15	1035	m^2	€100.00	3	0.5	Workzone
Bridge_bearing_ replacement	50	44	pc	€2,500.00	2		Detour

5.3. TRAFFIC AND GENERAL INPUT VARIABLES

The last worksheet to be entered is the worksheet *Traffic and general input*. These values are the same for all design alternatives. The values used for this case study and their sources will be discussed below.

5.3.1. TRAFFIC VARIABLES

Six variables fall under this category: *Average daily traffic (ADT), Normal traffic speed (S_n), Adjusted (work zone) traffic speed (S_a), Average extra travel time due to detour (DTT), Normal accident rate (A_n)* and *Adjusted (work zone) accident rate (A_a)*.

In theory all these variables are case specific. However in this case study the author used a national statistic for the determination of the *Normal accident rate* (A_n) and *Adjusted accident rate* (A_a) for a lack of case specific data.

The *Average daily traffic* (ADT) and the average *Normal traffic speed* (S_n) for the bridge have been determined from traffic measurement data from Provincie Zuid-Holland (2015). The most recent measurement data from 2011 showed a traffic intensity of 40,452 passenger car equivalent (PCE) per day. The model also allows for an annual rise in traffic intensity. The annual rise in traffic intensity has been determined by lineal extrapolation of the recorded intensity of the last 15 years. This annual rise was determined to be 463 PCE/year. The *normal traffic speed* (S_n) for the section of road is 50 km/h.

The A*djusted traffic speed* (S_a) is based on the assumption that the new bridge allows for a uncongested traffic flow during work zones. This means that the adjusted traffic speed is solely based on traffic speed limitation measures put in place along work zones and the assumption that the actual average traffic speed meets this speed limitation measure. The assumed traffic speed limitation measures are based on the Dutch CROW guidelines 96b (CROW, 2014) and are set to 30 km/h.

The average *Extra travel time during detour* (DTT) should be estimated by the user of the calculation tool. This is one of the parameters that is hard to estimate because it depends on the source and destination of the traffic passing the bridge. Data about these facts are hard to obtain. A very rough estimation therefore was used in this case analysis of 5 minutes. This value can vary extensively per case.

Normal traffic accident rate (A_n) has been split into values for accidents with resulting deaths and all other accidents. Both values have been taken as average national values because case specific values (rates for the specific road section) were not available. The values have been determined based on the database of SWOV (SWOV, 2009). This database provides data up to 2009. The observable trend of decreasing accident rates has been linearly extrapolated to 2015. This gives estimated values of $A_{n,death}$ = 2.5 deaths per billion vehicle kilometres and $A_{n,serious}$ = 100 serious injuries per billion vehicle kilometres.

The *Adjusted accident rate* (A_a) has been determined from literature sources. The FHWA references several sources that estimate an accident increase of 20% to 70% (depending on the source) during work zone (FHWA's office of operations, 2015). An average estimated 45% increase has been applied to the $A_{n.death}$ and $A_{n,serious}$. This gives values of $A_{a,death}$ = 3.265 deaths per billion vehicle kilometres and $Aa_{,serious}$ = 145 serious injuries per billion vehicle kilometres.

5.3.2. GENERAL INPUT VARIABLES

The last category of input variables for the model is the category *General input variables*. The variables that fall under this category are: *Discount factor* (r), *Construction unit costs* (CUC), *Activity unit costs* (AUC), *Disposal unit costs* (DUC), *Operation cost value* (V_{OC}), *User time value* (V_{UT}), *Accident cost value* (V_{AC}), *Shadow price* (SP), *Impact per kg of material j for environmental category i* ($EE_{i,j}$).

The Dutch Ministerie van Infrastructuur en Milieu asked advice from the Kennisinstituut voor Mobiliteitsbeleid on what discount factor to use. Their advice was to use a discount factor of 2.5% for LCC studies (Kennisinstituut voor Mobiliteitsbeleid, 2012). This is the discount factor that will therefore be used in this study as well.

The CUC, AUC and DUC are all based on estimations based on either cost price data available from Grontmij or estimations made with the help of experts at Grontmij. These values are all entered in the *Construction element database* and *Activity database* present in the spreadsheet calculation tool. When the user of the tool wishes to add elements or activities to the databases, the unit costs of these additions will have to be determined by the user of the calculation tool.

Figures for *Operation costs value* (V_{OC}), *User time value* (V_{UT}) and the *Accident cost value* (V_{AC}) were attempted to be gathered from literature or other sources. V_{oc} proved difficult to determine. The reason is that vehicle operation costs can vary depending on the speed at which the car is traveling. Average hourly values are therefore hard to find. Ehlen (1999) used a value of V_{oc} = $8.85/hour in 1999 dollars (about €10/hour in 2015 euros). Safi (2012) used a value of 79.6 SEK (Swedish Krona)/hour (about €8.50/hour). The Federal Highway Association published average vehicle operation values per kilometre (FHWA's office of operations, 2015). These values have been transformed to hourly values assuming a speed of 30 km/h (based on the speed limit during work zones) and 15% freight traffic. In this case estimations come to about V_{OC} = €8,-/hour.

V_{UT} values were also found in hourly units. But these values are very much dependant on the location of the road and the people that travel the road. The values found were based on figures from the United States but other values more appropriate to this case situation have not been found during the research. Assuming a 15% freight traffic and converting the values of 2010 dollars to 2015 euros (using index values from CBS). The value for V_{UT} was estimated to be about V_{UT} = €20,-/hour.

Accident cost values (V_{AC}) relating to the Dutch situation have been found in the literature. Here too the distinction has been made between accidents with resulting deaths $V_{OC,death}$ and other accidents $V_{oc,\ serious}$. (SWOV, 2014) published values for 2009. Converted to 2015 euros (using index values from CBS) $V_{OC,death}$ = €2,750,000/death and $V_{oc,\ serious}$ = €560,000/serious injury.

The *Shadow prices* (SP) per environmental impact are based on the values published by Rijkswaterstaat in a report written by TNO-MEP (2004). The values of these shadow prices are given in Table 3.

The environmental *Impact per kg of material j for category i* ($EE_{i,j}$) has been determined with the use of LCA-software GaBi. However for two types of material (asphalt and carbon fiber) GaBi could not provide the required values because they were not available in the database of the software. Values for asphalt were obtained from VWB Asfalt (2005). Values for carbon fiber were not obtained during the research.

All the values discussed in this paragraph (except $EE_{i,j}$) are summarized in Table 16. The values for $EE_{i,j}$ are displayed in Appendix E.

Table 16, Values and sources of traffic and general parameters

Variable	Value	Source
Average daily traffic (ADT)	40000 PCE	(Provincie Zuid-Holland, 2015)
Yearly rise in ADT	463 PCE	
Normal traffic speed (S_n)	50 km/h	(Provincie Zuid-Holland, 2015)
Adjusted traffic speed (S_a)	30 km/h	(CROW, 2014)
Extra travel time during detour (DTT)	0.0833 hours (5 minutes)	Rough estimate
Normal traffic accident rate ($A_{n,death}$)	2.5 deaths/billion PCE.km	(SWOV, 2009)
Adjusted accident rate ($A_{a,death}$)	3.265 deaths/billion PCE.km	(SWOV, 2009)
Normal traffic accident rate ($A_{n,death}$)	100 serious injuries/billion PCE.km	(SWOV, 2009)
Adjusted accident rate ($A_{a,death}$)	150 serious injuries/billion PCE.km	(SWOV, 2009)
Discount factor (r)	2.5%	(Kennisinstituut voor Mobiliteitsbeleid, 2012)
Operation cost value (V_{OC})	€8.-/hour	(FHWA's office of operations, 2015)
User time value (V_{UT})	€20.-/hour	(FHWA's office of operations, 2015)
Accident cost value deaths (V_{AC})	€2,750,000.-/death	(SWOV, 2014)
Accident cost value serious injuries (V_{AC})	€560,000.-/serious injury	(SWOV, 2014)

6. LCC RESULTS CASE STUDY

In this chapter the results of the case analyses will be discussed. Starting with an overview of the resulting outputs for concrete and FRP spans of 10, 15, 20, 25, and 30 meters in Paragraph 6.1. Next, in Paragraph 6.2, there will be a more in-depth investigation of the comparison between concrete and GFRP bridge decks per cost category. In Paragraph 6.3 uncertainties in the calculation will be taken into account. After that, in Paragraph 6.3, a sensitivity analysis will reveal the most influential input parameters and the effects of the most influential parameters will be investigated.

6.1. TOTAL LCC OF ALTERNATIVE DESIGNS

As a general presentation of the calculation tool's possibilities and to get an idea of the general economic competitiveness of the different deck designs the total LCC's of the three alternative bridge designs have been calculated over different bridge spans with equal life cycles of 100 years.

While the design calculations of GFRP bridge decks showed that GFRP road bridges with a span of about 24 meters are currently the limit (based on fabrication restrictions), GFRP bridge decks above this limit have been calculated for the sake of completeness. The results are shown in Figure 21.

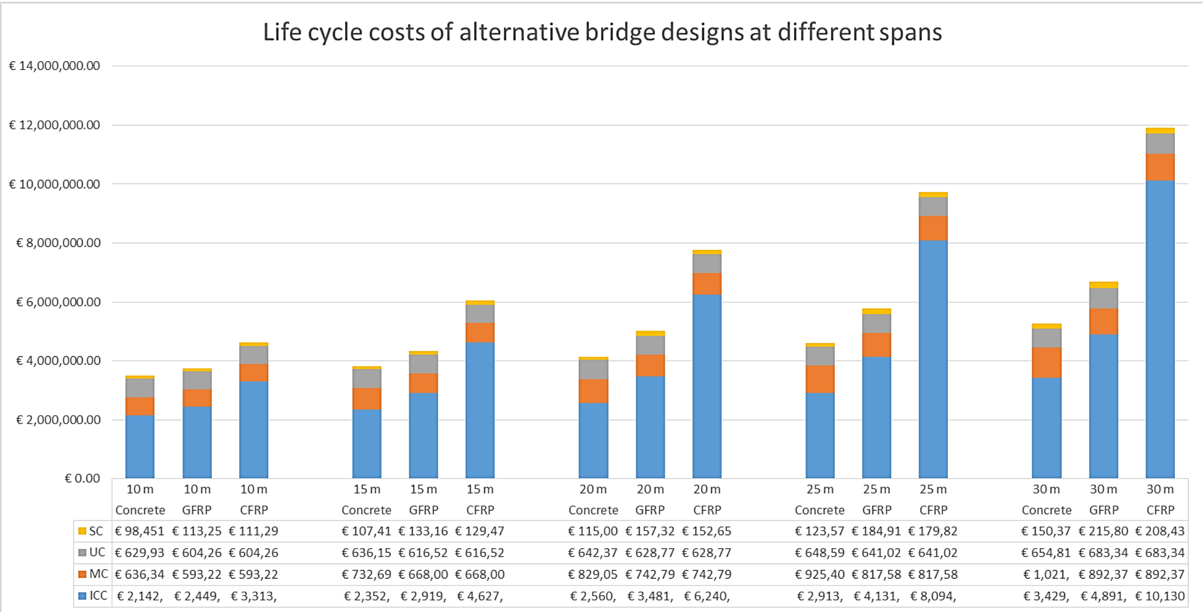


Figure 21, Total LCC for design alternatives at different spans for a life cycle of 100 years

Keeping in mind that the results above are based on the assumption that the input variables are static and accurately represent reality, a few things can be observed.

The first thing that can be noticed is that - using these inputs – concrete has the lowest LCC, GFRP second lowest and CFRP has by far the highest LCC. The difference in total LCC between GFRP and CFRP is caused almost entirely by the difference in ICC. The other costs are either completely the same (MC, UC) or just a little lower (SC). This means that CFRP will always be way less economically competitive than GFRP. It is therefore decided that further analyses will focus only on GFRP and concrete bridge decks.

The second thing that can be observed from Figure 21 is that the AC (ICC+MC) makes up the largest part of the total LCC. Of the AC the ICC makes up the largest part. This is a very interesting result because it directly influences the overall differences between the alternative bridge designs. The differences in MC, UC and SC between the different alternative designs have nearly no effect on the total LCC. One of the reasons for this is that the discount factor reduces the effect of future expenses (MC and UC) on the total LCC. The other reason is that most of the maintenance activities (and their accompanying MC and UC) are unrelated to the type of bridge deck (concrete or FRP) used in the design. Most of the maintenance costs are made up by maintenance activities that are necessary for both concrete bridges and FRP bridges. These activities are calamity maintenance (maintenance after calamity or inspection) and the replacement of bridge expansion joints.

This can be seen well in Figure 22 where the MC and UC have been displayed along the life cycle of the object. The UC and MC for the different design alternatives are very similar. The most notable differences between the two take place on the 15 and 25 year intervals. These are the intervals on which the replacement of the different pavements are scheduled. The rest of the costs are nearly identical.

The effects of discounting can also be seen well in Figure 22 by looking at the costs that take place on 30 year intervals. These costs are mainly caused by the replacement of the bridge expansion joints. At year 60 these costs are discounted to almost half of what they were on year 30, at year 90 it is only about a quarter of the costs compared to year 30.

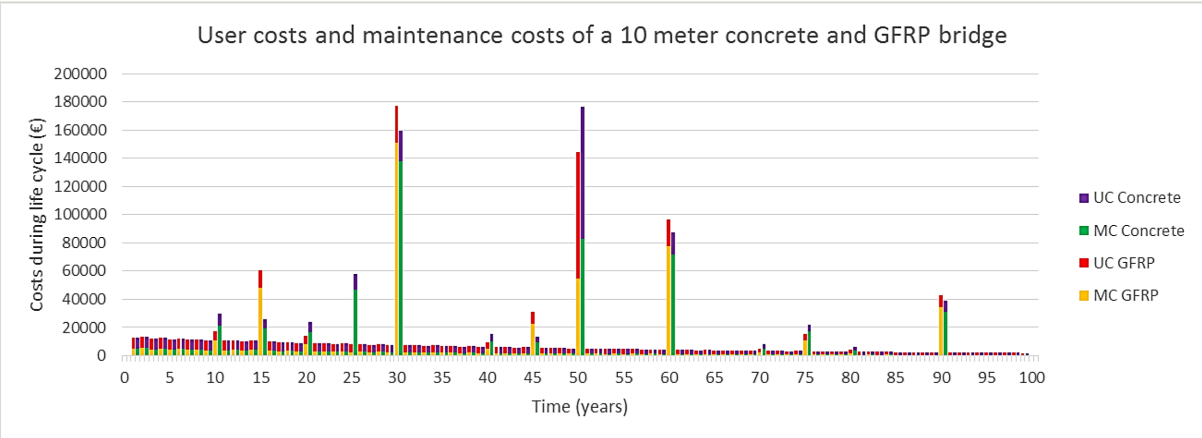


Figure 22, Comparison of user costs and maintenance costs of a 10 meter concrete and GFRP bridge

Figure 23 shows the total cumulative LCC for a 10 and 30 meter concrete bridge and a 10 and 30 meter FRP alternative. The increases to the total LCC are the result of the costs incurred during the lifecycle of the bridge as depicted in Figure 22. In Figure 23 it can be clearly seen that the similarities between the two maintenance schedules of a bridge with a concrete deck and an GRFP deck (and thus the similar UC and MC) make it that the total LCC increases rather equally during the lifespan of the different design alternatives.

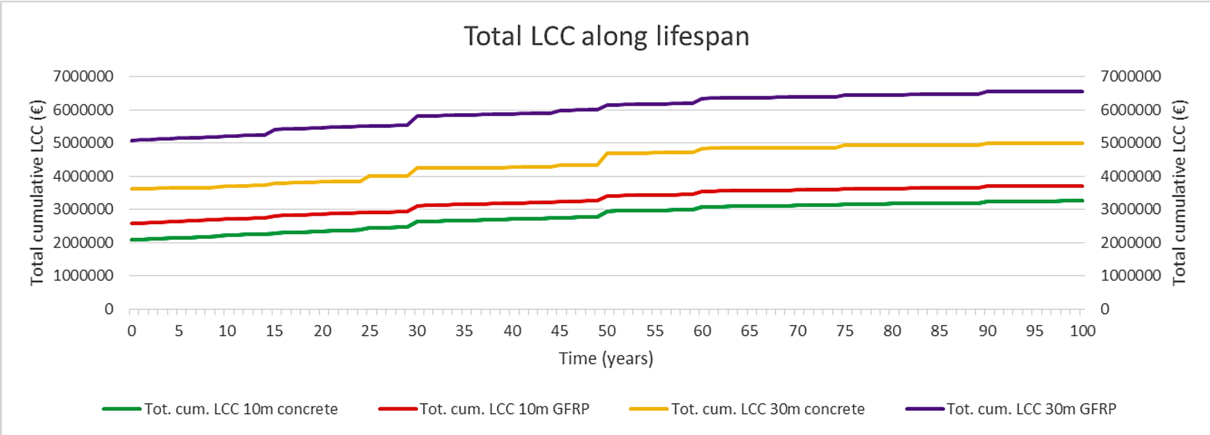


Figure 23, Total cumulative LCC displayed along the lifespan of the bridge

A third observation from Figure 21 is that – as can be expected - the total LCC increases when the span of the bridge increases. The rise in LCC has a weak exponential relation to the span of the bridge. This is explained by the fact that the deck not only increases in surface area but the deck also increases in thickness when spans become larger. Therefore the costs of the decks exponentially grows with span increase. This in turn means the ICC grows exponentially with span increase. Because of the large share that the ICC makes up of the total LCC this exponential trend is also present in the total LCC.

Combining the above observations of higher ICC of GFRP in comparison to concrete decks, the large contribution of ICC on the total LCC, and the exponential rise in ICC when the span increases, it can be seen that: while at 10 meters concrete and GFRP are relatively competitive, the difference in LCC becomes increasingly bigger. Thus at bigger spans it becomes increasingly more difficult for other costs (UC, MC, and SC) to compensate for the difference in ICC.

6.2. Results per cost category

6.2.1. Agency costs

As mentioned above the agency costs make up the most of the total LCC. In Figure 24 the agency costs are displayed in cumulative form along the lifespan of the bridge. The results are from a 10 meter concrete bridge, however the general distribution of the costs are similar for the other bridges that were investigated.

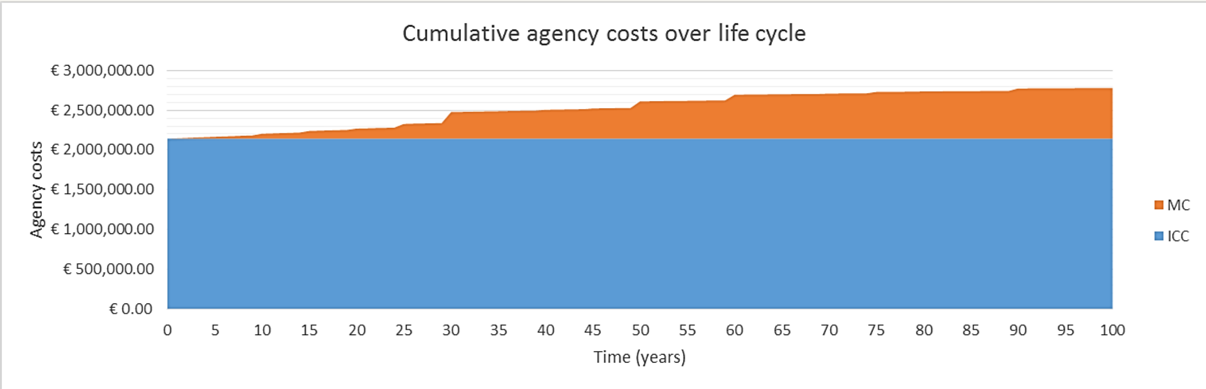


Figure 24, Cumulative agency costs over 100 years for a 10 meter concrete bridge

The effect of discounting the future cash flows of MC becomes clear from the fact that the MC tops off when the time approaches the end of the life cycle. Using this discount factor of 2.5% the total discounted MC over the life cycle is around 20% to 25% of the total AC. This is consistent with figures found in the literature.

6.2.2. User costs

The UC can be further deconstructed into VOC, TDC and TAC. The cumulative UC for a 10 meter concrete bridge are shown in Figure 25.

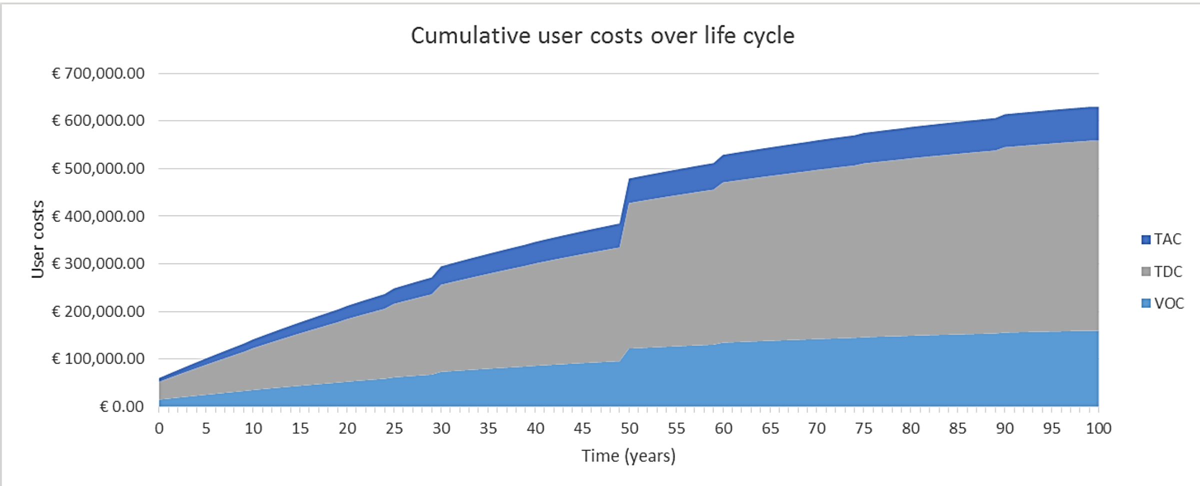


Figure 25, Cumulative user costs over 100 years for a 10 meter concrete bridge

Figure 25 shows that the TDC makes up most of the UC. VOC equals to about 2/5th of the TDC which is directly related to the V_{OC}-value compared to the V_{UT}-value. The TAC only contributes a small amount to the total UC.

Just as with the cumulative MC, the cumulative UC also is greatly influenced by the discounting of future cash flows.

6.2.3. Society costs

The SC, which are in this study the environmental costs, only contribute very little to the total LCC. When broken down into SC per material it becomes clear that steel contributes the most (about 80%) to the total SC. This is shown in Figure 26.

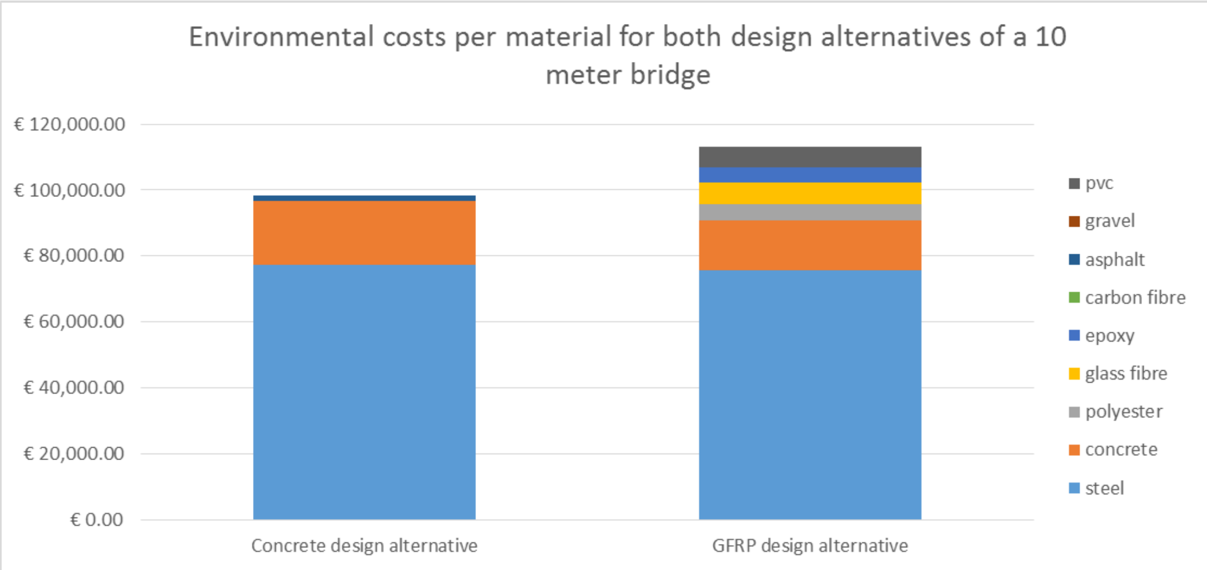


Figure 26, Society costs (environmental costs) per material for a 10 meter concrete bridge and GFRP bridge

In the base case bridge design - the Trekvlietbrug - about 80% of this steel comes from the large amount of sheet piles used in the design. These sheet piles are also present in the FRP alternatives. This is the reason that the SC differ only about 10% between the concrete and the FRP alternatives.

What also becomes apparent from Figure 26 is that the drop in steel and concrete from replacing the deck with a GFRP alternative is overshadowed by the contribution of the GFRP materials combined. This can be seen even better in Figure 27. In this figure only the bridge decks are compared with each other.

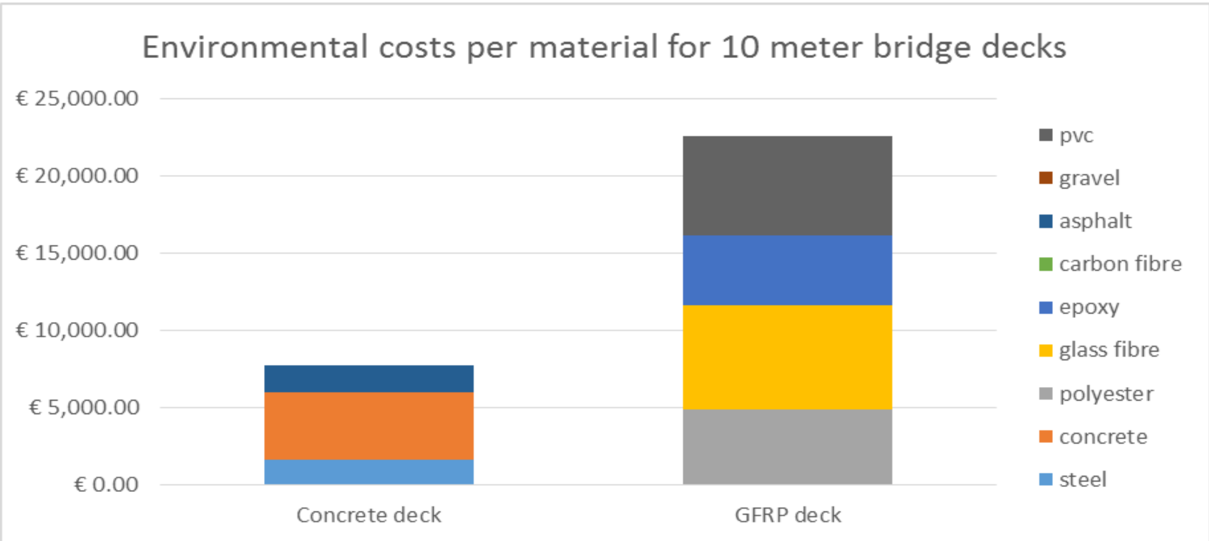


Figure 27, Environmental costs of the different bridge decks of the 10 meter bridge design alternatives

Ultimately, in this comparison this gives the GFRP bridge a higher environmental cost than the concrete alternative. This is consistent with the report of BECO (2013). However, it has to be said that optimization of the substructure (a lighter substructure because of the weight reduction of GFRP bridge decks) for bridge designs with GFRP decks can lower the environmental costs for GFRP bridges. It lies outside the scope of this research to investigate exactly how much can be saved on environmental costs by doing so, but by estimation it seems unlikely that the difference could make a bridge with an GFRP deck the alternative with the lowest environmental costs.

6.3. Uncertainty

While in the previous analysis the input values were kept static, in this section the uncertainties that are inherent to the input variables are investigated. For this the Excel add-in @Risk will be used. This add-in allows to execute Monte Carlo simulations to obtain probabilistic values for the output variables by equipping the input variables with a certain distribution.

The objective of this analysis is to assess the influence of uncertainty of input variables on the outcome of the calculation tool. Because the difference between concrete and FRP bridge decks is under investigation only the input variables that can differ between the two design alternatives will be assigned a probabilistic distribution. Input variables such as the discount factor (r) or the extra travel time (ETT) can be said to be uncertain as well, however these variables will be the same for both design alternatives. Because of this these variables will be assessed later in the report during the sensitivity analysis.

The construction unit costs (CUC) of the (FRP/concrete) deck and the pavement (asphalt/wearing course), the activity unit costs (AUC) of replacing asphalt/wearing course, the AUC of asphalt maintenance, the AUC of concrete repair and the AUC of calamity maintenance have been assigned a triangular distribution of -10% to +10% around the mean value.

The same triangular -10% to +10% has been assigned to the corresponding quantities (Cq and Aq) of the above unit costs.

To the different percentile additions to the *direct construction costs* (the *indirect construction costs, unassigned object risks*, *engineering costs* and *other additional costs*) (χ) a triangular distribution of -25% to +25% has been assigned.

To the activity duration (N) of the activities: *construction*, *replace asphalt, replace wearing course, asphalt maintenance* and *concrete repair* a triangular distribution of -50% to +50% was assigned. This high percentage of 50% is loosely based on the fact that estimating the duration of maintenance activities is very difficult and the duration estimations were not based on empirical data.

The input variables that are assigned a probabilistic value are displayed in Table 17 together with their uncertainty distributions. The above percentages used for the distributions are based on the percentages used in the base case SSK-cost estimation data provided by Grontmij.

Table 17, Input variables and their uncertainty distributions

Variable type	Variables	Type of distribution	Deviation from mean value (minimum to maximum values)
Construction unit cost (CUC)	GFRP deck, Concrete deck, Asphalt, Wearing course	Triangular	-10% to +10%
Activity unit cost (AUC)	Replace asphalt, Replace wearing course, Asphalt maintenance, Concrete repair, Calamity maintenance	Triangular	-10% to +10%
Construction element quantity (Cq)	Concrete deck, GFRP deck, Asphalt, Wearing course	Triangular	-10% to +10%
Quantity of units for activities (Aq)	Replace asphalt, Replace wearing course, Asphalt maintenance, Concrete repair, Calamity maintenance	Triangular	-10% to +10%
Percentile additions (χ)	Indirect construction costs, Unassigned object risks, Engineering costs, Other additional costs	Triangular	-25% to +25%
Activity duration (N)	Replace asphalt, Replace wearing course, Asphalt maintenance, Concrete repair, Calamity maintenance	Triangular	-50% to +50%

The results of the probabilistic calculations have been summarised in Figure 28. The figure displays the calculated LCC values together with the 95% certainty indications. These indicators show that, with these assumptions of uncertainty in the input variables, there is a 95% chance that the LCC output value will lie between these two values.

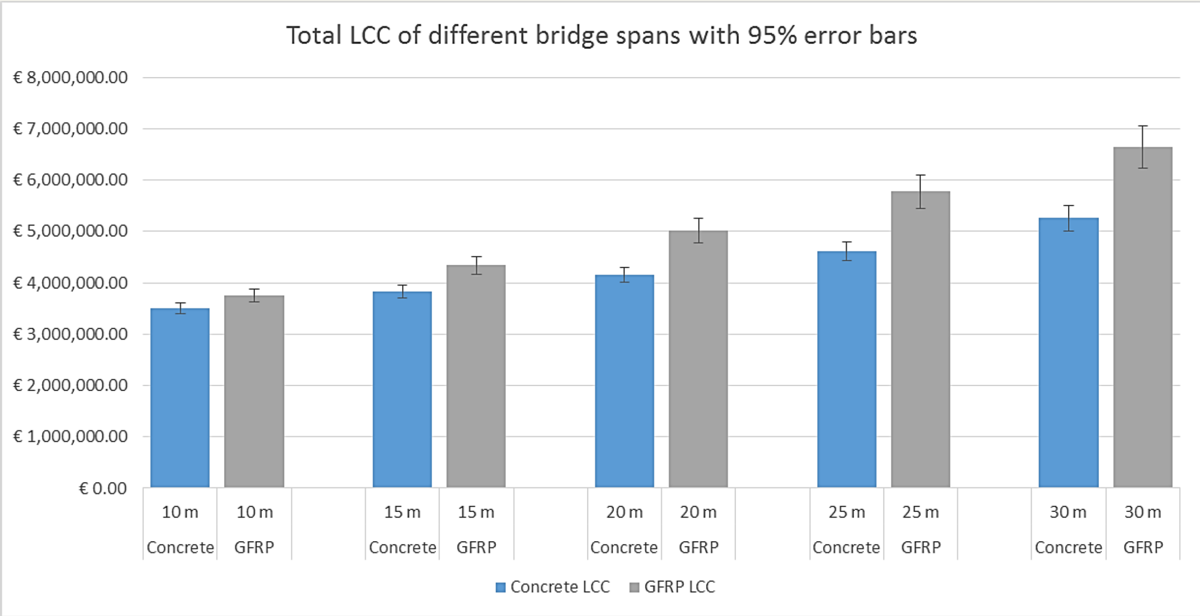


Figure 28, Total LCC with 95% certainty range

Figure 28 again shows that when span increases LCC differences between concrete and GFRP become larger. With the uncertainties modelled as described above there seems to be little to no chance that, with the assumptions used in this case, GFRP will outperform concrete in terms of LCC at short spans of 10 meters let alone at bigger spans.

6.4. Sensitivity analysis

In this section the influence of uncertainty of input variables will be assessed further. As mentioned, there are input variables that are uncertain but their uncertainty has not been incorporated into the Monte Carlo analysis because the values are the same for both design alternatives. Integrating them into the Monte Carlo analysis would skew the results because the difference between the design alternatives would be based on unequal values for these input variables. It is therefore decided to determine the most influential input variables by sensitivity analysis and then recalculate the results with certain ranges for these variables. This way it is possible to determine whether variation of certain input variables influence the results in any significant way.

The following variables have been incorporated into the sensitivity analysis:

Discount factor

As mentioned earlier the discount factor influences the effect of future cash flows on the total LCC. The MC and UC are influenced by this factor. The discount factor used in previous calculations was 2.5% based on the recommended value by the Kennisinstituut voor Mobiliteitsbeleid (2012). This used to be 4% and might again change in the future when the economic situation changes. Based on the discount factors used in the past it is decided to investigate the effect of a 1% change in discount factor in either direction this means a discount factor of 1.5% to 3.5%.

V_{OC}, V_{UT}, and V_{AC}

Based on the different values found in the literature for V_{OC} and V_{UT} the uncertainty of these values are estimated to be about 20% up and down. For all three variables this is the distribution used in the sensitivity analysis.

ADT and rise in ADT

The value used of 40000 PCE average daily traffic is thought to be quite exact by measurements. For good measure a 10% up and down variation will be used.

For the rise in ADT estimated to be 463 PCE per year based on linear extrapolation of historical measurements a variation of -50% to +50% is used. It is expected that personal mobility has almost reached saturation and thus the rise in traffic will halt to a maximum in the course of several years. On the other hand freight traffic is expected to keep rising (Bruinsma, Dijk, & Gorter, 2002). Over the course of a 100 years predictions about the future are very uncertain. A large variation of -50% to +50% seems appropriate.

DTT

The extra travel time due to detour is another variable that is very uncertain. The author does not have data available about the source and destination of traffic passing the bridge and thus alternative routes are hard to determine. A very wild guess of 5 minutes as the base value was chosen. The large uncertainty makes a large variation appropriate and therefore a variation of -50% to +50% is used.

A_n and A_a

The normal and adjusted accident rates are based on national averages. It is very well possible that the accident rate at the location of the bridge differs from the national average. Therefore a variation of -50% to +50% is used.

Length of work zone (L)

The length of the work zone is estimated according to the Dutch CROW guidelines 96b (CROW, 2014). This estimation is 0.5 km. In practice the length of the work zone might be different depending on specific maintenance activities. A 50% up and down variation has been assigned to assess the model's sensitivity to this variation.

Activity frequency

The activity frequency of asphalt replacement is set to 25 years and the frequency of wearing course replacement is set to 15 years based on estimates by maintenance experts at Grontmij. In the report of BECO (2013) these frequencies are rather different. They claim a life time for epoxy wearing course of 25 years and assume a replacement frequency of 15 years for asphalt. To investigate the influence of the variation of replacement frequencies, both values have been entered into the sensitivity analysis.

The above mentioned variation in input values are summarized in Table 18.

Table 18, Input variables and their distributions for sensitivity analysis

Variables	Deviation from mean value (minimum to maximum values)	Values used (minimum to maximum values)
Discount factor (r)	-40% to +40%	1.5% to 3.5%
V_{OC}	-20% to +20%	€6.40/h to €9.60/h
V_{UT}	-20% to +20%	€16.00/h to €24.00/h
$V_{AC, death}$	-20% to +20%	€2,200,000 to €3,300,000
$V_{AC, serious}$	-20% to +20%	€448,000 to €672,000
ADT	-10% to +10%	36000 PCE/day to 44000 PCE/day
Yearly rise in ADT	-50% to +50%	231.5 PCE/day to 694.5 PCE/day
DTT	-50% to +50%	2.5 minutes to 7.5 minutes
$A_{n, death}$	-50% to +50%	1.25 to 3.75 deaths / billion PCE.km
$A_{a, serious}$	-50% to +50%	50 to 150 serious injuries / billion PCE.km
Length of work zone (L)	-50% to +50%	0.25 km to 0.75 km
Frequency activity replace asphalt	-	15 to 25 years
Frequency activity replace wearing course	-	15 to 25 years

The sensitivity analysis has been performed on a concrete bridge of 10 meters. The results of the sensitivity analysis are presented as a tornado graph in Figure 29. The variables are listed from most influential to least influential with their respective range of influence on the LCC displayed next to them.

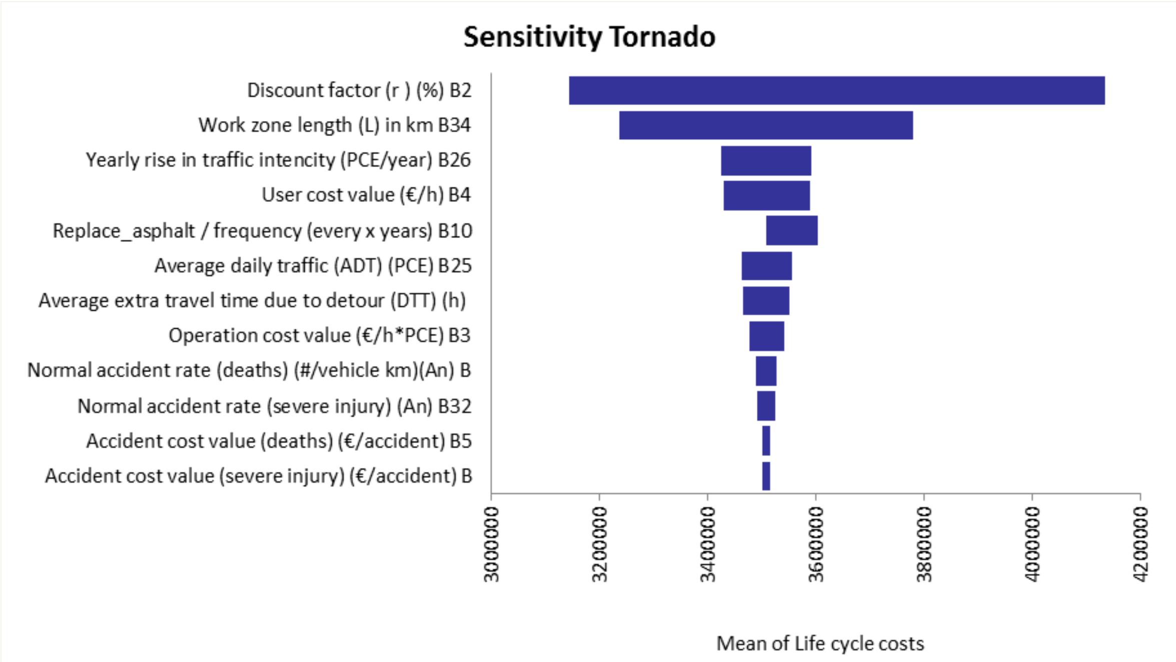


Figure 29, Sensitivity tornado for a 10 meter concrete bridge

The results of the sensitivity analysis in case of a 10 meter concrete bridge show that, of the variables taken into account, a variation in the discount factor (r) has by far the most influence on the total LCC. The second most influential variable is a change in work zone length (L). The change in work zone length can also be seen as a change in extra travel time (ETT), which is calculated based on the work zone length. All other variables only have a relatively small influence on the total LCC.

The sensitivity tornado shows the effects of variation of values of input variables on total LCC. However for the comparison between concrete and GFRP it would be more relevant to assess the effect on the difference in total LCC between the two design alternatives.

Keeping that in mind, there is one other variable that catches the attention. This is the *frequency* of the maintenance activity *replace asphalt*. The total spread as an effect of the variation of the input value for this variable is not as great as that of the variables *yearly rise in traffic intensity* and *user cost value* (V_{UT}). But if this variable is seen as the same variable as the variable *frequency* of the maintenance activity *replace wearing course* in the case of GRFP bridges then this becomes a more interesting variable. This is because unlike the other variables these variables can be different for the two design alternatives. The frequency for the replacement of the wearing course in case of an FRP deck can be, and is probably, different than the frequency for replacement of the asphalt in case of a concrete bridge deck. This means that when comparing the effects of the changes in the input variables on the difference in total LCC between the two design alternatives this variable is probably more relevant than the variables *yearly rise in traffic intensity* and user *costs value*.

Based on the above observations it is decided to investigate the effects of variation of input values on the difference in total LCC between the two design alternatives for the following four input variables: discount factor, extra travel time, frequency replacing asphalt and frequency replacing wearing course.

First in Figure 30 the results of a variation of the discount factor can be observed. This shows that while the effect on total LCC is large for both design alternatives, the difference between the two is nearly unnoticeable.

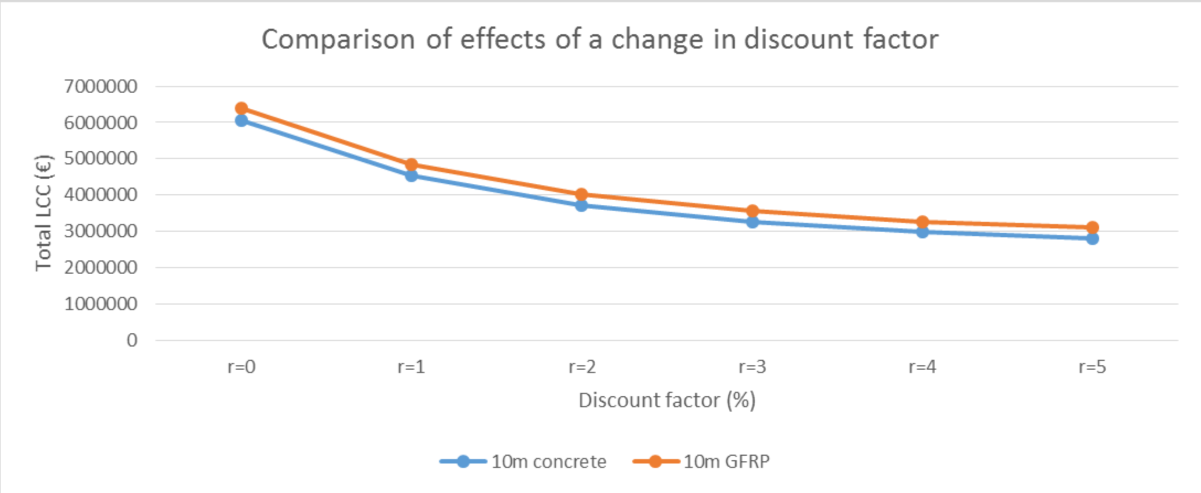


Figure 30, Effects of a change in discount factor on LCC for 10 meter bridges

In Figure 31 the effects of a variation in extra travel time (ETT) is shown. This shows that while with a calculated ETT of about 0.25 minutes in the case of an estimated work zone length of 0.5 km, GFRP has a higher total LCC. However one could argue that the way the model calculates the ETT is too simplified. As explained in Chapter 3, the model calculates ETT based on the assumption that there is uncongested traffic flow along the work zone and only the maximum speed limit adaptations along work zones (in this case from 50 km/h to 30 km/h) are the cause of extra travel time. In practice however, the loss in road capacity during work zones could cause congestion. This could lead to higher ETT is certain situations. It is therefore decided to assess the effects of higher ETT than would be calculated by the model based on work zone length and speed limits. The tool allows the user to enter a fixed value for the ETT to bypass the calculated ETT.

The results in Figure 31 show that, when the ETT rises to about 5 minutes, a 10 meter concrete and a 10 meter GFRP bridge have the same total LCC.

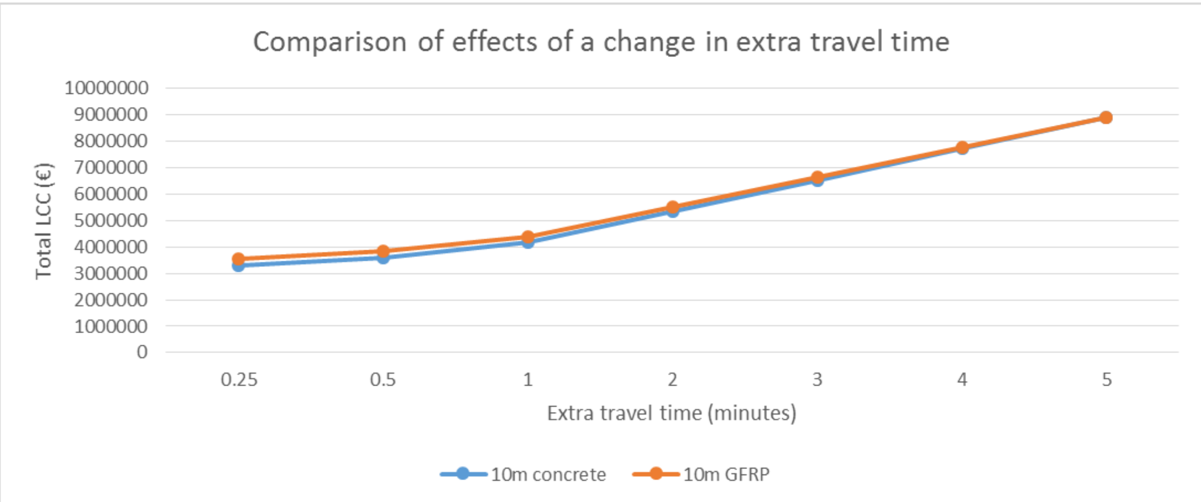


Figure 31, Effects of a change in extra travel time on LCC for 10 meter bridges

Next in Figure 32 the last two variables (asphalt replacement frequency and wearing course replacement frequency) are plotted in one graph. This clearly shows that while the effect on the total LCC is small, the effect on the difference in LCC between the two design alternatives is very significant. The original values as determined by expert estimation at Grontmij (asphalt 25 years, wearing course 15 years) are shown on the right, if these values are the other way around as per the report of BECO (2013) the results come much closer together.

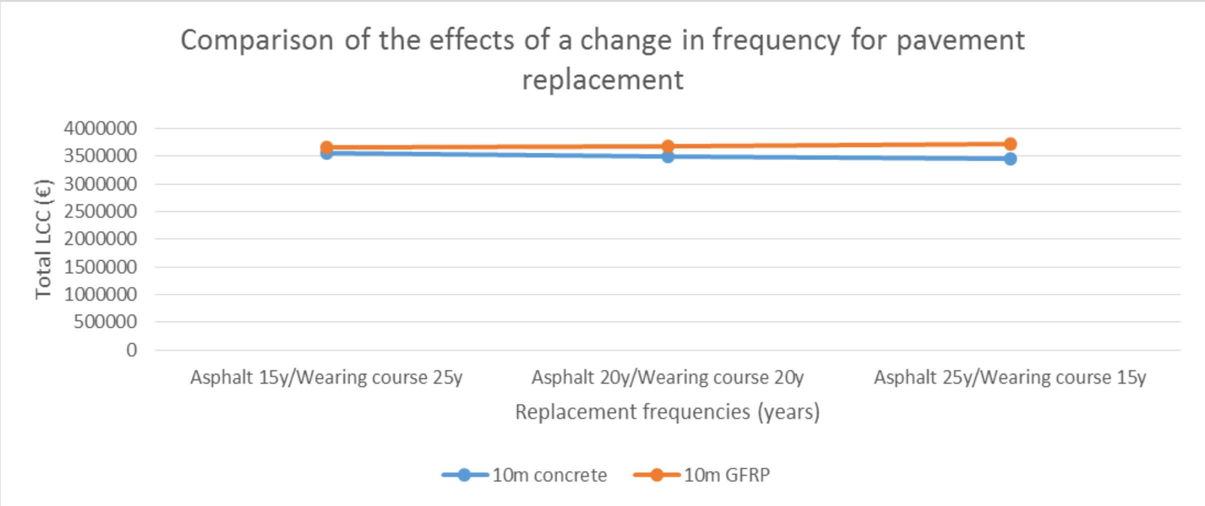


Figure 32, Effects of a change in frequencies for pavement replacement on total LCC for 10 meter bridges

Finally the effects of changes of input values for a combination of the above mentioned variables have also been assessed. This was done by assuming the values as found in the report by BECO (2013) for replacement frequencies of the different pavements. This means a 15 year frequency for asphalt and a 25 year frequency for the wearing course. Next the effects of a change in the discount factor was calculated again with these altered values for the frequencies of pavement replacement. This is shown in Figure 33. This shows that if the frequencies are in fact as mentioned in the BECO (2013) report GFRP and concrete would have equal LCC values at a discount factor of about 1.5%.

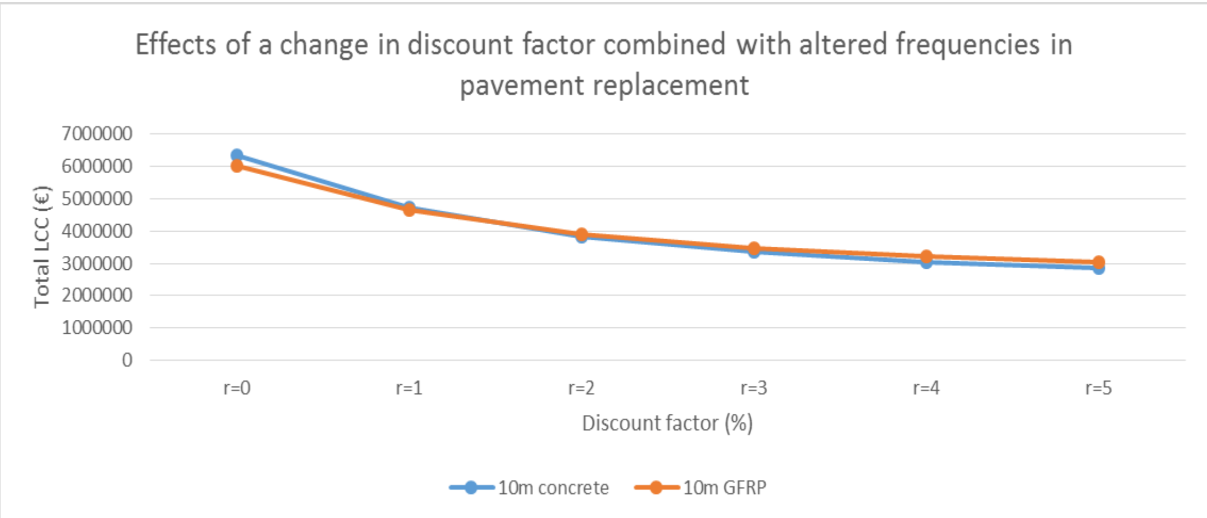


Figure 33, Combined effects of change in discount factor and pavement replacement intervals for 10 meter bridges

The same has been done for a change in ETT. This is shown in Figure 34. This shows that now only an extra travel time of about 1 minute is necessary for GFRP and concrete bridges to have the same total LCC.

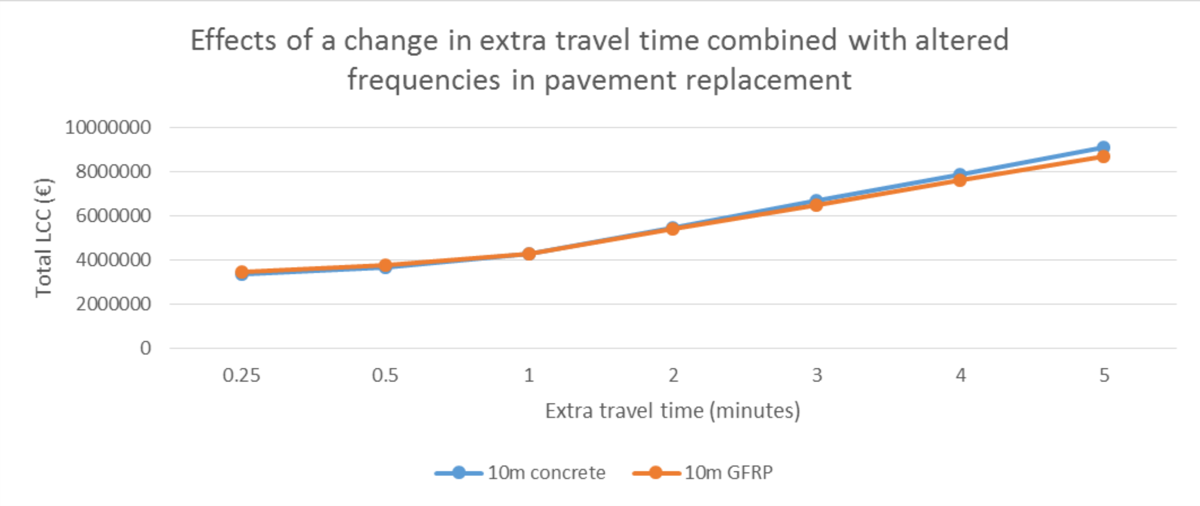


Figure 34, Combined effects of a change in extra travel time and pavement replacement frequencies for 10 meter bridges

One extra variable that has been investigated besides the ones selected above is a change in lifespan. During all the previous calculation the assumption has been that concrete and GFRP bridges have the same lifespan of a 100 years. There are claims that GFRP not only requires less maintenance but also has a longer overall lifespan than concrete. During the course of this research project there has not been found a reliable way to confirm these claims. However, assuming this is true, it is possible to investigate the effects on the total LCC. For convenience it is assumed that GFRP has twice the lifespan of concrete. The lifespan of concrete has been adjusted to 75 years while the lifespan of GFRP has been set to 150 years. All other variables have been kept to their original estimated values.

Figure 35 shows that this assumption would make GFRP the preferred design alternative based on total LCC at smaller spans but loses its advantage at larger spans (the construction costs of the second concrete bridge at t = 75 are included into the MC).

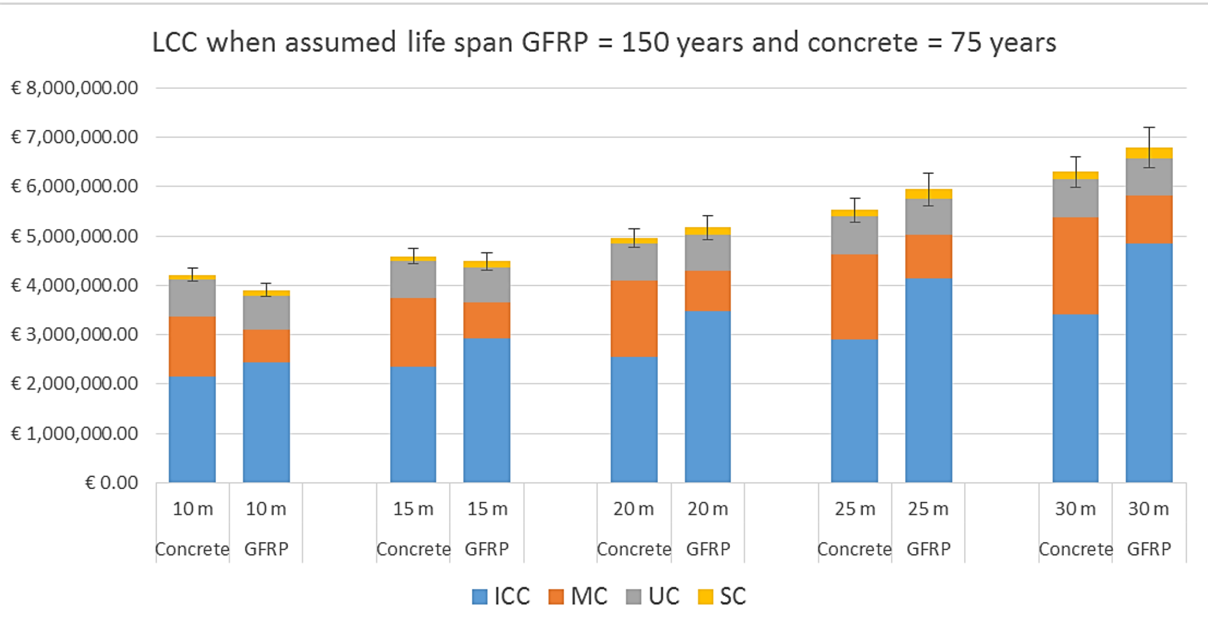


Figure 35, LCC results when GFRP has a lifespan of 150 years versus 75 years for concrete

7. DISCUSSION

In this chapter the research results are discussed. In Paragraph 8.1 the usefulness of the calculation tool will be discussed based on the results of the case study. In Paragraph 8.2 the results of the case study itself will be further discussed and a general picture of the competitiveness of FRP and concrete bridge decks is drawn.

7.1. USEFULNESS LCC CALCULATION TOOL

The developed model and resulting calculation tool have allowed the researcher to compare alternative bridge designs for the base case Trekvlietbrug based on their life cycle costs. Most input variables were obtained with enough certainty to allow for meaningful calculation outcomes. Some input variables were harder to determine but none of them influenced results in such a way that the results became untrustworthy.

When looking at the effects of uncertainty of the input variables related to material costs and quantities as done in Paragraph 6.5 it can be seen that the 95% spreads are relatively small compared to the differences between the two design alternatives. This means that uncertainty about these figures do not influence results enough to determine the results useless.

In Paragraph 6.6 the sensitivity of the model to changes in other input variables have been investigated. The discount factor showed to have the most influence on the total LCC results. However this variable did not have much influence on the difference between the LCC values of both design alternatives.

The second most influential variable was seen to be the extra travel time. As discussed in Paragraph 6.6 the way the model calculates the ETT can be questioned because the model does not account for possible congestion resulting from loss of road capacity during the presence of work zones. If one does want to use the tool in cases where congestion is very likely to occur, the tool allows to enter a fixed estimated ETT. The user of the tool would have to estimate the occurring ETT himself (or with other available tools/models).

Per individual case it should be assessed what assumptions are realistic concerning ETT during construction and maintenance. In the case of the Trekvlietbrug is does not seem an unrealistic assumption that uncongested traffic flow is possible during maintenance. This is because of the width of the bridge. This width might leave enough room for traffic to pass without congestion occurring when only one of the lanes is closed for maintenance. More accurate determination of effects of construction and maintenance on traffic flow is desirable however.

Just as with the discount factor, a large change in the input value for ETT would have to take place for there to be a change in the difference between the LCC of both design alternatives. This is because in our case there is only a very minimal difference in the costs that are affected by these two variables (user costs and maintenance costs). This small difference (as a result of very similar maintenance scenarios) causes the LCC of both design alternatives to change at a very similar rate.

This changes when the maintenance scenarios are altered. When the frequencies of the pavement replacements are altered in such a way that the difference in maintenance between the two design alternatives becomes larger, the effects of changing the discount factor and the ETT become much more pronounced. It is therefore very important that the maintenance scenarios are determined as accurately as possible in order to get the most meaningful results.

In our case study estimations for traffic hindrance during construction and maintenance were based on expert estimations. So were the maintenance activity frequencies and costs. These estimations can always be questioned. Preferably these numbers are based on empirical data. Especially the differences in construction execution time might have a significant contribution to the determination of user costs. More research can shed light on the actual differences between the two design alternatives.

One last discussion point is the question whether in practice stakeholders value the three different cost categories that were taken into account in this study (Agency costs, User costs and Society costs) equally. One can imagine that in situations when a client (agency) has a limiting budget, managing this budget (low agency costs) might be valued higher then reducing traffic delay due to construction and maintenance (low user costs) and having a low environmental impact. In other situations mitigating traffic disruptions due to construction and maintenance and minding the environment might have a higher priority. In this study however the different cost categories we simply added up. This assumes equal valuation of all cost categories.

If the user of the tool is aware of these limitations and keeps in mind their possible effects on the LCC results for the specific bridge under investigation, then this LCC calculation tool can be successfully used for estimating the LCC of different design alternatives in a quick and easy manner.

7.2. DISCUSSION OF RESULTS CASE STUDY

Looking at the results it becomes clear that bridges with FRP bridge decks at longer spans have a very hard time competing with bridges with concrete bridge decks. Taking into account the manufacturing limitations of FRP bridge decks (GFRP decks with spans of over 24 meters have been calculated to be very unlikely at the moment), the only alternative choice for concrete bridges with spans of 25 to 30 meters are CFRP bridge decks. These CFRP bridge decks have been calculated to have such high investment costs that FRP bridge decks for these spans are very unlikely to be economically preferable.

For spans of 10 to 24 meters only at the smallest spans are bridges with GFRP bridge decks somewhat likely to be able to compete with bridges with concrete bridge decks. The LCC of concrete bridges and GFRP bridges at a 10 meter bridge span are close enough to imagine scenarios in which GFRP becomes economically competitive. At larger spans the difference in LCC caused by the premium price of GFRP bridge decks are so large that it seems very unlikely that a GFRP bridge can compete economically with a concrete bridge.

The claim that GFRP should have a lower LCC because it requires less maintenance seems unlikely when only looking at maintenance costs. However, when also incorporating user costs this claim might be true is certain cases for bridges with shorter spans (10 to 15 meters). For example when the replacement of asphalt is set to every 15 years and the replacement of the epoxy wearing course is set to 25 years, combined with an ETT of about 1 minute (see Paragraph 6.6). These assumptions do not seem unrealistic for certain cases. More accurate determination of replacement intervals and ETT is recommended in order to draw more reliable conclusions for comparable cases.

Above statements are only applicable when assuming equal lifespans for GFRP and concrete bridge decks. When assuming longer lifespans for GFRP compared to concrete, GFRP becomes much more economically competitive at smaller spans. At larger spans however even with a longer lifespan GFRP has higher LCC compared to concrete. More accurate determination of lifespans of the two bridge decks are therefore recommended.

The above observations are all based on current GFRP production costs. There is a possibility that these costs will drop when GFRP becomes more used for bridge building due to economy of scale (or other unknown factors). With GFRP being about 2 to 2.5 times as costly per square meter bridge deck compared to concrete, some serious production costs drops would be necessary for GFRP to become attractive based on just initial investment costs. Combined with the possible savings on user costs and maintenance costs compared to concrete, GFRP would not have to actually become half the cost it is now to be economically attractive at smaller spans. However, for GFRP to become attractive at larger spans a drop in production cost is the only likely factor that will achieve this.

The claim that FRP is environmentally beneficial compared to concrete seems unlikely based on the calculations made for the case study. Reusability of FRP might lower impact on the environmental significantly. Specific plans for reusing FRP bridge decks would have to be made in order to support this argument.

The effect of environmental costs on the total LCC of bridges is so minimal that the difference in LCC between bridges with concrete bridge decks and bridges with FRP bridge decks will not be determined by their environmental costs. Based on LCC, environmental costs are therefore not a convincing argument to support either concrete bridge decks or FRP bridge decks. In practice environmental impact might be considered separately from LCC. Even when considered independently of LCC, FRP does not seem to offer a benefit compared to concrete either.

8. CONCLUSIONS AND RECOMMENDATIONS

In this chapter the conclusion of the research are drawn and based on the discussion and conclusions recommendation are given. The conclusions of the research are described in Paragraph 8.1. These conclusion give answers on the research questions. In Paragraph 8.2 some recommendations have been made to Grontmij and some general recommendation are made for further research.

8.1. CONCLUSIONS

For this research the aim was to develop a parametric calculation tool that is able to calculate life cycle costs of different bridge design alternatives and to apply this tool to a specific case in order to get an idea of the general economic competitiveness of FRP bridges compared to concrete bridges.

Based on literature review it was decided to include agency costs (initial construction costs and maintenance costs), user costs (traffic delay, vehicle operation and accident costs) and society costs (environmental costs). A model was constructed which describes the necessary input variables and calculations to be able to estimate total life cycle costs. This model was then used to develop the calculation tool using a spreadsheet computer program.

The Trekvlietbrug was selected for the case analysis, two alternative bridge designs were developed for this case. The only difference between these two designs was the type of bridge deck (including surface layer) that was used. The rest of the bridge (substructure) has been taken into account for the calculation for the entire LCC but the substructures of both bridge designs have been kept exactly the same. The developed bridge designs were entered into the developed calculation tool which then estimated the corresponding outputs.

Based on the results of the calculation tool the following conclusions can be drawn.

Based on the relatively small 95% certainty ranges of the calculated LCC and the results of the sensitivity analysis it can be concluded that the tool is accurate enough to aid in bridge superstructure material selection. The results of the specific case give a clear enough picture to draw some general conclusions about the competitiveness of bridges with FRP bridge decks compared to bridges with concrete bridge decks.

Social costs (environmental costs) only make up a very small part of the total LCC. In fact, the share of social costs is so small that the question remains whether they are at all relevant to the determination of total LCC. Maybe it would be better to consider environmental considerations separately from life cycle cost considerations.

The effect of the unit cost of the bridge deck is seen to be such a large contributor to the total LCC that the results are almost defined by it. Claims that the premium price of FRP over concrete can be negated by the savings on maintenance costs have been proven rather unlikely. While it seems likely that FRP requires less maintenance than concrete bridge decks, the effect of the savings in maintenance are dwarfed by the small share that maintenance costs make up of the total LCC. The reason for this is that future expenses are discounted to a point that only a fraction of the nominal maintenance costs remain (about 20% to 25% of the total agency costs).

In this particular case the other costs category, user costs, also does not contribute enough to the total LCC to negate the premium price of GFRP bridge decks. There might be situations in which user costs are much higher, such as when congestion occurs during maintenance or when work zones require detours regularly because of the small width of the bridge that total closure of the bridge is necessary. In these cases user costs might increase to a level that the higher investment costs of GFRP bridge decks will be cancelled out when looking at the total LCC.

The most influential input variables were found to be the discount factor and the extra travel time, especially if these variables are combined with larger differences in maintenance schedules between GFRP and concrete. The discount factor influences the results of both design alternatives pretty equally if there is only a small difference in maintenance costs and user costs to begin with (which was the case in this research). The extra travel time is largely dependent on the assumptions for the effect that maintenance activities will have on traffic flow. This effect should be assessed for each case individually and might make the decisive difference for determining the preferred bridge deck alternative based on total LCC. The determination of the maintenance scenarios for both bridges with GFRP and bridges with concrete bridge decks are critical for determination of LCC values. Especially the determination of the frequency of the replacement of the different pavement systems (asphalt versus epoxy wearing course) is significant.

One last variable that has a large influence on the results are the assumptions for the life spans of the different design alternatives. If the lifespan of GFRP bridge decks are significantly larger than that of concrete bridge decks, bridges with GFRP bridge decks become much more economically competitive. Still, this only counts for bridges with smaller bridge spans. At larger spans this effect is less significant.

In short, the results show that only at smaller spans there might be situations thinkable in which total LCC for bridges with GFRP bridge decks might be lower than for bridges with concrete bridge decks, this will only be the case if user costs are taken into account. The likelihood that GFRP will outperform concrete when only looking at agency costs seem very small to non-existent at this time. Society costs (environmental costs) have almost no effect on total LCC. The likelihood that bridges with GFRP bridge decks outperform bridges with concrete bride decks at larger spans (20 to 30 meter) is also very unlikely. Serious drops in manufacturing costs for GFRP would have to take place for this to be a likely possibility.

8.2. RECOMMENDATIONS

The following recommendations are made to Grontmij:

The first recommendation to Grontmij is to recognise the possibilities of FRP as a bridge construction material. While in our case FRP showed to be unfavourable in term of LCC based on the assumptions made, the advantages of FRP such as light weight and durability might offer true benefits in certain situations. FRP might not be beneficial in most situations but it might in some. It is therefore key to recognise these situations and the opportunities that go with them.

Grontmij can use the developed calculation tool to further investigate in what situations exactly bridges with GFRP bridge decks can be economically beneficial. It is now clear that at smaller bridge spans FRP can sometimes compete with concrete bridge decks. LCC results depend largely on the discount factor, extra travel time and the maintenance scenarios for both types of bridge decks. The discount factor is not under control of Grontmij and is not case specific. But the extra travel time and maintenance scenarios can maybe be controlled and are case specific. In this case study these variables were more or less estimated (albeit expert estimations). More accurate determination of these variables, preferably by using empirical data, can shed more light on the exact situations and conditions in which FRP is the preferable design choice. For example: more accurate determination of the differences between FRP and concrete construction duration and how construction processes affect traffic, more accurate determination of pavement replacement frequencies, and determination of how different types of environments affect maintenance scenarios.

The other variable that was determined to have a large influence on the results is the lifespan of the bridge decks. In this research the author was not able to further investigate the claims of longer lifespan of FRP compared to concrete. Further investigation of the actual expected lifespans of FRP and concrete bridge decks are necessary to determine more accurately how FRP bridge decks compare to concrete bridge decks.

Grontmij can also use the tool (if needed with adaptations) to compare LCC of other bridges besides FRP and concrete.

The following recommendation for further research are made in general:

In order to make FRP more attractive as a bridge building material in general and possibly also open up the possibility of using FRP at larger spans it seems logical to look for ways to lower the production costs of FRP bridge decks.

As mentioned in the discussion there are some limitations to the model that was used in this research. It might be interesting to investigate the effects of these limitations more extensively. Maybe there is a more accurate way to determine the effect of construction and maintenance activities on the traffic disruptions, while keeping in mind to not make the model too complicated to use.

Another discussion point is the weighing of the different cost categories. Currently all categories are assumed equally important. While this assumption might be theoretically correct, in practice investment decisions are likely to be less neutral. A way to analyse the value principals attach to the different cost categories and how they are taken into account in the decision making might give new insight into the most likely design alternative to win a tender.

Besides the discussion about the lifespan of FRP bridge decks compared to concrete bridge decks, another aspect that might be advantageous for FRP bridge decks is their reusability. If bridges are in need of replacement, not because of structural insufficiency (end of technical lifespan) but because of function changes due to a need for increased capacity (functional lifespan), the reusability of FRP bridge decks from one location to another might deliver a significant advantage over concrete bridge decks. This way, even if the structural lifespan might be equal, the functional lifespan of FRP decks can be increased dramatically. A further investigation might shed more light on the options of reusability and how this affects the LCC of FRP bridges.

REFERENCES

Astrom, T. B. (1997). *Manufacturing of Polymer Composites*. New York: Chapman & Hall. Retrieved from https://www.crcpress.com/product/isbn/9780748770762

BECO. (2013, September). Vergelijkende LCA studie bruggen: Vaststellen van duurzaamheidscore van bruggen uitgevoerd in staal, beton, composiet en hout. BECO. Retrieved from http://www.houtinfo.nl/bos-milieu/lca-bruggen-onderling-vergeleken

Boniou, A. (2013, March 12). About MAINLINE project [Text]. Retrieved October 4, 2015, from http://www.mainline-project.eu/

Bruinsma, F. R., Dijk, J. van, & Gorter, C. (2002). *Mobiliteit en beleid*. Uitgeverij Van Gorcum.

Burgoyne, C., & Balafas, I. (2007). Why is FRP not a Financial Success? In *Proc. 8th Intl. Conf. on FRP Reinforcement for Reinforced Concrete Structures, FRPRCS-8, Univ. of Patras, Patras, Greece*. Retrieved from http://www-civ.eng.cam.ac.uk/cjb/papers/cp74.pdf

CE Delft. (2003, April). Weging in DuboCalc: Toepasbaarheid van de preventiemethodiek. CE Delft. Retrieved from http://www.ce.nl/?go=home.downloadPub&id=72&file=03_7486_13.pdf

Chandler, R. F. (2004). *Life-cycle Cost Model for Evaluating the Sustainability of Bridge Decks: A Comparison of Conventional Concrete Joints and Engineered Cementitious Composite Link Slabs: a Thesis Submitted in Partial Fulfillment... Master of Science (Natural Resources and Environment)...* University of Michigan.

Chlosta, M. (2012). *Feasibility study on fiber reinforced polymer cylindrical truss bridges for heavy traffic*. TU Delft, Delft University of Technology. Retrieved from http://repository.tudelft.nl/view/ir/uuid:6dd0caf0-3128-4200-93a5-104ebbbc135f/

CROW. (2010). *Standaardsystematiek voor kostenramingen SSK-2010*. Ede: CROW.

CROW. (2014). *CROW-richtlijnen Werk in Uitvoering 96b*. Ede: CROW.

CUR commissie C 124. (2013). CUR Recommendation 96 “Fibre-reinforced polymers in civil load bearing structures” (CUR 96). Civieltechnisch centrum uitvoering research en regelegeving.

Das, P. C., Frangopol, D. M., & Nowak, A. S. (1999). *Current and Future Trends in Bridge Design, Construction and Maintenance: Safety, Economy, Sustainability and Aesthetics*. Thomas Telford.

Davidson, M., & Wit, R. (2003). Weging in Dubocalc: Toepasbaarheid van de preventiemethodiek. CE Opossingen voor milieu, economie en technologie. Retrieved from http://www.ce.nl/publicatie/weging_in_dubocalc/72

Ehlen, M. (1997). Life-Cycle Costs of New Construction Materials. *Journal of Infrastructure Systems*, *3*(4), 129–133.

Ehlen, M. (1999). Life-cycle costs of fibre reinforced-polymer bridge decks. *Journal of Materials in Civil Engineering*, *11*(3), 224–230.

FHWA's office of operations. (2015). Work Zone Road User Costs - Concepts and Applications. Retrieved August 27, 2015, from http://ops.fhwa.dot.gov/wz/resources/publications/fhwahop12005/sec2.htm

FiberCore Europe. (n.d.). Hoofdbrug Oosterwolde. FiberCore Europe. Retrieved from http://www.fibercore-europe.com/index.php?option=com_k2&view=item&id=521:hoofdbrug-oosterwolde-lift-bridge&Itemid=243&lang=en

Fiberline Composites. (n.d.). West Mill Bridge, England. Fiberline Composites. Retrieved from http://fiberline.com/west-mill-bridge-england

Hastak, M., Halpin, D., & Hong, T. (2004). *Constructability, Maintainability, and Operability of Fiber Reinforced Polymer (FRP) Bridge Deck Panels* (No. FHWA/IN/JTRP-2004/15, 2778). West Lafayette, IN: Purdue University. Retrieved from http://docs.lib.purdue.edu/jtrp/40

Hellweg, S., Hofstetter, T. B., & Hungerbuhler, K. (2003). Discounting and the environment should current impacts be weighted differently than impacts harming future generations? *The International Journal of Life Cycle Assessment*, *8*(1), 8–18.

Hollaway, L. (2012). *Polymer Composites for Civil and Structural Engineering*. Springer Science & Business Media.

Kennisinstituut voor Mobiliteitsbeleid. (2012, September). Advies te hanteren discontovoet bij de life cycle cost analyse. Retrieved from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2012/10/30/advies-discontovoet-life-cycle-cost-analyses/discontovoet-bij-de-life-cycle.pdf

Keoleian, G. A., Kendall, A., Dettling, J. E., Smith, V. M., Chandler, R. F., Lepech, M. D., & Li, V. C. (2005). Life-cycle cost model for evaluating the sustainability of bridge decks. Retrieved from http://deepblue.lib.umich.edu/handle/2027.42/84802

Kim, Y. J. (2014). *Advanced Composites in Bridge Construction and Repair*. Philadelphia, PA: Woodhead Pub.

KTH Royal Institute of Technology. (2009, February 18). ETSI Project. Retrieved from http://bridge.aalto.fi/fi/Etsiwww2/index.html

Moon, F. L., Aktan, A. E., Furuta, H., & Dogaki, M. (2009). Governing issues and alternate resolutions for a highway transportation agency's transition to asset management. *Structure and Infrastructure Engineering*, *5*(1), 25–39. http://doi.org/10.1080/15732470701322768

Murphy, N. (2013). *Feasibility Analysis of a Fiber Reinforced Polymer Bridge*. Retrieved from http://www.diva-portal.org/smash/get/diva2:639694/FULLTEXT02

Nijssen, R. P. L. (2013). Composieten Basiskennis.pdf. Hogeschool Inholland.

NIST US Department of Commerce. (2011, August 1). BridgeLCC. Retrieved October 2, 2015, from http://www.nist.gov/el/economics/bridgelcc.cfm

Pieters, D., & Pol, S. (2014). Spoortrogligger toegepast met vezel versterkte kunststoffen: Haalbaarheidsonderzoek.

Provincie Zuid-Holland. (2015). Intensiteit Provinciale wegen [Data bank]. Retrieved September 10, 2015, from http://staatvan.zuid-holland.nl/Paginas/Cijfers%20en%20kaarten/Tableau/Intensiteit-Provinciale-wegen.aspx

Safi, M. (2012, February). *LCC Applications for Bridges and Integration with BMS*.

Shah, R., Walsh, S., & Ross, A. (2013). Challenges and solutions for management of FRP usage in the UK rail sector. In *Proceedings of the 29th Annual ARCOM Conference*. Retrieved from http://www.arcom.ac.uk/-docs/proceedings/ar2013-0123-0134_Shah_Walsh_Ross.pdf

Spanbeton. (2015, September 4). Kennisportaal. Retrieved September 4, 2015, from http://www.spanbeton.nl/nl/media/kennisportaal/

Sundquist, H., & Karoumi, R. (2012). *Life Cycle Cost Methodology and LCC Tools*. ETSI. Retrieved from http://www.etsi.aalto.fi/Etsi3/PDF/TG3/LCC%20Description.pdf

SWOV. (2009). Werkelijk aantal doden en ernstig verkeersgewonden per afgelegde afstand (mld reizigerskilometers). Bron: CBS, IenM en DHD. Retrieved September 10, 2015, from https://www.swov.nl/ibmcognos/cgi-bin/cognos.cgi?b_action=powerPlayService&m_encoding=UTF-8&BZ=1AAAB7pUZHH542oVOXW~CIBT9M1C3F3Oh1o_HPtBSo8ummzXZM7PXhrUFQxuX7NePWhNjlmU3cM7J4cAhyLfjfL~dZWsZt511uJYPlHM9S6eMQyKFWLIJiGweZnKazMV

SzESSJNJnHoP_biZ26epV7Fcx5cuDNR2azqujrQt0NEroBIxqkIZytEFv1coU7YhG8o~QTrf6YK_BkzpUqsT7xDu6Cmv9WSHloJTpVO1FYQs0ngdwpu106dW5D6NrS~yyZkicfCWHpi48OtTfuvTnla5tg51XfXUg83ScbjebLN2vPYmXLL6rtc1ZmfL~x4LkLT4CEAYAjAEhBMg0isLoikB67xm7FuvLpyksnpRyngjlc8pDoBwZ5R_ULwaD3Qzya9hl9WIovezb~ACpc4us

SWOV. (2014). Factsheet kosten verkeersonveiligheid. SWOV. Retrieved from https://www.swov.nl/rapport/Factsheets/NL/Factsheet_Kosten_verkeersonveiligheid.pdf

Thinkstep. (2015, April 10). Description of the CML 2001 Method. Retrieved from http://www.gabi-software.com/support/gabi/gabi-lcia-documentation/cml-2001/

TNO-MEP. (2004, March 8). Toxiciteit heeft zn prijs: schaduwprijzen voor eco-toxiciteit en uitputting van abiotische grondstoffen binnen dubocalc.pdf. Rijkswaterstaat. Retrieved from http://publicaties.minienm.nl/download-bijlage/15533/toxiciteit-heeft-z-n-prijs-schaduwprijzen-voor-eco-toxiciteit-en-uitputting-van-abiotische-grondstoffen-binnen-dubocalc.pdf

Tromp, L., & De Boer, A. (2014). Developments in Dutch FRP design guidance for FRP in infrastructure. In *IABSE Symposium Report* (Vol. 102, pp. 2215–2222). International Association for Bridge and Structural Engineering. Retrieved from http://www.ingentaconnect.com/content/iabse/report/2014/00000102/00000014/art00003

Troyano, L. F. (2003). *Bridge Engineering: A Global Perspective*. Thomas Telford.

Tuakta, C. (2005). *Use of fiber reinforced polymer composite in bridge construction*. MIT. Retrieved from http://dspace.mit.edu/bitstream/handle/1721.1/31126/61165353.pdf?sequence=1

van der Velde, J., Klatter, L., & Bakker, J. (2013). A holistic approach to asset management in the Netherlands. *Structure and Infrastructure Engineering*, *9*(4), 340–348. http://doi.org/10.1080/15732479.2012.657650

VWB Asfalt. (2005, November). Asfaltverhardingen de juiste keus: Economische, milieu, maatschappelijke en technische overwegingen bij de keuze van verhardingsmaterialen. Benelux Bitume. Retrieved from http://www.asfaltblij.nl/media/1524/asfaltverhardingen-de-juiste-keus.pdf

Woodward, D. G. (1997). Life cycle costing—Theory, information acquisition and application. *International Journal of Project Management*, *15*(6), 335–344. http://doi.org/10.1016/S0263-7863(96)00089-0

Ye, L., Feng, P., & Yue, Q. (2012). *Advances in FRP Composites in Civil Engineering: Proceedings of the 5th International Conference on FRP Composites in Civil Engineering (CICE 2010), Sep 27-29, 2010, Beijing, China*. Springer Science & Business Media.

Appendix A: Developed LCC model

In this appendix the complete LCC model as developed in Chapter 3 can be found in Figure A1.

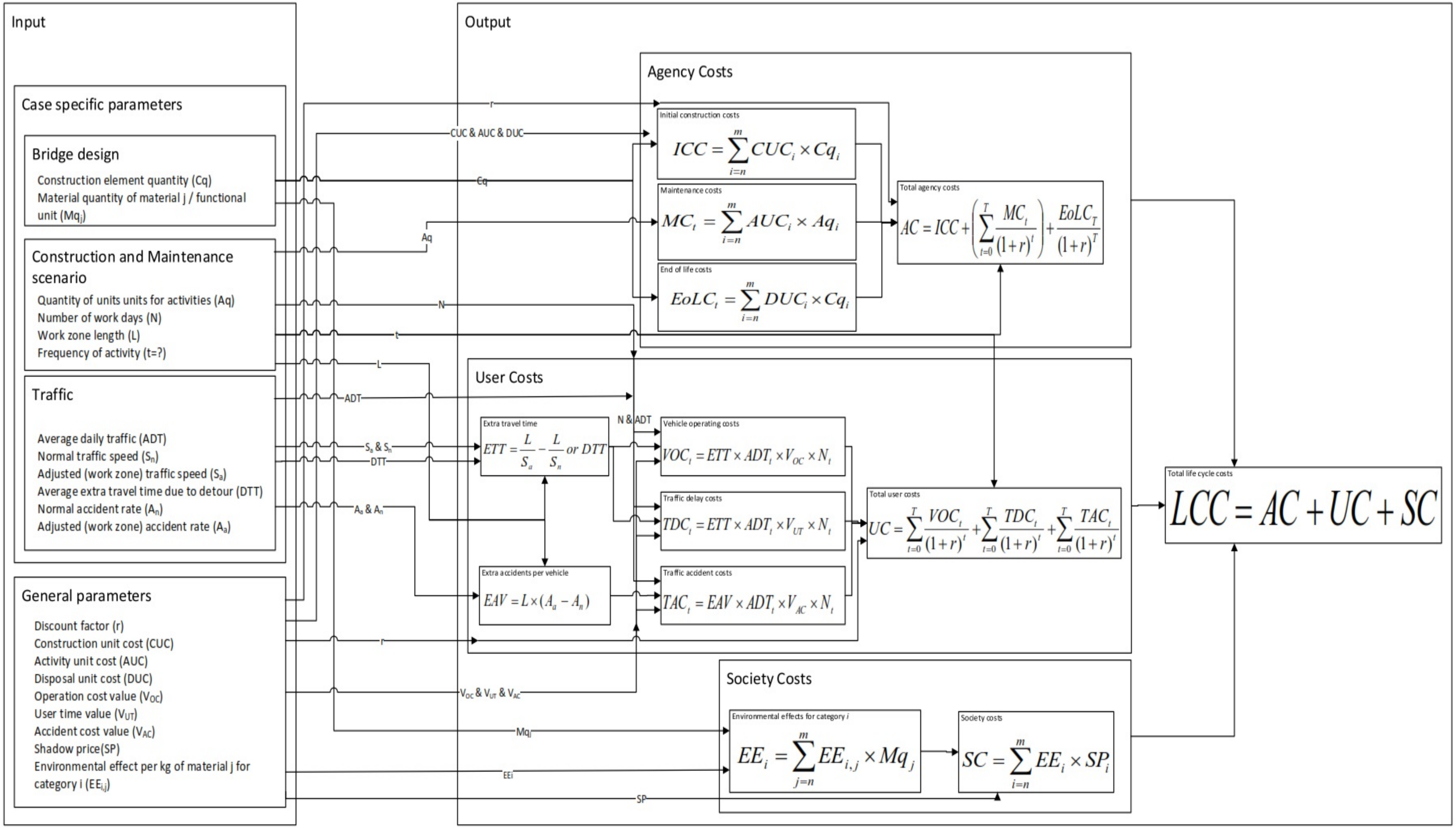


Figure A1, Developed LCC model

Appendix B: Examples worksheets

In this appendix the different worksheets that make up the LCC calculation tool will be displayed.

Figure B1, Construction element database

Figure B2, Activity database

Figure B3, Bridge design

Figure B4, Maintenance scenario

Figure B5, Traffic and general input

Figure B6, Agency costs

Figure B7, User costs

Figure B8, Society costs

Figure B9, Overview

Figure B10, Input and results glass

	A	B	C	D	E	I	J	K	L	M	N	O	P	Q
1	**Database**			2015		**Material quantities per unit**								
2	**Category**	**Item**	**Type**	**Construction unit price (CUP)**	**Unit**	**kg steel**	**kg concrete**	**kg polyester**	**kg glass**	**kg epoxy**	**kg carbon fibre**	**kg asphalt**	**kg gravel**	**kg pvc**
3	Structural_element	Pile_foundation	prefab. Piles 400x400mm, l=18m + add.i	€ 997.75	pc	615	6660	0	0	0	0	0	0	0
7														
8	Structural_element	Abutment	floor (d=1250mm),wall (d= 600mm)	€ 1,652.13	m	486	7499	0	0	0	0	0	0	0
12														
13	Structural_element	Concrete_deck	SKK 1000	€ 750.00	m2	319	1134	0	0	0	0	0	0	0
14	Structural_element	Concrete_deck	parapet	€ 380.00	m	0	0	0	0	0	0	0	0	0
15	Structural_element	Concrete_deck	edge elements	€ 176.00	m	0	0	0	0	0	0	0	0	0
16														
17	Structural_element	GFRP_deck	h=1190d=40	€ 1,528.30	m2	0	0	136	216	0	0	0	0	49
18														
19	Structural_element	CFRP_deck	h=960d=23	€ 4,429.28	m2	0	0	0	0	106	135	0	0	40
20														
21	Structural_element	Approach_slab	5x1x0,35	€ 1,740.00	pc	273	4047	0	0	0	0	0	0	0
22		Approach_slab	4x1x0,35	€ 1,400.00	pc	218	3238	0	0	0	0	0	0	0
23														
24	Structural_element	Sheet_pile_caps	900x600mm	€ 400.00	m	85	1250	0	0	0	0	0	0	0
25														
26	Structural_element	Sheet_piles	AZ37-700,lg=12m	€ 2,148.00	m	2129	0	0	0	0	0	0	0	0
29														
30	Structural_element	Grouted_anchors	lg=15m	€ 1,175.00	pc									
31	Structural_element	Grouted_anchors	lg=25m	€ 1,635.00	pc									
32														
33	Groundwork	Construction_pit_abutment	apply ground = 200 m3, remove ground	€ 6,336.75	pc	0	0	0	0	0	0	0	0	0
36														
37	Retaining_wall	Sheet_piles	AZ37-700,lg=12m	€ 2,148.00	m	2129	0	0	0	0	0	0	0	0
40														
41	Retaining_wall	Grouted_anchors	lg=15m	€ 1,175.00	pc	0	0	0	0	0	0	0	0	0
42	Construction	Grouted_anchors	lg=25m	€ 1,635.00	pc	0	0	0	0	0	0	0	0	0
43														
44	Pavement	Asfalt	d=12mm	€ 40.00	m2	0	0	0	0	0	0	278	0	0
45	Pavement	Bridge_expansion_joints	waterproof	€ 1,325.00	m	0	0	0	0	0	0	0	0	0
46	Pavement	Sloped_ground_cover	incl. ZC stab.	€ 40.00	m2	0	0	0	0	0	0	0	0	0
47	Pavement	Wearing_course	epoxy_aggregate	€ 65.00	m2	0	0	0	0	3	0	0	14	0
48														
49	Pipe_and_cable_work	Rainwater_drainage	unspecified	€ 3,000.00	pc	0	0	0	0	0	0	0	0	0
50														

... | Agency costs | User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element Database | ...

Figure B1, Construction element database

Maintenance database			Frequency (once every x years)	
Activity name	Activity unit price (AUP)	Unit	(devault values)	source:
Construction		times	100	expert estimation
Functional_inspection	€ 500.00	times	2	expert estimation
Cleaning_parapet_and_rainwaterdischarge	€ 1,000.00	times	1	expert estimation
Calamity_maintenance	€ 2,000.00	times	1	expert estimation
Technical_inspection	€ 5,000.00	times	10	expert estimation
Repaint_parapets	€ 150.00	m	15	expert estimation
Asphalt_maintenance	€ 25.00	m2	10	expert estimation
Replace_asphalt	€ 150.00	m2	25	expert estimation
Parapet_replacement	€ 400.00	m	60	expert estimation
Guard_rail_replacement	€ 300.00	m	30	expert estimation
Bridge_expantion_joints_replacement	€ 2,000.00	m	30	expert estimation
Replace_wearing_surface	€ 100.00	m2	15	expert estimation
Concrete_repair	€ 25.00	m2	15	expert estimation
Bridge_bearing_replacement	€ 2,500.00	pc	50	expert estimation
...add_activity				
...add_activity				
...add_activity				
...add_activity				
...add_activity				
...add_activity				
...add_activity				
...add_activity				
...add_activity				

... Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element Database | Activity database

Figure B2, Activity database

Bridge design

Bridge deck material	Concrete_deck
Bridge span (m)	30
Bridge width (m)	34.5
Deck surface (m2)	1035
Lifespan (years)	100

Construction inventory

Category	Item	Type	construction element quantity (Cq)	Unit	Construction unit costs (CUC) (/unit)	Construction costs (ICC) ()	Disposal unit cost	Disposal costs
Structural_element	Pile_foundation	prefab. Piles 400x400r	90	pc	997.75	89,797.50	0	0
Structural_element	Abutment	floor (d=1250mm),wall	72.7	m	1,652.13	120,109.78	0	0
Structural_element	Concrete_deck	SKK 1000	1035	m2	750.00	776,250.00	0	0
Structural_element	Approach_slab	5x1x0,35	67	pc	1,740.00	116,580.00	0	0
Structural_element	Sheet_pile_caps	900x600mm	104	m	400.00	41,600.00	0	0
Structural_element	Sheet_piles	AZ37-700,lg=12m	104	m	2,148.00	223,392.00	0	0
Groundwork	Construction_pit_abutment	apply ground = 200 m	2	pc	6,336.75	12,673.50	0	0
Retaining_wall	Sheet_piles	AZ37-700,lg=12m	114	m	2,148.00	244,872.00	0	0
Retaining_wall	Grouted_anchors	lg=15m	46	pc	1,175.00	54,050.00	0	0
Pavement	Asfalt	d=12mm	1035	m2	40.00	41,400.00	0	0
Pavement	Bridge_expansion_joints	waterproof	69	m	1,325.00	91,425.00	0	0
Pavement	Sloped_ground_cover	incl. ZC stab.	290	m2	40.00	11,600.00	0	0
Pipe_and_cable_work	Rainwater_drainage	unspecified	4	pc	3,000.00	12,000.00	0	0
Pavement	Wearing_course	epoxy_aggregate	0	m2	65.00	0.00	0	0
Structural_element	Grouted_anchors	lg=15m	42	pc	1,175.00	49,350.00	0	0
Structural_element	Concrete_deck	parapet	144.6	m	380.00	54,948.00	0	0
Structural_element	Concrete_deck	edge elements	144.6	m	176.00	25,449.60	0	0
...add_category	...add_item	..add_type		#N/A	#N/A	#N/A	#N/A	#N/A
...add_category	...add item	..add type		#N/A	#N/A	#N/A	#N/A	#N/A
...add category	...add item	..add type		#N/A	#N/A	#N/A	#N/A	#N/A
...add category	...add item	..add type		#N/A	#N/A	#N/A	#N/A	#N/A
...add category	...add item	..add type		#N/A	#N/A	#N/A	#N/A	#N/A
...add category	...add item	..add type		#N/A	#N/A	#N/A	#N/A	#N/A
...add category	...add item	..add type		#N/A	#N/A	#N/A	#N/A	#N/A

Material quantities per construntion element (Mqi,j)

Item	kg steel	kg concrete	kg polyester	kg glass	kg epoxy	kg carbon	kg asphalt	kg gravel	pvc
Pile_foundation	55,350.00	599,400.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Abutment	35,358.18	545,175.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Concrete_deck	330,056.53	1,173,858.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Approach_slab	18,291.00	271,175.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sheet_pile_caps	8,840.00	130,000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sheet_piles	221,395.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Construction_pit_abutment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sheet_piles	242,683.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grouted_anchors	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Asfalt	0.00	0.00	0.00	0.00	0.00	0.00	287,730.00	0.00	0.00
Bridge_expansion_joints	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sloped_ground_cover	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rainwater_drainage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wearing_course	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grouted_anchors	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Concrete_deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Concrete_deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
...add_item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
...add item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
...add item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
...add item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
...add item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
...add item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
...add item	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Material quantity per functional unit (Mqj)

kg steel	kg concrete	kg polyester	kg glass	kg epoxy	kg carbon	kg asphalt	kg gravel	pvc
911,974.11	2,719,610.73	0.00	0.00	0.00	0.00	287,730.00	0.00	0.00

... Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element Database | Activity database

Figure B3, Bridge design

	A	B	C	D	E	F	G	H	I	J
1	Maintenance Scenario						Activity duration (N)	Length of	Workzone (calculated ETT) or	
2	Activity name	frequency (every x years)	# of units (Aq)	type of unit	Activity unit price (AUP)	Maintenance costs (MCi)	(# of days)	work zone (L) (km)	Detour (specified ETT)?	Extra travel time (h
3	Construction	100	1	times	€ 3,442,640.82	€ 3,442,640.82	7	0.5	Workzone	0.006666667
4	Functional_inspection	2	1	times	€ 500.00	€ 500.00	1	0	Workzone	0
5	Cleaning_parapet_and_rainwaterc	1	1	times	€ 1,000.00	€ 1,000.00	1	0	Workzone	0
6	Calamity_maintenance	1	1	times	€ 2,000.00	€ 2,000.00	1	0	Workzone	0
7	Technical_inspection	10	1	times	€ 5,000.00	€ 5,000.00	2	0	Workzone	0
8	Repaint_parapets	15	142.8	m	€ 150.00	€ 21,420.00	3	0	Workzone	0
9	Asphalt_maintenance	10	1260	m2	€ 25.00	€ 31,500.00	0.2	0.5	Workzone	0.006666667
10	Replace_asphalt	25	1260	m2	€ 150.00	€ 189,000.00	3	0.5	Workzone	0.006666667
11	Parapet_replacement	60	142.8	m	€ 400.00	€ 57,120.00	1	0.5	Workzone	0.006666667
12	Guard_rail_replacement	30	142.8	m	€ 300.00	€ 42,840.00	1	0.5	Workzone	0.006666667
13	Bridge_expantion_joints_replacem	30	69	m	€ 2,000.00	€ 138,000.00	2	0.5	Workzone	0.006666667
14	Replace_wearing_surface	15	0	m2	€ 100.00	€ 0.00	3	0.5	Workzone	0.006666667
15	Concrete_repair	15	1100	m2	€ 25.00	€ 27,500.00	5	0	Workzone	0
16	Bridge_bearing_replacement	50	44	pc	€ 2,500.00	€ 110,000.00	5		Detour/specified	0.0833
17	...add_activity	0		0					Workzone	0
18	...add_activity	0		0					Workzone	0
19	...add_activity	0		0					Workzone	0
20	...add_activity	0		0					Workzone	0
21	...add_activity	0		0					Workzone	0
22										
23										
24										
25										
26	Maintenance schedul	year	0	1	2	3	4	5	6	7
27	Maintenance activity	Activity quantity (Aq) (times/year)								

User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element Database | Activity database ...

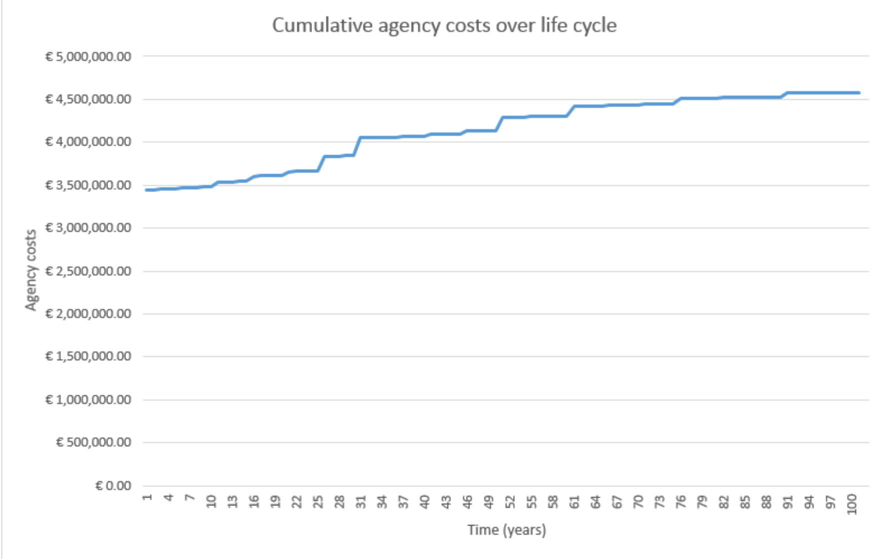
Figure B4, Maintenance scenario

	A	B	C	D	E	F	G	H	I	J
1	**Input general parameters**		**Source:**	**comments:**						
2	Discount factor (r) (%)	2.50%	Kennisinstituut voor Mobiliteitsbeleid (2012)							
3	Operation cost value (€/h*PCE)	8	FHWA (2015)	estimation at 15% freight | 2010 dollars:						
4	User cost value (€/h)	20	Rister & Graves (2002) ar	estimation at 15% freight | 1996/2010 dollars: 12.62/21.		index 1996:2015 (CBS): 148.2				
5	Accident cost value (deaths) (€/accident)	2750000	SWOV (2014)	source is in	2009 euros: 2600000	index 2009:2015 (CBS): 10	2750000			
6	Accident cost value (severe injury) (€/accident)	560000	SWOV (2014)	source is in	2009 euros: 530000	index 2009:2015 (CBS): 10	560000			
7	Shadow prices (SP) (€)									
8	Abiotic depletion elements (ADP) (€/Sb eq)	0.16	TNO-MEP (2004)							
9	Abiotic depletion fossil (ADP) (€/Sb eq)	0.16	TNO-MEP (2004)							
10	Global warming potential (GWP) (€/CO2 eq)	0.05	TNO-MEP (2004)							
11	Ozone depletion potential (ODP) (€/CFK-11 eq)	30	TNO-MEP (2004)							
12	Photochemical ozone formation potential (POCP) (€/C2H2 eq)	2	TNO-MEP (2004)							
13	Acidification potential (AP) (€/SO2 eq)	4	TNO-MEP (2004)							
14	Eutrofication potential (EP) (€/PO4 eq)	9	TNO-MEP (2004)							
15	Human toxicity potential (HTP) (€/1,4-DCB eq)	0.09	TNO-MEP (2004)							
16	Freshwater aquatic ecotoxicity potential (FAETP) (€/1,4-DCB eq)	0.03	TNO-MEP (2004)							
17	Marine aquatic ecotoxicity potential (MAETP) (€/1,4-DCB eq)	0.0001	TNO-MEP (2004)							
18	Terrestic ecotoxicity potential (TETP) (€/1,4-DCB eq)	0.06	TNO-MEP (2004)							
24	**Input traffic parameters**									
25	Average daily traffic (ADT) (PCE)	40000	Province Zuid-Holland	with linair growth will be 90000 in 2115 (see: 'traffic intensity')						
26	Yearly rise in traffic intencity (PCE/year)	463								
27	Normal traffic speed (Sn) (km/h)	50	Province Zuid-Holland	speed limit is 50 kmph, real avg. speed is 50						
28	Adjusted (work zone) traffic speed (Sa) (km/h)	30		estimation, critical but hard to determine						
29	Average extra travel time due to detour (DTT) (h)	0.0833		estimation, critical but hard to determine						
30	Normal accident rate (deaths) (#/vehicle km)(An)	2.5E-09	SWOV (2014)							
31	Adjusted (work zone) accident rate (deaths) (Aa)	3.625E-09	FHWA (2015)	between 20-70% increase (we take 45%)						
32	Normal accident rate (severe injury) (An)	0.0000001	SWOV (2014)							
33	Adjusted (work zone) accident rate (severe injury) (Aa)	0.000000145	FHWA (2015)	between 20-70% increase (we take 45%)						
34	**Environmental effect per impact category per kg material (EEi,j)**	steel	concrete	polyester	glass fibre	epoxy	carbon fibre	asphalt	gravel	pvc
35	Abiotic depletion elements (ADP)	-4.93E-06	1.88E-07	4.47E-06	9.15E-05	3.26E-05	0.00E+00	5.96E-09	4.52E-10	1.71E-05
36	Abiotic depletion fossil (ADP)	6.54E-03	1.80E-04	3.66E-02	1.22E-02	5.79E-02	0.00E+00	9.00E-04	1.38E-05	3.07E-02
37	Global warming potential (GWP)	1.24E+00	1.21E-01	3.05E+00	1.97E+00	8.25E+00	0.00E+00	5.00E-02	2.28E-03	2.87E+00
38	Ozone depletion potential (ODP)	1.11E-08	1.26E-12	8.42E-11	9.66E-11	0.00E+00	0.00E+00	2.80E-08	6.74E-13	0.00E+00
39	Photochemical ozone formation potential (POCP)	5.49E-04	2.33E-05	1.66E-03	-1.69E-03	2.27E-03	0.00E+00	7.10E-05	1.53E-06	1.56E-03
40	Acidification potential (AP)	3.54E-03	1.83E-04	5.24E-03	1.10E-02	2.13E-02	0.00E+00	2.70E-04	1.47E-05	1.98E-02
41	Eutrofication potential (EP)	2.80E-04	2.57E-05	6.41E-04	1.38E-03	4.22E-03	0.00E+00	3.40E-05	2.42E-06	1.46E-03
42	Human toxicity potential (HTP)	2.01E-01	2.40E-02	1.07E-01	4.69E-02	4.87E-01	0.00E+00	3.80E-03	1.49E-04	6.29E+00
43	Freshwater aquatic ecotoxicity potential (FAETP)	1.13E-02	1.54E-04	1.88E-02	2.32E-03	4.31E-03	0.00E+00	9.40E-04	1.23E-05	1.15E+00
44	Marine aquatic ecotoxicity potential (MAETP)	3.05E+02	3.35E+00	1.11E+02	1.17E+02	3.05E+02	0.00E+00	1.50E+00	2.56E-01	2.04E+02

Overview | Agency costs | User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element D ...

Figure B5, Traffic and general input

	A	B	C	D	E
1	**Agency costs**	€ 4,574,091.32		100.00%	
2	Assigned construction costs	€ 1,965,497.38		42.97%	
3	Unassigned construction costs	€ 294,824.61	15.00%	6.45%	
4	Direct construction costs	€ 2,260,321.99		49.42%	
5	One-off construction costs	€ 90,412.88	4.00%	1.98%	
6	Construction execution costs	€ 158,222.54	7.00%	3.46%	
7	General costs	€ 200,716.59	8.00%	4.39%	
8	Profit	€ 81,290.22	3.00%	1.78%	
9	Risk	€ 54,193.48	2.00%	1.18%	
10	Indirect construction costs	€ 584,835.71		12.79%	
11	Foreseen construction costs	€ 2,845,157.70		62.20%	
12	Unassigned object risks	€ 284,515.77	10.00%	6.22%	
13	Total construction costs	€ 3,129,673.47		68.42%	
14				0.00%	
15	Engineering costs	€ 227,612.62	8.00%	4.98%	
16				0.00%	
17	Other additional costs	€ 85,354.73	3.00%	1.87%	
18				0.00%	
19	**Total investment costs**	**€ 3,442,640.82**		75.26%	
20	**Initial construction costs (ICC)**	€ 3,442,640.82		75.26%	
21	**End of Life costs (EoLC)**	€ 0.00			
35	**Maintenance costs (MC)**	€ 1,131,450.50		24.74%	1.5923061

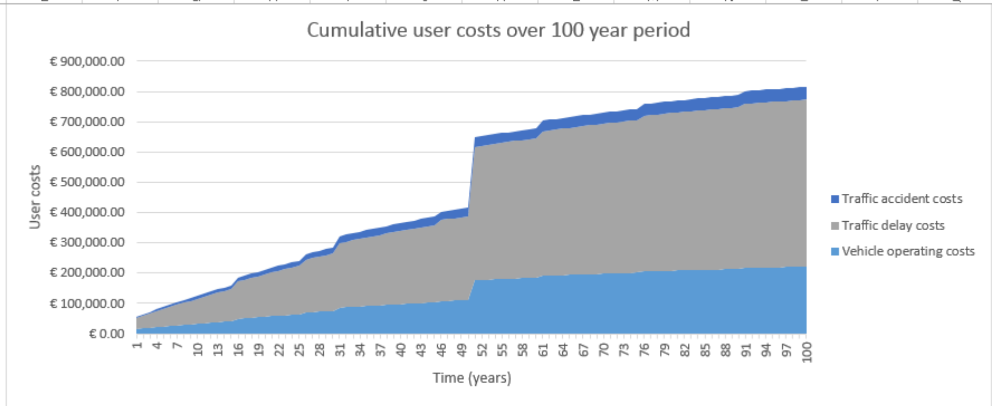


	Maintenance costs schedule	year	0	1	2	3	4	5	6	7	8	9	10	11
43	**Maintenance activity**	AUP (€)												
44	Construction	€ 3,442,640.82	€ 3,442,640.82	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
45	Functional_inspection	€ 500.00	€ 0.00	€ 0.00	€ 500.00	€ 0.00	€ 500.00	€ 0.00	€ 500.00	€ 0.00	€ 500.00	€ 0.00	€ 500.00	€ 0.00
46	Cleaning_parapet_and_rainwaterdischarge	€ 1,000.00	€ 0.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00	€ 1,000.00
47	Calamity_maintenance	€ 2,000.00	€ 0.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00	€ 2,000.00
48	Technical_inspection	€ 5,000.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 5,000.00	€ 0.00
49	Repaint_parapets	€ 21,420.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
50	Asphalt_maintenance	€ 31,500.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 31,500.00	€ 0.00
51	Replace_asphalt	€ 189,000.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
52	Parapet_replacement	€ 57,120.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
53	Guard_rail_replacement	€ 42,840.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
54	Bridge_expantion_joints_replacement	€ 138,000.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
55	Replace_wearing_surface	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00

Overview | Agency costs | User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element D ...

Figure B6, Agency costs

User costs	**€ 815,218.93**
Vehicle operating costs (VOC)	€ 220,823.75
Traffic delay costs (TDC)	€ 552,059.36
Traffic accidents cost (TAC)	€ 42,335.83



Vehicle operating costs schedule	year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Maintenance activity																			
Total nominal		14,933.33	2,158.03	2,182.72	2,207.41	2,232.11	2,256.80	2,281.49	2,306.19	2,330.88	2,355.57	2,856.32	2,404.96	2,429.65	2,454.35	2,479.04	10,014.93	2,528.43	2,553.
Total discounted		14,933.33	2,105.39	2,077.54	2,049.80	2,022.18	1,994.68	1,967.32	1,940.11	1,913.06	1,886.17	2,231.35	1,832.93	1,806.58	1,780.43	1,754.48	6,914.97	1,703.21	1,677.
Cumulative		14,933.33	17,038.73	19,116.27	21,166.07	23,188.25	25,182.93	27,150.26	29,090.37	31,003.43	32,889.61	35,120.96	36,953.89	38,760.47	40,540.90	42,295.39	49,210.36	50,913.57	52,591.

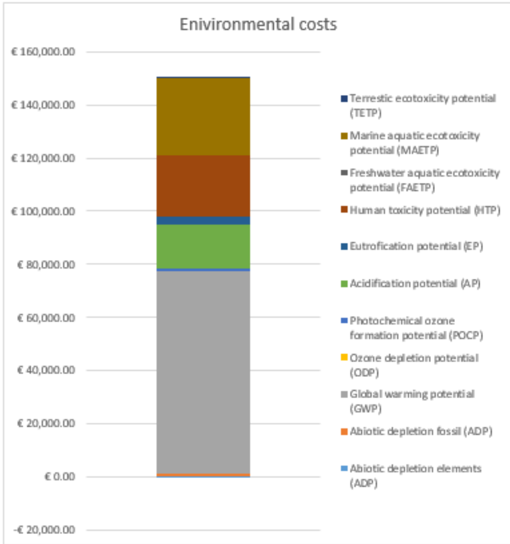
Trafic delay costs schedule	year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Maintenance activity																			
Total nominal		37,333.33	5,395.07	5,456.80	5,518.53	5,580.27	5,642.00	5,703.73	5,765.47	5,827.20	5,888.93	7,140.80	6,012.40	6,074.13	6,135.87	6,197.60	25,037.33	6,321.07	6,382.
Total discounted		37,333.33	5,263.48	5,193.86	5,124.51	5,055.45	4,986.71	4,918.31	4,850.29	4,782.65	4,715.44	5,578.38	4,582.32	4,516.46	4,451.08	4,386.21	17,287.42	4,258.03	4,194.
Cumulative		37,333.33	42,596.81	47,790.67	52,915.18	57,970.63	62,957.33	67,875.64	72,725.93	77,508.59	82,224.02	87,802.40	92,384.72	96,901.18	101,352.26	105,738.47	123,025.89	127,283.92	131,478.

Trafic accident costs schedule	year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Maintenance activity																			
Total nominal		3,961.13	572.43	578.98	585.53	592.08	598.63	605.18	611.73	618.28	624.83	757.65	637.93	644.48	651.03	657.58	2,656.50	670.68	677.
Total discounted		3,961.13	558.46	551.08	543.72	536.39	529.10	521.84	514.62	507.45	500.32	591.87	486.19	479.20	472.27	465.38	1,834.22	451.78	445.
Cumulative		3,961.13	4,519.59	5,070.67	5,614.38	6,150.77	6,679.87	7,201.71	7,716.33	8,223.78	8,724.10	9,315.97	9,802.16	10,281.37	10,753.63	11,219.02	13,053.24	13,505.02	13,950.

Overview | Agency costs | User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element D ...

Figure B7, User costs

	A	B	C	D
1	**Society costs (SC)**	**€ 150,373.92**		
2				
3	**Environmental effect (EEi)**	**Construction**	**Maintenance**	**Total life cycle**
4	Abiotic depletion elements (ADP) (Sb eq)	-3.98E+00	5.14E-03	-3.97E+00
5	Abiotic depletion fossil (ADP) (Sb eq)	6.71E+03	7.77E+02	7.49E+03
6	Global warming potential (GWP) (CO2 eq)	1.48E+06	4.32E+04	1.52E+06
7	Ozone depletion potential (ODP) (CFK-11 eq)	1.82E-02	2.42E-02	4.23E-02
8	Photochemical ozone formation potential (POCP) (C2H2 eq)	5.85E+02	6.13E+01	6.46E+02
9	Acidification potential (AP) (SO2 eq)	3.80E+03	2.33E+02	4.04E+03
10	Eutrofication potential (EP) (PO4 eq)	3.35E+02	2.93E+01	3.65E+02
11	Human toxicity potential (HTP) (1,4-DCB eq)	2.50E+05	3.28E+03	2.53E+05
12	Freshwater aquatic ecotoxicity potential (FAETP) (1,4-DCB eq)	1.10E+04	8.11E+02	1.18E+04
13	Marine aquatic ecotoxicity potential (MAETP) (1,4-DCB eq)	2.88E+08	1.29E+06	2.89E+08
14	Terrestic ecotoxicity potential (TETP) (1,4-DCB eq)	5.24E+03	4.23E+01	5.28E+03
15				
16	**Environmental impact costs (€) (SCi)**			
17	Abiotic depletion elements (ADP)	-€ 0.64	€ 0.00	-€ 0.64
18	Abiotic depletion fossil (ADP)	€ 1,074.38	€ 124.30	€ 1,198.68
19	Global warming potential (GWP)	€ 73,925.77	€ 2,157.98	€ 76,083.75
20	Ozone depletion potential (ODP)	€ 0.55	€ 0.73	€ 1.27
21	Photochemical ozone formation potential (POCP)	€ 1,169.78	€ 122.57	€ 1,292.35
22	Acidification potential (AP)	€ 15,214.35	€ 932.25	€ 16,146.60
23	Eutrofication potential (EP)	€ 3,017.35	€ 264.14	€ 3,281.48
24	Human toxicity potential (HTP)	€ 22,491.92	€ 295.21	€ 22,787.13
25	Freshwater aquatic ecotoxicity potential (FAETP)	€ 330.17	€ 24.34	€ 354.51
26	Marine aquatic ecotoxicity potential (MAETP)	€ 28,782.50	€ 129.48	€ 28,911.98
27	Terrestic ecotoxicity potential (TETP)	€ 314.27	€ 2.54	€ 316.81
28	Total	**€ 146,320.40**	**€ 4,053.52**	**€ 150,373.92**



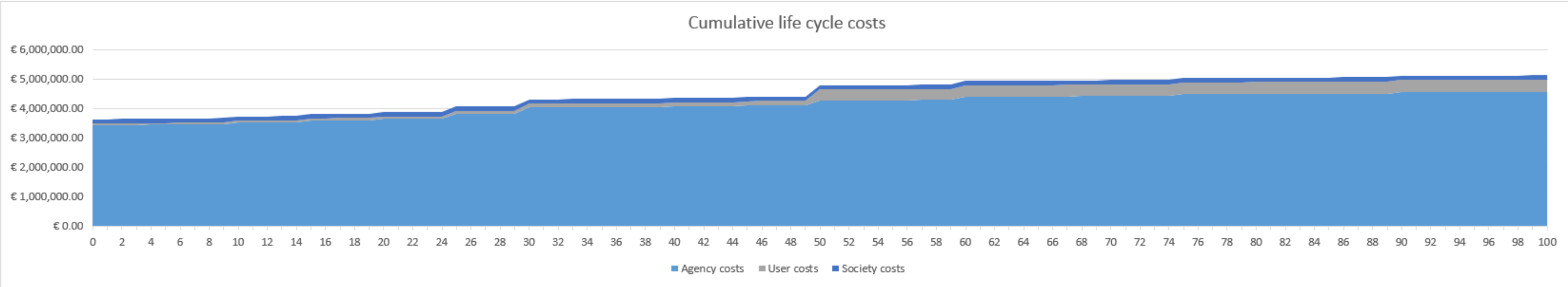
	A	B	C	D	E	F	G	H	I	J
32										
33	source:	GaBI	GaBI	GaBI	GaBI	GaBI	no data	(VWB Asfa	GaBI	GaBI
34	**Environmental effect per impact category per kg material (EEi,j)**	steel	concrete	polyester	glass fibre	epoxy	carbon fibre	asphalt	gravel	pvc
35	Abiotic depletion elements (ADP)	-4.93E-06	1.88E-07	4.47E-06	9.15E-05	3.26E-05	0.00E+00	5.96E-09	4.52E-10	1.71E-05
36	Abiotic depletion fossil (ADP)	6.54E-03	1.80E-04	3.66E-02	1.22E-02	5.79E-02	0.00E+00	9.00E-04	1.38E-05	3.07E-02
37	Global warming potential (GWP)	1.24E+00	1.21E-01	3.05E+00	1.97E+00	8.25E+00	0.00E+00	5.00E-02	2.28E-03	2.87E+00
38	Ozone depletion potential (ODP)	1.11E-08	1.26E-12	8.42E-11	9.66E-11	0.00E+00	0.00E+00	2.80E-08	6.74E-13	0.00E+00
39	Photochemical ozone formation potential (POCP)	5.49E-04	2.33E-05	1.66E-03	-1.69E-03	2.27E-03	0.00E+00	7.10E-05	1.53E-06	1.56E-03
40	Acidification potential (AP)	3.54E-03	1.83E-04	5.24E-03	1.10E-02	2.13E-02	0.00E+00	2.70E-04	1.47E-05	1.98E-02
41	Eutrofication potential (EP)	2.80E-04	2.57E-05	6.41E-04	1.38E-03	4.22E-03	0.00E+00	3.40E-05	2.42E-06	1.46E-03
42	Human toxicity potential (HTP)	2.01E-01	2.40E-02	1.07E-01	4.69E-02	4.87E-01	0.00E+00	3.80E-03	1.49E-04	6.29E+00
43	Freshwater aquatic ecotoxicity potential (FAETP)	1.13E-02	1.54E-04	1.88E-02	2.32E-03	4.31E-03	0.00E+00	9.40E-04	1.23E-05	1.15E+00
44	Marine aquatic ecotoxicity potential (MAETP)	3.05E+02	3.35E+00	1.11E+02	1.17E+02	3.05E+02	0.00E+00	1.50E+00	2.56E-01	2.04E+02
45	Terrestic ecotoxicity potential (TETP)	4.92E-03	2.72E-04	1.82E-03	1.56E-03	1.08E-02	0.00E+00	4.90E-05	3.51E-05	9.51E-03
46										

	A	B	C	D	E	F	G	H	I	J	K
47	**Environmental effect during construction (Eei,j x Mqj)**	steel	concrete	polyester	glass fibre	epoxy	carbon fibre	asphalt	gravel	pvc	total
48	Abiotic depletion elements (ADP)	-4.49E+00	5.11E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E-03	0.00E+00	0.00E+00	-3.98E+00
49	Abiotic depletion fossil (ADP)	5.97E+03	4.90E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.59E+02	0.00E+00	0.00E+00	6.71E+03
50	Global warming potential (GWP)	1.13E+06	3.30E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E+04	0.00E+00	0.00E+00	1.48E+06
51	Ozone depletion potential (ODP)	1.01E-02	3.44E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.06E-03	0.00E+00	0.00E+00	1.82E-02
52	Photochemical ozone formation potential (POCP)	5.01E+02	6.34E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E+01	0.00E+00	0.00E+00	5.85E+02
53	Acidification potential (AP)	3.23E+03	4.98E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.77E+01	0.00E+00	0.00E+00	3.80E+03
54	Eutrofication potential (EP)	2.55E+02	7.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.78E+00	0.00E+00	0.00E+00	3.35E+02

User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element Database | Activity database

Figure B8, Society costs

Bridge description		**Life cycle costs**	€ 5,138,953.17
Bridge material	Concrete_deck	Agency costs	€ 4,574,091.32
Bridge span (m)	30.0	User costs	€ 414,487.93
bridge width (m)	34.5	Society costs	€ 150,373.92
Deck surface (m2)	1035.0		



Costs during life cycle	year 0	1	2	3	4	5	6	7	8	9	10
Agency costs	3,442,640.82	3,447,301.23	3,452,605.76	3,457,041.60	3,462,090.53	3,466,312.63	3,471,118.27	3,475,136.93	3,479,711.01	3,483,536.02	3,533,292.30
User costs	56,227.79	56,227.79	56,227.79	56,227.79	56,227.79	56,227.79	56,227.79	56,227.79	56,227.79	56,227.79	57,628.06
Society costs	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92	150,373.92

Overview | Agency costs | User costs | Society costs | Bridge design | Maintenance scenario | Traffic and General Input | Construction element D ...

Figure B9, Overview

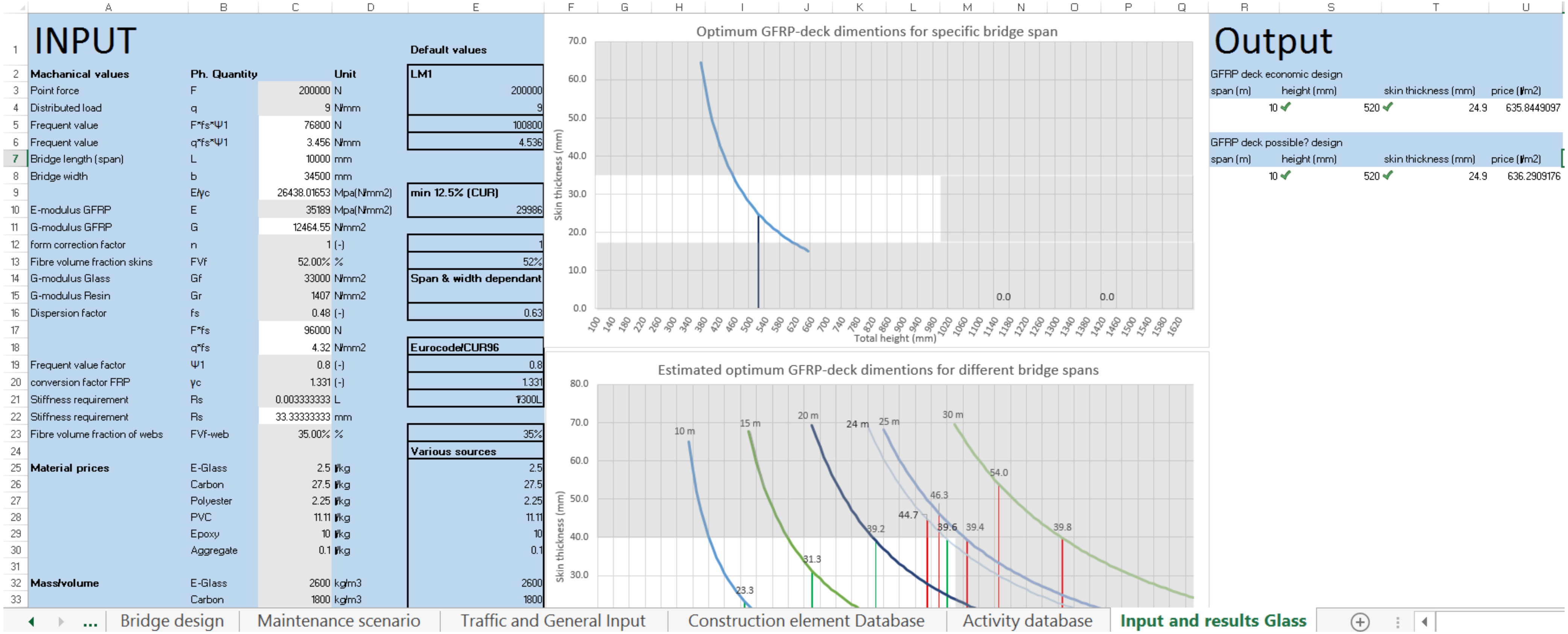


Figure B10, Input and results glass

APPENDIX C: DISPERSION FACTORS

In this appendix the dispersion factors (f_s) that have been calculated with the help of finite element software SCIA are shown in Table C1.

Table C1, Dispersion factors (f_s)

Dispersion factors												
Width (m)	**10**	**11**	**12**	**13**	**14**	**14.7**	**15**	**16**	**17**	**18**	**19**	**20**
Span (m)												
10	0.65	0.65	0.65	0.64	0.64	0.64	0.64	0.64	0.64	0.63	0.63	0.63
11	0.64	0.64	0.64	0.64	0.63	0.63	0.63	0.63	0.63	0.62	0.62	0.62
12	0.64	0.64	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.62	0.61	0.61
13	0.63	0.63	0.63	0.62	0.62	0.61	0.62	0.61	0.61	0.61	0.60	0.60
14	0.63	0.62	0.62	0.62	0.61	0.60	0.61	0.60	0.60	0.60	0.59	0.59
15	0.62	0.62	0.61	0.61	0.60	0.59	0.60	0.60	0.59	0.59	0.58	0.58
16	0.62	0.61	0.61	0.60	0.60	0.59	0.59	0.59	0.58	0.58	0.57	0.57
17	0.61	0.61	0.60	0.59	0.59	0.58	0.58	0.58	0.57	0.57	0.56	0.56
18	0.61	0.60	0.59	0.59	0.58	0.57	0.58	0.57	0.56	0.56	0.55	0.55
19	0.60	0.59	0.59	0.58	0.57	0.56	0.57	0.56	0.55	0.55	0.54	0.54
20	0.60	0.59	0.58	0.57	0.57	0.55	0.56	0.55	0.55	0.54	0.53	0.53
21	0.59	0.58	0.57	0.57	0.56	0.54	0.55	0.54	0.54	0.53	0.52	0.51
22	0.58	0.58	0.57	0.56	0.55	0.53	0.54	0.54	0.53	0.52	0.51	0.50
23	0.58	0.57	0.56	0.55	0.54	0.52	0.54	0.53	0.52	0.51	0.50	0.49
24	0.57	0.56	0.56	0.55	0.54	0.51	0.53	0.52	0.51	0.50	0.49	0.48
25	0.57	0.56	0.55	0.54	0.53	0.51	0.52	0.51	0.50	0.49	0.48	0.47
26	0.56	0.55	0.54	0.53	0.52	0.50	0.51	0.50	0.49	0.48	0.47	0.46
27	0.56	0.55	0.54	0.53	0.51	0.49	0.50	0.49	0.48	0.47	0.46	0.45
28	0.55	0.54	0.53	0.52	0.51	0.48	0.50	0.49	0.47	0.46	0.45	0.44
29	0.55	0.53	0.52	0.51	0.50	0.47	0.49	0.48	0.47	0.45	0.44	0.43
30	0.54	0.53	0.52	0.50	0.49	0.46	0.48	0.47	0.46	0.44	0.43	0.42
31	0.53	0.52	0.51	0.50	0.48	0.45	0.47	0.46	0.45	0.43	0.42	0.41
32	0.53	0.52	0.50	0.49	0.48	0.44	0.46	0.45	0.44	0.43	0.41	0.40

APPENDIX D: DESIGN ALTERNATIVES

For the different bridge design alternatives the following changes have been entered into the LCC calculation tool. In Table D1 are the changes for a 10 meter concrete bridge, Table D2 for a 15 meter concrete bridge, Table D3 for a 20 meter concrete bridge and Table D4 for a 25 meter concrete bridge.

The changes that have been made for the 10 meter GFRP bridge can be found in Table D5, for a 15 meter GFRP bridge in Table D6, for a 20 meter GFRP bridge in Table D7, for a 25 meter GFRP bridge in Table D8 and for a 30 meter GFRP bridge in Table D9.

Table D1, Design changes for 10 meter concrete bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	Concrete_deck	SJP 400	345	m^2
Pavement	Asfalt	d=12mm	345	m^2
Structural_element	Concrete_deck	Parapet	40	m
Structural_element	Concrete_deck	Edge elements	40	m

Table D2, Design changes for 15 meter concrete bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	Concrete_deck	ZIP 500	517.5	m^2
Pavement	Asfalt	d=12mm	517.5	m^2
Structural_element	Concrete_deck	Parapet	60	m
Structural_element	Concrete_deck	Edge elements	60	m

Table D3, Design changes for 20 meter concrete bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	Concrete_deck	ZIP 700	690	m^2
Pavement	Asfalt	d=12mm	690	m^2
Structural_element	Concrete_deck	Parapet	80	m
Structural_element	Concrete_deck	Edge elements	80	m

Table D4, Design changes for 25 meter concrete bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	Concrete_deck	ZIP 900	862.5	m^2
Pavement	Asfalt	d=12mm	862.5	m^2
Structural_element	Concrete_deck	Parapet	100	m
Structural_element	Concrete_deck	Edge elements	100	m

Table D5, Design changes for 10 meter GFRP bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	GFRP_deck	H=520t=25	345	m^2
Pavement	Wearing course	Epoxy_aggregate	345	m^2
Pavement	Asfalt	d=12mm	0	m^2
Structural_element	FRP_deck	Parapet	40	m
Structural_element	Concrete_deck	Edge elements	0	m

Table D6, Design changes for 15 meter GFRP bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	GFRP_deck	H=680t=33	517.5	m^2
Pavement	Wearing course	Epoxy_aggregate	517.5	m^2
Pavement	Asfalt	d=12mm	0	m^2
Structural_element	FRP_deck	Parapet	60	m
Structural_element	Concrete_deck	Edge elements	0	m

Table D7, Design changes for 20 meter GFRP bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	GFRP_deck	H=830t=40	690	m^2
Pavement	Wearing course	Epoxy_aggregate	690	m^2
Pavement	Asfalt	d=12mm	0	m^2
Structural_element	FRP_deck	Parapet	80	m
Structural_element	Concrete_deck	Edge elements	0	m

Table D8, Design changes for 25 meter GFRP bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	GFRP_deck	H=1020t=40	862.5	m^2
Pavement	Wearing course	Epoxy_aggregate	862.5	m^2
Pavement	Asfalt	d=12mm	0	m^2
Structural_element	FRP_deck	Parapet	100	m
Structural_element	Concrete_deck	Edge elements	0	m

Table D9, Design changes for 30 meter GFRP bridge

Category	Item	Type	construction element quantity (Cq)	Unit
Structural_element	GFRP_deck	H=1190t=40	1035	m^2
Pavement	Wearing course	Epoxy_aggregate	1035	m^2
Pavement	Asfalt	d=12mm	0	m^2
Structural_element	FRP_deck	Parapet	120	m
Structural_element	Concrete_deck	Edge elements	0	m

APPENDIX E: ENVIRONMENTAL IMPACT PER KG OF MATERIAL ($EE_{i,j}$)

In this appendix the environmental impact per kg of material j for impact category i are displayed. These have been determined with the help of LCA software GaBi or other literature sources if needed. Values can be found in Table E1.

Table E1, Impact per kg of material ($EE_{i,j}$)

Material / Impact category	Steel	Concrete	Polyester	Glass fibre	Epoxy	Carbon fibre	Asphalt	Gravel	PVC
Abiotic depletion elements (ADP)	-4.93E-06	1.88E-07	4.47E-06	9.15E-05	3.26E-05	0.00E+00	5.96E-09	4.52E-10	1.71E-05
Abiotic depletion fossil (ADP)	6.54E-03	1.80E-04	3.66E-02	1.22E-02	5.79E-02	0.00E+00	9.00E-04	1.38E-05	3.07E-02
Global warming potential (GWP)	1.24E+00	1.21E-01	3.05E+00	1.97E+00	8.25E+00	0.00E+00	5.00E-02	2.28E-03	2.87E+00
Ozone depletion potential (ODP)	1.11E-08	1.26E-12	8.42E-11	9.66E-11	0.00E+00	0.00E+00	2.80E-08	6.74E-13	0.00E+00
Photochemical ozone formation potential (POCP)	5.49E-04	2.33E-05	1.66E-03	-1.69E-03	2.27E-03	0.00E+00	7.10E-05	1.53E-06	1.56E-03
Acidification potential (AP)	3.54E-03	1.83E-04	5.24E-03	1.10E-02	2.13E-02	0.00E+00	2.70E-04	1.47E-05	1.98E-02
Eutrofication potential (EP)	2.80E-04	2.57E-05	6.41E-04	1.38E-03	4.22E-03	0.00E+00	3.40E-05	2.42E-06	1.46E-03
Human toxicity potential (HTP)	2.01E-01	2.40E-02	1.07E-01	4.69E-02	4.87E-01	0.00E+00	3.80E-03	1.49E-04	6.29E+00
Freshwater aquatic ecotoxicity potential (FAETP)	1.13E-02	1.54E-04	1.88E-02	2.32E-03	4.31E-03	0.00E+00	9.40E-04	1.23E-05	1.15E+00
Marine aquatic ecotoxicity potential (MAETP)	3.05E+02	3.35E+00	1.11E+02	1.17E+02	3.05E+02	0.00E+00	1.50E+00	2.56E-01	2.04E+02
Terrestic ecotoxicity potential (TETP)	4.92E-03	2.72E-04	1.82E-03	1.56E-03	1.08E-02	0.00E+00	4.90E-05	3.51E-05	9.51E-03
source:	GaBI	GaBI	GaBI	GaBI	GaBI	no data	(VWB Asfalt)	GaBI	GaBI

APPENDIX F: SCIA ENGINEER REPORT

In this appendix SCIA engineer report is shown. This report shows the calculations that were used to determine the dispersion factor: f_s.

1. Inhoudsopgave

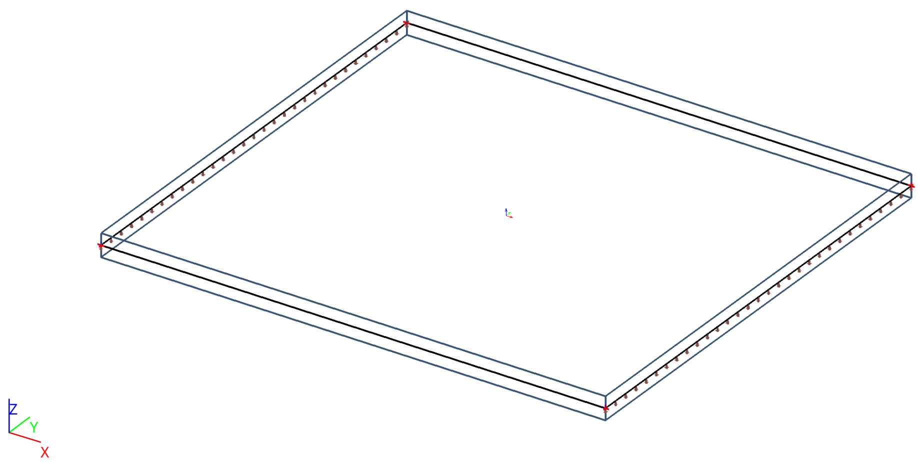
2. Invoer

2.1. Materialen

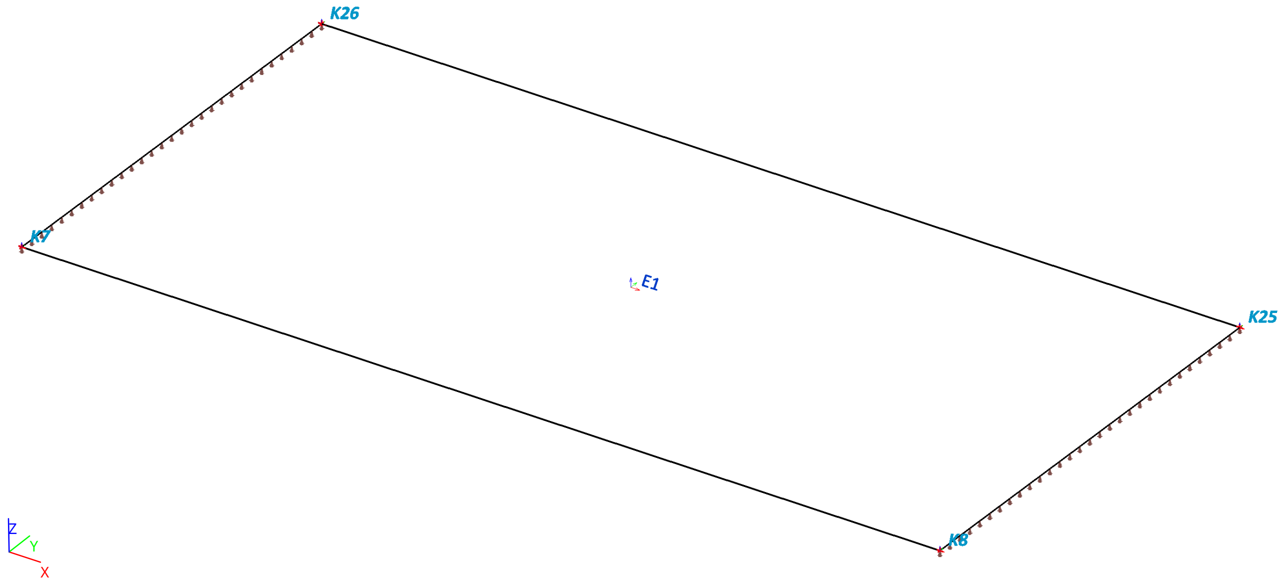
Staal EC3

Naam	Massa eenheid [kg/m^3]	E-mod [MPa]	Poisson - nu	Onderlimiet [mm]	Bovenlimiet [mm]	Fy (bereik) [MPa]	Fu (bereik) [MPa]
		G-mod [MPa]	Thermisch uitz. [m/mK]				
S 235	7850,0	2,1000e+05	0.3	0	40	235,0	360,0
		8,0769e+04	0,00	40	80	215,0	360,0

2.2. Rekenmodel



2.3. Rekenmodel



2.4. Knopen

Naam	Coördinaat X [m]	Coördinaat Y [m]	Coördinaat Z [m]
K7	-6,000	1,150	
K8	24,000	1,150	
K25	24,000	15,850	
K26	-6,000	15,850	

2.5. 2D-elementen

Naam	Laag	Type	Rekenmodel	Materiaal	Dikte type	D. [mm]	EEM model	Orthotropie
E1	Laag1	vloer (90)	Standaard	S 235		1000	Orthotroop	OT1

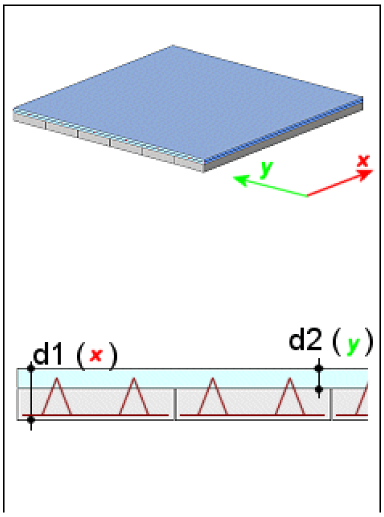
2.6. Ondersteuningen op 2D elementranden

Naam	2D-element Rand	Oors Coör	Pos x_1 Pos x_2	Z	Rx	Ry
Sle1	E1	Vanaf begin	0.000	Verend	Vrij	Vrij
	4	Rela	1.000			
Sle2	E1	Vanaf begin	0.000	Verend	Vrij	Vrij
	2	Rela	1.000			

2.7. Orthotropie

OT1	
Type van orthotropie	Twee hoogtes
Materiaal	S 235
Effectieve hoogte (d1) [mm]	1000
Effectieve hoogte (d2) [mm]	794
Torsie reductie coeff.	1
Afschuiving reductie coeff.	1.2
D11 [MNm]	1,9231e+04
D22 [MNm]	9,6263e+03
D12 [MNm]	4,0818e+03
D33 [MNm]	4,7621e+03
D44 [MN/m]	6,7308e+04
D55 [MN/m]	5,3442e+04

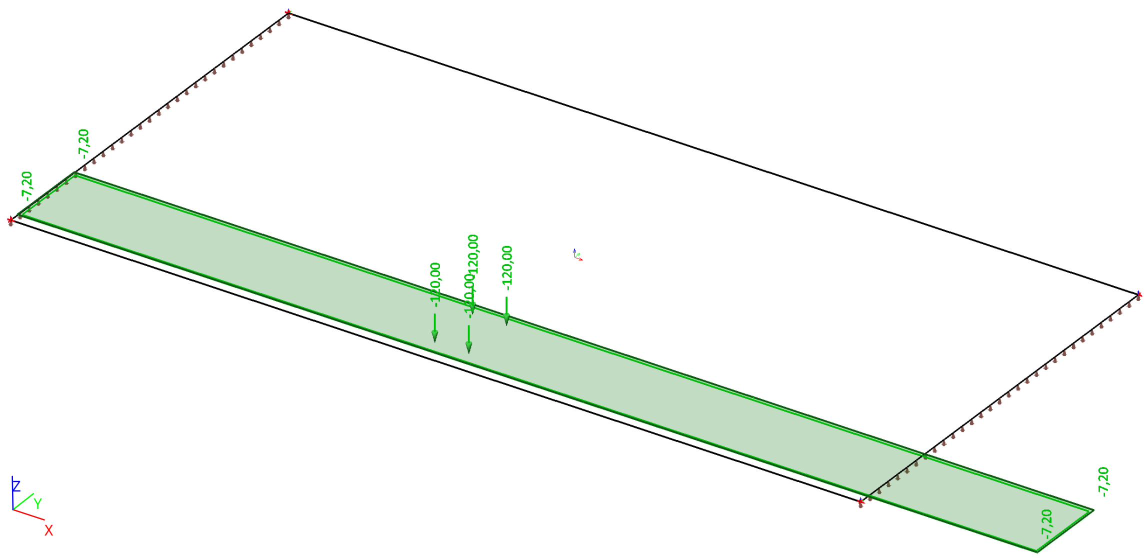
Afbeelding



2.8. Belastingsgevallen

2.8.1. Belastingsgevallen - BG2

Naam	Actie type	Lastgroep	Belastingtype
BG2	Permanent	LG1	Standaard



2.8.1.1. Vrije puntlast

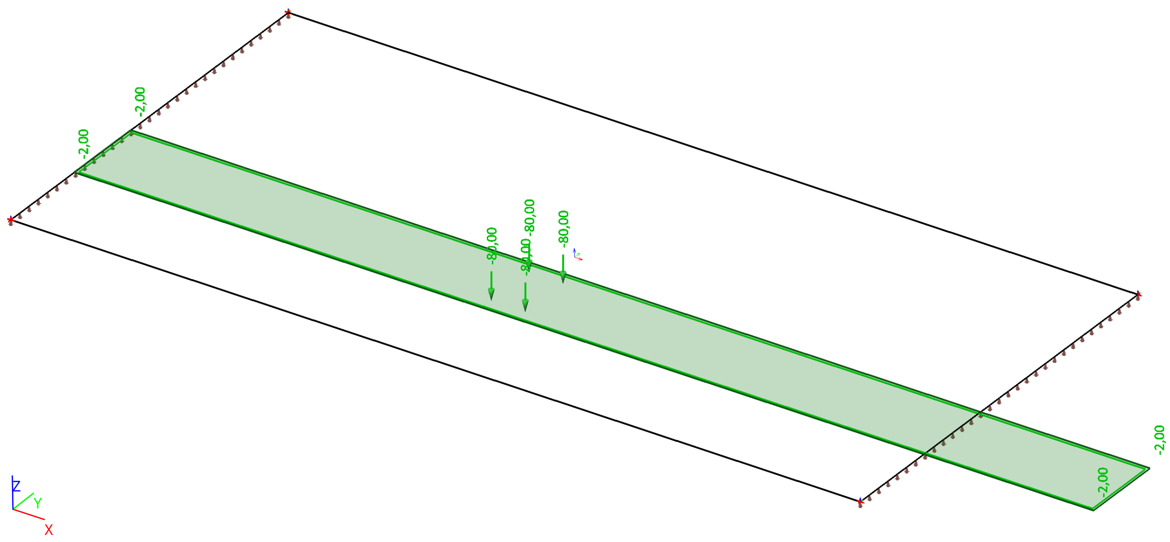
Naam	Belastingsgeval	Systeem	Type	Coördinaat X [m]	Coördinaat Y [m]	Coördinaat Z [m]	Waarde - F [kN]
FF1	BG2	GCS	Kracht	8,400	2,000	0,000	-120,00
FF2	BG2	GCS	Kracht	8,400	4,000	0,000	-120,00
FF3	BG2	GCS	Kracht	9,600	2,000	0,000	-120,00
FF4	BG2	GCS	Kracht	9,600	4,000	0,000	-120,00

2.8.1.2. Vrije oppervlakte last

Naam	Belastingsgeval	Rich	Type	Verdeling	q [kN/m^2]	Geldigheid	Selecteer	Systeem	Locatie
FF1	BG2	Z	Kracht	Gelijkmatig	-7,20	Alle	Auto	GCS	Lengte

2.8.2. Belastingsgevallen - BG3

Naam	Actie type	Lastgroep	Belastingtype
BG3	Permanent	LG1	Standaard



2.8.2.1. Vrije puntlast

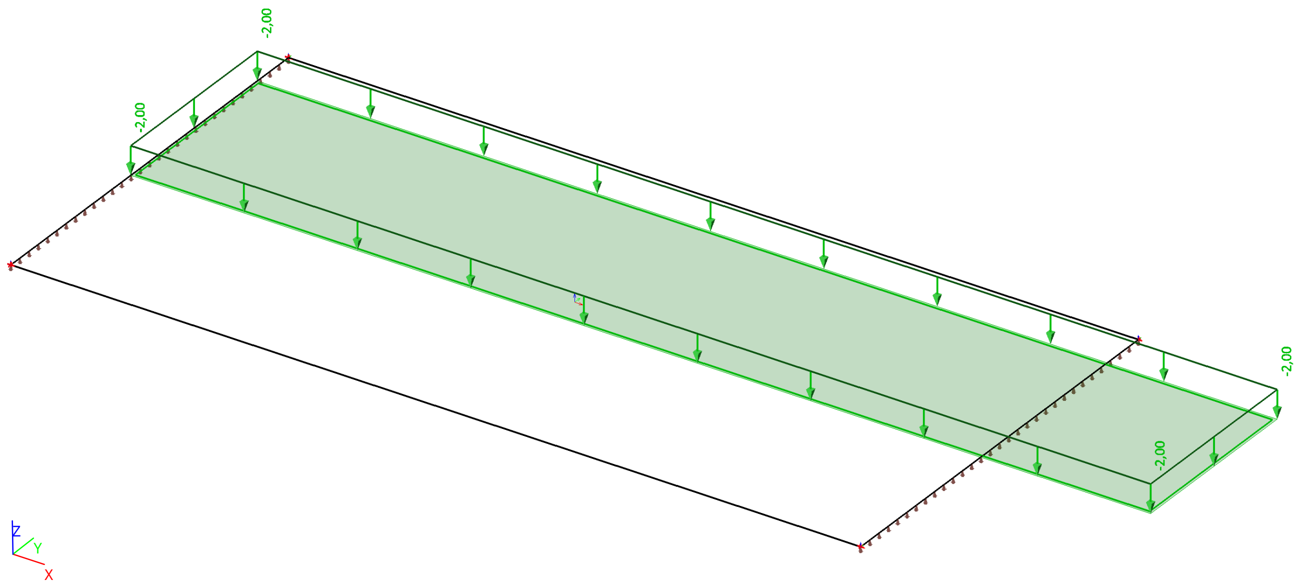
Naam	Belastingsgeval	Systeem	Type	Coördinaat X [m]	Coördinaat Y [m]	Coördinaat Z [m]	Waarde - F [kN]
FF5	BG3	GCS	Kracht	8,400	5,000	0,000	-80,00
FF6	BG3	GCS	Kracht	8,400	7,000	0,000	-80,00
FF7	BG3	GCS	Kracht	9,600	5,000	0,000	-80,00
FF8	BG3	GCS	Kracht	9,600	7,000	0,000	-80,00

2.8.2.2. Vrije oppervlakte last

Naam	Belastingsgeval	Rich	Type	Verdeling	q [kN/m^2]	Geldigheid	Selecteer	Systeem	Locatie
FF2	BG3	Z	Kracht	Gelijkmatig	-2,00	Alle	Auto	GCS	Lengte

2.8.3. Belastingsgevallen - BG4

Naam	Actie type	Lastgroep	Belastingtype
BG4	Permanent	LG1	Standaard



2.8.3.1. Vrije oppervlakte last

Naam	Belastingsgeval	Rich	Type	Verdeling	q [kN/m²]	Geldigheid	Selecteer	Systeem	Locatie
FF3	BG4	Z	Kracht	Gelijkmatig	-2,00	Alle	Auto	GCS	Lengte

3. Resultaat

3.1. Combinaties

3.1.1. Combinaties - Rijstrook 1+2+rest

Naam	Type	Belastingsgevallen	Coëff. [-]
Rijstrook 1+2+rest	Omhullende - uiterst	BG2	1,00
		BG3	1,00
		BG4	1,00

3.1.1.1. 2D element - Interne krachten; mx