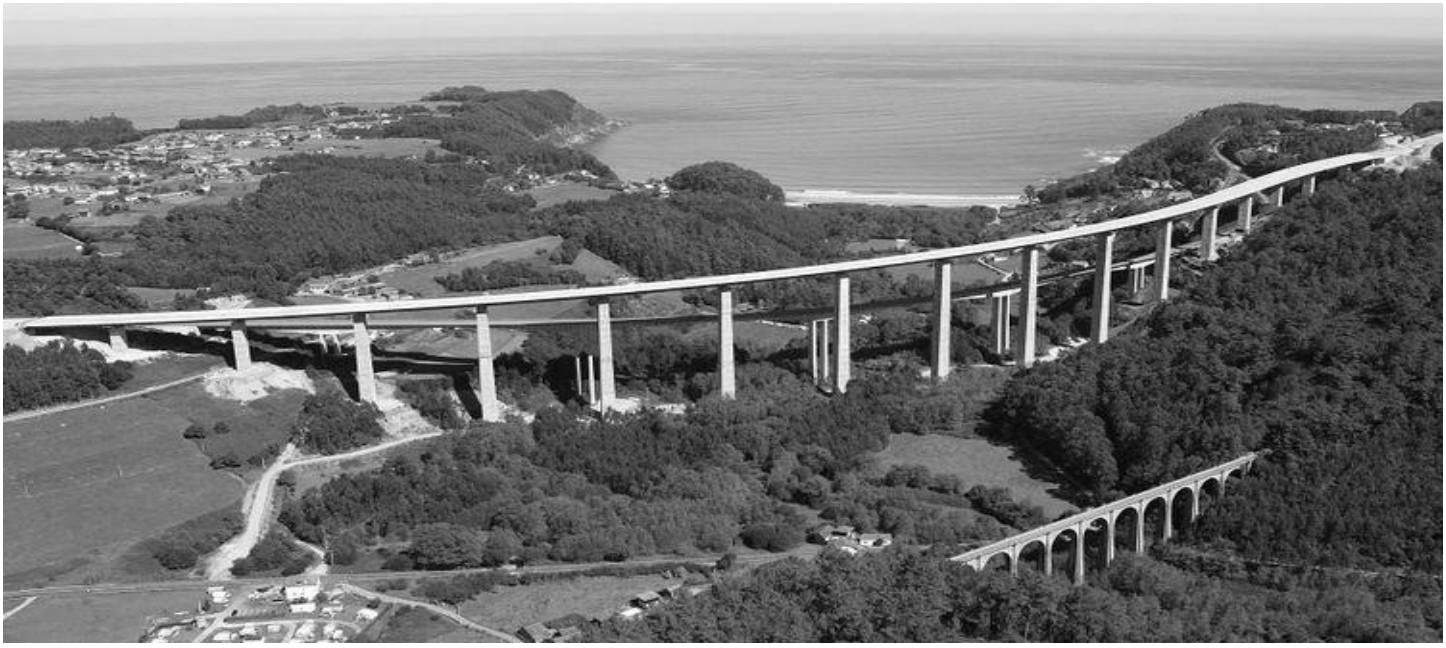
MASTER THESIS

MASTER OF SCIENCE IN CIVIL ENGINEERING & MANAGEMENT

IMPLEMENTATION OF PERFORMANCE AGE PRINCIPLES IN THE DECISION-MAKING PROCESS AT RIJKSWATERSTAAT



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EXECUTIVE SUMMARY

This thesis was conducted in the Netherlands under the supervision of Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Environment. A recent study has revealed that most bridges from the Dutch road network are replaced due to functional problems (e.g. bridge dimensions, traffic capacity, safety, landscape fragmentation, etc.). This means that the current asset management at Rijkswaterstaat focused on technical problems is not enough. New methodologies, procedures and tools should be developed to fill up the gap between functionality and technique analysis. The final goal would be to have an integrated approach in which technical and functional features are considered to make objective and sound decisions. Then, the problem statement of this research is as follows:

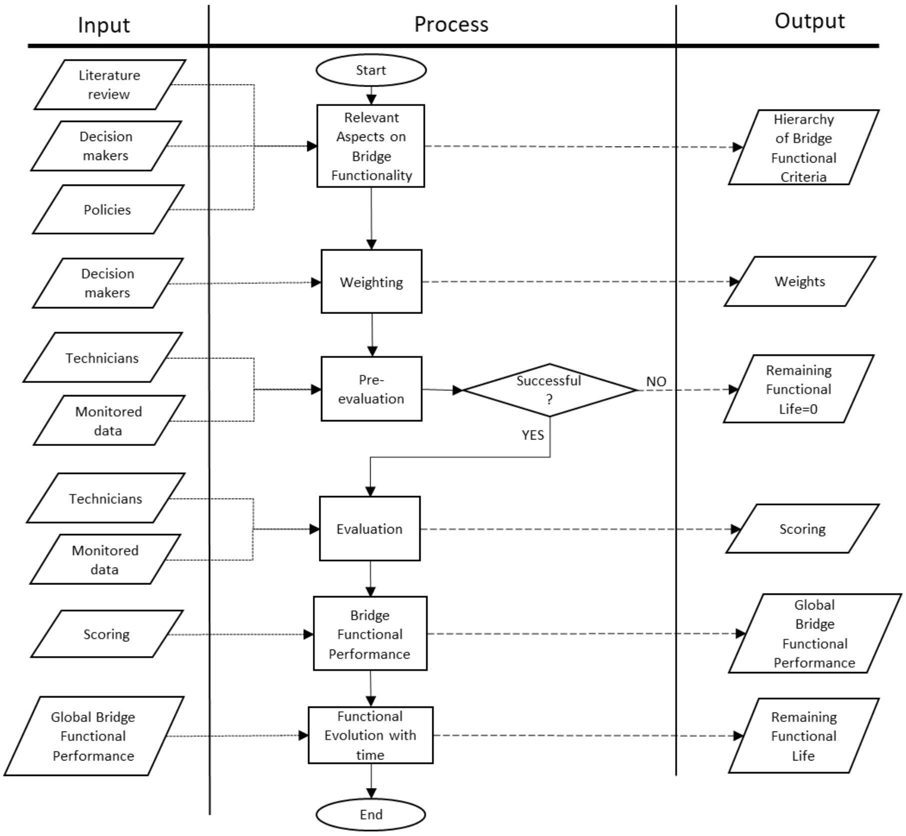
"*There is a lack of objective and standard decision-making procedure at Rijkswaterstaat when a bridge is replaced due to functional reasons*".

Within this framework, under the supervision of Rijkswaterstaat, it has been developed the Performance Age, a methodology which outcome is the age of a bridge according to its functional performance based on a series of performance indicators. The Performance Age is a first concept that can provide useful and objective information about the bridge functional performance, but certain limitations have been encountered that might jeopardize its implementation. The purpose of this research is developing a standard methodology that supports decision making at Rijkswaterstaat using the Performance Age principles. Consequently, the following research question has been formulated:

How can the Performance Age principles be applied to the decision-making process for bridge replacement at Rijkswaterstaat?

Based on the Performance Age research, a literature review and several interviews with different experts within Rijkswaterstaat and the Dutch Ministry of Infrastructure and Environment, the Performance Age methodology was improved and adapted to become useful for the decision-making procedure. The developed methodology can be seen in figure i.

The methodology starts with the determination of relevant aspects for bridge functional analysis. At this step, the methodology was moulded to include the decision-maker's point of view by means of an interview as an adequate contribution to ensure that the methodology aligns with reality. The outcome of this step is the Hierarchy of Bridge Functional Criteria. The Hierarchy of Bridge Functional Criteria is then weighted. Each aspect influencing functionality has a different importance, leading to different weights. Thereafter, the bridge is assessed in two-steps. First, a pre-evaluation step that aims to ensure that the bridge performs to a minimum level in those performance indicators which are essential for the proper bridge service (safety, traffic volume carried, load bearing capacity, bridge geometry and noise emissions). Technicians from Rijkswaterstaat and monitored data will be used to determine the score of the bridge in the pre-evaluation. A threshold is defined and if the bridge does not score above that threshold, the Remaining Functional Life is 0 so the bridge should be directly replaced. If the bridge succeeds the pre-evaluation, the rest of performance indicators are assessed



i. Steps for the methodology.

and scored in the evaluation by technicians and monitored data. The score is used to, with a set of mathematical equations, determine the Global Bridge Functional Performance, a number between 1 ("perfect") and 4 ("poor") that indicates how the bridge functionally performs. Finally, the Global Bridge Functional Performance is related with the Functional Evolution with time of the bridge and the Remaining Functional Life is obtained. The Remaining Functional Life would be an objective and sound information supporting decisions and improving the resource efficiency.

The outcome of the research shows the following results:

- *It is confirmed that the functionality assessment problem exists because technicians and decision-makers are aware of it and innovations in the field are welcomed if they help to improve the efficiency of asset management in the Netherlands.*
- *The Remaining Functional Life can be a useful tool for decision makers as it allows a repeatable, sound and objective procedure to make well-informed decisions among competing alternatives.*
- *The methodology can allow decision-makers to make decisions based on empirical grounds rather than the subjective justifications that are currently used. This will help decision makers to defend their decisions against the stakeholders.*
- *Involving decision-makers in the design of the methodology is an adequate approach to focus efforts in the right direction and to inculcate an ownership feeling with the methodology that eases its implementation.*
- *The information given by the methodology (remaining functional life and the performance score in the performance indicators) will allow decision makers to make more precise replacement strategies, planning and prioritization among different alternatives.*

- *The functional performance can be well-studied with a set of 10 performance indicators validated by technicians and decision-makers. It can be seen in table ii.*

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Safety	Users	Safety to users
Accessibility	Traffic flow	Traffic volume carried
	Bridge physical features	Load bearing capacity Bridge geometry
	Intervention	Maintenance hindrance
	Resilience to climate change	Resilience to extreme weather events
Society	Social hindrance	Aesthetics
Environment	Sustainability	Noise emissions Presence of polluting substances Landscape fragmentation

ii. Hierarchy of Bridge Functional Criteria for Rijkswaterstaat.

- *The methodology will improve the Life Cycle Management at Rijkswaterstaat by including the Life Cycle Performance to the already implemented Life Cycle Costs and Life Cycle Risks.*
- *The Remaining Functional Life can be integrated in the Economic End of Life Indicator (EELI) used at Rijkswaterstaat to decide on bridge interventions more precisely and make a more efficient use of the resources.*

Based on the results of the study, certain recommendations are given:

- The information obtained from this research should be added to DISK (the bridge management system from Rijkswaterstaat).
- Rijkswaterstaat should ensure that the workers are aware of the functionality problem and presentations might be useful. Workers would be more eager to use new methodologies and give ideas for other potential researches.
- Rijkswaterstaat should improve the knowledge sharing and reduce the information fragmentation within the organization in order to ease the implementation of novel procedures and tools.
- It is recommended that Rijkswaterstaat starts monitoring adequate data to determine the functional performance objectively.
- It is strongly recommended that Rijkswaterstaat reduces the uncertainty of the methodology by studying further the functional evolution curves and the assessment scale.

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PREFACE

This report has been written on behalf of my Master Thesis of the Master of Science in Civil Engineering and Management in the faculty of Engineering Technology at University of Twente, collaborating with Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Environment.

The research lasted from 8 months, from February 2018 until October 2018. This report aims to explain a methodology that helps to make decisions about the replacement of bridges, focused on the functional bridge performance. Unlike most asset management strategies focused on technical performance or economics, the study of functionality gives a new insight to the asset management field. The topic was started in 2017 by a student from TUDelft, Yue Xie, who developed the foundations of the current research, with great results. In this research, the Performance Age principles are used to develop a methodology that adapts better to the decision-making process and helps Rijkswaterstaat to further develop innovative strategies to maintain an updated road network and provide better services to citizens.

This topic called my attention since the beginning due to the little research done, with the respective room for improvement, and the importance that asset management have in the efficient use of the resources financed by the taxpayers. Along the research, I discovered an unknown field for me and I found out how is to work for a company like Rijkswaterstaat, in which new ideas are always welcomed. On the other hand, I have also encountered time challenges, busy agendas of colleagues I needed help from, the language barrier (thanks Google translator) and of course, certain procrastination. All in all, helped me to be persistent in order to achieve the goal set in the beginning of the year.

Moreover, I would like to thank my supervisors Andreas Hartmann and Marc van Buiten from University of Twente, Daan Shraven from Delft University of Technology and Jaap Bakker, from Rijkswaterstaat. Without their feedback, comments and guidance, this research would have not been possible, at least not with the same outcome. Despite their full agendas, they were always up to help me with any problem with a smile and let me to use my own ideas in a field of knowledge in which they are great experts.

Furthermore, I appreciate all the advices and time spent by all the colleagues from Rijkswaterstaat and the Ministry of Infrastructure and Environment who cooperated in this research to add the expert's point of view to a theoretical framework.

Finally, I would like to thank my family and friends for their support along these 9 months when the energy was getting low, and during these 2 years away from them.

Saúl Cuendias González

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1.INTRODUCTION

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1.1 Introduction to the Research Topic

Mobility is essential for the economic and societal development of current societies (Strauss, et al., 2016). Despite the effort put from the governments to enhance public transportation, private vehicles are still the main transportation modality (Figure 1). This means that a safe and smooth road traffic flow is a must for the wealthy of the countries and any disruption may have important negative consequences for the economy. However, keeping a road network updated and safe is currently a complex task for road managers and the challenges will increase in the future.

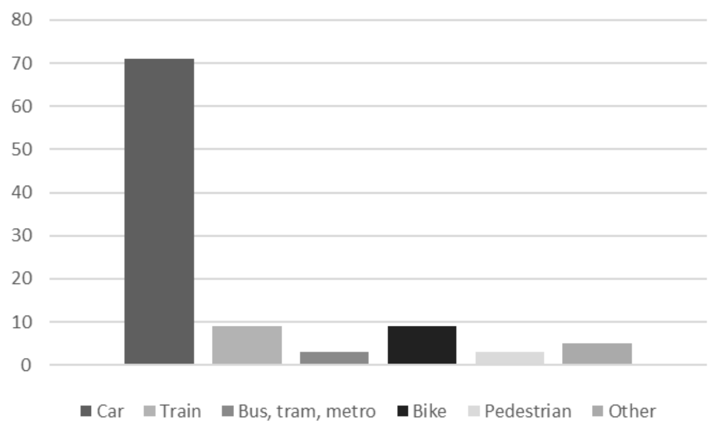

Figure 1. Distance travelled of Dutch people by different means of transport in 2014 (Statistics Netherlands, 2016).

To understand the future of road management, a black period of history, the World War II, must be brought back. Along the WWII (1939-1945), railways, bridges, factories, farms, agricultural areas and even whole cities were destroyed (Jiménez, 2012). When it came to an end, a heavy construction period came in all the European countries to rebuild the continent. In the case of the Netherlands, from 1950 to 1975 the yearly economic growth was about 7% and the population increased from 10 to 13.6 million inhabitants, a 36% (Verlaan & Schoenmaker, 2013; Statista, 2017). These numbers were reflected in the infrastructure investments (see Figure 2), most of which are visible nowadays and are still the backbone of the country (Rijkswaterstaat, 2007).

Figure 2 shows the influence of the past in the current asset management and the associated challenges for asset managers in the following decades. From 1966 until 1975, around 1200 bridges or viaducts were built. Considering that those bridges were designed to last from 50 to 80 years (design life), their service life is coming to an end in the next decades (Rijkswaterstaat, 2016). The infrastructure is starting to feel the age and deterioration and degradation starts to be present on the assets. This situation challenges road managers to find out suitable and well-founded plans to replace or renovate the bridge stock. Moreover, now more than ever before the pressure on budgets hinders and shapes decision making. Therefore, it is essential to develop a strategy to face the problems to come in the next decades in terms of infrastructure asset management so that the Netherlands can continue to deliver high standard infrastructure to the society to support economic, societal and environmental development (Verlaan & Schoenmaker, 2013; COST, 2014).

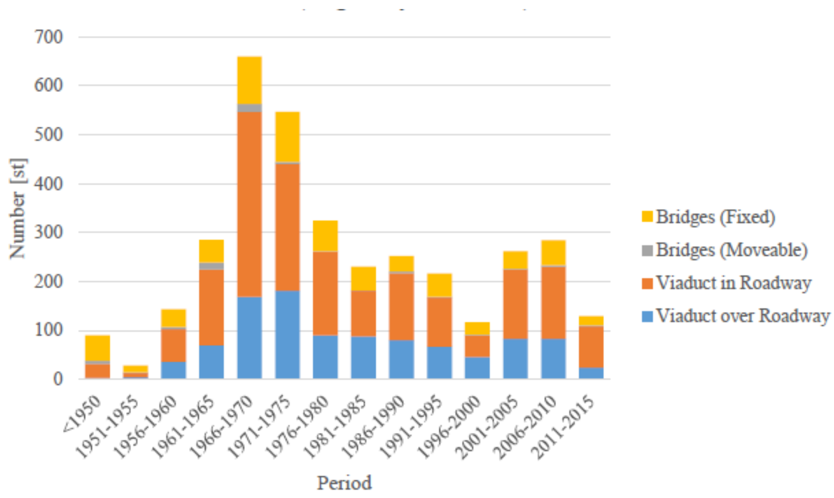

Figure 2. Construction years of concrete viaducts and bridges (Highway Network) in the Netherlands (XIE, 2017).

Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Environment, is the responsible party to find solutions to the infrastructure interventions to come. To assess those interventions, the GPO (Grote Projecten en Onderhoud - Great Projects and Maintenance) department has started the V&R (Vervanging en Renovatie - Replacements and Renovations) Programme. This programme has different objectives: predict the replacement costs to timely inform politicians about the necessary budget allocation, determine what will be the required functional demands for new infrastructure, study those assets in which maintenance is not enough to ensure the proper technical and functional performance and make an efficient resource allocation to update an old network.

As part of the Replacement and Renovations Programme, an indicator was developed to determine when a structure should be replaced. It is called Economic End of Life Indicator (EELI) and it makes a statement on economic grounds to what extent the maintenance of an aging structure is still financially viable relative to a 1 on 1 replacement (Bakker, Roebers, & Knoops, 2016). The advantage of this indicator is that considers the whole lifecycle of the asset in order to make a decision in terms of money. According to this, there are two possible interventions for existing structures: 1. Maintaining the structure and replace it in the expected replacement year; 2. Directly replace the structure and maintain the new built structure.

EELI calculates the Life Cycle Costs (LCC) for both cases. In order to evaluate the bridge, both possible interventions are compared on a ratio to 1. If the result is less than 1, it is still profitable to maintain the structure and replace it in the future. On the other hand, if the result is more than 1, maintaining the structure is not economically feasible anymore and a direct replacement is more interesting.

EELI is a great tool to evaluate the technical aspects that lead to bridge replacement based on costs of maintenance or replacement. However, technical problems are not the only reason for bridge replacement. For instance, a study ordered by Rijkswaterstaat discovered that it is just a small percentage from the total replacements. From a total of 219 replaced bridges, just an 11.1% were replaced due to technical reasons while the functional reasons correspond to the rest 88.9% (Iv-Infra b.v., 2016). Technical problems are caused by degradation of different parts of bridges until when it is no longer economically maintainable, so the bridge has to be replaced. The functional reasons are related to more intense use, heavier loads, climate change, new regulations, urban planning, changes in societal needs or even improvements in technology that make the bridge unable to fulfil the requirements (Hertogh & Bakker, 2016; Fuch G. , Keuning, Mante, & Bakker)

Within this framework, Yue XIE, a student from Delft University of Technology who realised her master thesis at Rijkswaterstaat, introduced in 2017 a new concept: the Performance Age. The Performance Age expresses the age of a bridge according to its functional performance based on a set of performance criteria and indicators (XIE, 2017). According to this definition, a very old bridge could perform well and have a performance age lower than its chronological age or the other way around, a young bridge constructed in an area with a big sudden development could not be able to perform according to new and unplanned requirements in the design, becoming an old bridge in functional terms. It is a methodology that could help the countries facing the same problems as the Netherlands to determine the expected life of bridges according to functional performance and make better and well-informed decisions for bridge interventions.

The research by XIE (2017) is an interesting approach for a topic for which there is lack of studies. Currently, performance is basically studied for the initial construction time requirements, when the system is intact (Biondini & Frangopol, 2016). However, bridges can last more than 100 years, and the environment can change radically, so the study of the performance along the life of the bridge is essential to decide among interventions. The lack of studies cause that the performance-based decisions are being made arbitrarily with the expertise and opinion of decision-makers, with no standard procedure that ensures uniformity and equality.

In the European Union, within the frame of COST (European Cooperation in Science & Technology), it has been developed the Action TU1406, whose aim is to standardize the quality specifications for roadway bridges at a European level (Matos, Amado, Fernandes, & Galvão, 2017). This is a step forward to achieve a uniform, effective and repeatable methodology to manage the bridge stock all around Europe and become the foundations for the global bridge management. Anyway, COST (2014) affirms that there are still large deviations in the performance indicators so new research is required and the Performance Age, with indicators defined specifically for decision makers can add valuable information to the whole field of asset management.

To sum up, civil infrastructure systems are the backbone of modern society and among the major drivers of the economic growth and sustainable development of countries (Biondini & Frangopol, 2016). It is then a strategic priority to develop methods that help decision makers to choose the best and most effective options for the current and future citizens and the Performance Age methodology could give useful inputs on this direction.

1.2 Problem Statement

The general objective of every research is to find solutions to identified problems. Then, the first logical step is to define what is happening. Along this section the author defines the problem statement, the objective of this research, the research questions and the limitations and delimitations of the research.

Problem statement: *There is a lack of an objective and standard decision-making procedure at Rijkswaterstaat when a bridge is replaced due to functional reasons.*

1.2.1 Research goal

The research goal is to *develop an objective and standard methodology that supports decision making at Rijkswaterstaat using the Performance Age Principles.*

From the main goal and the problems stated above, the following sub-goals are created:

- Improve and adapt the Performance Age methodology developed by XIE (2017) for this research.
- Define bridge performance criteria/indicators relevant for decision making.
- Relate the EELI and the Performance Age.
- Validate the methodology by applying it to real bridges from the Dutch road network.

Once all the research goals are studied and a solution is found, the research will be successfully terminated, and the methodology developed will help to reach sound and objective decisions in the replacements of highway fixed concrete bridges due to functional reasons.

1.2.2 Research questions

The goal of this research combined with the background about the research topic have led to the following research question.

How can the Performance Age principles be applied to the decision-making process for bridge replacement at Rijkswaterstaat?

This research question will only be properly answered once a structured research has been made. Therefore, the main question is divided into several sub-questions that will help in the development of this research. The following sub-questions are defined:

- *How can the Performance Age methodology by* XIE (2017) *be improved?*
- *Which criteria/indicators influence the bridge performance according to decision makers?*
- *How can the Performance Age be used in the calculation of EELI?*
- *How does the Performance Age work in real case studies?*

These questions will be answered along the different sections of the research in the most adequate way for each.

1.2.3 Limitations and delimitations

Along this section, the research limitations in terms of content and the research delimitations in terms of scope will be addressed.

The limitations are matters and occurrences that arise in a study which are out of the researcher's control. They limit the extensity to which a study can go, and sometimes affect the end result and conclusions that can be drawn (Simon & Goes, 2013). In this study, there are the following:

Qualitative methodology limitations

Certain relevant information for the development of this research will come from the opinions and experience of decision makers. The indicators chosen for the evaluation of the bridge functional performance will be decided by the author from literature review and from information retrieved from decision makers. The nature of this information is not objective which could limit the study if applied in a different environment. In the case of this study, interviewed decision makers will be the ones taking the real decisions about bridge replacement for Rijkswaterstaat, so it will not limit this research itself, but it could be an issue if the results are extrapolated to another company or country.

Case study limitations

Whether the information retrieved from case studies can be generalized or not is always unclear. In this case, case studies are a limited population of bridges as well as the restrictions of time of the research. Therefore, the outcomes of the case studies can be discussed.

Meetings limitations

The information retrieved from meeting with decision makers and technicians may not be as precise as desired due to time restrictions or difficulties to arrange meetings. The author will try to get the most precise answers, but it is not fully in his hand to get a good result.

Apart from the limitations, the research also has delimitations. The delimitations are those characteristics that directly arise from limitations in the scope of the study and by specific decisions made by the researcher during the study plan. This is essential to make sure what is in the domain of my research and what is not and to limit the extensity to which a study can go (Simon & Goes, 2013). This research is delimited in the following aspects:

Highway fixed concrete bridges

This research will be focused on highway fixed concrete bridges (including viaducts) in the Netherlands. This is a direct requirement from Rijkswaterstaat. The reason for which these bridges are chosen is the importance they have in the whole network to allow a fluent traffic along the main backbones of the country. There are 1515 viaducts and more than 600 concrete bridges in the highway network, numbers that explain how these structures are essential for the mobility and their bad performance can cause great negative influence on the country. Congestion harms the economy and wastes time, fuel (increase of greenhouse gas emissions) and money. Furthermore, a poor bridge conditions can force trucks to detour to alternative routes, leading to increased travel time and delays and increasing freight impacts to other communities (Federal Highway Administration, 2016). In Figure 3, the bridges of study of this research are shown. The study focuses on the bridge over which the highway passes (1), the road under that bridge (1'), the bridge over the highway (2) and the road on that bridge (2'). Basically, two bridges and three roads are the goal of this research.

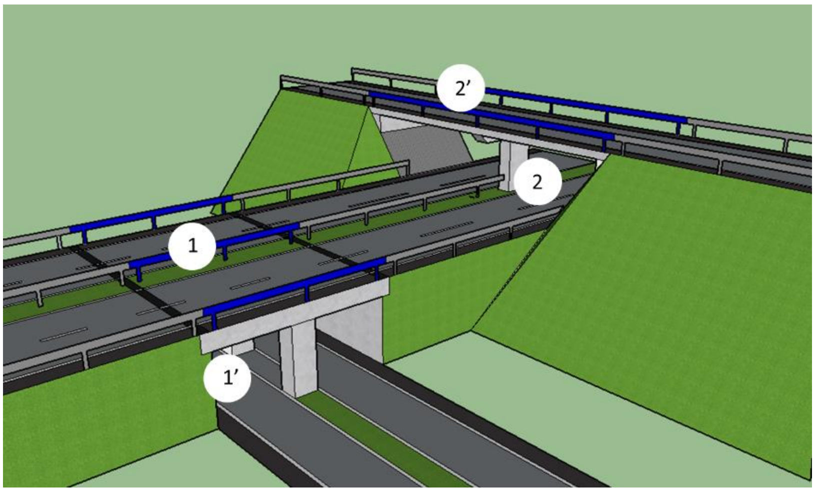

Figure 3. Bridges of study. (1) Bridge over which passes the highway, (1') Road under the highway bridge, (2) Bridge over the highway and (2') Road on the bridge over the highway.

Therefore, the rest of the bridges (moveable or steel) were intentionally left out of the scope of this research to make this study feasible in terms of time and content. The study of just a type of bridge will increase the precision of the outcomes and it will make easier the data gathering process from professionals in the sector.

<u>Object level</u>

Decision-making in highway project management is performed at two levels: the object level and the network level. At object level, a particular highway object is considered so that the optimal maintenance and rehabilitation options are selected for the object, whereas at network level, the projects that will produce the maximum system-wide are selected (Jiang, 1990). Even though Rijkswaterstaat is interested in getting a method useful for network level decisions, the Performance Age has to be first fully applicable in an object level and this is the goal of this research. However, once this is done, future research would be recommended on network level because a unique bridge could be a bottleneck in the whole network and a global vision would be of great utility for the network performance and replacement prioritization decisions.

1.3 Research Design

1.3.1 Research approach

In this part, the different steps that will be followed to reach the goal of this research are shown. The research could be roughly divided in nine steps that can be seen in Figure 4.

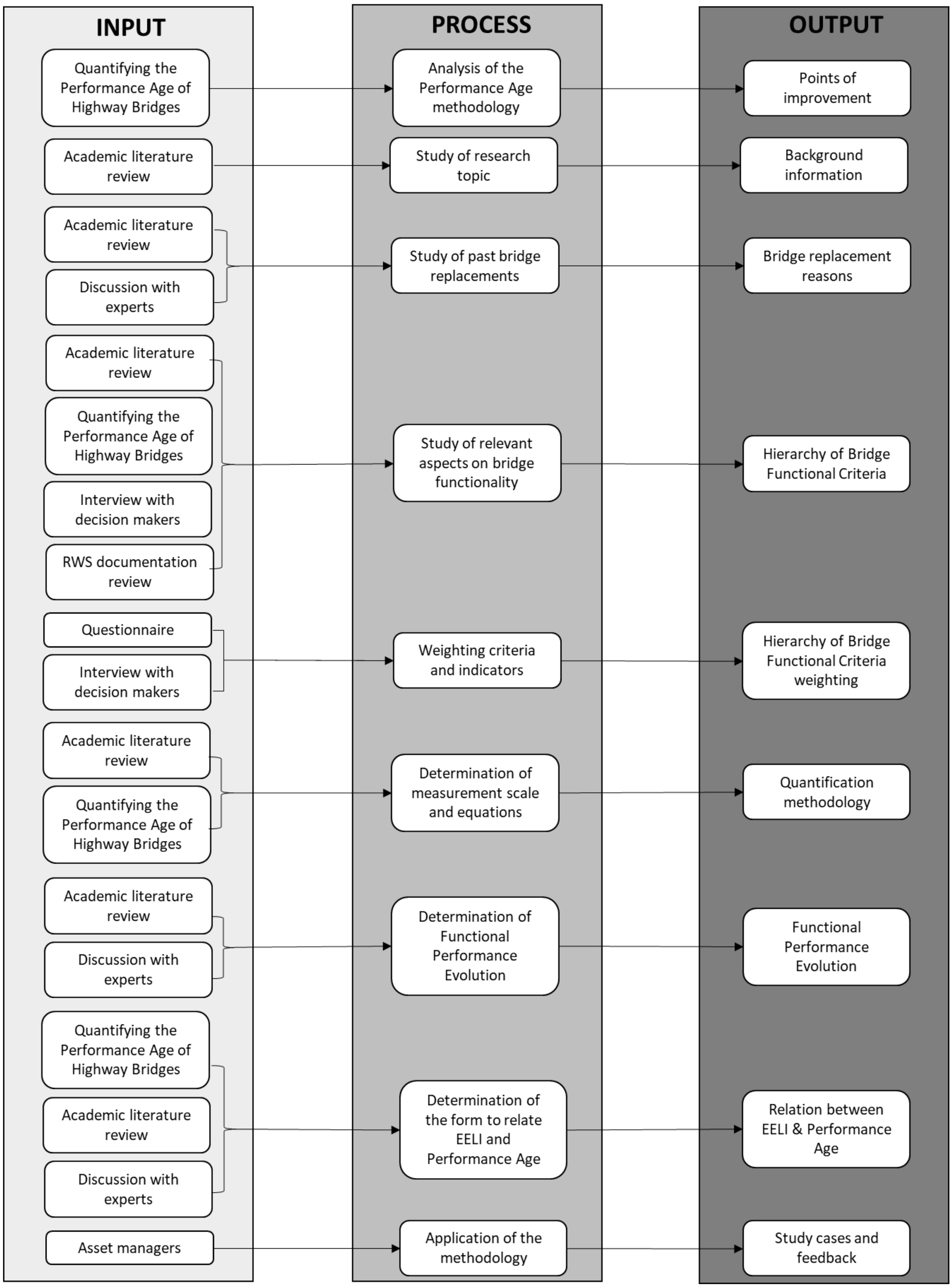

Figure 4. Steps to achieve the goal of the research.

1.3.2 Research methodology

Along this point it will be discussed the tools that will be used to achieve the research objectives and to answer the research questions of this study. For the different stages of the research, different strategies will be used, and they are now described.

Literature review

A literature review is a selection of available documents (both published and unpublished) on the topic, which contain information, ideas, data and evidence written from a particular standpoint to fulfil certain aims or express certain views on the nature of the topic and how it is to be investigated, and the effective evaluation of these documents in relation to the research being proposed (Hart, 1998). For this research, this is the first step to get a comprehensive understanding about the current research of bridge performance. The research by Yue XIE will be firstly studied and the problems to be solved identified. Then, the criteria/indicators will be better described according to literature in terms of decision makers. Since this study is done for Rijkswaterstaat, their literature will also be an essential part of this research. During the quantification methodology, literature review will continue to be crucial, so a critical evaluation of the sources is a must for the success of the study.

Interviews

An interview is a guided, purposeful conversation between two or more people. Its purpose is to collect data from respondents (Hartmann, 2016). Interviews are very valuable to obtain qualitative information for the research. Considering the little information available in literature about asset functional performance, interviews will be used to approach experts in different areas within Rijkswaterstaat and the Dutch Ministry of Infrastructure and Environment and make sure that the developed methodology corresponds to reality. For this research, interviews will be either done on person or by email. Depending on the situation, they are structured or semi-structured interviews.

Structured interviews were used when the researcher prepared a set of questions to guide the interviewees. This was the case of the decision-maker's interview, in which the performance indicators relevant for them were retrieved, together with other valuable information for a better implementation of the methodology. Along the research, other interviews structured interviews were done with experts from Rijkswaterstaat to find out relevant information from different data bases and that helped to direct the research in the right direction.

Unstructured interviews occurred in different occasions. The researcher had valuable informal conversations with experts from Rijkswaterstaat that provide valuable insights for the research. Furthermore, for the case studies, experts from different departments were approached by email to obtain relevant information to evaluate the bridges.

Quantitative analysis

Quantitative Analysis investigates statistics sources by mathematical or computational tools and provide observable results (Given, 2008). This methodology provides the user with a remaining functional life number, obtained after following a set of mathematical steps developed by the author. Only when every step is completed, the methodology will give valuable results.

Case studies

Case studies focus on collecting information about a specific object, event or activity in which the author is interested in (Hartmann, 2016). The methodology will be first theoretically developed. However, to make out of it something useful for Rijkswaterstaat, it is crucial to know whether it works in real cases. Then, it will be put in practice and the information retrieved used to improve the methodology. This is done by choosing a bridge and evaluating it with the developed methodology. The information from the bridge is obtained from different sources: interviews with experts or data bases from Rijkswaterstaat.

1.4 Report Structure

The research will have the following structure. In chapter 2, the general background needed to develop the methodology is explained. First, the actual problem that led to this research is explained. Then, technical and functional end of life will be distinguished since they are essential definitions for the research. Following, reasons of bridge replacement either from technical or functional reasons are shown according to literature review and technicians' expertise. The research by Yue Xie is explained later and the weak points determined in order to improve it. Finally, the impact that the methodology might have in the decision-making process is explained.

In chapter 3, the methodology that the user has to follow to obtain the Remaining Functional Life is clearly explained step by step. First the Hierarchy of Bridge Functional Criteria and then the weighting, followed by the bridge evaluation and finally, the determination of the Remaining Functional Life.

Chapter 4 focuses on the application of the methodology for Rijkswaterstaat. The steps in chapter 3 will be shaped according to the Dutch characteristics and the methodology will be put in practice with a bridge from the Dutch Network.

Finally, chapter 5 focuses on the conclusions, recommendations and limitations of this research.

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2.BACKGROUND

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2.1 Introduction

In this section, the foundation over which the methodology will settle down is explained. The background will ensure the necessity of the methodology and will give useful input for the methodology development.

First, the existing problem for which this study is created is explained. Then, the different end of life types that a bridge can suffer are explained. Potential reasons for bridge replacement are then showed. The reasons are very important for the methodology since they serve as guidelines over which the methodology should focus on. Forth, the research by Yue Xie will be analysed in order to find out the limitations. Finally, how the decision making is currently working in the Netherlands is explained.

2.2 Research Problem

Assets have been traditionally analysed, and interventions executed from a technical point of view. Concrete cracks, structural deflections, erosion, fatigue, foundation deficiency, water leakage or potholes are examples of technical issues in which the assets can be studied (COST, 2014). However, a study realised in the Netherlands found out that this approach has limitations to make an efficient resource allocation among competing alternatives. For instance, from a selection of 219 already demolished bridges, 88.9% were demolished not from technical reasons but from functional reasons (Iv-Infra b.v., 2016). This means that the technical analysis is not enough to achieve the goals and needs of the network. Klatter, H.E. et al. (2006) confirms that the functional lifetime is often dominant in bridge replacement. More than two decades ago, Humplick & Paterson (1994) already mentioned that functionality, environmental impact, technical issues, finance and institutional issues should be considered as a whole to assess the performance of the network and the consequent interventions. However, efforts did not follow that direction and the importance of functional issues had been commonly neglected. Lately, COST (2017) introduced a new framework where the importance of societal aspects and other activities influenced by the road network, together with technical aspects, should be considered as part of the asset analysis and decision-making process.

The general problem that this research aims to solve is the lack of functional evaluation of assets in practice and in literature. As confirmed by Dutch policy makers, bridges, and have been traditionally evaluated in technical terms and it is still the leading factor for the reinforcement, renovation or replacement of this elements. Such an evaluation is not enough to reach the required high-performance level of the assets. Ensure that the bridge does not collapse is essential for the network, but it is a problem that does not happen often. On the other hand, that the bridge does not fulfil functional requirements has been discovered to be a much more recurrent problem which is not considered as much as it should.

In order to level the functional and the technical analysis, this study aims to provide the user with an objective and sound procedure to study the functional performance of bridges. It will give new insights in a field in which subjective and own criteria of policy makers is the only way to decide the interventions in an asset with low functional performance. Furthermore, since the methodology predicts when the bridge should be replaced due to functionality, policy makers can prioritize interventions.

This research will use as a foundation the Performance Age methodology developed by XIE (2017). The Performance Age has been a first approach to the functional analysis problem and made a great step forward in order to reach a high-performance level of the road network. However, certain aspects need revision to make from that methodology a fully usable tool for Rijkswaterstaat.

2.3 End of Life

In the previous paragraph, it has been shown the problem between functional and technical behaviour in order to determine the bridge end of life. There are certain differences when a bridge reached the technical end of life or when it reaches the functional end of life. In the next paragraphs, this important differentiation is done.

2.3.1 Bridge technical end of life

In infrastructure management, there are two terms commonly found referring to bridge technical end of life. The first is the "Technical Service Life", which corresponds with the period of use expected in the design phase. It is the age for which the bridge is designed but it rarely corresponds with reality and the bridge lasts less or longer. Materials deterioration, aggressive atmosphere, traffic flow or loads are possible causes of a different service life than the expected in the design. The second is the "Technical End of Life", which means that a structure is unrepairable or there is no option to repair or upgrade the structure to the required technical level. According to Rijkswaterstaat technicians, technical end of life rarely happens. Currently there are enough technologies, construction techniques and materials to allow the reparation of most of the bridges (Bakker, Roebers, & Knoops, 2016).

Considering that any bridge (or almost any) can be repaired or upgraded, costs dominate decisions. For instance, decisions are basically made in economic terms. Similarly to the previous definitions, in the economic field there are two main terms. The first is "Economic Life", defined as the expected period during which an asset is useful to the average owner. It is an average forecasted replacement interval. An individual asset will in reality usually not exactly last the average life, but shorter or longer. The economic life is therefore, not a justification for a replacement decision (Bakker, Roebers, & Knoops, 2016). The second term is the "Economic End of Life". The Economic End of Life (EELI) has been developed by Rijkswaterstaat and its defined as follows:

*"The EELI is an indicator that makes a statement of economic grounds to what extent the maintenance of an aging structure is still financially viable to a 1 on 1 replacement. EELI compares the Life Cycle Costs (LCC) of maintaining an aging object and replace it in a statistically expected replacement year with the direct object replacement and the subsequent maintenance (*Figure 5*). In the first case, the maintenance of an aging structure will typically have an increasing maintenance need and therefore,*

increasing costs. With the direct replacement, the maintenance costs are lower, and the new object provides usually a functionality not comparable with an old structure" (Bakker, Roebers, & Knoops, 2016)

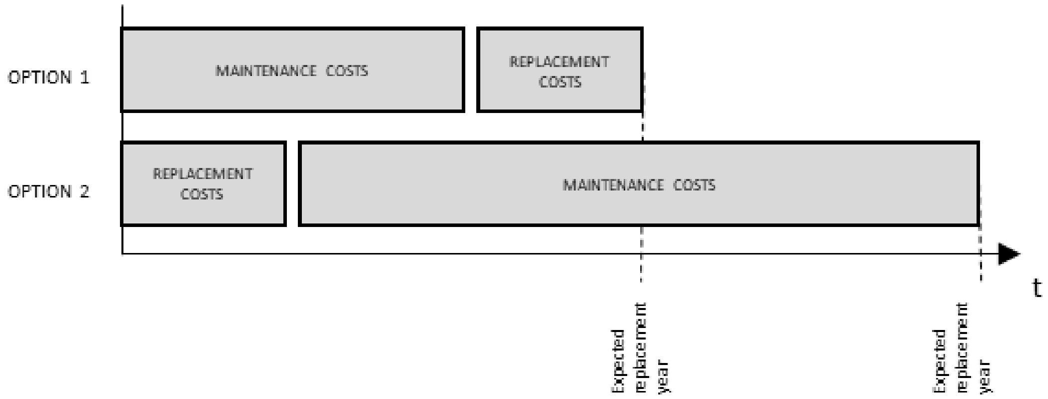

Figure 5. EELI graphic description.

In the study by Iv-Infra b.v. (2016), that found out the relevance of functional problems in bridge replacement, three options are considered for the end of technical life:

1. The construction is no longer possible used safely.
2. The requested performance cannot be delivered with regular maintenance.
3. The required maintenance is too expensive.

Options 1 and 2 correspond with the Technical End of Life while option 3 directly relates to the Economic End of Life. Considering the expertise of technicians from Rijkswaterstaat, who expressed that the third option is the most common in asset management, in this research the Economic End of Life will be considered the main indicator that shows that a bridge should be replaced due to technical (economic) reasons.

2.3.2 Bridge functional end of life

The bridge functional performance is defined as the "bridge ability to deliver the adequate functional requirements". Then, the bridge functional end of life happens when the bridge cannot deliver the adequate functional requirements.

While technical end of life depends on the bridge structural behaviour or on the soil bearing capacity, the functional end of life is mainly affected by the changing environment requirements, such as traffic volume, traffic weight or area development. When the requirements of the environment change, the bridge can be adjusted accordingly or not. If the adjustment is not possible but new requirements must be met, then the bridge reaches the functional end of life.

In reality, the functional end of life is more complex. Often there is a combination of functional bottlenecks and desired adjustments that lead to a redesign of a part of that network, considering future functional developments. The current functioning of an individual object is just one of the variables. Knowledge of performance of the network and its individual assets is, however, important for any investment decision to reach a high efficiency level (Bakker, Roebers, & Knoops, 2016). In order to study when a bridge reached the functional end of life, it has been recently developed the Performance Age, that tells how old a bridge is according to its functional performance based on a set of performance indicators (XIE, 2017).

2.3.3 Technical vs functional end of life

The definition of technical and functional end of life has been clearly explained above. However, with the following metaphor the reader will be able to better understand the difference between the two cases (Figure 6).

When you have an old car, it would lead to two situations. The first one relates to the maintenance of the car. As the car gets older, it will require more invasive and frequent maintenance, increasing the operational costs. The technical problems of the vehicle will increase the costs until a moment when it is not economically maintainable anymore, leading to the technical (economic) end of life. The second option is whether that car is the proper one for the present. Here you may think about if it is big enough for a bigger family, fast enough to drive with the current speed limits or safe enough according to the new regulations. In the case the car does not accomplish these new requirements, then the car reaches the functional end of life.

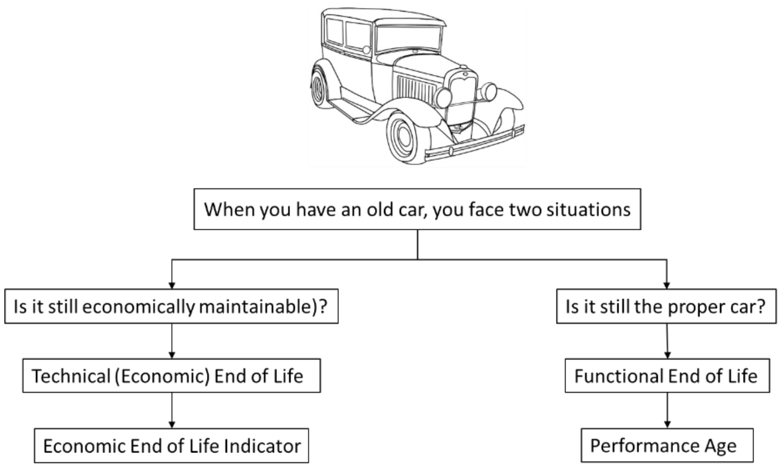

Figure 6. Metaphor to distinguish between technical end functional end of life.

These two options could be extrapolated to bridges and both should be studied in depth to ensure that the best decisions are made.

2.4 Bridge Replacement Reasons

The reasons of bridge replacement are a way to show specific problems that affect the road network, both from technical and functional nature. While the problem determination explains the issues that affect the road network, the reasons for asset replacement are focused on object level and could provide trustful information about which problems road managers can encounter in the bridges that lead to low performance and replacement. There is a relation between the replacement reasons and how an asset performs. For instance, those reasons that can be seen more often will have a bigger influence in the performance. Then, the replacement reasons will be used as the foundation over which the methodology stands.

The reasons for replacement due to functional reasons are rarely found in literature. As said before, the functional analysis is not a common evaluation of assets. Moreover, functionality is highly influenced by the environmental changes, which complicates the prediction and universalization of functional problems. Then, the expertise of technicians will be also considered as input to provide a better overview of the situation.

In the next title, the replacement reasons in the Netherlands are explained. Although particular of this country, there might be similarities with other countries in similar situations and they could serve as an example. However, the user of the methodology should determine the replacement reasons in the area of interest.

2.4.1 Technical bridge replacement reasons

From literature, technical deficiencies come from degradation caused for example by natural aging, environmental circumstances, material quality or execution works of the different elements of the bridges (COST, 2014). When serious technical deficiencies occur, bridges are restricted to light vehicles, are closed or require immediate rehabilitation to remain open (Dunker & Rabbat, 1990). The degradation leads to a moment in time when it is no longer economically maintainable, so the bridge has to be replaced. In the end, it is an economic reason.

The end of technical lifespan has various causes (Iv-Infra b.v., 2016):

- Aging leads to important technical defects.
- Change of use leads to technical problems faster.
- Due to outdated technology the object is no longer maintainable. For example, because replacement parts are no longer available.
- Changes in standards lead to a different assessment of the structural safety as a result of which a bridge no longer meets the standards.
- Lack of maintenance or wrong procedures leads to technical defects.

Despite being the reasons that people may relate the most with bridge demolition, technical reasons are, according to Iv-Infra b.v. (2016), just a small percentage (11.1%) from the total, what leads us to find out which are the main source of demolition reasons.

2.4.2 Functional bridge replacement reasons

A bridge is replaced due to functional reasons when it cannot deliver the adequate functional requirements (Functional End of Life). In other words, when the design is outdated (Federal Highway Administration, 2014b). In the study by Iv-Infra for Rijkswaterstaat, bridges demolished due to functional reasons can be all captured under two categories (Iv-Infra b.v., 2016):

1. Improving the traffic flow in the road network (extra lane, acceleration lanes, rush-hour lane, intersection).
2. Railway construction (freight transportation lane or high-speed lane).

Although the functional reasons found in the study are just the two named above, other may happen. Literature shows that the asset management field is not yet very aware of the importance of functional problems in bridge replacement and therefore, it was not possible to find too many functional reasons when reviewing other studies. In order to complete this research, the author decided to determine other functional reasons for bridge replacement by discussing with supervisors, by self-reflecting and by asking technicians from Rijkswaterstaat with expertise in the field. The obtained reasons may not have happened yet, but they lead to a much more complete list of potential replacement reasons and then, provide a broader methodology. The determined potential functional replacement reasons are the following:

a. **Traffic intensity:** an increase in the number of vehicles over and under the bridge and the related congestion could be a functional reason for which the bridge does not perform as required.
b. **Traffic physical dimensions:** the traffic loads, width and height is increasing (mainly in freight transport), which can lead to an obsolete infrastructure to deliver an adequate traffic capacity for the users. Furthermore, the European Regulations are introducing changes to accommodate new dimensions requirements and bridges should be ready to accomplish the changes.
c. **External factors:** new urban developments or changes in the urban planning could have consequences to the bridges as they may be placed in an inadequate location for the new road network layout or hinder the comfort of the new neighbours. Some examples are:
    - Increasing urbanisation might lead to house construction close to highways, becoming the road a visual and noise hindrance problem for new neighbours. Their complaints might cause the construction, for example, of a tunnel to reduce the hindrance.
    - Intervention in the road network for road widening may also require the widening of the bridges.
    - Railway construction may be affected by the highway bridge and the bridge has to be replaced (Iv-Infra b.v., 2016).

    Furthermore, external parties who do not agree with the bridge performance anymore because it does not fulfil their requirements may also lead bridge replacement.

d. **Risks:** the appearance of a blackspot in a bridge where traffic accidents happen often. Due to the importance of safety in the network, the elimination of that conflictive point could lead to bridge replacement.
e. **Maintenance:** the options that the bridge gives for maintainability are essential for the good performance of the structure in periods of intervention. In order to achieve this, the road on the bridge should be as much flexible as possible, allowing traffic detour in the other traffic

direction during interventions. Then, isolation of the lanes of both directions (fixed barriers or gap between platforms) may lead to traffic problems during the maintenance of the bridge and the consequent bottleneck. If bottlenecks occur very often, the bridge may be considered for replacement.

f. **Natural environment:** the climate change is affecting the road network in terms of heavier rain and more recurrent floods. They can cause congestion and safety issues for the traffic. Floods will happen more often and a bridge that cannot perform properly under these new circumstances could be considered for replacement. Another reason may be that the bridge has been built with substances that have been discovered to be risk-polluting substances, like asbestos for example. Furthermore, the negative influence of the bridge in the fauna movement under the road (habitat fragmentation) could be considered another functional replacement reason.

The current research is focused on functional issues. Then, the reasons above mentioned will be the foundation over which the rest of the research will stand on by relating the reasons with the way to objectively measure how the bridge performs in those facts.

2.5 Performance Age Methodology

Bridge Management Programmes have not focused on bridge functional performance. This is translated in a very limited amount of literature on the topic. For instance, most of the literature can be found in the research by Yue Xie. XIE (2017) made a great research work finding out what has been done in the field and with that as a foundation, she developed the Performance Age. The Performance Age is a methodology that delivers the age of a bridge according to its functional performance by analysing a set of performance indicators.

The Performance Age is highly affected by the environmental changes, which are directly related to a higher or lower Performance Age. For instance, new industrial areas development, new neighbourhoods or the interaction with other transportation modalities are examples of environmental changes that may affect the Performance Age. New industrial areas and neighbourhoods may lead to higher traffic intensities, traffic loads or even noise emissions for which the bridge is not adequate anymore or not as much adequate as it should. This will lead to an increase of the Performance Age. However, it may also happen that the Performance Age decreases. For example, a new road is built and the pressure on the actual bridge reduces, which also leads to a better performance in the selected set of indicators of study. It can be concluded that the Performance Age is an indicator of how the bridge adapts to the environment.

The Performance Age has been created due to the interest of Rijkswaterstaat to stay updated about the network problems. Considering the limitations of the bridge technical analysis, the Performance Age would allow Rijkswaterstaat to make a better and more integrated evaluation of the road network and, in the end, make decisions based in a larger set of criteria.

The analysis of the Performance Age methodology is essential for the realisation of this research since it is the foundation over which it settles down. Then, the procedure should be examined and understood to use it and to find out potential points of improvement.

2.5.1 Procedure

The Performance Age is a methodology to analyse the bridge functional performance. XIE (2017), the first developer of the concept, defined it as the age of bridges according to its functional performance. The determination of the Performance Age follows certain steps as represented in Figure 7, which are explained in detail:

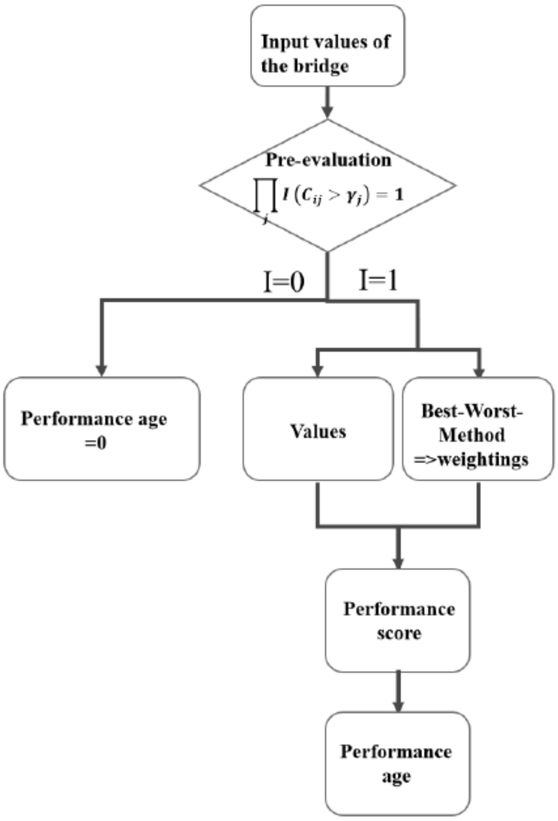

Figure 7. Quantification Methodology (XIE, 2017)

1. <u>Performance Criteria and Indicators:</u> the age has been determined by studying certain indicators from the bridges (Figure 8). The indicators were retrieved from a deep literature review and validated with the expertise of technicians of Rijkswaterstaat in a workshop.

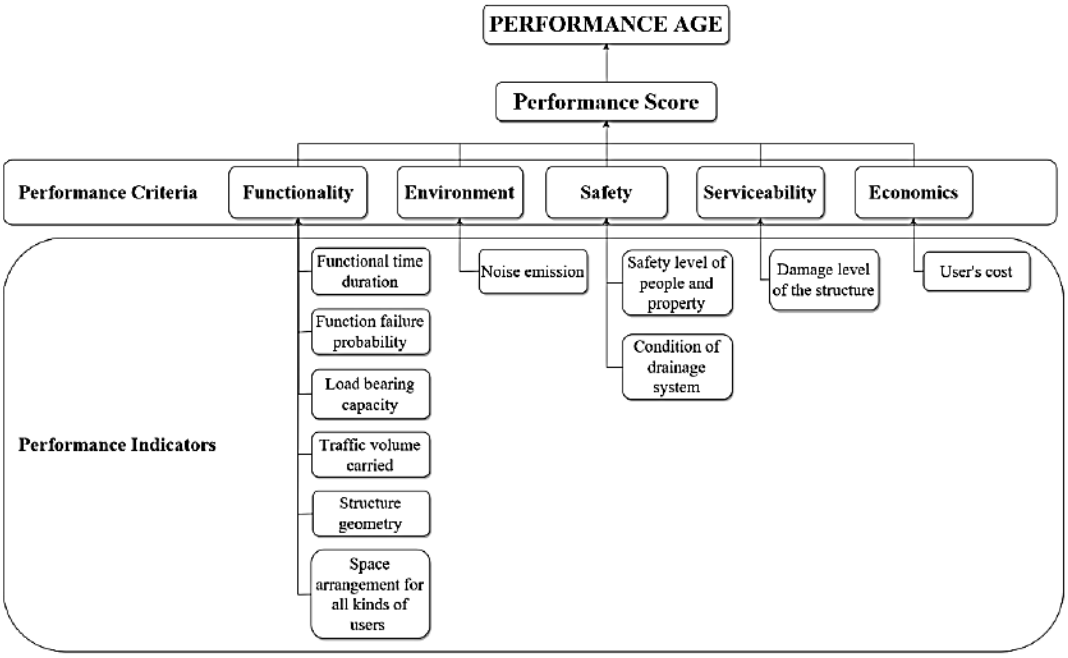

Figure 8. Validated Performance Model with the key performance indicators (XIE, 2017).

2. Bridge Pre-Evaluation: bridge assessment in which the user of the method could ensure that all the bridges reach a minimum score in each indicator. Whenever a bridge was filtered out in this step, it was estimated that they are at the end of their functional life and they should be replaced as soon as possible. The bridges that succeed the filtering can continue to the calculation of the Performance Age.
3. Weighting: the calculation of the Performance Age starts with the determination of the importance (weight) of each criteria and indicators. Those weights were determined by using the Best Worst Method, a Multi-Criteria-Decision-Making Method (MCDM), and the input of technicians through questionnaires.
4. Performance Score: the next step is the determination of the Performance Score of the bridge. To do it, bridge owners are asked to evaluate the bridges according to the Performance Model and with a predefined set of steps and equations, the Performance Score in a scale from 1 to 5 is determined.
5. Performance Age: the last step is to determine the Performance Age, which is done by the following equation:

$$Performance\ Age = 80 - \left[\frac{Performance\ score - cutoff\ value}{5 - cutoff\ value}\right] \times 80$$

The outcome of the last step is an exact number of years, which implies whether the bridge is old, younger or the same age as its real age. In addition, it suggests a replacement year by subtracting the Performance Age to the average replacement age of 80 [approx. from 80.2 years (Iv-Infra b.v., 2016)].

2.5.2 Problems and limitations

In the review of the research by Yue, the author identified certain issues that may hinder the implementation of the Performance Age or reduce the possibilities of the methodology. There are problems of different nature and effect:

1. Criteria definition: according to the technicians that assisted to the workshop executed by Xue Xie, the definition of the criteria is not the most adequate and some of them could lead to confusion in the decision-making process.
2. Performance Model approach: The Performance Model has been created based on the expertise of technicians. The problem of using their expertise is that technicians are not the ones who make the end decisions on bridge interventions, which limit their impact in the methodology output. For that reason, a decision-makers approach might be better to validate the model according to the points considered more important during decision making.
3. Performance Score: The Performance Score is calculated using equations created by Yue Xie. However, when reviewing them, it has been found that certain equations are not correct and cannot give proper results.
4. Performance Age equation: The developed equation to determine the Performance Age should be revised. If the values of the criteria/indicators equal to 1 or 2, the bridge does not pass the pre-evaluation phase and the Performance Age is 0 so replacement is needed. On the other hand, a bridge that passed the pre-evaluation can just score 3, 4 or 5. With a score of 3, the residual life of the bridge is already 27 years. The equation should be revised so that the Performance Age of a bridge that passes the pre-evaluation starts from 0 instead of 27 years.

$$Performance\ Age = 80 - \left[\frac{Performance\ score - cutoff\ value}{5 - cutoff\ value}\right] \times 80$$

5. The outcome of the Performance Age methodology is a number that reflects how old is the asset in functional terms and in how many years the asset should be replaced. However, this number is not useful when making replacement decisions. It would be better to give the information as the remaining functional life.
6. Functional Performance Evolution with time: The linear relation used to represent the evolution of the Performance Age is not the most adequate. The evolution of the functional performance is not linear in time. Unfortunately, the lack of models in the field of functional performance makes it difficult to determine how the functional performance evolves with time. For this research, it should be tried to find a better approximation with reality of that evolution.
7. EELI-Performance Age: The relation between EELI and Performance Age is misunderstood in the current study. There is a double correlation between EELI and the Performance Age which reduces the usefulness and effectiveness of the methodology.
8. Subjectivism: The research is limited by the subjectivism when evaluating the indicators. Indicators are evaluated according to a scale, but the score is given by a technician, which may not be the most adequate way and may change from expert to expert. For that reason, the

introduction of monitored data from Rijkswaterstaat and thresholds in the scale could add objective information to the method which is more reliable than the experts' opinions.

The eight points above mentioned may limit the implementation of the methodology. This research, which is based on the Performance Age, aims to solve the limitations and create an available and useful tool in the decision-making process.

2.6 Decision Making at Rijkswaterstaat

The main goal of this research is to apply the Performance Age principles to improve decision-making at Rijkswaterstaat. Then, in this paragraph the decision-making process is studied and how the Performance Age principles can contribute to make better decisions analysed.

The Performance Age main goal is to determine when a bridge should be replaced. The replacement decisions are not done at Rijkswaterstaat but in the Dutch Ministry of Infrastructure and Environment. Then, in order to find out how the decision-making procedure works, a meeting was arranged with policy makers in June 2018. Policy makers can be identified as decision-makers.

The first part of the meeting aimed to find out how the decision-making process work. The limitation of time did not allow to go very deep in the topic, but a simplified process can be seen in Figure 9.

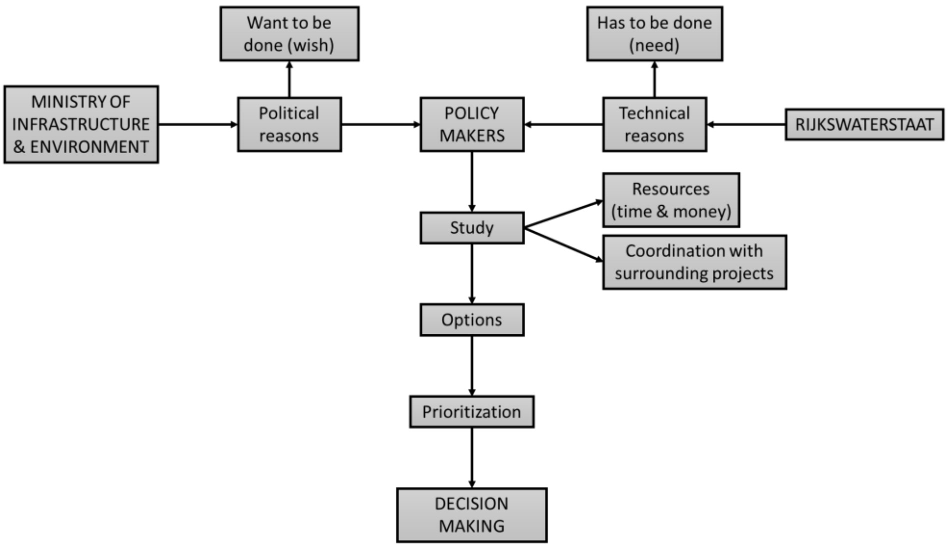

Figure 9. Decision-making process in the Netherlands.

Policy makers receive information from the political side (Ministry of Infrastructure & Environment), which are those projects that politicians want to do, and from the technical side (Rijkswaterstaat), which are those projects that have to be done. With this information, Policy Makers study and evaluate the incoming projects. The studies are used to determine which resources the project requires, whether there are other projects planned in the surroundings so that they could be grouped and manage them more efficiently, etc. The study provides different solutions to the projects, which are then prioritized. The prioritization is the last step to define which projects will be realized. This is a simplification of the decision-making process because in reality, more facts influence the decisions.

After the explanation of the decision-making process, the Performance Age idea was discussed. Policy makers considered that is a tool that could allow them to improve the decision-making and then, would be eager to have it. According to policy makers, currently is not common to make decisions based on functional performance of assets. Decisions are governed by the technical performance while the functionality is studied in a later stage once the replacement decision has been made, to ensure that the new bridge accomplishes with the actual functional requirements. According to policy makers, traffic capacity is the only functional aspect that might have certain importance in the current decision-making process. This differs from the study by Iv-Infra b.v. (2016) and the reason could be whether that the interviewees never faced a situation in which functionality was a problem or that they do not recognize functional problems, but they relate them to the technical field in which they have more expertise. Nevertheless, there is a gap between the functional and the technical study of bridges.

Policy makers consider that an integrated approach in which functional and technical performance are part of the bridge evaluation would be useful in the future when more precise decisions need to be done due to the limited budget and the growing number of interventions to happen. However, the transition from technical to functional-technical approach will be slow. The reason is that there are a lot of projects going on with great influence on road network performance and budget. Then, decision-making needs to be based in trustful and well-proved methodologies. In other words, policy makers think that tools like the Performance Age or similar will be moderately implemented and it will take time until they are part of the normal decision-making procedure.

About the methodology itself, policy makers believe that it has potential to help the decision-making process. They appreciate that there is work done in this direction and the refined tool can become an important contribution to the transition from technical to functional-technical evaluation. For instance, the Performance Age can help policy makers in different ways:

1. Informed decisions: although it seems that it was not a problem for the interviewees, the report by Iv-Infra b.v. (2016) ensures that almost 90% of bridges are replaced due to functional problems. However, there is not a universal method to assess the functional performance of bridges to make well-informed and objective decisions. The lack of a procedure based on empirical facts complicates the defence of the decisions against the ministry or the public.
2. Replacement predictions and planning: the methodology aims to provide the user with useful information about when the bridge should be replaced due to functional problems. This prediction will help to plan the interventions
3. Resource efficiency: a better prediction of when the bride should be replaced and more time to plan the intervention will help to make an easier resource allocation.

4. New constructions input: the functional problems detected by the Performance Age can be used as input the bridge of replacement. The problems should be used as design parameters for the new bridges and reduce the chance of functional problems happening again.
5. Initiator: the existence of the methodology can bring to life other similar tools that study functionality. If a stronger focus is put on functionality, more people will be aware of the problem and it will be tried to be solved.

It can be concluded that the Performance Age is a methodology which could give a new vision to the decision-making field, and hopefully, help to improve the decision-making procedures. In Figure 10, the outputs of this research are included in the decision-making process. For the application of the methodology to the Netherlands, the input from decision-makers in those aspects they would consider important about functionality is introduced in the methodology. This would help to make the methodology more precise on the one hand, and to create an ownership feeling with policy makers that eases the implementation of the methodology.

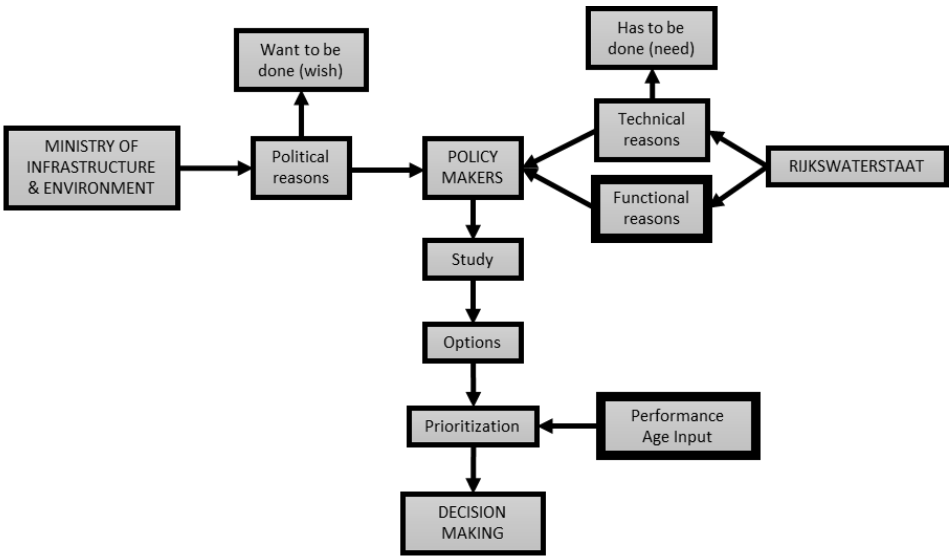

Figure 10. Decision-making in the Netherlands including functional performance study.

2.7 Conclusion

The paragraphs above justify the development of a methodology to evaluate the functional performance of bridges. It has been seen that there is a recurrent problem that needs further analysis and this research can move a step forward to improve how bridges are managed and how the replacement decisions are done. By the end of this report, the reader should find out a new way to evaluate bridges and their functional performance improving the efficiency of resources and helping to keep an updated road. In the next chapter, the methodology is developed.

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3.IMPROVED PERFORMANCE AGE METHODOLOGY

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3.1 Introduction

Along this chapter, the author will develop a methodology whose aim is to find a proper way to evaluate the functional performance of bridges and give an approximate time for bridge replacement as the bridge reaches the end of its functional life. The methodology will have four main steps:

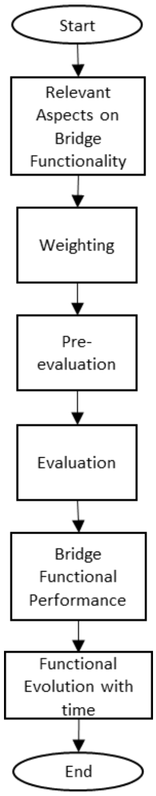

Figure 11. Methodology main steps.

1- Functional Assessment of Bridges: step focusing on the determination of those aspects relevant for the bridge functional performance. The outcome is a table, the Hierarchy of Bridge Functional Criteria, which shows what has to be assessed to define the functional performance of bridges.
2- Weighting: determination of the importance of the relevant aspects defined in the previous step. Each factor influences functional performance to a different degree and those degrees or weights are defined in this step.
3- Pre-evaluation: it is the first step of the bridge assessment. The pre-evaluation aims to evaluate the bridge functional performance on those indicators that are essential to maintain the bridge. Technicians judgement and monitored data are used to score each indicator on a pre-defined scale. If the indicators score is under a threshold, the bridge should be directly replaced.
4- Evaluation: the second step of the bridge assessment, which consists on the appraisal of the bridge functionality on the rest of the aspects that were not part of the pre-evaluation.

Technicians judgement and monitored data are used to score each indicator on a pre-defined scale

5- Bridge Functional Performance: The scores obtained in the bridge assessment are used combined with the weighting to determine which is the final bridge performance using a set of mathematical equations.
6- Functional Evolution with time: the bridge functional performance score is related with the functional evolution with time of bridges. The relation allows the user to find out which is the remaining functional life of the bridge.

The final goal is that the methodology influences the decisions about bridge interventions by providing sound and trustful information that decision makers can combine with the technical and political data. That integrated evaluation would improve the resource efficiency and help to maintain an updated road network.

In the following paragraphs, the methodology is explained step by step.

3.2 Relevant Aspects on Bridge Functionality

The determination of those aspects that influence the bridge functionality is the first step of the methodology. The bridge functional analysis is based on the study of certain aspects of the bridge, called Performance Indicators, which are parameters that describe a performance aspect. They are a common way to measure how assets behave and it is frequently found in literature, although focused on technical analysis. The Hierarchy of Bridge Functional Criteria is a framework in which those Performance Indicators are expressed and classified for a better understanding in order to follow a standard functional evaluation.

The Hierarchy of Bridge Functional Criteria can be expressed in different ways which were evaluated by the author. XIE (2017) proposed a model based on Performance Criterion and Performance Indicators, as can be seen in Figure 8. In terms of bridge evaluation, COST (2014), which is looking for a standardization of bridge quality at a European level, proposes to start the evaluation with the definition of the bridge goals. To align this research with the European Standards, the goals will be used as a foundation for the Hierarchy of Bridge Functional Criteria. The goals will be expressed as broad goals in what is called "Goal Categories". This definition was found in a book by Sinha & Labi (2007) in which the performance measures about transportation transit are described in Goal Categories, Subcategories and Performance Measures (Performance Indicators). The author considered that this categorization fits with the current research and therefore, will be used for the Hierarchy of Bridge Functional Criteria structure. The structure can be seen in Table 1.

Table 1. Proposed blank Hierarchy of Bridge Functional Criteria.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Goal Category 1	Subcategory 1	Performance Indicator 1
	Subcategory 2	Performance Indicator 2
		Performance Indicator 3
Goal Category n	Subcategory n	Performance Indicator n

Considering the model structure, the next paragraphs aim to describe how the model should be filled up. It basically consists in three steps:

1. Determination of the Goal Categories.
2. Determination of the Goal Subcategories.
3. Determination of the Performance Indicators.

3.2.1 Goal Categories

A performance goal is a type of property or behaviour that is required on a structure during its lifetime based on the assessment of different performance indicators (COST, 2014). They are an essential part of road bridge management, which involves balancing costs, opportunities and the mentioned performance goals. The definition of the Performance Goals is essential to ensure that the effort is focused on what really matters (WS Atkins Consultants LTD., 2002). Performance Goals vary among countries or even cities since each face different situations leading to different policies. Therefore, there is not a unique and universal set of goals although there might be similarities. For example, all the road networks strive for safety and a good traffic flow.

Despite the disparity among the goals categories that users may need, for this research it has been done a deep literature review from which Table 2 was developed. Such a complete table required a deep literature review with the challenge that the focus on bridge functionality is very small. In Appendix 1, the sources for each indicator can be found.

Table 2. Goal categories from literature.

GOAL CATEGORY	DEFINITION
Availability	Time duration in which the bridge is functional, and its functions can be fulfilled in a sufficient level.
Accessibility	It relates to the primary function of the structure for traffic. This means that the vehicles should be able to cross on or under the bridge.
Economics	Refers to the costs against benefits. Two different costs can be distinguished: direct (costs throughout the whole life cycle of the bridge-LCC analysis) and indirect (costs for users as accident costs and detour and delay costs). As benefits, it can be found the local and regional development due to the bridge presence.
Environment	Influence of the bridge on its direct physical environment. It can be divided in two stages: construction ($C0_2$ footprint, greenhouse gas emissions, resource consumption or waste generation) and operation (noise emissions of traffic, landscape fragmentation or the presence of high-risk polluting substances (asbestos, etc.)).
Flexibility	Compatibility of the bridge and adaptability to accommodate substantial changes in the future at a lower cost.
Health	Health of the inspection personnel, who should be in good health with respect to physical, mental and societal views.
Politics	Country politic situation that determines the projects to be done according to the policies developed by decision makers and with a great influence in the bridge replacement.
Reliability	The likelihood that the structure fails to provide its functions within a time interval.
Safety	It can be structural or to users. Structural safety relates to the ability of the structure to stay stable during its operation. Safety to users relates to the injuries or fatalities per unit of transportation A reduction in these numbers will be reflected in a higher safety for users.
Security	It refers to the adequate performance of the bridge according to vandalism, terrorism and human errors.
Maintainability	The ease to prevent the bridge from functional failure and to reduce the time to repair the bridge due to functional failure.
Ergonomics	It refers to the accessibility for inspection and maintenance. Workers should have an adequate space to complete the inspection and maintenance tasks properly.

Serviceability	It concerns about the technical performance. It includes the measurement of aspects like crack widths, vibrations, deflections, stress and state of concrete and steel elements, etc. to determine how the structure performs.
Society	It refers to the impact that the bridge has on the citizens and their satisfaction with the road network.
Durability	A durable structure shall meet the requirements of serviceability, strength, and stability throughout its intended service life.
Sustainability	It refers to the protection of the natural environment while enhancing the performance of bridges. Sustainability makes sure that the environment effected by the bridge is protected.

Such a deep literature review does not ensure fully completeness, so the user should make sure that the goals required for each particular situation are in the model. If not, the table is opened to the incorporation of new goals. This research aims to set a strong foundation for bridge functional analysis, but it should be flexible enough to be adapted if required.

From the list, the user should choose those categories relevant for the situation of study. Each Goal Category should be explained to reduce future uncertainties, as well as an explanation of the reasons to choose those categories. With the same objective, the author recommends relating the Goal Categories with the replacement reasons. This will ensure that the Goal Categories reflect the asset reality. It could be done with a table like Table 3.

Table 3. Relation between functional replacement reasons and Goal Categories.

Goal Cat. / Reasons	Goal Category 1	Goal Category n
Reason 1	Relation of Goal Category 1 with replacement reason 1.	Relation of Goal Category n with replacement reason 1.
Reason n	Relation of Goal Category 1 with replacement reason n.	Relation of Goal Category n with replacement reason n.

3.2.2 Goal subcategories

The next level of definition of the Hierarchy of Bridge Functional Criteria is the Goal Subcategories. The Goal Subcategories help to classify the Performance Indicators and to ease the model understanding. They serve as a link between the Goal Categories and the Performance Indicators. Goal subcategories are then, very dependent on Goal Categories and the Performance indicators chosen by the user. For that reason, a list of Goal Subcategories as done in the Goal Categories will not be useful due to the possible variations. The user is responsible to select them, making sure that there is a logical back and front relationship with the Goal Categories and Subcategories respectively.

3.2.3 Performance Indicators

The next step is to find out adequate Performance Indicators that reflect whether the goals are achieved or not. A Performance Indicator can be defined as a parameter that quantitatively describes a performance aspect (Dette & Sigrist, 2011). Performance Indicators should be objective so that all stakeholders (including the general public) can agree upon. When this happens, and all stakeholders agree on a common set of performance measures, they have a common language with which consensus can be reached. In order to verify that a bridge meets all the performance requirements, different indicators must be defined (Dette & Sigrist, 2011).

Performance Indicators in the road sector have been around for some years already, but the importance has been always mainly given to technical performance indicators. However, in the early 90s, the International Organisation for Economic Co-Operation and Development (1994) carried out a research in which a good number of functional performance indicators were found as a way to realize an analysis based on economic and social grounds (COST, 2014). Some of those indicators were, for example, the satisfaction with the road condition, the satisfaction with travel time, the average road user costs or the road surface roughness.

Since the research from the International Organisation for Economic Co-Operation and Development in 1994, the research continued mainly based on technical criteria. We are usually more interested about a collapsing bridge that a bridge whose functionality is not as good as required although it happens more often and causes huge disturbances from a social, economic and environmental point of view. Lately, COST (2014) made a great step forward to integrate functional and technical bridge analysis, although this last one still reigns over the functionality when referring to performance indicators. In this research, functionality will become the main character and it will receive the importance it should have according to the impact in the replacement interventions.

The author made a deep literature review to find out performance indicators that may affect the functional performance. Appendix 2 shows the outcome of that research. However, the table is opened, and new performance indicators are added if the case requires it. The user of the methodology is responsible to choose which indicators are adequate and whether others should be added or not.

The table includes several indicators (more than 80) that could be used to study the performance of the bridges. However, a selection of those important should be done. In order to avoid future discussions, the author recommends a justification of the selection or not of the Performance Indicators.

The author, from the experience achieved during the research, recommends a study of the available data before the Performance Indicators selection. Ideally, indicators should be measurable, objective and testable. Those characteristics mean that the indicators should be evaluated according to data monitored by road managers. Unfortunately, the author encountered the problem that commonly there is not available data from all the indicators. For that reason, if the user is willing to have a well-founded and objective methodology, those indicators with available data should be selected to avoid future problems. When there is a lack of data, the expertise of technicians is the only solution, which is not objective, but it may be an acceptable option.

3.2.4 Conclusion

When the Goal Categories, Goal Subcategories and Performance Indicators have been chosen, then the Hierarchy of Bridge Functional Criteria is developed, and the bridge analysis can continue. The Hierarchy of Bridge Functional Criteria is essential to determine the bridge functional performance, so it should be completed before proceeding.

The Hierarchy of Bridge Functional Criteria is particular to each country and even to each bridge. The model cannot be considered a universal set of indicators to study the bridges in functional terms because of the possible variation of interest between countries, cities, ministries, organizations, etc. which would lead to different indicators. For that reason, the user of the methodology must ensure that the Hierarchy of Bridge Functional Criteria developed adjusts to the circumstances in order to obtain trustful and reliable results.

3.3 Weighting

The next step of the methodology is the weighting. In the Hierarchy of Bridge Functional Criteria, those factors that affect the bridge functional performance are selected. However, not every individual factor has the same impact on the global bridge functional performance. For that reason, the weighting aims to determine which is the importance of each element individually for the determination of the functional performance. Since the goal of this research is to use the Performance Age principles to improve the decision-making at Rijkswaterstaat, will be the decision-makers who will give the weights.

In the research by XIE (2017), a novel procedure to determine the weightings was used, the "Best-Worst Method". The BWM is a methodology based on Multi-Criteria Decision Making that uses two vectors of pairwise comparisons to determine the weights of criteria. First, the best (e.g. most desirable, most important), and the worst (e.g. least desirable, least important) criteria are identified by the decision-maker, after which the best criterion is compared to the other criteria, and the other criteria to the worst criterion (Rezaei, 2016). Since it was used in the previous research with good results and theoretically is better than the most-commonly used method "Analytic Hierarchy Process", the method is explained in detail in Appendix 3. The user of the methodology might use other methods if desired. For example, the most common in civil engineering are the already mentioned "Analytic Hierarchy Process (AHP)", the "technique for order of preference by similarity to ideal solution (TOPSIS)" or "Choosing By Advantages (CBA)" (Abdel-malak, Issa, Miky, & Osman, 2017).

3.4 Bridge Assessment

The Bridge Assessment is the third step in the methodology. It refers to the evaluation of the actual bridge condition using the performance indicators selected in the Hierarchy of Bridge Functional Criteria. The assessment will be done using two different inputs: experts' evaluation and monitored data.

The bridge assessment is divided in three steps:

1. Pre-evaluation: assessment of those indicators that have an essential role in the bridge functional performance.
2. Evaluation: assessment of all the indicators.

3. Bridge Functional Performance: evaluation and weighting combined to find out the global bridge functional performance.

3.4.1 Pre-evaluation

The pre-evaluation is a first step in the analysis of the functional performance in which the asset is studied according to a set of indicators. The pre-evaluation is done based on a screening theory, which aims to filter out the unqualified alternatives (Hwang & Yoon, 1981). Within this theory, there are three options (Hwang & Yoon, 1981):

- Conjunctive screening: the evaluation is acceptable if it equals or exceeds a minimum score on each indicator.
- Disjunctive screening: the evaluation is acceptable if it equals or exceeds a minimum score on at least one indicator.
- Lexicographic screening: it ranks the indicators on importance and the evaluate assets that exceed the requirements of the most important criteria move on to the next phase.

All the three methods are non-compensatory methods, which means that a criterion with poor performance cannot be compensated by the good performance of other criterion. For a pre-evaluation, just those essential indicators are chosen, and they cannot be compensated. Among the three options, conjunctive screening will be done to those pre-selected indicators in this step.

To make sure that the pre-evaluation is done in a sound and objective way, the author has developed a set of steps that should be followed to realise the pre-evaluation. They can be seen in grey in the following Figure 12:

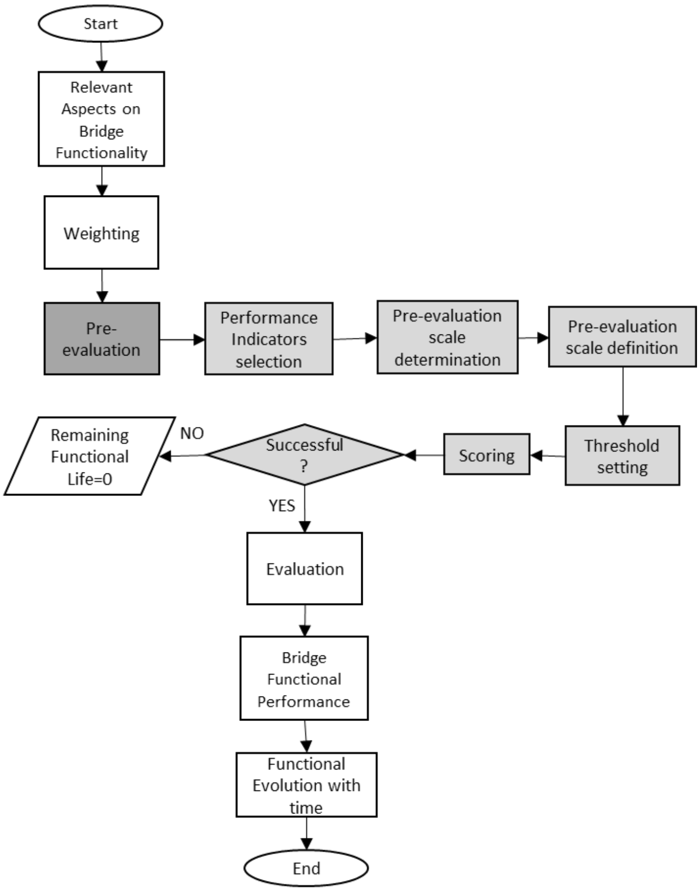

Figure 12. Pre-evaluation steps.

1. <u>Performance Indicators selection.</u>

For this method, the author recommends to pre-evaluate the bridge just in those Performance Indicators that are essential for the adequate (sufficient) functional performance of the asset (disjunctive screening). Then, the user has to choose which of the indicators from the Hierarchy of Bridge Functional Criteria should be used from the pre-evaluation. This will reduce the workload and ensures that the bridge is not replaced due to issues that are not important. Civil asset replacements are usually big investments and it is preferably to delay them in time to use all the value of the asset and to have available budget for other interventions with higher priorities.

2. <u>Pre-Evaluation Scale Determination.</u>

Whether the pre-evaluation is successful or not has to be determined by scoring the asset in the essential Performance Indicators. The author recommends developing a scale in which the different Performance Indicators score is clearly explained. To determine the type of scale more adequate for this research, a deep literature review has been done (see Appendix 5). The literature review was based on the study of bridge technical performance, but it can be used also for functional performance. The literature review revealed that there are several ways to analyse the condition of bridges and it is a decision of the user to choose the most preferable. In the selection, it is essential that every scale number chosen is discrete and simple to differentiate from others and requires a clear definition (Austroads, 2015).

3. Pre-Evaluation Scale Definition.

Once the scale has been chosen, the user should define what means each score for each performance indicator. This deep level of definition is important to ensure that the chosen score matches with the reality of the asset. Therefore, the user should make sure that the definition is clear for each score, avoiding confusion and misunderstanding in the scoring stage. Table 4 is an example of the possible table to score the asset in each performance indicator according to the predefined scale.

Table 4. Blank table with definitions for the scoring in the pre-evaluation.

CONDITION / INDICATOR	PERFECT [Score=1]	GOOD [Score=2]	FAIR [Score=3]	POOR [Score=4]
Performance Indicator 1	Definition of the “perfect” state for Performance Indicator 1.	[…]	[…]	Definition of the “poor” state for Performance Indicator 1.
Performance Indicator 2	[…]	[…]	Definition of the “fair” state for Performance Indicator 2.	[…]
Performance Indicator n	[…]	Definition of the “good” state for Performance Indicator n.	[…]	[…]

4. Threshold setting.

The last step is to determine which is the threshold of the pre-evaluation. The user should define which is the minimum score the asset can achieve to succeed the pre-evaluation. If the pre-evaluation indicates that the bridge is under that score, the bridge cannot continue to the evaluation phase.

The threshold setting highly depends on the nature of the Performance Indicators. If they can be measured with monitored data and there are network thresholds, the same threshold could be used in the scale. For example, the load capacity of bridges is set in network level to allow the transit of heavy vehicles in all the network. In this case, that threshold can be used. If the threshold cannot be directly determined from available data, the user should define it with his own knowledge or with recommendations from experts.

5. Scoring.

The scoring is the stage in which the bridge is assessed according to the scale defined before. The scoring can be done two ways:

- Objectively: when the performance indicators can be monitored and measured in quantitative data, the score can be given directly by the user from that data.
- Subjectively: if the performance indicators cannot be monitored, the presence of technicians to assess the asset is essential. They will score the bridge according to their

expertise. In this case, it is recommended to prepare a workshop with experts in which the asset is scored consensually.

6. <u>Go or not go.</u>

The last step is to determine what to do with the bridge by assessing the scores given by experts and monitored data. If all the Performance Indicators score above the previously define threshold, the bridge succeeds the pre-evaluation and can continue to the evaluation. Otherwise, the bridge is considered at the end of its functional life or obsolete and it should be considered for direct replacement.

3.4.2 Evaluation

Bridges that succeed the pre-evaluation can go to the next step: the evaluation. The evaluation is a compensatory method in which the bridge is analysed according to the Performance Indicators determined in the Hierarchy of Bridge Functional Criteria. It is a compensatory method because the good performance of certain aspects can compensate the low performance of others. To ensure that the compensation is fair, the Performance Indicators have different weights as given in paragraph 3.3. This ensures that a bad performance of an important indicator is reflected in a lower global performance.

The evaluation procedure can be seen in grey in Figure 13:

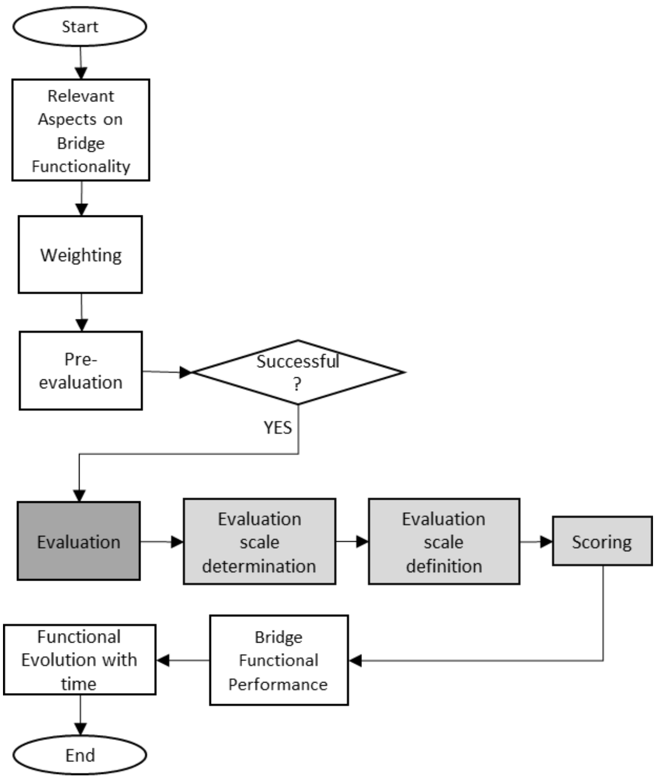

Figure 13. Evaluation procedure.

1. <u>Evaluation Scale Determination.</u>

The author recommends evaluating the bridge according to a scale. First, the user should determine which scale would adjust better to each case. As seen in Appendix 5, different scales can be used, and the user should determine which adapts better to the study case. It is recommended to use the same as in the pre-evaluation. Performance indicators assessed in the pre-evaluation should be included in the evaluation too so using the same scale reduces the workload since they were already assessed.

2. Evaluation Scale Definition.

Once the values of the scale are determined, each performance indicator should be clearly defined as done in Table 4 for the pre-evaluation. The user should define what means each score for each performance indicator. This deep level of definition is important to ensure that the chosen score matches with the reality of the asset. Therefore, the user should make sure that the definition is clear for each score, avoiding confusion and misunderstanding in the scoring stage.

3. Scoring.

The scoring is the stage in which the bridge is assessed according to the scale defined before. The scoring can be done two ways:

- Objectively: when the performance indicators can be monitored and measured in quantitative data, the score can be given directly from that data. Score from monitored data is would be ideal to get proper answers.
- Subjectively: if the performance indicators cannot be monitored, the presence of technicians to assess the asset is essential. They will score the bridge according to their expertise. In this case, it is recommended to prepare a workshop with 3 to 5 experts in which the asset is scored.

Following the 3 steps above, the user should be able to evaluate the asset. With this information, the bridge functional performance can be determined.

3.4.3 Bridge Functional Performance

In the Bridge Functional Performance, the weighting (paragraph 3.3) and the evaluation (paragraph 3.4.2) are combined to find out the global bridge functional performance. A set of pre-defined mathematical equations make possible the relation. The outcome of this step is the score of the bridge in the scale chosen before.

Six steps have to be followed to reach the Bridge Functional Performance score. They can be seen in grey in Figure 14.

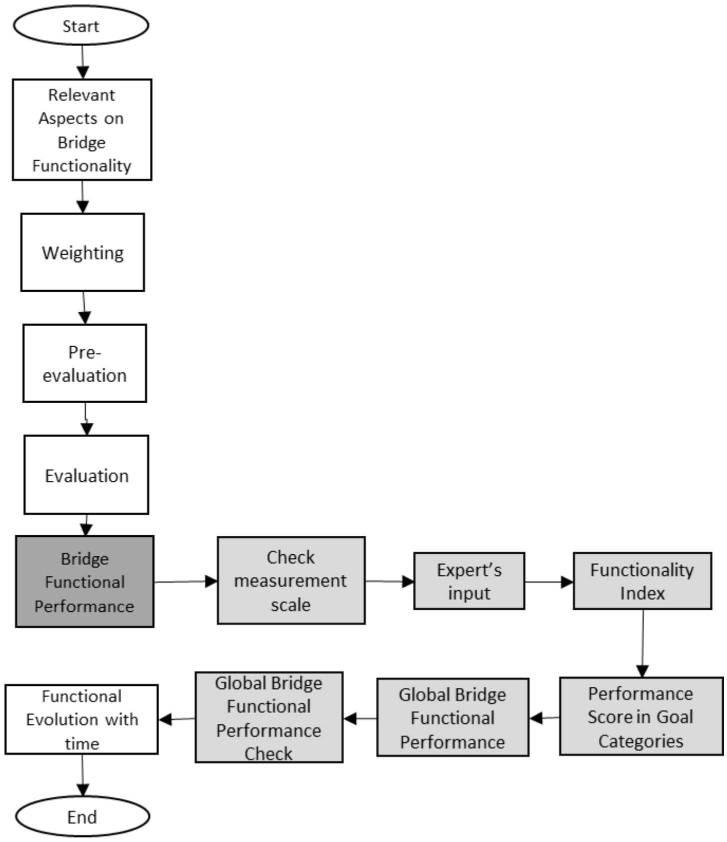

Figure 14. Bridge Functional Performance Score determination steps.

STEP 1. Check measurement scale.

The measurement scale of the Bridge Functional Performance must be the same as in the Evaluation phase. To continue with the example shown in Table 4, the 4-points scale should be used in this step.

$$M = [m_1, m_2, m_3, m_4] = [\,perfect, good, fair, poor]$$

The measurement scale has been defined in a numerical scale that corresponds to the qualitative bridge state.

$$S = [s_1, s_2, s_3, s_4] = [1, 2, 3, 4\,]$$

STEP 2. Experts input (R_y)

In the evaluation step, technicians studied the bridge functional performance by analysing and scoring the Performance Indicators according to a scale. That evaluation can be transformed into a matrix as follows:

$$R_y = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \dots & \dots & \dots & \dots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix}$$

For the Goal Category *y*, in the matrix the rows refer to the Performance Indicator while the columns refer to the grade given to that Performance Indicator from the numerical scale set in step 1. For example, r_{11} means that r% of experts consider that the Performance Indicator 1 is in perfect condition (s_1=1) whereas r_{22} means that r% of experts consider that the Performance Indicator 2 is in good condition (s_2=2). In this case, we have chosen a 4 points scale. If the chosen scale would be other, *m* would correspond to the amount of points of that scale.

STEP 3. Functionality Index (FI)

The Functionality Index refers to the state of the bridge according to each Performance Indicator analysed by technicians. The performance of an individual bridge can be considered by reviewing the performance of the individual indicators. To determine the Functionality Index (CI), we need to multiply the experts' input (R) by the numerical scale (S). The numerical scale (S) has to be transposed for the multiplication.

$$FI_y = R_y \times S^T$$

STEP 4. Performance in Goal Categories (Z)

The Performance of the bridge in each Goal Category (Z) is obtained by multiplying the relative weights (w) of each indicator by the Functionality Index (FI). In this research, the weights would be those obtained from decision makers (Table 13).

$$Z_y = w_y \times FI_y$$

Steps 2, 3 and 4 must be done for each Goal Category until it is obtained the performance of the bridge in each Goal Category.

STEP 5. Global Bridge Functional Performance (P)

The Global Bridge Functional Performance (P) is obtained by multiplying the relative weights of each Goal Category (W) determined previously by the performance of the bridge in each Goal Category (Z).

$$P = W_y Z_y$$

The Global Bridge Functional Performance will deliver the final score of the bridge of study according to the scale defined before.

STEP 6. Global Bridge Functional Performance Check.

The Global Bridge Functional Performance is limited by the Functionality Index of the indicators selected for the pre-evaluation. Those indicators are essential for the proper functional performance of the bridge and therefore, they cannot be compensated with the score of other performance indicators. For that reason, if the Global Bridge Functional Performance is greater than the Functionality Index of an essential indicator, the Global Bridge Functional Performance will reduce to the Functionality Index of that indicator. It can be explained as follows:

If $P < FI_{\text{essential indicator pre-evaluation}} \rightarrow P = P$

If $P > FI_{\text{essential indicator pre-evaluation}} \rightarrow P = FI_{\text{essential indicator pre-evaluation}}$

The limitation can be seen the following example 1:

Example 1. In the pre-evaluation, three performance indicators are considered essential. They are called PI_1, PI_2 and PI_3. Then, we have two more performance indicators which are not essential: pi_1 and pi_2. Considering a 4 points scale (1-perfect; 2-good; 3-fair; 4-poor). Each performance indicator has the following characteristics.

Table 5. Bridge condition limitation example.

Performance Indicator	Functionality Index (FI)	Weight (W) (%)	Residual Life Associated to FI (years)
PI1	3	30	10
PI2	2	20	30
PI3	2	25	30
pi1	1	10	60
pi2	3	15	10

According to the data in the table, we can calculate the Global Bridge Functional Performance:

$$Global\ Bridge\ Functional\ Performance^{*} =$$
$$= \sum_{i=1}^{n} CI_n W_n = 3 * 0.3 + 2 * 0.2 + 2 * 0.25 + 1 * 0.1 + 3 * 0.15 = 2.35$$

*: the example is a simplification of the Bridge Functional Performance explained before and that is why the equation does not correspond with step 5, but it follows the same principle.

A Global Functional Performance of 2.35 would mean a residual life of approximately 24 years. However, PI_1 limits that residual life to 10 years because it is an essential indicator. In this case, the Global Bridge Functional Performance corresponds to the Functionality Index of PI_1, so it should be 3 instead of 2.35.

Appendix 6 , the Bridge Functional Performance procedure is shown.

3.5 Remaining Functional Life

3.5.1 Introduction

The Remaining Functional Life is the last step of the methodology. It is calculated out of the score obtained in the Global Bridge Functional Performance. In the previous research on the Performance Age by (XIE, 2017), the Performance Age was determined using the following equation:

$$\text{Performance Age} = 80 - \left[\frac{\text{Performance score} - \text{cutoff value}}{5 - \text{cutoff value}}\right] \times 80$$

In which the “Performance score” corresponds to the “Global Bridge Functional Score”, the cut-off value for this case is 2 (the threshold on a scale of 5 points) and 80 comes from the predicted functional life of the bridges in the Netherlands (Iv-Infra b.v., 2016). However, this equation several problems from different nature:

1. Equation problem: the equation has a problem already stated in the background of this research. The pre-evaluation in XIE's methodology (2017) assesses all the performance indicators, unlike the current research in which just the essential indicators are part of the pre-evaluation. In XIE (2017), when the scores of the performance indicators equal to 1 or 2, the bridge does not succeed the pre-evaluation phase, the Performance Age is 0 and direct replacement is recommended. On the other hand, a bridge that succeeds the pre-evaluation can just score 3, 4 or 5 in the 5-point scale. With a score of 3, the residual life of the bridge is already 27 years [((3-2)/(5-2))*80≈27]. This means that there are 27 years with no information about the asset functional performance.
2. Principles of the equation: the equation supposes a linear evolution of the functional performance in time. However, although there is no literature to confirm it, common sense and technicians' expertise states that the evolution in time of the functional performance is likely to resemble to the deterioration curves used in asset management and maintenance practices. Deterioration curves use inspection data and/or age information to provide information regarding the future condition of the structure or the rate at which the structure is likely to deteriorate (Austroads, 2015). Figure 15 shows a deterioration curve. In the early days of operation, the bridge reduces its technical performance slowly. However, as it gets older, the deterioration occurs faster than in the new asset.
3. Precision of the results: the Performance Age is calculated from an equation with problems, considering an evolution that might not correspond to reality and the bridge is evaluated subjectively by experts. Despite these limitations, the result is an exact number with no representation of the potential errors that the methodology could have. If the errors are not considered and the methodology is used to make decisions, it may lead to an inefficient use of resources. A bridge with lower calculated Performance Age that it actually has can lead to faster replacement than required.

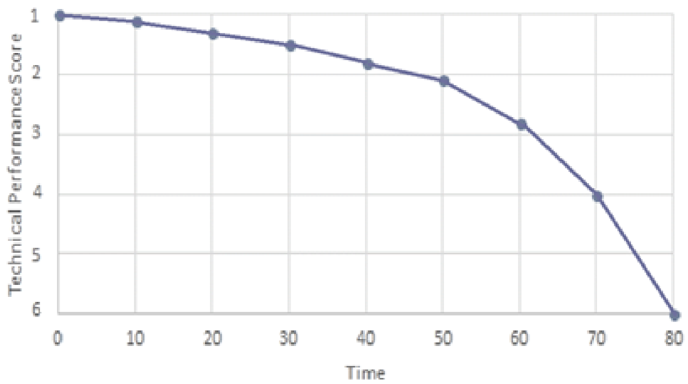

Figure 15. Technical condition curve. Random values given by the author.

4. Usefulness: the Performance Age has as outcome the age of a bridge according to its functional performance based on a set of performance indicators. However, this does not directly say when the bridge should be replaced, which is what interests more to the decision makers. (XIE, 2017) solved this by using an average functional life of 80 years, from which the

Performance Age could be subtracted, and the remaining functional life determined. However, this is not handy since it requires further calculations to determine when the bridge should be replaced.

Due to the limitations explained above, the Performance Age will be calculated differently for the current research.

3.5.2 Calculation

The problems stated above are solved in this research considering three aspects:

1. *Performance Age becomes Remaining Functional Life.*

The actual age of the bridge is not valuable for decision-makers because it does not directly say when the bridge should be replaced. Then, the Remaining Functional Life will be the outcome of this methodology. This will allow decision-makers to have an idea about the network intervention requirements and help to allocate the resources in the most adequate and efficient way. In essence, it is the same as the Performance Age, but the information is given in a more useful format.

2. *The remaining functional life will be determined using a functional evolution curve like the technical condition curves.*

The condition curves represent a logical evolution of the technical performance and the studies in the topic confirm the shape of the curve. They are used by asset managers to determine when interventions should be done in bridges using monitored or inspected data. In the field of functional performance, there has not been any research that studies how the functional performance evolves with time because current asset management practices are still based on technical aspects. However, experts from Rijkswaterstaat agree that the functional evolution resembles more to the condition curve than to a linear evolution like that chosen by XIE (2017). In general, an asset has a perfect functional performance in the first years of life because the requirements have been introduced in the design process and they did not change yet. However, as the asset gets older, the requirements will change faster, and the asset will reduce its performance at a higher pace.

The main difference between technical and functional evolution curves is the great influence that the environment has on the functional performance. The technical performance is based on the inner bridge behaviour, with the performance of the different materials and elements that after several studies in different conditions, can lead to a relatively precise curve. However, the functional performance is greatly affected by the environment: increase of traffic, more accidents, bigger or heavier trucks, people's aesthetics opinion, etc. In Figure 16, environmental changes that can influence the functional performance of the bridge are represented: the development of an industrial area (steep functional performance decrease-between year 50 and 30 of remaining life) reduces the functional performance due to traffic increase while the opening of a new bridge (when the remaining functional life is 30) improves the functional performance (and the remaining functional life increases) due to traffic decrease, for example. Then, the environmental changes influence the performance indicators, which influence the functional remaining life. This effect of the environment, with improvements or deterioration in the performance, makes it especially challenging to model a precise curve.

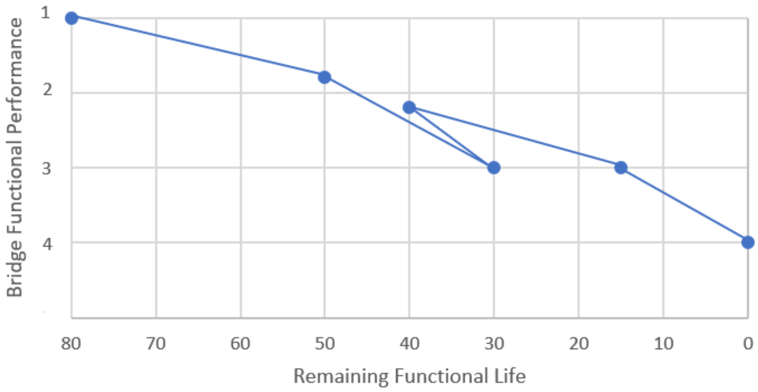

Figure 16. Functional evolution curve (including environmental changes).

Appendix 7 shows how the environmental changes can affect the functional evolution of bridges. It is out of the boundaries of this research to precisely determine how the curve develops with time, but the reader can see in the appendix which is the influence of the changes of the traffic intensity on the functional evolution curve using past trends.

For this research, the representation of the functional evolution with time has been supposed according to the expertise of technicians, who suggested the different values referring to the curve. A bridge in perfect condition has a remaining life of 80 years, which is the average functional life for Dutch bridges (Iv-Infra b.v., 2016). Then, it is considered that a bridge can be half of its life (40 years) with a "good" functional performance. The functional performance, similarly to the technical condition, would reduce faster as the bridge gets older. This is translated in that a bridge continues his functional deterioration another 35% of its life with a "fair" performance (from 40 to 12 years of remaining life). Finally, the functional performance drops faster in a "poor" condition which lasts from 12 until the end of life. A bridge with a Global Functional Performance Score of 4 still has certain lifespan because functional replacements are not as urgent as a bridge with high collapsing probabilities.

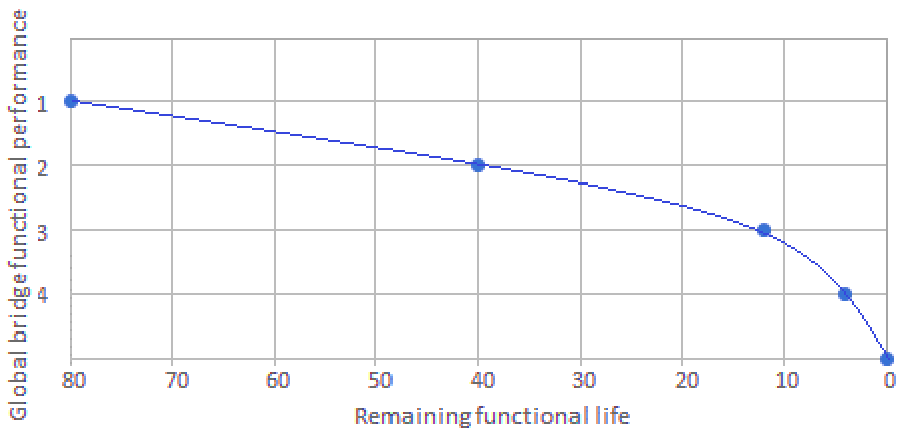

Figure 17. Functional evolution curve.

3. Consideration of methodology uncertainties.

The functional evolution curve is an assumption and therefore, there are uncertainties involved. The methodology has a limited precision due to (see Figure 18):

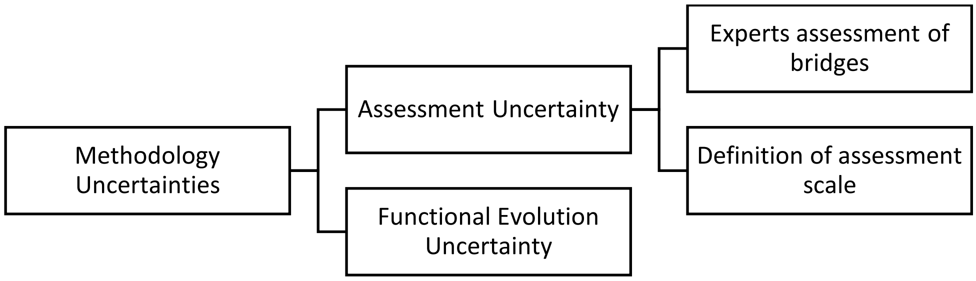

Figure 18. Uncertainties involved in the determination of the Remaining Functional Life.

a. *Assessment uncertainty*. The methodology has certain subjectivism that reduces the precision of the measurements. It has two different sources:
   i. Expert's assessment: if the assessment cannot be done with monitored data, experts are the most trustful source of information. However, human decisions are always affected by certain subjectivism, which introduces a potential uncertainty in the results.
   ii. Definition of measurement scale. The measurement scale to assess the bridge in the pre-evaluation and the evaluation has to be defined by the user. Depending on the expertise of the user and the available information, the precision of the scale can vary, and so the uncertainties of the methodology.

b. *Functional Evolution uncertainty*. The functional evolution curve used to determine the Remaining Functional Life is a supposition. It is not the goal of this research to define such a curve and therefore, the uncertainty will be larger than when more research is done, and the curve shape is better predicted. However, as a future prediction, uncertainty will be always present.

These uncertainties have an impact on the results of the methodology and should be represented on it. The two types of uncertainties are included in the methodology as follows:

- Assessment uncertainty = ±10 years[1]. This uncertainty is constant with the evolution in time of the bridge performance. With the current knowledge in the field, expert assessment is needed so uncertainty will remain until monitored data is used to assess the bridge. The uncertainty related with the measurement scale is also constant with the current methodology. It will reduce when more countries are aware of the functionality problem and new investigations are developed to measure the functional performance.
- Functional Evolution Uncertainty = ±10% of the Remaining Functional Life[1]. This uncertainty varies with time, which is represented in the percentage. As time passes, the occurrence of events is better controlled and then, the uncertainties are smaller. When the prediction comprises a longer time span, uncertainty is also larger.

Then, if a bridge has a remaining functional life of 20 years, the uncertainty is 20*0.1+10=2+10=12 years. Then, the remaining functional life ranges from 8 to 32 years.

3.6 Performance Age-EELI Relationship

One of the initial goals of this research was to determine the relationship between the Performance Age and the Economic End of Life Indicator (EELI) developed by Rijkswaterstaat. As a reminder, the EELI is an indicator that makes a statement on economic grounds to what extent the maintenance of an aging structure is still financially viable to a 1 on 1 replacement (Bakker, Roebers, & Knoops, 2016). It is calculated as follows:

$$EELI = \frac{LCC_1}{LCC_2} = \frac{\text{LCC of maintaining a structure and replacing in a statistically expected replacement year}}{\text{LCC of direct replacement and subsequent maintenance}}$$

Depending on the result of the EELI, two suggestions for intervention are possible:

- If the EELI<1, the bridge should be maintained and replaced in a statistically expected replacement year.
- If the EELI>1, it is recommended to directly replace the bridge and maintain it.

In the previous research by XIE (2017), the Performance Age and the EELI were related using the residual functional life (equal to 80-Performance Age) as the “expected replacement year.” In EELI. The author of this research agrees that this input for the EELI is more adequate and precise than what is currently in use: an average service life of bridges of 80 years. Then, the expected replacement year is the bridge construction year plus 80. However, this is a statistical number which means that 50% of the expected replacement years are underestimated and 50% overestimated. However, a certain chronological age does not mean that the bridge cannot provide the required services. Depending on

[1] Defined by the author. Variations are possible.

the environmental conditions, traffic intensities or loads, etc., the bridges have different behaviour and it does not make sense to evaluate them all with the same end of life. Then, the EELI and Performance Age combination ensures that the bridge is assessed by how it works and not by how old it is.

XIE (2017) also suggested a combination of the EELI and the Performance Age to determine intervention strategies (see Table 6). In this case, the author does not agree with the approach because it makes a double relation. Once the residual life of the Performance Age is included in the calculation of the EELI, it does not make sense to determine strategies combining the EELI output and the residual life of the Performance Age output.

Table 6. Replacement Strategies based on Combination of EELI and Performance Age (XIE, 2017)

Strategies		Performance Age (residual life)		
		= 0	< technical rest service life	> technical rest service life
EELI	>1	Replace the bridge as soon as possible	Invest less money on maintenance and replace the bridge when it reaches the end of Performance Age	Look into other parameters
	<1	Look into other parameters	Invest more money on maintenance and replace the bridge when it reaches the end of Performance Age	Do not replace the bridge and remain current maintenance strategies till one of the parameters reaches its limitation

Then, in this research the Remaining Functional Life is used as an input for the calculation of the EELI. The Remaining Functional Life will be used for the calculation of the LCC_1 as it is the one that needs an expected replacement year. For the LCC_2, the time that the bridge will be maintained after replacement can be those 80 years of design life because the Remaining Functional Life will be also 80 since the bridge is new-built and should logically be in perfect condition. In the following Figure 19, the combination and intervention strategies are shown.

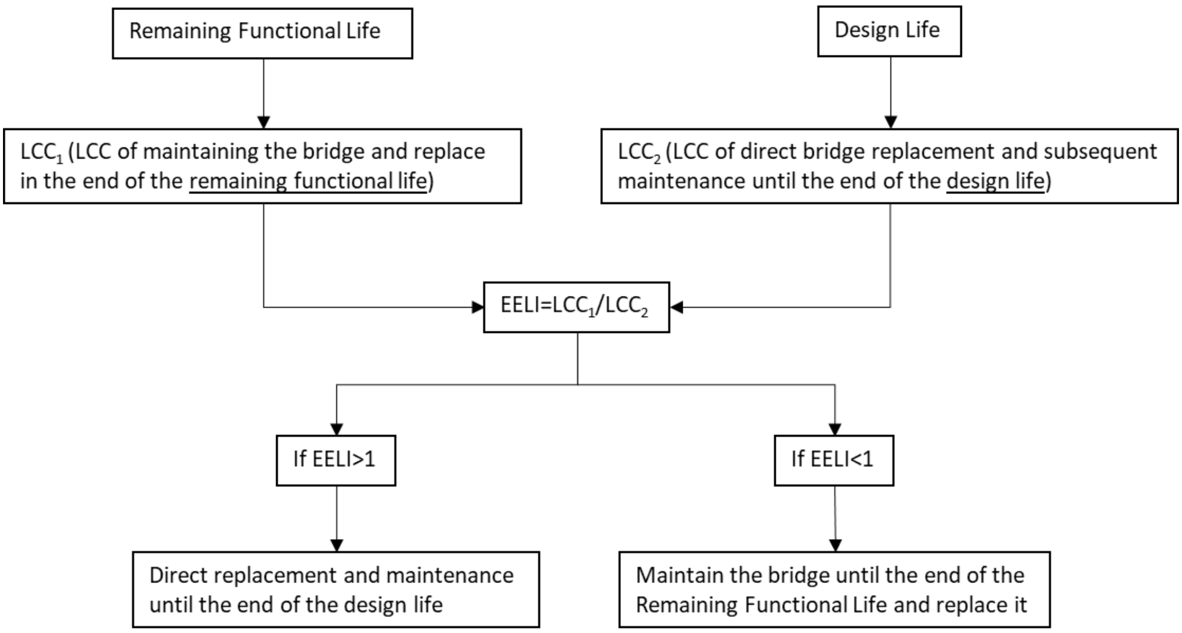

Figure 19. Combination of the EELI and the Performance Age (Remaining Functional Life).

3.7 Conclusion

The methodology is summed up in the steps shown in Figure 20, with its corresponding inputs required in each step and the consequent outputs.

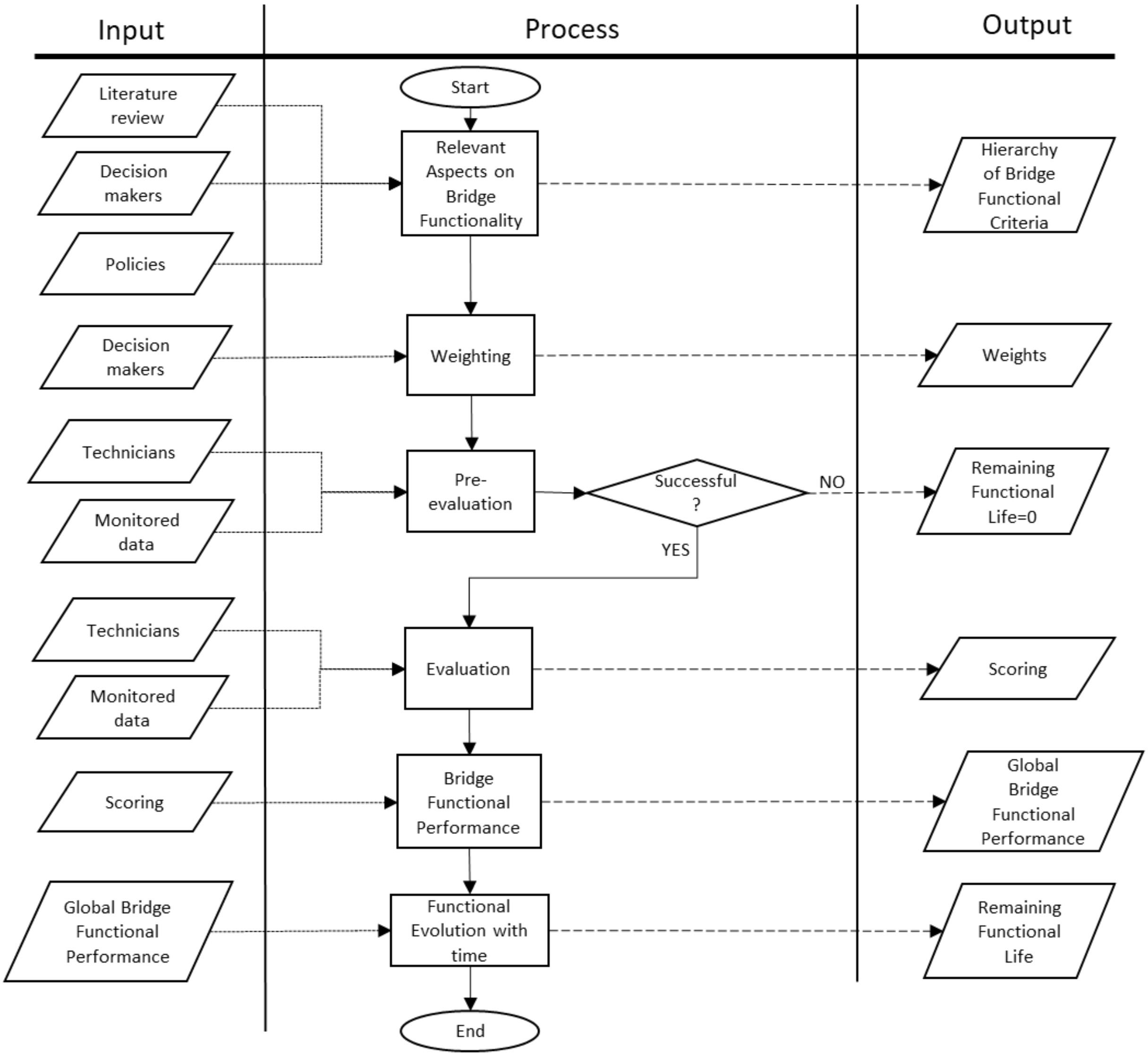

Figure 20. New Performance Age Methodology

The methodology starts with the determination of relevant aspects for bridge functional analysis. Decision-maker's input and policies from the country of study are important sources of information to ensure a methodology aligned with reality. The relevant aspects are classified in the Hierarchy of Bridge Functional Criteria. Then, the Hierarchy or Bridge Functional Criteria is weighted. The relative importance of each aspect influencing functionality is determined. Then, the bridge is assessed in two-steps. First, a pre-evaluation step that aims to ensure that the bridge performs to a certain level in those performance indicators which are essential to provide a minimum bridge service. The bridge must be above a pre-defined threshold when scored in the indicators using monitored data (or technicians' expertise if no monitored data available). If any indicator does not score above the threshold, the bridge should be directly replaced. Otherwise, the bridge can continue to the evaluation step, in which the rest of the indicators from the Hierarchy of Bridge Performance Criteria are assessed with either monitored data or technician's expertise. A series of mathematical equations is used to relate the weights and the evaluation scores to determine the Global Bridge Functional Performance. Finally, the Global Bridge Functional Performance is related with the Functional Evolution with time of the bridge and the Remaining Functional Life is obtained.

This methodology, based on the Performance Age methodology developed by XIE (2017), has introduced several improvements from that first version that should ease the implementation of the methodology. The improvements are the following:

- Criteria definition: a deep literature review from reliable sources was developed to determine which criteria might influence the bridge functionality. A list was created with precise definitions. The definitions were a point of discussion in Yue's research while it was clearly explained in this research.
- Decision-maker's input: decision-makers are considered a very valuable source of information for this methodology since they will be the final users of the outcome, so their inputs should play an important role in the design. Their input was used to define a two-step bridge assessment (pre-evaluation and evaluation) and to determine which is the most adequate format to deliver them the information. Visual information in radial graphs and GIS maps were recommended, although the last was not implemented.
- Remediation of the equation limitations: the determination of the Global Bridge Functional Performance is based on the equations developed by XIE (2017), however several steps were not correct in that first version. In this research, the calculations perfectly work and it has been demostrated.
- Functional Evolution with time: the linear relation by Yue has been transformed into a curve similar to a technical condition curve. In the first years of the asset, the bridge functionality deteriorates slower because the bridge is designed considering the present and certain predictive requirements. However, as the bridge gets older, the probability of environmental changes that affect functionality is higher. This is translated in a faster functional deterioration. This evolution curve has been created with the input of technicians, but it needs further research to ensure that it is the most adequate.
- In this research, it has been decided to deliver the Performance Age in terms of remaining life. This is a small change that can ease the understanding and the implementation.

The developed methodology has, then, improved since the first version, and the introduction of decision makers is a point which can enhance the application of the methodology. Finally, a standard and based on facts methodology is available to decide on functional performance replacements.

4. PERFORMANCE AGE METHODOLOGY AT RIJKSWATERSTAAT

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4.1 Introduction

This chapter aims to apply the methodology to a real bridge from the Dutch Highway Network. For instance, a fixed highway concrete bridge. This chapter will serve as a validation of the methodology, determining whether it is objective and standard as desired in the research goal. A successful methodology can create a new field of expertise within Rijkswaterstaat and the Replacements and Renovations Programme, with currently a focus on technical assessment but with an eye on the future asset management. Asset management composed of an integral technical and functional bridge assessment.

4.2 Replacements and Renovations Programme

The current research has been ordered by Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Environment. To be precise, by the Great Projects and Maintenance department (In Dutch, GPO-Grote Projecten en Onderhoud). This department is responsible of the Dutch National Replacements and Renovations programme (in Dutch, V&R - Vervanging en Renovatie). V&R programme focuses on those assets in which the technical or functional requirements cannot be longer guaranteed by regular maintenance as they arrive to their end of life (Rijkswaterstaat, 2013).

Large parts of the networks managed by Rijkswaterstaat have been in used for more than 50 years. The age, combined with a more intense use, heavier trucks and more extreme weather conditions increase the loads on the infrastructure. Rijkswaterstaat sees the future interventions as an opportunity to update an old network. The V&R programme aims to coordinate and optimize the renovations and replacements and those assets that are crucial links in the network but that reach their end of life and make sure that the new assets comply with the future requirements both technical and functional along their lifespan (Rijkswaterstaat, 2016). Structures built now may still be in used after one century so the influences of the physical and socio-economic environment (now and in the future) have to be considered in order to redesign the structure according to new possible demands in the future (Bernardini, et al., 2014). V&R programme also focuses on predicting the replacement costs in order to timely inform politicians about the allocation of the necessary budget (Bakker, Roebers, & Knoops, 2016).

Currently, the Replacements and Renovations Programme is just focused on bridge technical performance and this research would be an interesting tool to improve the bridge evaluation by introducing the functional performance, give better recommendations and finally, make better replacement decisions.

4.3 Methodology Application

4.3.1 Bridge selection

For this example, the Schielandweg bridge from Appendix 11 has been selected. It is a bridge in the highway A20 from Gouda to Rotterdam, the recommended area by technicians due to the high traffic intensities and congestion.

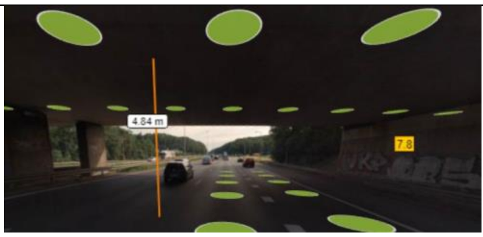
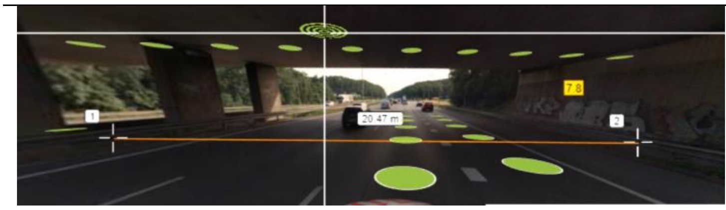
Figure 21. Schielandweg bridge.

BRIDGE CHARACTERISTICS (From RWS Bridge Management System – DISK)

Road	A20 Gouda-Rotterdam
Bridge Name	Schielandweg
ID in DISK	38A-122-01
Province	Zuid-Holland
Municipality	Zuidplas
Corridor/Economic importance	KP Gouwe -KP Terbregseplein
Hectometre	42.7
Construction year	1983
Object dimensions (m)	Length: 53.21; Width: 20.08
Object Type	Concrete viaduct
Cultural/historical value	Green
Economic Network Category	Orange (C): Connections with high intensities and great importance from spatial economic policy
Traffic intensity	90300 vehicles/year in weekdays, from which 9610 are trucks.
Object quality (Risk level)	2
Replacement value (K€)	3000-5000
Load class	60
Theoretical end of life	2063
Technical end of life	Unknown
EELI	0.39

From the software "StreetSmart", the following images and measurements of the bridge were retrieved:

Table 7. Bridge physical features.

PICTURE (FROM STREETSMART)	DESCRIPTION
	Top view of the bridge
	Layout of the bridge and the roads.
	Bridge over A20 Direction: Gouda-Rotterdam Height=5.11 m
	Bridge over A20 Direction: Gouda-Rotterdam Width=21.15 m Around 2.5 m extra in the right shoulder.
	Bridge over A20 Direction: Rotterdam-Gouda Height=4.84 m
	Bridge over A20 Direction: Rotterdam-Gouda Width=20.47 m Around 3 m extra in the right shoulder.

	Road crossing A20 on bridge Direction: W-E Width= 8.42 No extra width available
	Road crossing A20 on bridge Direction: E-W Width=8.35 m No extra width available
	Bridge deck view for visual inspection Direction: Gouda-Rotterdam No height incident marks.
	Bridge deck view for visual inspection Direction: Rotterdam-Gouda No height incidents marks.

4.3.2 Relevant Aspects for Bridge Functionality

In the next paragraphs, the aspects that influence bridge functionality in the Netherlands are studied and shown in the Hierarchy of Bridge Functional Criteria following the steps previously shown in the methodology.

4.3.2.1 Goal Categories

The Goal Categories for the case of Fixed Highway Concrete Bridges in the Netherlands will be determined in this paragraph. When doing the literature review, performance goals are mainly found in terms of RAMS (Reliability, Availability, Maintainability and Safety). This is a common way to study infrastructure performance worldwide. However, it is mainly focused on technical aspects. In order to complete RAMS, Rijkswaterstaat developed an enlarged classification named RAMSSHEEP (Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economics, Politics) (Ministry of Infrastructure and the Environment , 2012). This extended version of RAMS fits better in the consideration of technical, environmental and social aspects of bridges but still considers technical aspects that are out of the boundaries of this research. Then, other Goal Categories should be found.

In a deep literature review whose outcome was Table 2, there are several Goal Categories that better adapt to the functional performance of bridges. Anyway, not all of them are adequate for the case faced in this research. For that reason, they are discussed, and the proper ones selected according to three parameters:

1. Opinion of experts from Rijkswaterstaat.
2. Functional bridge demolition reasons.
3. Elimination of overlapping among the different categories

In the following paragraphs, the importance of each category will be explained in relation with the current study.

- **Availability, accessibility and reliability:** the reason to explain the three categories together is the relation among them and the potential overlapping if all of them are part of the methodology, aspect that should be avoided as much as possible. Availability indicates when the bridge is functional and can provide these functions at a sufficient level (Rijnen, 2016). An existing bridge can be available just for existing, but it may be closed to traffic. Accessibility means that the vehicles are able to cross on or under the bridge. Reliability refers to the time the bridge provides its functions. As it can be seen in the definition, all three relate to the functions of the bridge but small differences allow accessibility to be at a higher level than the rest. On the one hand, a bridge can be available but not accessible, becoming a useless bridge. However, accessibility ensures availability. On the other hand, if the bridge is accessible, it means the traffic moves and the bridge is reliable to provide its functions. Then, an accessible bridge is at the same time reliable and available. To conclude, accessibility will be a goal category.
- **Economics:** money is always one of the main elements in decision making procedures. Between the costs considered in the definition of economics, the direct costs influence more the economics because it comes from the construction and maintenance. However, those costs are included in another methodology developed by Rijkswaterstaat, the EELI (Bakker, Roebers, & Knoops, 2016) , so it will not be part of this study. Indirect costs fit better within this research. User costs from traffic accidents and detour and delay costs are part of indirect costs. They are important elements that may influence the replacement, but they come from safety or accessibility problems respectively. To avoid overlapping with safety or accessibility, economics is not considered in the methodology.
- **Environment and sustainability:** these two goal categories can be overlapped. Sustainability refers to the protection of the natural environment while environment includes that natural but also the human transformed area. Then, sustainability will be merged into environment. In the definition of environment, it can be found the influence during construction and during operation. This research, focused on existing bridges, is just influenced by the impact during operation since the construction impact happened in the past. That is noise emissions from traffic, landscape fragmentation and the presence of polluting substances.
- **Flexibility:** bridges are structures with life spans of 80 years average. Then, the capacity to adapt to future requirements and being able to perform properly during their whole lives is essential for every asset. When making decisions, the adaptability of the bridge to future changes can be a key

point. A bridge able to fulfil future needs will be maintained longer than the one which will be soon outdated and not chance for improving is available. However, flexibility could be defined as accessibility in the future. Then, it is included in accessibility.

- **Health:** this aspect is mainly referred to the health of the inspection personnel, who should be in good health with respect to physical, mental and societal views (Rijnen, 2016). Since the inspection is essential to find out the state of the bridge, the health of the workers should be taken into account. Health is essential, but a bridge will not be replaced because of this reason. If the health is compromised, more adequate inspection methods should be found to ensure the proper bridge performance. Then, this category will not be included in this study.
- **Politics:** the influence of politicians is rarely considered in Bridge Management Systems even though they have an essential role in the decision process. In the Netherlands, the road network plays its political role by keeping the Netherlands competitive, accessible, liveable and safe (Ministry of Infrastructure and the Environment, 2011). It is not an aspect commonly named in literature, but it is present at Rijkswaterstaat as part of the RAMSSHEEP framework. In this research, politics is not considered. Politics has a bigger influence on a network level while on specific objects, politic decisions rarely cause bridge replacement,
- **Safety:** safety is a goal that can be seen in most of the literature. While structural safety is essential for the good performance, it related with technical replacement reasons, which are out of the scope of this research. Safety to users fits better in this research. It relates to the injuries or fatalities per unit of transportation (Ministry of Infrastructure and the Environment , 2012). A reduction in these numbers will be reflected in a higher safety to users. It is essential that the structure provides a service, but always under certain safety parameters and it cannot be admissible that a bridge becomes a blackspot in the road network. Therefore, due to the importance given in literature and the influence in decision making, safety is considered a critical goal category for the Performance Age.
- **Security:** this is a goal just found at Rijkswaterstaat as part of the RAMSSHEEP framework. Referring to vandalism, terrorism and human errors, it will not be assessed in this methodology. Vandalism is related with low impact problems to the adequate bridge performance, and then, with no influence in the replacement decisions. Visual hindrance from graffiti may happen but with maintenance it can be easily solved. The performance according to terrorism and human errors, although with high impact, is very uncertain and with low chance to happen.
- **Maintainability:** the bridge should be able to be maintained so the initial performance can be restored after the use and damage. Every bridge can be technically maintained and taken back to the adequate performance level because there are enough techniques available. The technical maintenance is determined, therefore, according to the costs of the interventions. However, for this study, maintenance can have a big influence in the traffic flow. The influence of the maintenance will be then considered as a goal subcategory of Accessibility but not as a Goal Category.
- **Ergonomics:** according to Rijnen (2016), ergonomics refers to the accessibility for inspection and maintenance. It is directly related with health, so again, if the current inspection and maintenance

procedures are not ergonomic for workers, new methods should be found. It will not be a replacement reason and it will not be part of this study. Though, it should be considered when building new bridges.

- **Serviceability:** serviceability appears in literature mainly related with the technical state of the bridge and it is measured with technical parameters (crack widths, deflections and vibrations, stress and state of concrete and steel elements, etc.). Any bridge should ensure the stability of the structure, but it is technical in nature, not related with the functional performance in which this study is focused on. Then, it will not be a goal category of the Performance Age.
- **Society:** bridges are made for people and they have a huge influence on the society (Dette & Sigrist, 2011). They are part of the economic engine of the country, allowing people and goods movement around the country and enhancing regional development. Therefore, the satisfaction of society is important for the road network. This satisfaction will be dependent on different elements: aesthetics, cultural heritage of the bridge, comfort when using, providing equal opportunities to every citizen, etc. Even though it is a goal which is not really explicitly named in the literature, the society influences the progress of projects nowadays. Therefore, it would be a mistake to neglect this group of people and their satisfaction should be a goal to consider in the Performance Age.
- **Durability:** a durable structure shall meet the requirements of serviceability, strength, and stability throughout its intended service life (Dette & Sigrist, 2011). Again, as serviceability, it is related with technical performance of the bridge, which is out of the scope of this research.

From Table 2, the goal categories adequate for the Netherlands have been reasonable chosen. They are **Safety**, **Accessibility**, **Society** and **Environment**. In order to reinforce the selection, the goal categories will be related with the replacement reasons (see Table 8).

Table 8. Relation between Replacement Reasons and Goal Categories.

Reasons \ Goal Cat.	Safety	Accessibility	Society	Environment
Traffic intensity	There is a direct relation between the number of vehicles and the number of accidents.	The Intensity(I)/Capacity(C) ratio determines the chance of bottleneck.	Traffic congestion has a great negative influence on the network users' satisfaction.	The number of vehicles and the presence of congestion will influence the noise and air pollution in the bridge environment.
Bridge physical dimensions		The width, height or load bearing capacity, or the road can influence the traffic access to the bridge.		
External factors		Projects to increase the traffic capacity of the road may lead to bridge widening.	Societal complaints about location of bridges can become an important reason for replacement.	
Risks	An increase of accidents in the bridge can make it become a blackspot in the road network.	The frequency of accidents and the time until the road is cleared after an accident influences the transit on the bridge.	Citizen's safety feeling is of great importance when using the road network and blackspots may discourage users to use that road.	
Flexibility		The road flexibility to detour the traffic within the bridge can have a great influence on the	The avoidance of closing the bridge in case of maintenance can have a	

		accessibility. The more flexible, the less disruptions on traffic under important maintenance interventions.	positive influence in user's satisfaction.	
Environment	The climate change will cause heavier rains, creating a dangerous road surface.	The climate change (more floods, heavier rains) can cause a great influence on traffic transit across the bridge at normal speed.	Clean air, appropriate natural environment for fauna can become important points of complain for the citizens.	The presence of risk-polluting materials in the bridge or the landscape fragmentation can cause negative environmental impact.

To conclude, the goal categories considered relevant for this research are:

- **Safety:** the bridge should be safe for traffic transit in terms of number of accidents, injuries and fatalities.
- **Accessibility:** the bridge should be available to be used and should accomplish with its primary function: allow traffic movement over physical obstacles without closing the way underneath.
- **Society:** the bridge should realise its primary functions without hindering the citizens and improving the welfare of the society.
- **Environment:** the bridge should realise its primary functions without influencing negatively the environment and be able to adapt to the environmental changes.

The Goal Categories would be shown in the Hierarchy of Bridge Functional Criteria as follows (Table 9):

Table 9. Hierarchy of Bridge Functional Criteria with Goal Categories for the Netherlands.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Safety		
Accessibility		
Society		
Environment		

4.3.2.2 Goal Subcategories

In the current research in focused on the bridges in the Netherlands, the Goal Subcategories have been selected directly from the Goal Categories. This allows a better explanation of the Goal Categories and will be an intermediate step to determine the important Performance Indicators. For the study case, the defined subcategories are the following:

- Safety
  - **Users**: the safety to users in the bridge has to be ensured (Ministry of Infrastructure and the Environment , 2012) and a higher chance of fatalities in the bridge may be translated in bridge replacement.
- Accessibility
  - **Traffic flow:** it refers to the cars using the bridge and the number of bottlenecks produced.
  - **Bridge physical dimensions:** referring to the geometry and load bearing capacity of the bridge.

- **Intervention**: during bridge maintenance, the traffic capacity may be affected, creating or increasing congestion in the bridge and reducing its functionality. Then, it is a special situation that should be studied due to its effect in accessibility.
- **Resilience to climate change:** the ability of the bridge to resist to the future situations caused by climate change. The higher frequency and impact of heavy rains can influence the traffic speed and therefore, the accessibility.

▪ Society
  - **Aesthetics**: they are determined by the external design of the structure (mainly colour and shape of the visible surface) (Rijnen, 2016). The appearance should comply with the directives and the urban landscape (Oslakovic, Høj, & Klanker, 2017). The appearance of a bridge, although difficult reason for replacement, can be important for the stakeholders. A bridge close by a residential area could cause visual hindrance to the neighbours who would push to replace it. The other way around, an iconic bridge because of its design could cause a feeling of ownership that make the citizens to defend its maintenance even though it may not be profitable anymore.

▪ Environment:
  - **Sustainability:** related with the direct impact on the nature of the bridge by means of noise, the existence of polluting substances in the construction materials or the problems it can cause to the fauna if the bridge has not been built as it should.

The subcategories that better explain the goals are shown in the following Table 10.

Table 10. Hierarchy of Bridge Functional Criteria with Goal Categories and Subcategories for the Netherlands.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Safety	Users	
Accessibility	Traffic flow	
	Bridge physical dimensions	
	Intervention	
	Resilience to climate change	
Society	Social hindrance	
Environment	Sustainability	

4.3.2.3 Performance Indicators

The Performance Indicators for the Dutch bridges is done now. The Indicators are all retrieved from Appendix 2. From that table, the essential indicators to study the situation have been selected based on three parameters:

▪ Relevance: the indicators should be relevant for measuring the bridge performance. Just those that have an influence in how the bridge provides its service in a proper way will be analysed.
▪ Avoid overlapping and repetition: each performance indicator must be studied deeply to avoid overlapping. The goal is to have just those indicators relevant and with no interaction among each other.

- Experts recommendation: technicians from Rijkswaterstaat with expertise in the field were asked in order to find out what they consider as important indicators to measure the functional performance.
- Policy makers input: policy makers recommended certain indicators based on the importance they have in the decision-making process, which is an important aspect that distinguish this research from the previous from XIE (2017).

In Appendix 9, the reasons to include or neglect the Performance Indicators from Appendix 2 is shown. The indicators that were finally chosen are the following:

Table 11. Selected Performance Indicators and their definition.

PERFORMANCE INDICATOR	DEFINITION
Safety to users	Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities.
Traffic volume carried	Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society.
Load bearing capacity	Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic.
Bridge geometry	Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service.
Maintenance hindrance	Whether and to what extent the bridge maintenance requirements influence in the bridge functional performance.
Resilience to extreme weather events	Whether the bridge performance is affected by floods or heavy storms.
Aesthetics	Whether the public is satisfied with the aesthetic appearance of the bridge.
Noise emissions	Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment.
Presence of polluting substances	Whether the bridge construction materials contain polluting materials that can cause a negative impact in the environment. The most common is the presence of asbestos in the bridge structure.
Landscape fragmentation	Whether the bridge causes hindrance in the connection between parts of the city or between fauna habitats.

4.3.2.4 Conclusion

The Hierarchy of Bridge Functional Criteria for this research can be seen in Table 12.

Table 12. Hierarchy of Bridge Functional Criteria for the study cases.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Safety	Users	Safety to users
Accessibility	Traffic flow	Traffic volume carried
	Bridge physical features	Load bearing capacity Bridge geometry
	Intervention	Maintenance hindrance
	Resilience to climate change	Resilience to extreme weather events
Society	Social hindrance	Aesthetics
Environment	Sustainability	Noise emissions Presence of polluting substances Landscape fragmentation

The Hierarchy of Bridge Functional Criteria has been developed for the case of the Netherlands and for fixed highway concrete bridges. Such a model has been created as a general foundation over which the functional performance of the bridge will be studied. The content has been determined from literature and technicians' expertise. The Hierarchy of Bridge Functional Criteria can be used as a reference for all the bridges, however they should be evaluated individually and shape the model in each situation if required.

4.3.3 Weighting

The next step is to determine the weighting, which refers to the relative importance of each goal category and performance indicator. In the methodology explanation, this step was further explained, and the Best-Worst Method was developed further as an option to determine the weights.

For this research, with a focus on the decision-making process and how the Performance Age principles can improve it, decision-makers are approached to determine the weights. This ensures that the application of the methodology corresponds to reality by implementing the expertise and working procedures of decision-makers. The limitations of time and the difficulties to arrange meetings with decision-makers impeded to get the weights by means of questionnaires as recommended in the methodology. In this case, decision-makers gave the weights in an informal way during a meeting and those are the weights that will be used (see Figure 22). It is the only information available and then, the most reliable now. In the future, this might need review to adjust the values if other decision-makers do not agree with it.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR		
Safety	Users	Safety to users	+	++
Accessibility	Traffic flow	Traffic volume carried	++ +	[illegible]
	Bridge physical features	Available load bearing capacity	+	++
		Bridge geometry	+	++
	Intervention	Maintainability	0	++
	Resilience to climate change	Vulnerability against floods		++
		Vulnerability against storms		+
Society	Social hindrance	Aesthetics	0	+
		Noise emissions	+	+ ++
Environment	Sustainability	Noise emissions		
		Presence of high-risk polluting substances	0	+++
		Landscape framentation	0	++++

Figure 22. Policy Makers weighting on Hierarchy of Bridge Functional Criteria (picture).

Figure 22 shows the importance of the performance indicators for decision makers in a code of crosses (0: no important; ++++: maximum importance). Decision-makers divided the weighting in two steps, a pre-evaluation and an evaluation. The pre-evaluation determines whether the bridge can be analysed in other terms (evaluation) or its functional performance is so low that it should be directly replaced. The two-step bridge evaluation had been proposed before the meeting with decision makers and it was, then, confirmed with their input as an adequate procedure. In the pre-evaluation, decision makers selected (1) Safety to users, (2) Traffic volume carried, (3) Load bearing capacity, (4) Bridge geometry and (5) Noise Emissions. Then, these are the indicators which must be always accomplished and cannot be compensated so a low performance in one means that the bridge needs replacement and weighting then is not needed.

For the evaluation, the weights must be transformed in weights adequate to fit in the methodology (see Table 13).

Table 13. Weighted Hierarchy of Bridge Functional Criteria for evaluation according to decision makers.

GOAL CATEGORY (G.C.)	Normalized Weight in % (W)[2]	SUBCATEGORY	PERFORMANCE INDICATOR	Global weight from PM[3]	Normalized weight in % from PM[4]	Weights per G.C. in % (w)[5]
Safety	**8**	Users	Safety to users	++	8	**100**
Accessibility	**48**	Traffic flow	Traffic volume carried	++++	16	**36**
		Bridge physical features	Load bearing capacity	++	8	**16**
			Bridge geometry	++	8	**16**
		Intervention	Maintenance hindrance	++	8	**16**
		Resilience to climate change	Resilience against extreme weather events	++	8	**16**
Society	**4**	Social hindrance	Aesthetics	+	4	**100**
Environment	**40**	Sustainability	Noise emissions	+++	12	**30**
			Presence of polluting substances	+++	12	**30**
			Landscape fragmentation	++++	16	**40**

*In **bold**, weights used for methodology.

In order to ease the calculation, an excel programme has been created. The first step of that programme is introducing the weights as seen below.

WEIGHTING			
Goal Categories	**W**	**Performance Indicators**	**w**
Safety	8%	Safety to users	100%
Accessibility	48%	Traffic volume carried	36%
		Load Bearing Capacity	16%
		Bridge Geometry	16%
		Maintenance hindrance	16%
		Resilience extreme weather events	16%
Society	4%	Aesthetics	100%
Environment	40%	Noise emissions	30%
		Presence of polluting sustances	30%
		Fauna habitat fragmentation	40%

4.3.4 Bridge Assessment

4.3.4.1 Pre-evaluation

The pre-evaluation is an important step to ensure that just those bridges with problems big enough to hinder the functionality are considered. In this paragraph, the pre-evaluation steps (Figure 23) are applied to selected bridge:

[2] Refers to the importance (weight) that each Goal Category has on the global performance of the bridge. In the Quantification Methodology (5.4.1), refers to W. Extrapolated from the "Global weight in % from PM".
[3] Refers to the weights given by Policy Makers in + scale. They are weights referring to the whole framework, not to each Goal Category. They cannot be used for the Quantification Methodology.
[4] Refers to the weights given by Policy Makers in % scale. They are weights referring to the whole framework, not to each Goal Category. They cannot be used for the Quantification Methodology.
[5] Refers to the importance (weight) of each Performance Indicator within the Goal Category it belongs to. In the Quantification Methodology (5.3.2), refers to w. Extrapolated from the "Global weight in % from PM".

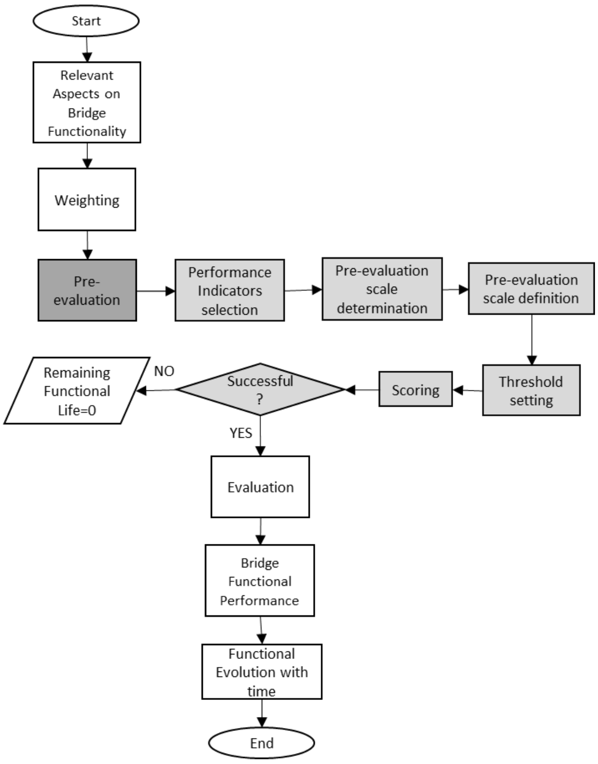


Figure 23. Pre-evaluation steps

1. <u>Performance Indicators selection.</u>

In the case study, the recommendations from decision-makers will be considered. They suggested a double evaluation, in which the first step corresponds to the pre-evaluation. For them, the most important indicators that every bridge should fulfil, and therefore should be part of the pre-evaluation, are the those in Table 14.

Table 14. Hierarchy of Bridge Functional Criteria for pre-evaluation according to decision makers.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Safety	Users	Safety to users
Accessibility	Traffic flow	Traffic volume carried
	Bridge physical features	Load bearing capacity
		Bridge geometry
Environment	Sustainability	Noise emissions

The bridge should be evaluated in each of the indicators to ensure that it accomplishes with the minimum requirements that allow the bridge to continue providing its service.

2. <u>Pre-Evaluation Scale Determination.</u>

For this study, it has been chosen a 4-point scale which has been defined from a combination of scales from Appendix 5.

Table 15. Chosen scale for the pre-evaluation and meaning.

# scale	Condition	Condition definition
1	Perfect	The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge.
2	Good	The bridge functional performance is acceptable, but it is no longer as desired.
3	Fair	The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences.
4	Poor	The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment.

The scale of four points is recommended by the ISO 55000 Asset Management Standards, which means that it is a scale widely used and that the methodology adapts to the international practice (Austroads, 2015).

3. <u>Pre-Evaluation Scale Definition.</u>

In Table 16, a scale was developed for the case of fixed highway concrete bridges in the Netherlands. It is a scale that mainly contain qualitative data that need assessment of experts and some qualitative data, that might be obtained from the monitored network data.

4. <u>Threshold setting.</u>

For the study case, it has been decided to select a score of 3 (“Fair”) as the threshold in the defined pre-evaluation scale. This means that a bridge must score at least 1, 2 or 3 in each of the five performance indicators above selected. In that case, the bridge succeeds the pre-evaluation and can proceed to the evaluation. If any of the indicators scores 4 (“poor”), the bridge must be directly replaced.

5. <u>Scoring.</u>

In Table 16, each indicator is scored (yellow highlight). In the column to the right side, the reasons for the score are given. In Appendix 13, the sources used to score the indicators can be found.

6. <u>Go or not go.</u>

All the performance indicators score greater 3 or higher, which means that the bridge succeeded the pre-evaluation and can continue to the evaluation. After the weighting, the number of experts answering the questionnaire should be filled. In this case, just the author did it. In reality, it is recommended to use the expertise of various technicians to get more reliable answers. Then, each score is given in terms of number of experts that gave a certain score to the indicator. As a conclusion, the pre-evaluation is checked, and the user gets two outputs: “Continue Evaluation” if the bridge succeeds the pre-evaluation or “Consider Direct Replacement” if any of the indicators score “poor”.

Table 16. Scale and definitions for the pre-evaluation in the Dutch case.

	CONDITION / INDICATOR	**PERFECT** [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	**GOOD** [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	**FAIR** [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	**POOR** [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	**REASONING**
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	No data. The A20 was considered the most dangerous road in the NL in 2010 (7,5 accidents/km in six months) but no info about the road on bridge. 3 to be in the safe side and succeed the pre-evaluation.
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.85 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.85 ≤ I/C ratio ≤ 0.9[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	According to excel file, the I/C on the bridge is 0.38 (Figure 33).
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	It is load class 60, which means that it can carry until 60 tons trucks. Currently, that is above the load maximum limitation.
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it allows increase of the traffic dimensions.	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and the bridge becomes a bottleneck in the network.	The road under the bridge (A20) has an I/C ratio of 0.96, which means that it requires expansion. However, the current bridge geometry does not allow the expansion.
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	The assumed noise emissions are 69.5 dB and the threshold is 69.6 dB. There are still 0.4 dB of slack.

[1]: (XIE, 2017)

[2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)

4.3.4.2 Evaluation

The evaluation defined in chapter 3.4.2 will be now applied to the case of the Netherlands. The steps explained before are followed:

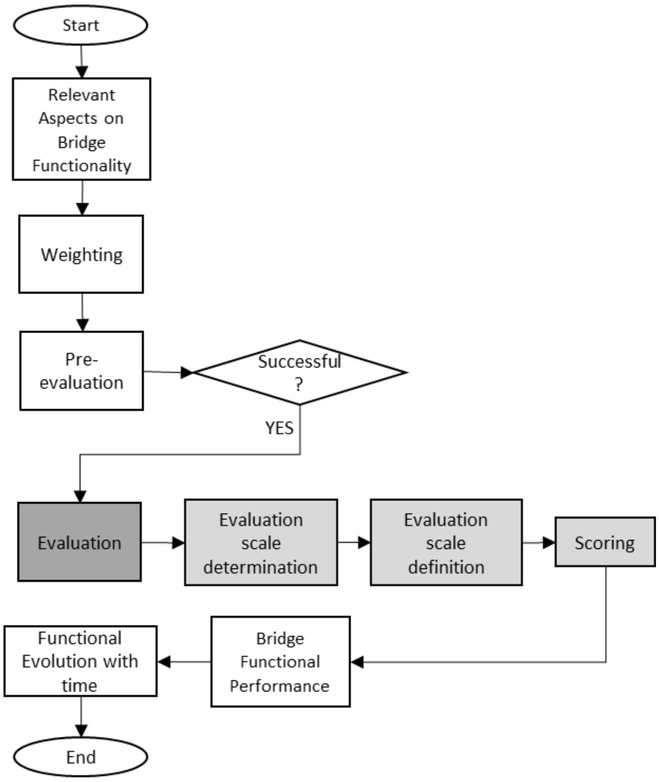


Figure 24. Evaluation procedure.

1. <u>Evaluation Scale Determination.</u>

The author proposes the evaluation with a scale from 1 to 4, from perfect to poor. It is the same scale as in the pre-evaluation, so the scale can be seen in Table 15.

2. <u>Evaluation Scale Definition.</u>

The scale from 1 to 4 is defined according to each performance indicator in Table 17. It is used to allow the technicians to evaluate the bridge.

3. <u>Scoring</u>

In Table 17, each indicator is scored (yellow highlight). In the column to the right side, the reasons for the score are given. In Appendix 13, the sources used to score the indicators can be found.

Table 17. Scale and definitions for the evaluation in the Dutch case.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	REASONING
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	No data. The A20 was considered the most dangerous road in the NL in 2010 (7,5 accidents/km in six months) but no info about the road on bridge. 3 to be in the safe side and succeed the pre-evaluation.
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.85 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.85 ≤ I/C ratio ≤ 0.9[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	According to excel file, the I/C on the bridge is 0.38 (Figure 33).
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	It is load class 60, which means that it can carry until 60 tons trucks. Currently, that is above the load maximum limitation.
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it allows increase of the traffic dimensions.	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and the bridge becomes a bottleneck in the network.	The road under the bridge (A20) has an I/C ratio of 0.96, which means that it requires expansion. However, the current bridge geometry does not allow the expansion.
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	No information about required maintenance. On the bridge, the traffic intensity is low, and the bridge is wide enough to move the traffic. Under the bridge, the traffic intensity is high, but the road is wide enough move the traffic with no big hindrance.
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	According to experts, currently the risk of floods in the A20 area is very low but, in several decades, it might be an issue.
Societ y	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	There is not any bridge in the A20 with aesthetical problems.

Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	The assumed noise emissions are 69.5 dB and the threshold is 69.6 dB. There are still 0.4 dB of slack.
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	According to DISK, it does not contain asbestos. Under legal levels of fine particles in the whole A20.
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	Placed in an urban area so no fauna and it does not divide any city.

[1]: (XIE, 2017)

[2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)

4.3.5 Bridge Functional Performance

The excel file is used in to determine the Bridge Functional Performance. It follows the steps of chapter 3.4.3. Several inputs need to be introduced by the user and the excel programme delivers the results. In the legend, it can be seen the meaning of the colours in the excel sheet.

LEGEND
INPUT
CALCULATION
INTERMEDIATE RESULT
FINAL RESULT
CORRECT
PROBLEM

Step 1. Determine the measurement scale.

SCALE	
Qualitative	**Quantitative**
Perfect	1
Good	2
Fair	3
Poor	4

Step 2. Experts input (R).

The input is entered in two steps. First the scores of the pre-evaluation and then the scores of the evaluation.

PRE-EVALUATION

Introduce the number of experts that gave a certain score to a particular indicator.

	Perfect	Good	Fair	Poor
GC1: Safety				
Safety to users		0	1	
GC2: Accessibility				
Traffic volume carried	1			0
Load Bearing Capacity	1			
Bridge Geometry			1	
GC4: Environment				
Noise emissions		1		
PRE-EVALUATION CHECK	CONTINUE EVALUATION			

EVALUATION

Introduce the number of experts that gave a certain score to a particular indicator.

	Perfect	Good	Fair	Poor
GC1: Safety				
Safety to users	0	0	1	0
GC2: Accessibility				
Traffic volume carried	1	0	0	0
Load Bearing Capacity	1	0	0	0
Bridge Geometry	0	0	1	0
Maintenance hindrance		1		
Resilience extreme weather events	1			
GC3: Society				
Aesthetics	1			
GC4: Environment				
Noise emissions	0	1	0	0
Presence of polluting sustances	1			
Landscape fragmentation	1			

The expert's input must be shown as the percentage of experts that consider that certain indicator has certain score. Then, the previous input is translated into the adequate format:

EXPERTS INPUT IN %

	Perfect	Good	Fair	Poor
GC1: Safety				
Safety to users	0%	0%	100%	0%
GC2: Accessibility				
Traffic volume carried	100%	0%	0%	0%
Load Bearing Capacity	100%	0%	0%	0%
Bridge Geometry	0%	0%	100%	0%
Maintenance hindrance	0%	100%	0%	0%
Resilience extreme weather events	100%	0%	0%	0%
GC3: Society				
Aesthetics	100%	0%	0%	0%
GC4: Environment				
Noise emissions	0%	100%	0%	0%
Presence of polluting sustances	100%	0%	0%	0%
Landscape fragmentation	100%	0%	0%	0%

Step 3. Functionality Index.

Calculated by multiplying the expert's input in % by the quantitative measurement scale.

FUNCTIONALITY INDEX (FI)

	FI
GC1: Safety	
Safety to users	3.00
GC2: Accessibility	
Traffic volume carried	1.00
Load Bearing Capacity	1.00
Bridge Geometry	3.00
Maintenance hindrance	2.00
Resilience extreme weather events	1.00
GC3: Society	
Aesthetics	1.00
GC4: Environment	
Noise emissions	2.00
Presence of polluting sustances	1.00
Landscape fragmentation	1.00

Step 4. Performance of bridge in Goal Categories (Z).

Determined multiplying the Functionality Index (FI) by the weight (w) defined in 4.3.3.

PERFORMANCE OF BRIDGE IN GOAL CATEGORIES (Z)

	w	z		
GC1: Safety	w	z		
Safety to users	100%	3.00		
			Z1	**3.00**
GC2: Accessibility	w	z		
Traffic volume carried	36%	0.36		
Load Bearing Capacity	16%	0.16		
Bridge Geometry	16%	0.48		
Maintenance hindrance	16%	0.32		
Resilience extreme weather events	16%	0.16		
			Z2	**1.48**
GC3: Society	w	z		
Aesthetics	**100%**	1.00		
			Z3	**1.00**
GC4: Environment	w	z		
Noise emissions	30%	0.60		
Presence of polluting sustances	30%	0.30		
Landscape fragmentation	40%	0.40		
			Z4	**1.30**

Step 5. Global Bridge Functional Performance (P).

Determined multiplying the Performance of Bridge in Goal Categories (Z) by the Weight (W) defined in 4.3.3.

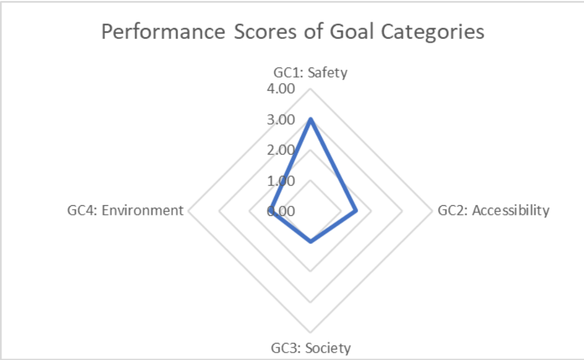
GOAL CATEGORIES	W	Z		
GC1: Safety	8%	3.00		
GC2: Accessibility	48%	1.48		
GC3: Society	4%	1.00		
GC4: Environment	40%	1.30	P	1.51

STEP 6. Global Bridge Functional Performance Check.

It can be seen that the Global Bridge Functional Performance is 1.51. However, the bridge geometry, an essential indicator in the pre-evaluation, scores 3. In this case, 3 is the limiting functional performance.

Worst essential PI	3.00
P CHECK (FINAL P)	**3.00**
P CHECK (FINAL P)	**FAIR**

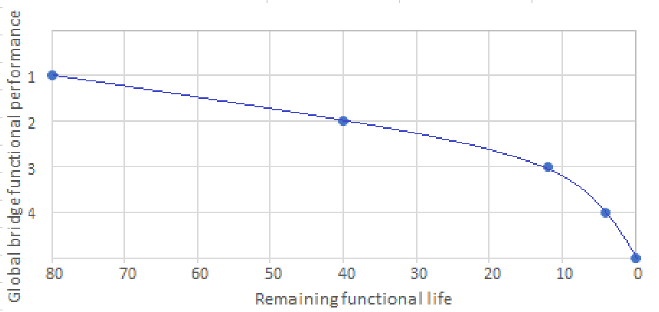
Finally, the excel also shows a radial graph the user can use to easily see how the bridge performs in each Goal Category and the reason why the bridge requires intervention. In the radial graph, the closer to the centre, the better the performance.



4.3.6 Remaining Functional Life

The curve shown in paragraph 3.5 is also used for the determination of the remaining functional life of the study case. The curve has been represented in excel and a Global Bridge Functional Performance Score of 3 corresponds to a Remaining Functional Life of 12 years.

REMAINING FUNCTIONAL LIFE



GLOBAL BRIDGE FUNCTIONAL PERFORMANCE SCORE	**3.00**

REMAINING FUNCTIONAL LIFE	**12**	**YEARS**

Figure 25. Global Bridge Functional Performance evolution with time in the Netherlands.

4.3.7 Results

In order to The final result of the methodology includes the uncertainties. Then, a bridge with a Global Bridge Functional Performance of 3.00, has a Remaining Functional Life of between 0.8 and 23.2 years, with an average of 12 years.

UNCERTAINTIES							
Assessment uncertainty	±	10	years				
Functional Evolution Uncertainty	±	10%	of remaining functional life				
				FROM	MEAN	TO	
REMAINING FUNCTIONAL LIFE WITH UNCERTAINTY				0.80	12	23.20	YEARS

Table 18. Results of the Case Study.

RESULTS	
Global Bridge Functional Performance	3 (FAIR)
Bridge construction year	1983
Bridge theoretical replacement year	2063
EELI with replacement in 2063	0.39
Remaining Functional life (years)	Min: 0.8; Mean: 12; Max: 23.2
Bridge functional replacement year	From 2018 until 2042.

It can be seen that the results vary from the theoretical replacement year. However, considering the traffic congestion on the A20 and the lack of space under the bridge to extend the road, the replacement in 2063 does not seem feasible. For instance, the replacement year obtained with the methodology is more real. However, it has to be considered the great uncertainty and the lack of precision of the results, which hinders its use in decision-making.

4.3.8 Conclusions

The study case validates the methodology. For instance, the methodology is not difficult in nature since the number of inputs is short enough to make it applicable from an early stage. However, the obtention of those inputs is more complex. The nature of the functional performance, in which the environment has an enormous influence, and the data available, challenges the implementation of this research.

First of all, those aspects that influence the functional performance of bridges should be determined. In this case, decision-makers were the source of that information, but it does not mean it is the only option. The number of indicators is enormous, and a good selection is essential to obtain reliable results. Anyway, experts other than decision makers considered that the selection was a great contribution of this research, so it can be concluded that this step was successfully achieved. Furthermore, the weights given were accepted because it is the only data available. However, for each bridge those weights should be assessed. Depending on the situation, they might have different values. This review for each bridge would increase the workload of the methodology, which might reduce the acceptance of the methodology.

Focusing on the calculation itself, the main problem has been encountered in the pre-evaluation and evaluation of the bridge. Rijkswaterstaat owns an enormous quantity of monitored data, but it is fragmented among the organization, it is not accessible for everyone, it is outdated or simply cannot be used for the bridge of study. This creates difficulties to assess the bridge functional performance in an objective way. The alternative to monitored data would be expert's input. This option was used but not as successfully as predicted. The reason for it might have been a lack of a clear action plan since an early stage. Some of the experts interviewed were not able to answer the questions, either because they did not have the information, the time or the motivation to do it. This should have been predicted and a group of experts involved since the beginning of the research in order to increase the response level.

Finally, although the methodology works, the level of uncertainty is very high. The bridge of study has a range of 22.4 years from the minimum to the maximum remaining functional life. Considering that bridges have a remaining life of around 80 years, the precision is too low to consider this methodology fully usable. Luckily, the precision can be increased with the utilization of monitored data and with further studies in the field of functional deterioration. Considering the growth of big data and the relevance that functionality seems to have on asset management, both aspects will probably be researched, and more concise results will be available.

5.CONCLUSIONS, LIMITATIONS, DISCUSSIONS AND RECOMMENDATIONS

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5.1 Introduction

In this chapter, the conclusions of the study, the discussion, the recommendations and the limitations and suggestions for further research are shown.

In the conclusions, the main findings of the research are shown. Then, the discussion explains the implications of the results and shows to which extent the research achieved the goals and the research questions shown in the introduction. Thereafter, recommendations focus on aspects that should be done to achieve a successful implementation of the methodology. Finally, the challenges encountered along the research, the limitations of the research and suggestions for further research are discussed.

5.2 Conclusions

The goal of this research was developing a methodology that supports decision making for functional bridge replacement at Rijkswaterstaat using the principles of the Performance Age. In order to do that, the Performance Age methodology was analysed, the problematic points discovered, and the methodology adapted to the new requirements. The new methodology with the different inputs, steps and outputs can be seen in Figure 26.

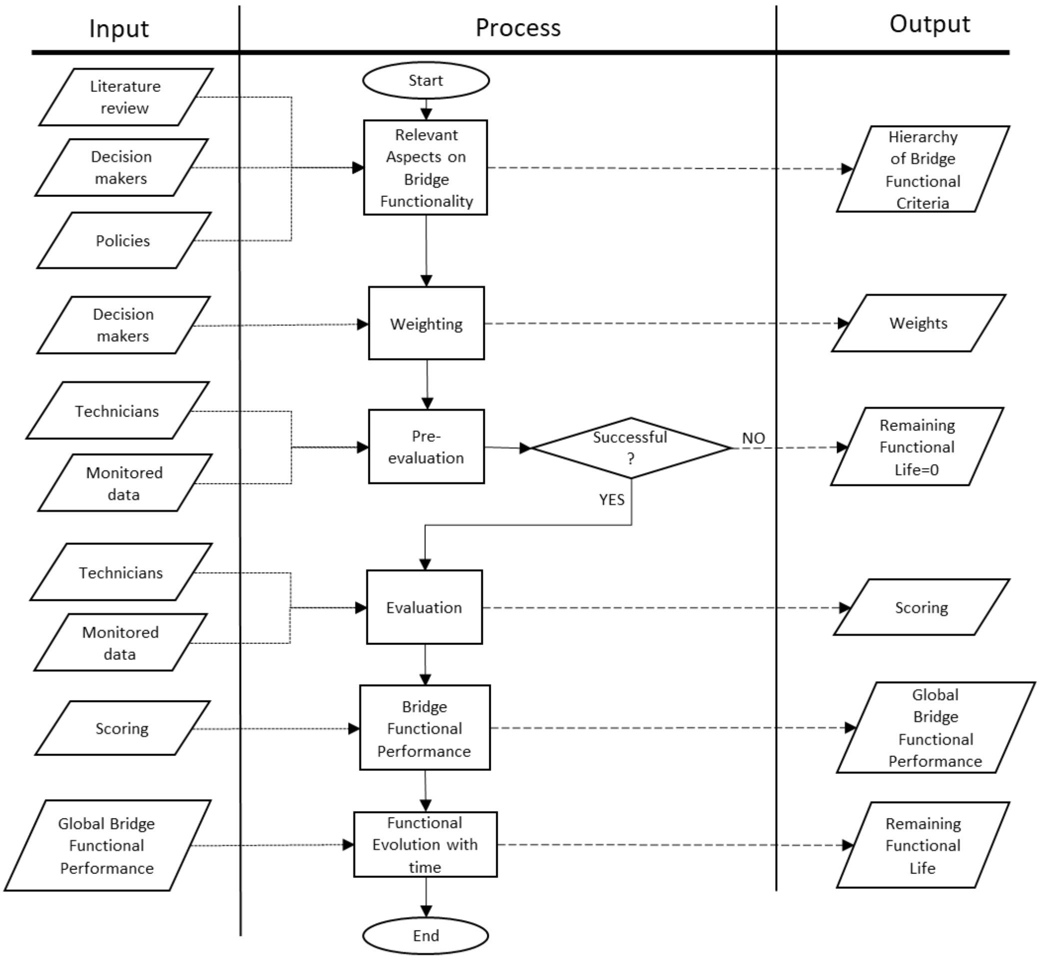

Figure 26. Methodology inputs, process and outputs.

The methodology starts with the determination of relevant aspects for bridge functional analysis. At this step, the methodology was moulded to include the decision-maker's point of view by means of an interview as an adequate contribution to ensure that the methodology aligns with reality. The outcome of this step is the Hierarchy of Bridge Functional Criteria. The Hierarchy of Bridge Functional Criteria needs to be weighted. Each aspect influencing functionality has a different importance, leading to different weights. Then, the bridge is assessed in two-steps. First, a pre-evaluation step that aims to ensure that the bridge performs to a certain level in those performance indicators which are essential for the proper bridge service (safety, traffic volume carried, load bearing capacity, bridge geometry and noise emissions). Technicians from Rijkswaterstaat and monitored data will be used to determine the score of the bridge in the pre-evaluation. A threshold is defined and if the bridge does not score above that threshold, the Remaining Functional Life is 0 so the bridge should be directly replaced. If the bridge succeeds the pre-evaluation, the rest of performance indicators are assessed and scored in the evaluation by technicians and monitored data. The score is used to, with a set of mathematical equations, determine the Global Bridge Functional Performance, a number between 1 and 4 that indicates how the bridge functionally performs. Finally, the Global Bridge Functional Performance is related with the Functional Evolution with time of the bridge and the Remaining Functional Life is obtained.

The research found out certain aspects that can contribute to increase the knowledge in a field with limited study until date. The research will contribute in different aspects to Rijkswaterstaat, to decision-making and to the field of knowledge:

For Rijkswaterstaat:

- <u>Relevance of the performance indicators:</u> this methodology has made a deep research on the performance indicators that can influence the functional performance. The Hierarchy of Bridge Functional Criteria ensures that Rijkswaterstaat evaluates functionality considering the right indicators, which are totally separated from the traditional technical approach.
- <u>EELI input:</u> the Economic End of Life Indicator (EELI) is currently calculated using a design life for bridges of 80 years to determine the bridge remaining life. However, the design life is set in the design process and the bridge performance changes in time depending on several aspects. If the remaining life used to calculate the EELI is obtained following this method, the measurement would be more precise and related to the current condition of the bridge, as soon as the precision of the methodology increases.
- <u>Input for new constructions:</u> the evaluation of the functionality tells which the performance of different aspects of the asset from objective sources is. If a bridge has to be replaced, Rijkswaterstaat will own valuable information about the asset and ensure that new constructions accomplish with the functional requirements.
- <u>Life Cycle Management:</u> this methodology also has an influence in the Life Cycle Management, which has become an important working methodology at Rijkswaterstaat and in Asset Management in general. LCM consists of three different interrelated elements: costs (Life Cycle Costs), risks (Life Cycle Risks) and performance (Life Cycle Performance). Rijkswaterstaat

has already methods to measure the Life Cycle Costs (EELI) and the Life Cycle Risks (RAAMSSHEEP) but there is not a methodology to assess the performance and that way, complete the Life Cycle Management circle. This study will provide information about how the bridge is performing and then, help to close the Life Cycle Management circle.

For decision makers:

- Decision-makers point of view: the decision-makers point of view has been included in the methodology in the selection of the indicators and their weighting. Considering that the goal of this research was to use the principles Performance Age methodology to make better decisions, then matching the methodology to the working procedures of decision makers will ease the implementation. Decision-makers will, moreover, have certain ownership feeling as they were part of the methodology design and they will feel more familiar with the tool for its use.
- Subjectivism decrease: currently, decision-makers who need to replace a bridge due to a low functional performance, can just justify it with their own expertise and maybe the study of certain factors. However, following the methodology developed in this research they will be able to have an objective and repeatable methodology applicable to all the bridges in the network. Decision makers will then be able to make well-informed decisions based on empirical ground and defend their decisions from the public or the ministry.
- Resource efficiency: the replacement of bridges requires a lot of limited resources. The methodology application will increase knowledge about the bridge and the replacements due to functional reasons will be done just in the right moment. Replacement strategies, planning and prioritization will be more precise, leading to more efficient use of resources.
- More adequate output for decision-making: in this research, the Performance Age output was changed from the previous research by XIE (2017). Instead of the age of the bridge, now the methodology directly delivers the Functional Remaining Life, which eases the work of decision makers. Furthermore, the unavoidable uncertainties are considered in this research, improving the consistency of results.

For the field of knowledge:

- Technical-Functional Balance: currently the technical performance leads over the functionality. For instance, functionality is rarely considered and Rijkswaterstaat does not have any methodology to assess it. With the implementation of the Performance Age in Asset Management, the distance between technical and functional performance will reduce. Considering the importance of functionality in the replacement decisions, the balance of both considerations is essential to ensure a high-performance road network.
- Transition tool: the research can open a new world of possibilities in a field with little research. The spread of the Performance Age principles can lead to new similar methodologies that help to move on from the technical approach to an integrated approach in which the technical and the functional performance are considered.

5.3 Discussion

In this section, the research question is answered. The whole research aims to solve the question and to give inputs in the topic. The question is the following:

How can the Performance Age principles be applied to the decision-making process for bridge replacement at Rijkswaterstaat?

The research question is answered in different aspects along the whole research:

Decision-makers involvement in the methodology design

To get a proper implementation of the methodology in the decision-making process, it is essential to involve decision-makers in the methodology's design process. In this research, decision-makers were interviewed to first, show them the potential of the methodology, and second, to get inputs. Those inputs were essential to develop a methodology that focuses on those aspects considered in the decision-making process. For instance, decision-makers were asked to weight the Hierarchy of Bridge Functional Criteria. The weighting has a great influence in the Remaining Functional Life they will use to make decisions.

This involvement has also an indirect associated positive point. An ownership feeling is created between decision-makers and the methodology as they have been part of the design. This could ease the implementation as they would feel more enthusiastic to use something in which their knowledge is included.

Decision-making process

It is important to determine how the decision-making process works. In this research, a simplified decision-making process was obtained during the interview with decision-makers. In that process, there are two main moments in which the bridge functional performance should be present. First, together with the technical reports that Rijkswaterstaat delivers, the functionality should be assessed. This way, decision-makers will obtain more complete information with a combination of technical, functional and political aspects. After several studies, decision-makers have to prioritize interventions and choose among competing alternatives. The Remaining Functional Life can be used to prioritize interventions using objective and well-grounded information if a bridge is replaced due to functionality.

Change the Performance Age outcome

In the first version of the Performance Age by XIE (2017), the outcome was the age of the bridge according to its functional performance. This age was an exact number that required further mathematical operations to obtain the remaining life (80 minus the Performance Age). In this research, it was discovered that this input is not the most practical for decision-making and it gives an exact number with a methodology that has certainly several uncertainties.

In this research, it has been decided to change the outcome of the methodology and directly give decision-makers the remaining functional life. Then, they will directly know when an intervention is required and mobilize resources with that goal. Furthermore, the lack of precision of the methodology has been considered and the Remaining Functional Life incorporates the uncertainties involved. Then, the methodology more precise results in which the limitations of the process are involved.

Relevance for the decision-making process

Decision-making currently lacks from a well-informed, objective and empirical-grounded methodology to justify the bridge replacement decisions due to functionality. Then, it is important to show them the help this methodology can provide. With this methodology, decisions can be defended and justified against the Ministry and general public, reducing the pressure on decision-makers when just their own subjective conclusions can be used to make functional-related decisions.

5.4 Recommendations

In this section, recommendations to achieve a successful implementation of the methodology are elaborated. The recommendations aim to improve the methodology in the future, as well as general comments that can help Rijkswaterstaat to make a better use of asset management. The recommendations can be read in the following list:

- The author encountered certain lack of aware about functional problems. Then, it is recommended that Rijkswaterstaat informs employees in the road departments about the fact that functionality is leading replacement decisions. That might lead to new ideas to study functional performance and maybe, create a group that study the topic if enough people are interested. Similarly, more decision-makers should be involved and the problems with the current technical analysis explained. Rijkswaterstaat should strive for that knowledge sharing with everyone.
- It is recommended that Rijkswaterstaat improve the knowledge sharing along the organization. They have enormous amount of information available, researches in different areas, monitored data, etc. However, it is just accessible to certain departments or people just do not know that someone else is working on that. This leads to inefficiency and rework, so I would recommend some knowledge sharing system where workers can get to know what others do.
- It is recommended to get inputs from more decision-makers in order to obtain more reliable weighting results. Using the BWM explained in Appendix 3 or similar methods can also provide better results.
- When applying the methodology to real bridges, it is recommended to review the weighting factors. Depending on the bridge location and the characteristics of the environment, the weights might change. For example, noise emissions are more relevant in a city than in the countryside.

- In order to reach an adequate implementation, the scoring scale developed should be reviewed. Asset managers stated that most of the bridges would score "good" or "fair" in most of the indicators. Then, it would become a 2-points scale which is not adequate. In this context, it should also be highlighted that in the study case, there are several indicators with a "perfect" score, which could cause doubts about the statement of asset managers. Anyway, it should be reviewed, and the best option applied.
- It is recommended that Rijkswaterstaat uses the Remaining Functional Life to calculate the EELI. It would provide more precise results and better decisions would be made.
- It is recommended to apply the methodology to a larger set of bridges. Ideally, a workshop with experts from different departments would be the best way to get valuable information about the potential of the methodology.
- When the methodology is fully developed and functional, it is recommended that Rijkswaterstaat includes the information in DISK data base.

5.5 Limitations of Study and Suggestions for Further Research

In this section, challenges encountered during the research, limitations of the study and recommendations for further research are discussed.

In the side of challenges, time was the main problem. Arrange meetings was a tough task due to the busy schedules of decision makers and technicians. That problem will be encountered when any new methodology or tool out of the normal working tasks is created. Furthermore, the summer time led to the delay of the research due to holidays of supervisors or interviewees. Another challenge was to motivate people about the methodology. Although in first instance they were enthusiastic, when they were asked for time-consuming tasks, the motivation dropped drastically, hindering the research results.

5.5.1 Limitations

Apart from those challenges, the research has certain limitations:

- The methodology has been developed for fixed highway concrete bridges (or viaducts) and it is limited to those. Other kind of bridges or assets might require changes in the Hierarchy of Bridge Functional Criteria and on the Weighting.
- The number of interviewed decision makers (2) limited the obtaining of statically significant results in the weighting of the Performance Indicators.
- Weighting. Due to the lack of time and the difficulties to meet decision makers, the weighting was not done with the recommended questionnaire but with a basic score system during a meeting with decision makers. Then, the weights might not be as precise as required considering the great influence they have on the results of the methodology.
- Limitations of the scale. As said before, asset managers stated that the 4-point scale might not be reliable because most of bridges would score 2 or 3 in all the indicators. If this limitation is

confirmed in the application to a larger set of bridges, then the scale might limit the usefulness of the methodology.

- ❖ Precision of the deterioration curve. The Remaining Functional Life-Global Bridge Performance Score curve has been supposed due to lack of studies in the area. The values have been discussed and accepted by technicians from Rijkswaterstaat, but there is no empirical information that confirms the curve.
- ❖ Supposition of uncertainties. The values of the uncertainties were supposed because there were not resources to go deep into the uncertainties encountered along the whole methodology process and decision-making.
- ❖ Precision. The methodology, due to the involved uncertainties, does not give precise results. Further research on functional evolution curves and the utilization of monitored data will increase the precision, as well as the chance of implementation. With the current outcomes, it seems difficult that the methodology becomes a decision tool.
- ❖ Monitored data availability. The available data to evaluate the bridge quantitively requires a lot of research work along and across the several Rijkswaterstaat departments or databases. This requires a great number of connections in the different departments and an enormous workload that might hinder the utilization of objective monitored data.
- ❖ Study cases. The application of the methodology to real bridges was not possible as desired in the beginning. For instance, the first plan was to study between 20 and 30 bridges during a workshop with 3 to 5 experts. The second plan was to study 5 bridges with a questionnaire delivered to asset managers. Any of these of options succeeded. Finally, the author retrieved objective data to study the performance indicators from several departments and objectively scored one bridge from the A20 between Gouda and Rotterdam. This application of the methodology cannot be used to validate the methodology.
- ❖ Decision-making: the final users of the methodology are decision-makers and their decisions are not just based on the technical or functional performance of the bridge, but there are several other factors that might influence whether the bridge is replaced or not, and when. In these cases, the influence of the methodology is limited or obviated.
    - *Resource Availability*: depending on the available resources allocated for bridge interventions, decision-makers might be obligated to anticipate or delay the bridge intervention, no matter the functional performance results.
    - *Project Clustering*: similar activities in the area or road where the bridge is located can lead to project clustering, aiming to make a more efficient use of resources. Moreover, other interventions in the bridge road (e.g. road widening) will lead to bridge replacement is the bridge does not have enough space in the shoulders to accommodate the new road widening. Any of these options consider the functional performance of the bridge for the replacement, but external factors.
    - *Risk Acceptance*: It is unknown how decision makers will react against certain risks or an insufficient performance of the bridge. For example, they could decide to extend

the bridge life under certain risks or with a lower performance than initially wanted due to project clustering, budget limitation, etc.

- *External Stakeholders:* Provinces or municipalities can influence replacement decisions if the intervention hinders the normal performance of other activities in the region, city, etc. Other action groups (e.g. environmental protection groups) can also influence decisions if for example, the bridge replacement jeopardizes the environment (fauna, flora, waterflows, air pollution…). In these cases, decision might be taken with no consideration of the bridge functional performance.

5.5.2 Recommendations for further research

In this section, recommendations for future research are discussed. The development of this recommendations would improve the accuracy of the methodology and improve the efficiency of the decision-making process. The future research should follow the next directions:

Study of functional evolution curves

Similarly to the technical deterioration, functional performance have an evolution with time that might be modelled. The lack of studies could be due to the impact that the environmental changes have in the functional performance and the difficulty to predict them. In this research, the functional evolution curve was supposed. However, it would be interesting to study it and determine whether those curves can be done, or the variety is too big to allow the generalization. In Appendix 7, a introduction to the study can be found.

Methodology uncertainties

The results of the research consider several uncertainties from different nature (decision-making and methodology) but their impact on the Remaining Functional Life has just been supposed. A further research that could investigate, at least the decision-making uncertainties could be interesting since it would give better results to the methodology and review and improve the decision-making process.

Expansion to network level

Already recommended by Xue Xie, it is recommended to expand the methodology into a network level. When making replacement decisions, asset managers have to consider the influence on the road network. Furthermore, other interventions in the network may influence the interventions on the bridge. Then, a global consideration can improve the resource efficiency and the prioritization among competing alternatives.

GIS Map representation

The outcome of the Performance Age could be shown in a GIS Map with all the information of the asset. That representation would help either technicians or decision makers to determine the current condition of the bridge and make well-informed and sound decision in an easier and more visual way.

Furthermore, the chance to see the all the bridges characteristics in such a map can help to group interventions and reduce budget and time for construction.

Application to other assets

Functional performance is present in every asset and it has been concluded that this methodology can give valuable input about it. Once the methodology is fully developed and applicable, it might be interesting to extent its influence zone to other kind of bridges or assets under the responsibility of Rijkswaterstaat.

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6.BIBLIOGRAPHY

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7.APPENDIX

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Appendix 1. Goal Categories, definitions and sources.

GOAL CATEGORY	DEFINITION	SOURCE
Availability	Time duration in which the bridge is functional, and its functions can be fulfilled in a sufficient level.	(Ministry of Infrastructure and the Environment , 2012) (European Committee for Electrotechnical Standardization, 1999) (Gov.uk, 2013) (Ministry of Infrastructure and the Environment, 2011) (Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Accessibility	It relates to the primary function of the structure for traffic. This means that the vehicles should be able to cross on or under the bridge.	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Haas, Felio, Lounis, & Falls, 2009)
Economics	Refers to the costs against benefits. Two different costs can be distinguished: direct (costs throughout the whole life cycle of the bridge-LCC analysis) and indirect (costs for users as accident costs and detour and delay costs). As benefits, it can be found the local and regional development due to the bridge presence.	(Guedella Bustamante & Fernández Flores, 2017) (Oslakovic, Høj, & Klanker, 2017) (Ministry of Infrastructure and the Environment , 2012) (Haas, Felio, Lounis, & Falls, 2009) (Ugwu & Haupt, 2007) (COST, 2014) (Wagner & van Gelder, 2013) (Dette & Sigrist, 2011) (Patrício & Almeida, 2017) (Federal Highway Administration, 2014a) (Hartgen, Fields, & San Jose, 2013) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Environment	Influence of the bridge on its direct physical environment. It can be divided in two stages: construction ($C0_2$ footprint, greenhouse gas emissions, resource consumption or waste generation) and operation (noise emissions of traffic, landscape fragmentation or the presence of high-risk polluting substances (asbestos, etc.)).	(Ministry of Infrastructure and the Environment , 2012) (Ugwu & Haupt, 2007) (Oslakovic, Høj, & Klanker, 2017) (Dette & Sigrist, 2011) (Gov.uk, 2013) (Ministry of Infrastructure and the Environment, 2011) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Guedella Bustamante & Fernández Flores, 2017) (Haas, Felio, Lounis, & Falls, 2009) (COST, 2014) (Wagner & van Gelder, 2013) (Hartgen, Fields, & San Jose, 2013) (Haas, R.; Falls, L. C.; Tighe, S., 2003) (Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Flexibility	Compatibility of the bridge and adaptability to accommodate substantial changes in the future at a lower cost.	(Kamali & Hewage, 2017)
Health	Health of the inspection personnel, who should be in good health with respect to physical, mental and societal views.	(Oslakovic, Høj, & Klanker, 2017) (Ugwu & Haupt, 2007) (Haas, Felio, Lounis, & Falls, 2009) (Wagner & van Gelder, 2013) (Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Politics	Country politic situation that determines the projects to be done according to the policies developed by decision makers and with a great influence in the bridge replacement.	(Oslakovic, Høj, & Klanker, 2017) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Reliability	The likelihood that the structure fails to provide its functions within a time interval.	(Haas, Felio, Lounis, & Falls, 2009) (Ministry of Infrastructure and the Environment , 2012) (European Committee for Electrotechnical Standardization, 1999) (Haas, R.; Falls, L. C.; Tighe, S., 2003) (Gov.uk, 2013) (Ministry of Infrastructure and the Environment, 2011) (Wagner & van Gelder, 2013) (Patrício & Almeida, 2017) (Hartgen, Fields, & San Jose, 2013) (Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2015) (Rijkswaterstaat, 2013) (COST, 2014)
Safety	It can be structural or to users. Structural safety relates to the ability of the structure to stay stable during its operation. Safety to users relates to the injuries or fatalities per unit of transportation A reduction in these numbers will be reflected in a higher safety for users.	(Ministry of Infrastructure and the Environment , 2012) (European Committee for Electrotechnical Standardization, 1999) (Oslakovic, Høj, & Klanker, 2017) (Ugwu & Haupt, 2007) (Haas, R.; Falls, L. C.; Tighe, S., 2003) (Haas, Felio, Lounis, & Falls, 2009) (COST, 2014) (European Committee for Standardization, 2005) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Hartgen, Fields, & San Jose, 2013) (Federal Highway Administration, 2014a) (Rijnen, 2016) (CROW, 2002) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (Rijkswaterstaat Dienst Infrastructuur, 2009) (Rijkswaterstaat Grote Projecten en Onderhoud, 2015) (Rijkswaterstaat, 2013)
Security	It refers to the adequate performance of the bridge according to vandalism, terrorism and human errors.	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Oslakovic, Høj, & Klanker, 2017) (Ministry of Infrastructure and the Environment , 2012) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Maintainability	The ease to prevent the bridge from functional failure and to reduce the time to repair the bridge due to functional failure.	(Ministry of Infrastructure and the Environment , 2012) (European Committee for Electrotechnical Standardization, 1999) (Hartgen, Fields, & San Jose, 2013) (Wagner & van Gelder, 2013) (Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009)

Ergonomics	It refers to the accessibility for inspection and maintenance. Workers should have an adequate space to complete the inspection and maintenance tasks properly.	(Rijnen, 2016)
Serviceability	It concerns about the technical performance. It includes the measurement of aspects like crack widths, vibrations, deflections, stress and state of concrete and steel elements, etc. to determine how the structure performs.	(Strauss, Bergmeister, Mandić Ivanković, & Campos e Matos, 2017) (European Committee for Standardization, 2005) (COST, 2014) (Federal Highway Administration, 2014a) (Dette & Sigrist, 2011) (Patrício & Almeida, 2017) (Humplick & Paterson, 1994) (Hartgen, Fields, & San Jose, 2013)
Society	It refers to the impact that the bridge has on the citizens and their satisfaction with the road network.	(Guedella Bustamante & Fernández Flores, 2017) (Dette & Sigrist, 2011)
Durability	A durable structure shall meet the requirements of serviceability, strength, and stability throughout its intended service life.	(Dette & Sigrist, 2011) (European Committee for Standardization, 2005) (Federal Highway Administration, 2014a)
Sustainability	It refers to the protection of the natural environment while enhancing the performance of bridges. Sustainability makes sure that the environment effected by the bridge is protected.	(Oslakovic, Høj, & Klanker, 2017) (Rijnen, 2016) (Hartgen, Fields, & San Jose, 2013)

Appendix 2. List of potential Performance Indicators for the Hierarchy of Bridge Functional Criteria.

FUNCTIONAL PERFORMANCE INDICATOR	DEFINITION
# deaths by traffic accidents per year	Number of death people by traffic accidents per year on or under the bridge.
# hospitalized by traffic accidents per year	Number of hospitalized people by traffic accidents per year on or under the bridge.
# only material damage accidents	Number of material damage accidents per year on or under the bridge.
Adaptability	The capacity of the asset to adjust to future changes.
Adequate signalling	Whether the drivers receive adequate and enough information with the road signs.
Aesthetical value	The appearance of the bridge should comply with the directives, as well as urban landscape.
Aesthetics	Whether the public is satisfied with the aesthetic appearance of the bridge.
Availability of information panels	Whether the drivers are well informed about the road conditions with information panels.
Available height under bridge(m)	Distance under the bridge available for traffic flow.
Available space for emergency services	Whether there is enough space on the bridge sides to allow the transit of emergency services.
Available space to accept future road widening	Whether there is enough space on the bridge sides to allow road widening.
Available width on bridge(m)	Distance of the bridge deck available for traffic flow.
Available width under bridge(m)	Distance under the bridge available for traffic flow.
Bridge Condition index	Refers to technical performance, not to functional.
Bridge geometry	Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service.
Climate adaption	The ability of the asset to adjust to future situation caused by climate change.
CO_2 footprint	CO2 emissions produced during the bridge lifecycle.
Comfort level	To what degree the users of the provided services are satisfied.
Condition of drainage system	Whether the drainage system is in good condition to drain the water from the bridge surface.
Condition of the security screens and handrails	Whether the protection system for users is in good condition.
Congestion	Whether the bridge acts as a bottleneck for the road.
Contribution to regional economic development	Whether and to what extent the bridge stimulates or hinders the regional economic development.
Construction costs	The costs associated with the construction of a new bridge replacing the current one.
Country economic situation	The economic situation indicates which are the investments priorities and the funds availability for bridge replacement.
Cultural value	Whether the bridge has cultural importance for society.
Current condition of materials	Refers to the deterioration degree of bridge materials.
Damage level of structure	The damage or defects and the consequences on the bridge performance.
dB produced by the contact road surface-tire (roughness)	Noise emissions in dB of the contact between the road surface and the vehicle tyre.
dB produced by the expansion joints	Noise production in dB of the expansion joints when a vehicle passes over them.
Dismantling problems	Concerns to the possible problems associated with the bridge dismantling due to negative environmental impact. The dismantling of the bridge could cause environmental problems which would lead to the life extension of the bridge.
Ergonomics	Ergonomics requirements in respect to the accessibility for inspection and maintenance.
Function failure probability	Refers to the chance that the bridge does not fulfils its function. It is contrary to functional time duration.
Functional time duration	Refers to the time in which the bridge is functional, and its functions can be fulfilled.
Funds availability	Whether there are enough funds to allow a bridge replacement.
Greenhouse gas emissions	The emissions of greenhouse gases during the lifecycle of the bridge.
Health	Refers to the health problems that the inspection and maintenance of the bridge could cause on the personnel.
I/C ratio	Reflected in traffic volume carried.
Increase of travel time by alternative route	The average increase of time in minutes of detouring the traffic through an alternative route if the bridge is closed.
Increase of travel time by alternative transportation	The average increase of time in minutes of using an alternative transportation if the bridge is closed.

Influence in local economy	Influence of the bridge on the region in terms of jobs, workforce stability, etc.
Inspection rating	Score obtained by the bridge during inspection.
International Roughness Index (IRI)	Reflects the roughness of the road surface.
Landscape fragmentation	Whether the bridge causes hindrance in the connection between parts of the ty or between fauna habitats.
Life cycle cost	Cost of the bridge throughout its whole life, while fulfilling its performance requirements.
Load bearing capacity	Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic.
Maintainability	The easiness with which the bridge can be maintained over time and the related impact of maintenance on the traffic flow.
Maintenance hindrance	Whether and to what extent the bridge maintenance requirements influence in the bridge functional performance.
Maintenance pollution	The generated pollution during maintenance activities.
Maintenance works durability	Duration of the maintenance activities in the bridge.
Maintenance works frequency	The regularity with which the bridge has to be maintained.
Maintenance works impact on traffic	Impact of the maintenance activities in the normal traffic flow.
New design and construction costs	The cost of the design and construction of a new bridge replacing the existing one.
New design and construction time	The time required to design and construction of a new bridge replacing the existing one.
Noise emissions	Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment. The noise emissions caused by defective surface are not considered since they can be repaired, and the bridge maintained longer.
Number of bottlenecks	Number of bottlenecks produced due to the bridge in a year.
Number of inhabitants	Number of inhabitants in a certain area that may affect the traffic intensity on the bridge.
Operational costs new bridge	The costs of keeping the new bridge functioning and reaching the minimum requirements.
Politics	Concerns to political-administrative requirements that influence the bridge performance.
Possibility to detour traffic on bridge	Whether the bridge is flexible to allow traffic detour on the bridge during maintenance.
Predicted growth of inhabitants	Predicted number of inhabitants in a certain time period that may affect the traffic intensity on the bridge.
Presence of polluting substances	Whether the bridge construction materials contain polluting materials that can cause a negative impact in the environment. The most common is the presence of asbestos in the bridge structure.
Priority of the asset on network level	The importance of the bridge in the network meaning a bigger influence in traffic hindrance if not performing well.
Probability of being affected by earthquake	Probability that the bridge is affected by a flood affecting the safety of the bridge.
Probability of being affected by flood	Probability that the bridge is affected by a flood affecting the safety and the traffic flow on the bridge.
Projects in the same network	Whether there are planned, in execution or executed projects in the bridge network that may affect the minimum requirements of the bridge.
Project risk	The risk associated to a replacement of the current bridge.
Quality of materials	Quality of construction materials used in the construction and maintenance of the bridge.
Resilience to extreme weather events	Whether the bridge performance is affected by floods or heavy storms.
Reusability	Whether the bridge has been built with reusable or recyclable materials that could ease the bridge dismantling.
Safety to users	Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities.
Service life	Period of time after construction in which the bridge is in used and all minimum requirements are met or exceeded.
Space arrangement for all kind of users	The bridge should provide reliable space arrangements for users also for future developments.
Speed limits	Maximum speed allowed on the bridge.
Stakeholder participation	The stakeholder involvement that may affect the future of the project.
Standard requirements change	Whether a change in the regulation lead to a bridge impossibility to accomplish the requirements.
Structure Age	Age of the structure in years since its construction.
Traffic capacity	Maximum number of vehicles that can cross the bridge in a time unit according to the design.
Traffic hindrance costs	The costs associated with the traffic detour during the construction of a new bridge.
Traffic intensity	Average number of vehicles that occupy the bridge during a period of time.

Traffic volume carried	Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society.
User delay costs	The costs for users derived from traffic congestion caused by the bridge.
Visibility	Whether the bridge provides good sightlines and illumination conditions for users.
Vulnerability against drought	Whether the bridge foundations can be affected by drought.
Vulnerability against floods	Whether the road capacity is or will be affected due to floods.
Vulnerability against storms	Whether the road capacity is or will be affected due to heavy rain.
Vulnerability to heat stress	Whether the bridge can be affected by heat stress.
Waste production	Refers to the waste generated by the demolition of the old bridge and the construction of the new one.
Water retainability	Whether and to what extent the road surface retains water affecting the safety and the traffic flow on the bridge.

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Appendix 3. Best-Worst Method explanation.

Best-worst Method (BWM)

The Best Worst Method (BWM) is a multi-criteria decision-making method (MCDM) developed by Jafar Rezaei in 2015. It uses two vectors of pairwise comparisons to determine the weights of criteria. First, the best (e.g. most desirable, most important), and the worst (e.g. least desirable, least important) criteria are identified by the decision-maker, after which the best criterion is compared to the other criteria, and the other criteria to the worst criterion (Rezaei, 2016). It is the methodology used by XIE (2017) in the first research about the topic to determine the weights.

How the BWM works?

The BWM is composed by 7 steps (Rezaei, Jafar, 2015; Rezaei, Nispeling, Sarkis, & Tavasszy, 2016):

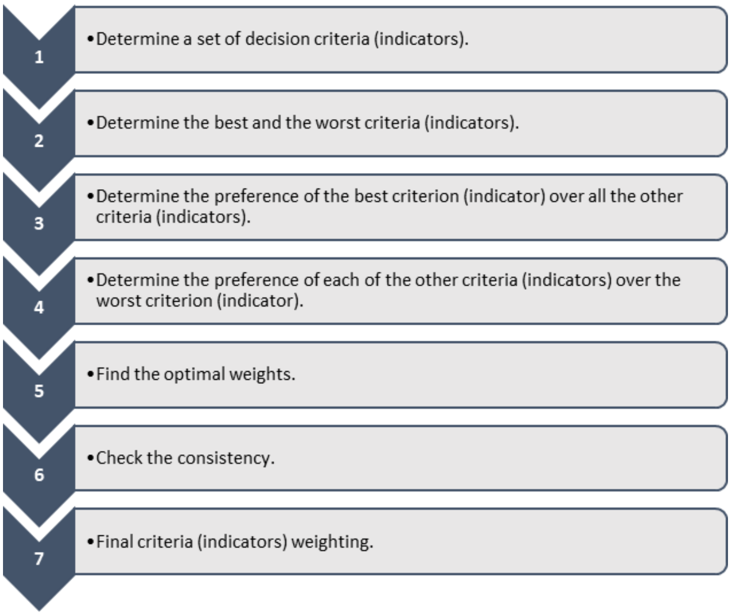

Figure 27. BWM steps to determine the weighting (XIE, 2016).

With the realization of all the steps for, first the goal categories and second, the performance indicators, the relative importance of each elements used to analyse the performance of the bridge is determined.

Selection of the methodology

The BWM has been selected as a possible weighting methodology for the following reasons:

- BWM is the method originally used by XIE (2017) to determine the Performance Age and it worked well. This reference eases the task and allows the current research to fix the problems that may have arisen in the previous research. Furthermore, the developer of the BWM, Jafar Rezaei, was a supervisor of Yue XIE. He is then familiar with the Performance Age and would be more eager to help if required.

- Despite being a new method, it has become a very popular method for MCDM in the last years.
- For this research, the number of comparisons is big since all the elements of the model should be weighted. BWM reduces the work compared with for example, the AHP. For example, considering 10 decision criteria, BWM requires 17 comparisons (2n-3=2x10-3=17) while AHP requires 45 comparisons (*n(n-1)/2=10(10-1)/2=45),* almost a third less.
- The reliability is very important for this method because its main outcome is to be used in costly and relevant decisions for the country. According to Rezaei (2015), the final weights derived from BWM are very reliable and provide more consistent comparisons than the more commonly used methodology, AHP.

Application of BWM

The Best-Worst methodology steps will be explained further in this paragraph. Those steps should be done two (or three[6]) times for the Hierarchy of Bridge Functional Criteria structure that has been chosen: first for the goal categories and then for the performance indicators (see Figure 28). Following, the whole weighting procedure will be shown, but just for the goal categories as example. It should be repeated for the performance indicators.

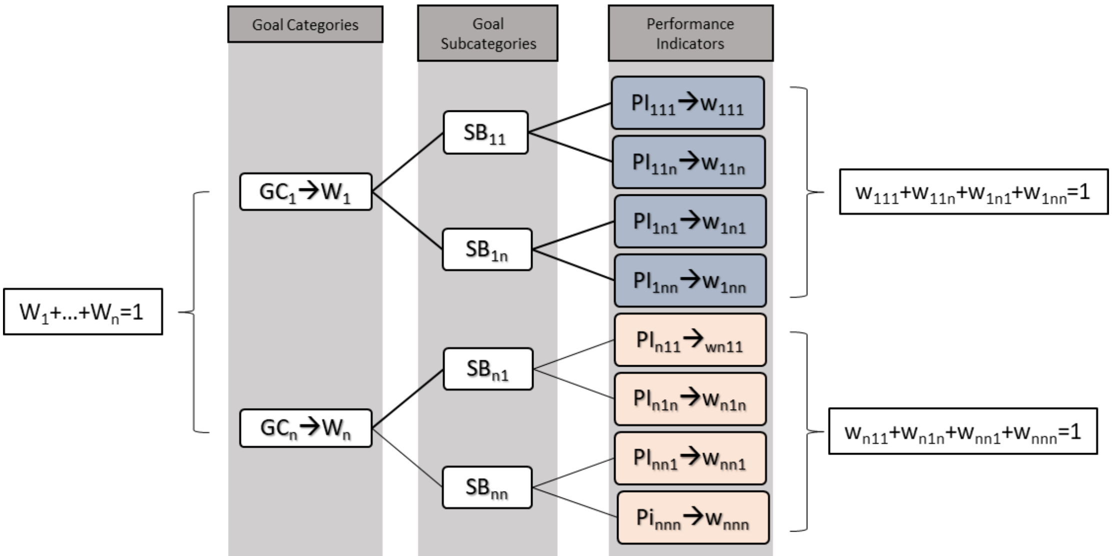

Figure 28. Theoretical weighting for the model.

Step 1*. Determine a set of decision indicators (GC_1, GC_2,..., GC_n) that should be weighted. As an example, four Goal Categories will be chosen. The user will use those he or she considers adequate for the methodology. Those categories are:

- Safety (GC_1)

[6] The goal subcategories do not require weighting if the number of performance indicators is not too big and the performance indicators and the Goal Categories can be directly related. The elimination of the subcategories in the weighting reduce the workload so it is recommended if possible.

- Accessibility (GC_2)
- Society (GC_3)
- Environment (GC_4)

Step 2*. Determine the best (most desirable, most preferred or most important) and the worst (least desirable, least preferred, least important) criteria to be used for the decision environment.

Step 3*. Determine the preference of the best criterion over all the other criteria. For BWM, it is recommended a scale from 1 (C_x equally important than C_y) to 9 (C_x is extremely more important than C_y) (Table 19).

Table 19. The fundamental scale for pairwise comparison of AHP (Saaty T. L., 2008)

Scales	Degree of preference	Explanation
1	Equal importance	Two elements contribute equally to the objective.
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one element over another.
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one element over another.
6	Strong plus	
7	Very strong importance	One element is favoured very strongly over another; its dominance is demonstrated in practice.
8	Very, very strong	
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation.
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

This scale includes even numbers, which are used to express intermediate values but that in practice are not too used and they may cause more stress in the determination of Best-Worst criterion. For that reason, they will be eliminated, and the scale reduced to a 1 to 5, just using the odd numbers of the 1-9 scale. The final preference scale is shown in Table 20.

Table 20. Levels of preference for the scaling. Adapted from (XIE, 2017)

Scales	Degree of preference	Explanation
1	Equal importance	Two elements contribute equally to the objective.
2	Moderate more important	Experience and judgement slightly favour one element over another.
3	Strongly more important	Experience and judgement strongly favour one element over another.
4	Very strongly more important	One element is favoured very strongly over another; its dominance is demonstrated in practice.
5	Extremely more important	The evidence favouring one element over another is of the highest possible order of affirmation.

The resulting Best-to-Others vector would be:

$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where, a_{Bj} indicates the preference of the best criterion *B* over criterion *j*.

Step 4*. Determine the preference of each of the other criteria over the worst criterion. A number between 1 and 5 is assigned in this case as well. The Others-to-Worst vector would be:

$Aw = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$, where, a_{jW} indicates the preference of the criterion *j* over the worst criterion *W*.

Steps 2, 3, and 4 should be determined by a questionnaire delivered to decision makers, who will give their insights to the methodology at this point. An example of the questionnaire can be found in Appendix 4. It is recommended to develop the questionnaire by digital means in order to ease the understanding, the answer retrieving as it can be easily done through the computer and the further answer evaluation by the author.

Step 5. Find the optimal weights$(w_1^*, w_2^*, \dots, w_n^*)$.

The optimal weight for the criteria is the one where, for each pair of w_B/w_j and w_j/w_W, we have $w_B/w_j=a_{Bj}$ and $w_j/w_W=a_{jW}$. To satisfy these conditions for all j, we should find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_w} - a_{jW}\right|$ for all j is minimized.

It can be transferred to a linear programming problem with a unique solution:

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{ for all j}$$

$$\left|\frac{w_j}{w_w} - a_{jW}\right| \leq \xi, \text{ for all j}$$

$$\sum_j w_j = 1$$

$$w_j \geq 1, \text{ for all j}$$

By solving this problem, the optimal weights $W = (W_1^*, W_2^*, \dots, W_n^*)$ and the optimal value of ξ^* are obtained. $\xi^L$is considered as a consistency index. That is, the closed the value of ξ^* to zero, the higher the level of consistency of the comparisons.

Step 6. Check the consistency.

In order to check the reliability of the comparisons, a consistency ratio is proposed (Rezaei, Best-worst multi-criteria decision-making method, 2015).

$$Consistency\ Ratio = \frac{\xi^*}{Consistency\ Index}$$

The bigger the ξ^*, the higher the consistency ratio, and the less reliable the comparisons become.

Table 21. Consistency Intex (CI) table (Rezaei, Jafar, 2015).

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency Index (Max ξ^*)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Step 7. Final weighting.

The final weights for the Goal Categories are $W = (W_1^*, W_2^*, \dots, W_n^*)$.

The process above explained should be done also for the Performance Indicators. The performance indicators' weight is determined in families of Goal Categories. Then, the sum of the weights of the Performance Indicators that are part of each Goal Category should be 1 or 100% (see Figure 28). The final weights for the Performance Indicators are w.

By following the seven steps above, the user will be able to determine the impact of individual indicators on the global bridge performance. Furthermore, it is the moment in which the decision makers give their insights to the methodology by telling which factors are influential in their decisions and to what extent.

[Blank on purpose]

Appendix 4. Questionnaire.

As decision makers with influence in bridge replacement decisions, you would have different considerations when you decide. Following, a set of criteria are considered to evaluate the bridge functional performance in order to make replacement decisions more accurate and allow a better strategic investment.

The criteria are defined as follows:

- **Safety:** the bridge should be safe for traffic transit in terms of number of accidents, injuries and fatalities.
- **Accessibility:** the bridge should be available to be used and should accomplish with its primary function: allow traffic movement over physical obstacles without closing the way underneath.
- **Society:** the bridge should realise its primary functions without hindering the citizens and improving the welfare of the society.
- **Environmental sustainability:** the bridge should realise its primary functions without influencing negatively the environment and be able to adapt to the environmental changes.

The outcome of the following questionnaire is to determine the weighting of the Performance Categories. To determine it, it has been decided to use the Best-Worst Method (BWM). BWM is a multi-criteria decision-making method that uses two vectors of pairwise comparisons to determine the weights of criteria.

First, the best (e.g. most desirable, most important) criterion is identified by the decision-maker. In this example, the decision-maker chooses “Accessibility” as the most important criterion.

1. Which criterion do you think is the most important?

☐ Safety
■ Accessibility
☐ Society
☐ Environmental Sustainability

Second, the worst (e.g. least desirable, least important) criterion is identified by the decision-maker. . In this example, the decision-maker chooses “Society” as the least important criterion.

2. Which criterion do you think is the least important?

☐ Safety
☐ Accessibility
■ Society
☐ Environmental Sustainability

Third, the best criterion is compared to the other criteria. Decision-makers must give their preferences of the best criterion over the other criteria.

3. You have chosen ACCESSIBILITY as the most important criterion. Could you indicate the preference of this criterion over the other criteria? Use a number between 1 and 5 to show the preference of the MOST IMPORTANT criterion over the other criteria.

	Safety	Society	Environmental Sustainability
ACCESSIBILITY	2	5	4

Where the scale means:

1: Equal importance
2: Moderate more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

When analysing the results of the example, we can see that safety is the second most important (accessibility is moderate more important -2- than safety) while society is the least important (accessibility is extremely more important -5- than society)

Fourth, other criteria to the worst criterion. Decision-makers must give their preferences of the other criteria over the least important criterion.

4. You have chosen SOCIETY as the least important criterion. Could you indicate the preference of this criterion over the other criteria? Use a number between 1 and 5 to show the preference of the LEAST IMPORTANT criterion over the other criteria.

	SOCIETY
Safety	4
Accessibility	5
Environmental sustainability	2

Where the scale means:

1: Equal importance
2: Moderate more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

When analysing the results of the example, we can see that environmental sustainability is just moderate more important -2- than the least important criterion. On the other hand, accessibility is extremely more important -5- than society.

Appendix 5. Bridge condition assessment standards defined and used in different BMS and references. Adapted from Wang & Elhag (2008).

BMS/references	**Assessment standards and their meanings**
NBI condition ratings (Dunker & Rabbat, 1995)	0–9: 0 – Failed condition, 1 – imminent failure condition, 2 – critical condition, 3 – serious condition, 4 – poor condition, 5 – fair condition, 6 – satisfactory condition, 7 - good condition, 8 – very good condition, 9 – excellent condition
New York BMS (Dunker & Rabbat, 1995) (Testa & Yanev, 2002) (Yanev, 1998)	1–7: 1 – Potentially hazardous, 3 – serious deterioration, 5 – minor deterioration, 7 – excellent or new condition, 2, 4 and 6 – between two adjacent ratings
Denmark BMS (Bevc, Mahut, & & Grefstad, 2001)	0–5: 0 – No or insignificant damage, 1 – small damage, 2 – some damage, 3 – significant damage, 4 – serious damage, 5 – ultimate damage (total failure)
Finland BMS (Hearn, 2007)	0-4: 0 – New or like new, 1 – good, 2 – satisfactory, 3 – poor, 4 – very poor
Norway BMS (Hearn, 2007)	1-4: 1 – minor damage, 2 – average or slight damage, 3 – serious damage, 4 – critical damage
UK BMS (Hearn, 2007)	1-5: 1 - As new condition or defect has no significant effect, 2 - early signs of deterioration, minor defect/damage, 3 - moderate defect/damage, 4 - severe defect/damage, 5 - the element is non-functional/failed.
Swiss BMS (Roelfsta, Hajdin, Adey, & Brühwiler, 2004)	1–5: 1 – good, 2 – acceptable, 3 – damaged, 4 – bad condition, 5 – alarming
Virginia BMS (Scherer & Glagola, 1994)	3–9: 3 – Poor condition, 4 – marginal condition, 5 – generally fair condition, 6 – fair condition, 7 – generally good condition, 8 – good condition, 9 – new condition
Slovenian BMS (Stochino, Fadda, & Mistretta, 2018)	1-4: 1 – normal condition, 2 – retrofitting needed, 3 – urgent intervention, 4 – out of service
Australian BMS (Austroads, 2015)	1-4: 1 – good, 2 – fair, 3 – poor, 4 – very poor
Infrastructure Rating in the Netherlands (M.J.Kallen & Noortwijk, 2006)	0-5: 0 – perfect, 1 – very good, 2 – good, 3 – reasonable, 4 – mediocre, 5 – bad
(Liang, Wu, & Liang, 2001)	Grades I–V: I – non-damage, II – light damage, III – moderate damage, IV – severe damage, V – unfit for service
(Liu, Hammad, & Itoh, 1997a) (Liu, Hammad, & Itoh, 1997b)	Levels I–V: I – very serious deterioration, II – serious deterioration, III – aggravating deterioration, IV – minor deterioration, V – no deterioration (looks like new)
(Frangopol, Kong, & Gharaibeh, 2001)	States 1–5: 1 – unacceptable, 2 – fair, 3 – good, 4 – very good, 5 – excellent
(Miyamoto, Kawamura, & Nakamura, 2000) (Miyamoto, Kawamura, & Nakamura, 2001)	0–100: 0–19 – Dangerous, 20–39 – slightly dangerous, 40–59 – moderate, 60–79 – fairly safe, 80–100 – safe
(ARRB Group, n.d.)	1-4: 1 - New or good, 2 - minor defects, 3 – moderate defects, 4 – severe defects
(Stochino, Fadda, & Mistretta, 2018)	1-5: 1 – in service, 2 – little deterioration, 3 – severe deterioration, 4 – urgent deterioration, 5 – out of service
(XIE, 2017)	1-5: 1 – extremely good, 2 – good, 3 – average, 4 – poor, 5 – extremely poor

[Blank on purpose]

Appendix 6. Application of the Bridge Functional Performance steps.

A bridge functional performance is defined according to four (y) Goal Categories (GC): Accessibility (GC_1), Safety (GC_2), Society (GC_3) and Environment (GC_4). Each category is, at the same time, defined by a set of Performance Indicators that express how the bridge performs in each certain Goal Category. For example, the Performance Indicators of accessibility (1) are: bridge geometry (PI_{11}), traffic volume carried (PI_{12}) and functional time duration (PI_{13}). The same for the rest of Goal Categories. Determine the functional performance of this bridge.

Step 1. Determine the measurement scale.

$$M = [m_1, m_2, m_3, m_4, m_5] = [perfect, good, fair, poor]$$

The measurement scale has been defined in a numerical scale that corresponds to the qualitative bridge state.

$$S = [s_1, s_2, s_3, s_4, s_5] = [1, 2, 3, 4]$$

Step 2. Experts input (R).

Experts will analyse the bridge functional performance by analysing the Performance Indicators according to the measurement scale determined in Step 1.

For the Goal Criteria "Accessibility" (GC_1), the outcome of the assessment is a matrix as follows:

$$R_1 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \end{bmatrix}$$

Where r_{11} means that r% of experts consider that the Bridge Geometry (PI_{11}) is in extremely poor condition (s_1=1) whereas r_{23} means that r% of experts consider that the Traffic Volume Carried (PI_{12}) is in average condition (s_3=3).

It is required to obtain the experts input for the rest of the Goal Categories. In the end, we would have: R_1 (Accessibility), R_2 (Safety), R_3 (Society) and R_4 (Environment)

Step 3. Functionality Index.

$$FI_y = R_y \times S^T$$

For the previous example of Goal Category "Accessibility", it is as follows.

$$FI_1 = R_1 \times S^T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} = \begin{bmatrix} FI_{11} \\ FI_{12} \\ FI_{13} \end{bmatrix}$$

It is required to obtain the Functionality Index for the rest of the Goal Categories. In the end, we would have: FI_1 (Accessibility), FI_2 (Safety), FI_3 (Society) and FI_4 (Environment)

Step 4. Performance of bridge in Goal Categories (Z).

The Performance of the bridge in each Goal Category (Z) is obtained multiplying the relative weights (w) of each indicator by the Functionality Index. For the Goal Category "Accessibility", it has been determined that the weights of each Performance Indicator are w_{11}, w_{12}, w_{13}.

$$Z_y = w_y \times CI_y$$

$$Z_1 = w_1 \times CI_1 = \begin{bmatrix} w_{11} & w_{12} & w_{13} \end{bmatrix} \begin{bmatrix} FI_{11} \\ FI_{12} \\ FI_{13} \end{bmatrix}$$

It is required to obtain the bridge performance for each Goal Category. In the end, we would have: Z_1 (Accessibility), Z_2 (Safety), Z_3 (Society) and Z_4 (Environment).

Step 5. Global Bridge Functional Performance (P).

The Global Bridge Functional Performance is obtained by multiplying the relative weights of each Goal Category (W) by the bridge performance for each of each Goal Category. The W were obtained before, and the result was: W= [W_1, W_2, W_3, W_4].

$$P = W_y Z_y$$

$$P = \begin{bmatrix} W_1 & W_2 & W_3 & W_4 \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \end{bmatrix} = Global\ Bridge\ Functional\ Performance$$

STEP 6. Global Bridge Functional Performance Check.

The Global Bridge Functional Performance is limited by the Functionality Index of the indicators selected for the pre-evaluation. Those indicators are essential for the proper functional performance of the bridge and therefore, they cannot be compensated with the score of other performance indicators. For that reason, if the Global Bridge Functional Performance is greater than the Functionality Index of an essential indicator, the Global Bridge Functional Performance will reduce to the Functionality Index of that indicator. It can be explained as follows:

If $P<FI_{\text{essential indicator pre-evaluation}}$ →P=P

If $P>CI_{\text{essential indicator pre-evaluation}}$ →$P=CI_{\text{essential indicator pre-evaluation}}$

Appendix 7. The environmental influence on the Global Bridge Functional Performance curve.

The functional performance is highly influenced by the environment. The functional performance reflects how the bridge acts against the number of vehicles crossing it, the rain in a heavy storm, the load of a truck or an animal that wants to cross the road. These external influences are what make challenging to determine the functional evolution curve and to make a precise curve require resources that are not available in the current research. However, some ideas of how the evolution might be determined will be shown now using the example of the performance indicator "Traffic Volume Carried". The reason to choose this indicator is its great importance on the bridge functional performance and the data availability.

A literature research was done to find out which might be the future evolution of the traffic intensity. Numbers are not specific from a bridge but for the whole Netherlands, but it can give an idea of the future traffic situation. In Figure 29 it can be seen how the number of vehicles evolved until the present following an almost constant growing trend. That trend has been extrapolated for the future (mean evolution). However, the future uncertainty allows a fast-growing scenario (quick evolution) or a slow-growing scenario (slow evolution) in the number of cars. In this case the quick and slow evolution are assumptions. It is also supposed that the number of vehicles will not reduce according to the trends.

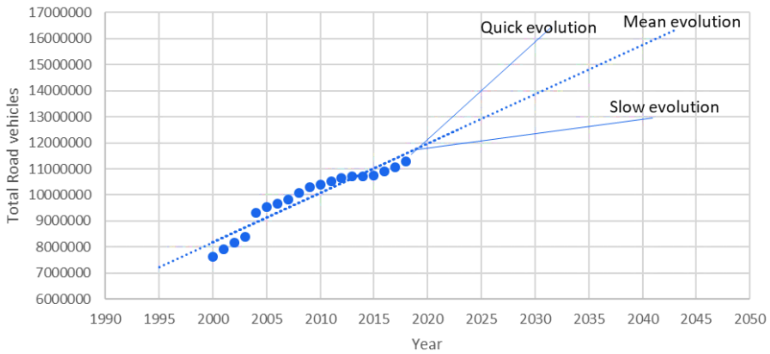

Figure 29. Total road vehicles in the Netherlands and potential future evolutions.

The scoring of the Traffic Volume Carried should be objectively done using the Intensity/Capacity ratio. The number of vehicles crossing the bridge in a period of time is the Intensity. The number of cars that can cross the bridge in a period of time is the capacity, which remains constant because the bridge is not upgraded. Then, the only variable is the intensity that can be directly related with the number of vehicles in the Dutch network. The outcome of this relation is Figure 30 . This figure represents three I/C ratio scenarios. The number of cars is increasing (at three different paces), which means that the traffic intensity will also increase. If the capacity is constant, then there are three scenarios as well for the I/C ratio evolution (fast-growing scenario, mean-growing scenario and slow-growing scenario).

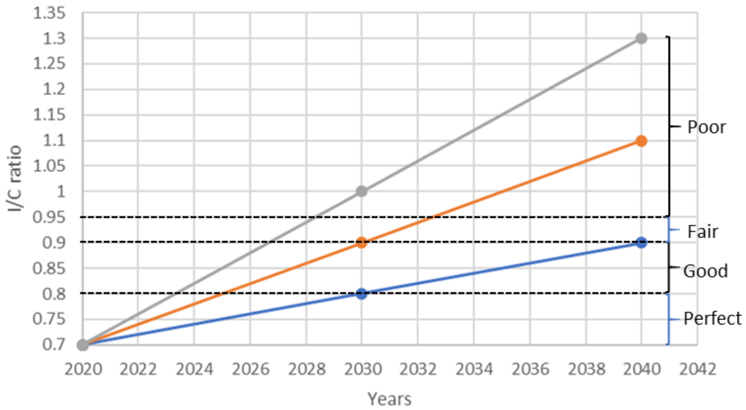

Figure 30. I/C ratio evolution with time. Upper line: fast-growing scenario. Middle line: mean-growing scenario. Lower line: slow-growing scenario.

In the scoring scale, the "Traffic Volume Carried" condition states have been defined according to the following thresholds of the I/C ratio:

1. Perfect condition → I/C≤0.8.
2. Good condition → 0.8<I/C≤0.9.
3. Fair condition → 0.9<I/C≤0.95.
4. Poor condition → I/C>0.95.

The thresholds are represented in Figure 30. With the thresholds and the I/C ratio evolution curves, it is possible to determine when a bridge changes from one condition state to another. In the curves from Figure 30, it can be seen that the bridge will change from "Perfect" to "Good" between 2023 (t_{min})and 2030 (t_{max}) depending on the traffic intensity evolution with a more probable changing year at 2025 (see Figure 31). The same principle can be followed to determine when the bridge will change from "Good" to "Fair" or to find out how long a bridge will be in a certain condition state. Using the future trends for all the performance indicators selected in the Hierarchy of Bridge Functional Criteria, the performance evolution curve could be constructed more precisely. The procedure to translate the trends to the functional evolution curve is out of the scope of this research due to the lack of resources but interesting for further research,

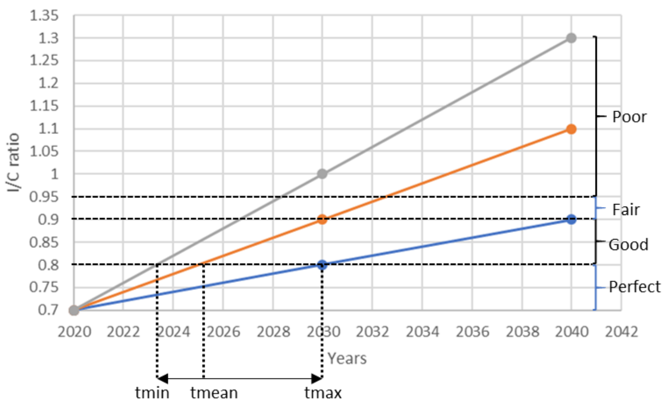

Figure 31. I/C ratio evolution with time. From Perfect to Good condition state.

Appendix 8. Summary of Methodology Steps.

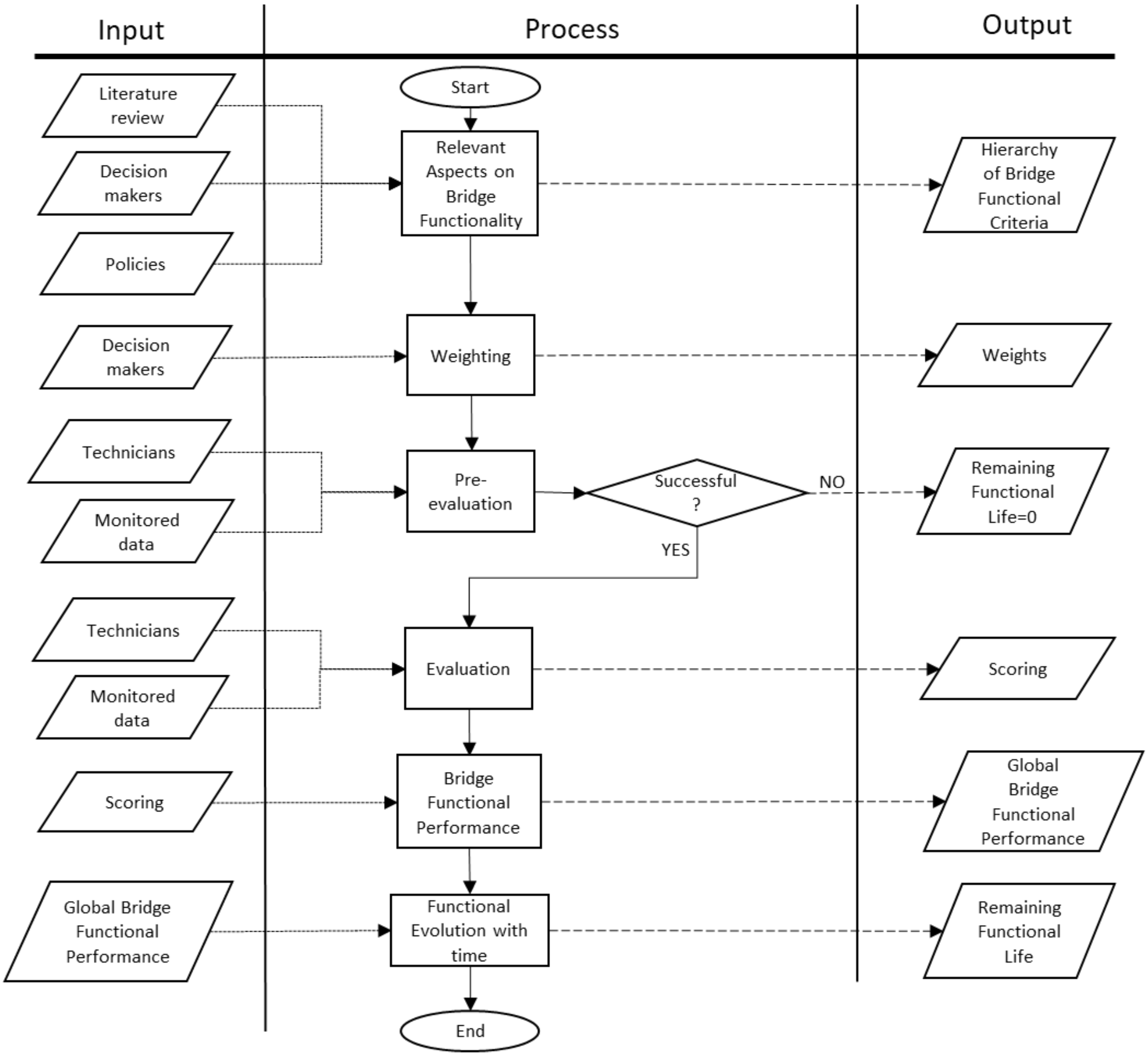

Figure 32. Methodology Main Steps.

The methodology is shortly explained below with the steps and sub-steps. The aim of this summary is to bring together the essential information of all the procedure so that the reader can create a picture of the whole process in a quick look.

1. HIERARCHY OF BRIDGE PERFORMANCE INDICATORS

This step aims to determine those aspects that influence the bridge functional performance. Consists of the following sub-steps:

1.1. Determination of the Goal Categories: the goal categories influencing the functional performance should be found and described. In order to select the relevant ones, it is recommended to consider experts and decision-makers opinions and policies (See 3.2.1).

1.2. Determination of the Performance Indicators: the performance indicators influencing the functional performance should be found and described. In order to select the relevant ones, it is recommended to consider experts and decision-makers opinions and policies (See 3.2.3).

1.3. Determination of the Goal Subcategories: goal subcategories fall between the Goal Categories and the Performance Indicators. Their goal is to create a logic relation between the two and to logically classify them. The user can determine them with an analysis of the goals and the indicators (See 3.2.2).

2. WEIGHTING

2.1. Determination of the weights of the Goal Categories and the Performance Indicators: the relative influence that each Goal Category and Performance Indicator has on the bridge functional performance has to be found out. The weights should be obtained from decision-makers to adapt the methodology to their reality (See 3.3). In Appendix 3, a recommended methodology to get the weights is explained.

3. PRE-EVALUATION

This step aims to ensure that the bridge succeed to give a minimum service in those indicators with the greatest influence in bridge performance. It is composed by 6 sub-steps:

3.1. Selection of the essential Performance Indicators: from the list of performance indicators developed before, those whose good performance is essential for an adequate functional performance should be selected. It is recommended to use decision-maker's input for the selection.

3.2. Determination of the pre-evaluation scale: different scales are used to evaluate the bridge performance. The user should choose the most adequate for the particular case. A review of the scoring systems used is recommended to adapt the methodology to reality.

3.3. Definition of each score in the scale for each performance indicator: in order to ease the scoring, each score should be defined for each performance indicator. Policies can be used to relate the description of the indicator and the score.

3.4. Determination of the pre-evaluation threshold: the bridges can provide an adequate service until a moment in time when they should be replaced. That replacement moment is represented in the threshold and the user must decide which is the minimum score with which a bridge is still acceptable.

3.5. Pre-evaluation scoring: the bridge should be assessed according to the before-defined scale by technicians with knowledge about the bridge of study and/or monitored data if available.

3.6. Deciding whether the bridge can continue to evaluation or should be replaced: a bridge that scores in any of the essential indicators below the threshold must be directly replaced and the remaining functional life is 0. If it scores above the threshold, the evaluation can start.

A detailed explanation of the steps can be found in chapter 3.4.1.

4. EVALUATION

This step aims to assess the rest of the indicators that, although with less importance than those in the pre-evaluation, still influence bridge functional performance.

4.1. Determination of the evaluation scale: different scales are used to evaluate the bridge performance. The user should choose the most adequate for each case. A review of the scoring systems used is recommended to adapt the methodology to reality.
4.2. Definition of each score in the scale for each performance indicator: in order to ease the scoring, each score should be defined for each performance indicator. Policies can be used to relate the description of the indicator and the score.
4.3. Evaluation scoring: the bridge should be assessed according to the before-defined scale by technicians with knowledge about the bridge of study and/or monitored data if available.

A detailed explanation of the steps can be found in chapter 3.4.2.

5. BRIDGE FUNCTIONAL PERFORMANCE

This step aims to combine the bridge results of the previous three steps and give as a result the functional performance score of the bridge.

5.1. Check measurement scale: ensure that the scale chosen for the Bridge Functional Performance corresponds to the scale used in the evaluation.
5.2. Processing the evaluation input to an adequate format: represent the scores in a matrix in which the columns refer to the score and the rows to the % of experts that selected that particular score.
5.3. Determination of the Functionality Index: the functionality index refers to the functional condition of the bridge in each performance indicator. The scoring input should be multiplied by the scale.
5.4. Determination of the performance of the bridge in each goal category: the weights of the performance indicators are multiplied by the Functional Index, obtaining the performance of the bridge in each goal category.
5.5. Determination of the global performance of the bridge: the global performance is the final score of the bridge according to the scale defined before. It is obtained multiplying the performance in each goal category by the weight of each goal category.

A detailed explanation of the steps can be found in chapter 3.4.3.

6. FUNCTIONAL EVOLUTION WITH TIME

This step aims to determine what is the remaining functional life of the bridge based on the score obtained before and the evolution with time of functional performance.

6.1. Determination of the Functional Evolution with time of the bridge: functional performance evolves with time similarly to the technical performance. It is required to find out how that evolution in time develops. It can be represented in a graph Remaining Functional Life-Global Bridge Functional Performance.

6.2. Determination of the Remaining Functional Life: from the graph, the Remaining Functional Life can be graphically obtained. The curve can also be approximated by equations and make use of them to get more precise results.

6.3. Application of the adequate uncertainties to the Remaining Functional Life: several uncertainties are involved along the whole methodology. In order to give a result that corresponds to the precision of the methodology, it is essential to include uncertainties.

A detailed explanation of the steps can be found in chapter 3.5.

Appendix 9. Performance indicators considered during the realization of the research and the reasons to include them (grey) or not (white) in the application for Rijkswaterstaat.

PERFORMANCE INDICATOR	REASON
# deaths by traffic accidents per year	Reflected in safety to users.
# hospitalized by traffic accidents per year	Reflected in safety to users.
# only material damage accidents	Reflected in safety to users.
Adaptability	Reflected in bridge geometry.
Adequate signalling	A lack of signals would lead to their installation, not to the bridge replacement.
Aesthetical value	The aesthetical value is a barrier for the replacement. A bridge considered a monument due to its design cannot be replaced. It will be always maintained.
Aesthetics	The users and other stakeholders are becoming a big influence in the decisions and their satisfaction is therefore essential to ensure that the bridge fits in the environment and does not create any kind of hindrance that can cause complaints.
Availability of information panels	A lack of information panels would lead to their installation, not to the bridge replacement.
Available height under bridge(m)	Reflected in bridge geometry.
Available space for emergency services	Reflected in bridge geometry.
Available space to accept future road widening	Reflected in bridge geometry.
Available width on bridge(m)	Reflected in bridge geometry.
Available width under bridge(m)	Reflected in bridge geometry.
Bridge Condition index	Refers to technical performance, not to functional.
Bridge geometry	The bridge should have enough width and height to provide the required service and to ensure that all the traffic can go on or under it.
Climate adaption	Reflected in vulnerability to climate floods and storms.
CO2 footprint	In the analysis of existing bridges, the CO_2 emissions have been produced in the construction which was in the past. The emissions of a static structure are zero, so it does not make sense to study it. A bridge would not be replaced because of this reason because a new one would produce more $C0_2$ than the existing one.
Comfort level	The comfort level of the driver is mainly referred to the vibrations, which are produced by a defective asphalt which would require maintenance, not replacement.
Condition of drainage system	Whether the drainage system is in good condition is an aspect that can be fixed with maintenance, so the bridge does not need to be replaced according to this indicator.
Condition of the security screens and handrails	The condition of security screens and handrails may have an influence on the bridge safety, but it is not important enough to produce bridge replacement. Replacement of security screens and handrails could be done.
Congestion	Reflected in traffic volume carried.
Construction costs	The construction costs of a new bridge do not say anything about the performance of the existing bridge.
Contribution to regional economic development	The bridge influences the economy by providing adequate performance in terms of traffic flow, which is reflected in traffic volume carried.
Country economic situation	Country economic situation may influence the decisions, but it does not influence the functional performance of the bridge.
Cultural value	The cultural value is a barrier for the replacement. If the bridge has cultural value, it cannot be demolished so it should not be in the method. A bridge with a significant cultural value will always be maintained.
Current condition of materials	Refers to technical performance, not to functional.
Damage level of structure	Refers to technical performance, not to functional.
dB produced by the contact road surface-tyre (roughness)	The asphalt roughness is not a bridge replacement reason. Maintenance can be done to extend the life of the bridge.
dB produced by the expansion joints	Defective expansion joints may lead to uncomfortable noise. However, maintenance can fix this problem and keep the bridge functional longer.
Dismantling problems	If a bridge does not accomplish the functional requirements, solutions will be found to dismantle the bridge.
Ergonomics	The ergonomics for maintenance is reflected in maintainability.

Function failure probability	Refers to the chance that the bridge does not fulfils its function. It is contrary to functional time duration, so it is again reflected in the traffic volume carried and in maintainability.
Functional time duration	Refers to the time in which the bridge is functional, and its functions can be fulfilled. In normal conditions, it is reflected in the traffic volume carried because the I/C ratio reflects if there is congestion or not. During intervention, it is reflected in maintainability since it shows the hindrance of the interventions in the traffic flow.
Funds availability	Availability of funds may influence the decisions, but it does not influence the functional performance of the bridge.
Greenhouse gas emissions	Similar to CO2 emissions, the emissions of a static structure are zero, so it does not make sense to analyse it. A bridge would not be replaced because of this reason because a new one would produce more greenhouse gas emissions than the existing one.
Health	Reflected in maintainability.
I/C ratio	Reflected in traffic volume carried.
Increase of travel time by alternative route	Although it may affect the replacement decision, it is not directly related with the bridge functional performance.
Increase of travel time by alternative transportation	Although it may affect the replacement decision, it is not directly related with the bridge functional performance.
Influence in local economy	The bridge influences the economy by providing adequate performance in terms of traffic flow, which is reflected in traffic volume carried.
Inspection rating	Refers to technical performance, not to functional.
International Roughness Index (IRI)	Reflects the roughness of the road surface. A bad surface would be translated into maintenance, not into replacement of the whole bridge.
Landscape fragmentation	The location or characteristics of the bridge can become a negative influence for the citizens or for the fauna if it interrupts the movement or is located in an inadequate position.
Life cycle cost	The costs are the result of other facts like maintenance (technical, not functional) or congestion. Then, they are reflected in other indicators.
Load bearing capacity	The main function of a bridge is to allow traffic flow between two separated lands, for all the traffic. Then, it should have enough load bearing capacity to ensure a smooth and safe flow.
Maintainability	The easiness with which the bridge can be maintained over time. It relates to maintenance, not to replacement.
Maintenance hindrance	The maintenance can influence the time the bridge is accessible, and then, has a big influence on the performance.
Maintenance pollution	If the required maintenance is very polluting, the bridge might be replaced. However, it is more probable that a new maintenance technique with less environmental impact is found before replacing the bridge.
Maintenance works durability	Reflected in functional time duration.
Maintenance works frequency	Reflected in functional time duration.
Maintenance works impact on traffic	Reflected in functional time duration.
New design and construction costs	The costs of a new bridge do not say anything about the existing bridge.
New design and construction time	The costs of a new bridge do not say anything about the existing bridge.
Noise emissions	The road traffic produces high noise emissions which can create a great hindrance for people or fauna. It must be ensured that the bridge noise emissions satisfy the requirements.
Number of bottlenecks	Reflected in functional time duration.
Number of inhabitants	The number of inhabitants affects the bridge according to the traffic intensity, which is reflected with I/C ratio.
Operational costs new bridge	The operational costs of a new bridge do not say anything about the performance of the existing bridge.
Politics	Politics may affect the bridge replacement, but not how the bridge performs.
Possibility to detour traffic on bridge	Reflected in maintainability as an option to reduce traffic hindrance during bridge maintenance.
Predicted growth of inhabitants	The growth of population will be reflected in a growth in traffic intensity, which is reflected with I/C ratio.
Presence of polluting substances	The environmental impact of polluting substances may have an influence in the replacement decisions if the bridge becomes a health problem for people or fauna.
Priority of the asset on network level	The importance on network level would relate more to the replacement reasons than to the functional performance.
Probability of being affected by earthquake	An earthquake would cause structural dangers which are intrinsically technical problems. The bridge cannot provide its function if the structure is affected but it is a consequence of technical failure.
Probability of being affected by flood	Reflected in vulnerability against floods.

Project risk	The risk of building a new bridge does not say anything about the current bridge performance.
Projects in the same network	Other projects may become a bridge replacement reason, but it does not say anything about the bridge performance.
Quality of materials	Refers to technical performance, not to functional.
Resilience to extreme weather events	The performance of the bridge against floods or heavy storms have a big influence in the safety and accessibility of the bridge.
Reusability	A bridge with more reusable materials might be easier to replace. However, it will never be the main reason for replacement and just in very particular cases might have an influence, so it is not considered in this case.
Safety to users	Safety is essential in any infrastructure, so it should be ensured in the bridge under all the circumstances.
Service life	Refers to technical performance, not to functional.
Space arrangement for all kind of users	Reflected in bridge geometry.
Speed limits	The speed limits are a determined in network level, not on the bridge itself. If the speed has to be reduced in the bridge, it will be due to a low performance in other indicators (e.g. safety or traffic capacity).
Stakeholder participation	The bridge performance is not affected by the stakeholder participation.
Standard requirements change	The change in the regulations are a reason to replace the bridge, but it is not affecting its functional performance.
Traffic capacity	Reflected in traffic volume carried.
Traffic hindrance costs	Traffic hindrance costs are a consequence of the traffic congestion. The congestion affects the bridge functional performance, but the costs are just an effect of the congestion, which is reflected in traffic volume carried.
Traffic intensity	Reflected in traffic volume carried.
Traffic volume carried	The bridge should be able to carry the required traffic without becoming a network bottleneck, which makes the success of this indicator essential for the proper bridge functional performance.
User delay costs	The user delay costs are a consequence of the traffic congestion. The congestion affects the bridge functional performance, but the costs are just an effect of the congestion, which is reflected in traffic volume carried.
Visibility	Lack of visibility may cause accidents (reflected in safety to users).
Vulnerability against drought	Drought may cause problems in the bridge foundations and the abutment. However, it is a technical problem more than functional.
Vulnerability against floods	Whether the road capacity is or will be affected due to floods.
Vulnerability against storms	Whether the road capacity is or will be affected due to heavy rain.
Vulnerability to heat stress	Heat stress may cause technical problems like cracking, but the functional problems would just be a consequence of technical problems.
Waste production	The waste production of a static structure is zero (except from maintenance). A bridge would not be replaced because of this reason because a new one would produce more waste than the existing one.
Water retainability	The retainability of the road surface affects the safety and traffic flow but it can be fixed with maintenance activities. Bridge replacement is not required.

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Appendix 10. Excel file for the calculation of the Global Bridge Functional Performance.

WEIGHTING			
Goal Categories	W	Performance Indicators	w
Safety	8%	Safety to users	100%
Accessibility	48%	Traffic volume carried	36%
		Load Bearing Capacity	16%
		Bridge Geometry	16%
		Maintenance hindrance	16%
		Resilience extreme weather events	16%
Society	4%	Aesthetics	100%
Environment	40%	Noise emissions	30%
		Presence of polluting sustances	30%
		Fauna habitat fragmentation	40%

1. SCALE

Qualitative	Quantitative
Perfect	1
Good	2
Fair	3
Poor	4

CODE OF COLOURS
INPUT
CALCULATION
INTERMEDIATE RESULT
FINAL RESULT
CORRECT
PROBLEM

Bridge Assessment

Number of experts answering	1

2. PRE-EVALUATION

Introduce the number of experts that gave a certain score to a particular indicator.

	Perfect	Good	Fair	Poor	NUMBER OF ANSWERS CHECK
GC1: Safety					
Safety to users		0	1		OK
GC2: Accessibility					
Traffic volume carried	1			0	OK
Load Bearing Capacity	1				OK
Bridge Geometry			1		OK
GC4: Environment					OK
Noise emissions		1			OK

In the **check number answers,** it is checked that the number of answers are not bigger than the number of respondents.

PRE-EVALUATION CHECK	CONTINUE EVALUATION

In the **pre-evaluation**, it is checked if the essential performance indicators selected before are above the threshold.
If essential indicators are above the threshold--> continue evaluation.
If essential indicators are below the threshold--> consider direct replacement

3.EVALUATION

Introduce the number of experts that gave a certain score to a particular indicator.

	Perfect	Good	Fair	Poor	NUMBER OF ANSWERS CHECK
GC1: Safety					
Safety to users	0	0	1	0	OK
GC2: Accessibility					
Traffic volume carried	1	0	0	0	OK
Load Bearing Capacity	1	0	0	0	OK
Bridge Geometry	0	0	1	0	OK
Maintenance hindrance		1			OK
Resilience extreme weather events	1				OK
GC3: Society					
Aesthetics	1				OK
GC4: Environment					
Noise emissions	0	1	0	0	OK
Presence of polluting sustances	1				OK
Landscape fragmentation	1				OK

4. EXPERTS INPUT IN %

	Perfect	Good	Fair	Poor
GC1: Safety				
Safety to users	0%	0%	100%	0%
GC2: Accessibility				
Traffic volume carried	100%	0%	0%	0%
Load Bearing Capacity	100%	0%	0%	0%
Bridge Geometry	0%	0%	100%	0%
Maintenance hindrance	0%	100%	0%	0%
Resilience extreme weather events	100%	0%	0%	0%
GC3: Society				
Aesthetics	100%	0%	0%	0%
GC4: Environment				
Noise emissions	0%	100%	0%	0%
Presence of polluting sustances	100%	0%	0%	0%
Landscape fragmentation	100%	0%	0%	0%

The experts input in % refers to the percentage of experts from the total

FUNCTIONAL INDEX (FI)

	FI
GC1: Safety	
Safety to users	3.00
GC2: Accessibility	
Traffic volume carried	1.00
Load Bearing Capacity	1.00
Bridge Geometry	3.00
Maintenance hindrance	2.00
Resilience extreme weather events	1.00
GC3: Society	
Aesthetics	1.00
GC4: Environment	
Noise emissions	2.00
Presence of polluting sustances	1.00
Landscape fragmentation	1.00

The functional index states the bridge condition in each performance indicator according to the technicians scaling.

6. PERFORMANCE OF BRIDGE IN GOAL CATEGORIES (Z)

GC1: Safety	w	z		
Safety to users	100%	3.00		
			Z1	3.00

GC2: Accessibility	w	z		
Traffic volume carried	36%	0.36		
Load Bearing Capacity	16%	0.16		
Bridge Geometry	16%	0.48		
Maintenance hindrance	16%	0.32		
Resilience extreme weather events	16%	0.16		
			Z2	1.48

GC3: Society	w	z		
Aesthetics	100%	1.00		
			Z3	1.00

GC4: Environment	w	z		
Noise emissions	30%	0.60		
Presence of polluting sustances	30%	0.30		
Landscape fragmentation	40%	0.40		
			Z4	1.30

The Performance of the bridge in each Goal Category (Z) is obtained by multiplying the relative weights (w) of each indicator by the Functional Index (FI).
Z=Σ w*FI

7. GLOBAL BRIDGE FUNCTIONAL PERFORMANCE (P)

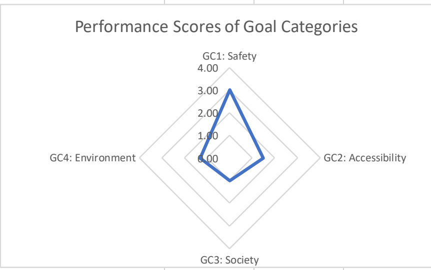
GOAL CATEGORIES	W	Z		
GC1: Safety	8%	3.00		
GC2: Accessibility	48%	1.48		
GC3: Society	4%	1.00		
GC4: Environment	40%	1.30	P	1.51

The Global Bridge Functional Performance (P) is obtained by multiplying the relative weights of each Goal Category (W) by the performance of the bridge in each Goal Category (Z).

Worst essential PI	3.00
P CHECK (FINAL P)	3.00
P CHECK (FINAL P)	FAIR

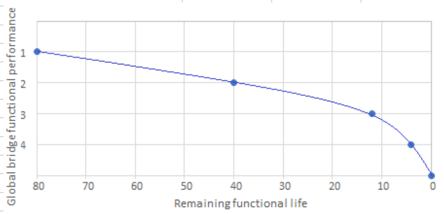
P CHECK refers to the step 6 in the methodology.
If P<FI $_{\text{essential indicator pre-evaluation}}$ →P=P
If P>FI $_{\text{essential indicator pre-evaluation}}$ →P=FI $_{\text{essential indicator pre-evaluation}}$

8.RADIAL GRAPH



The radial graph shows the score of each particular Goal Category so the user can see where the bridge might fail in a quick look. According to the scale developed, the perfect performance is reflected in lines close to the center of the graph. The closer to the sides of the graph, the lower the functional performance and viceversa.

9.REMAINING FUNCTIONAL LIFE



The remaining functional life has been determined dividing the evolution curve in three parts, and representing each part with a straight line. It gives approximate values. The equations of the lines are as follow:
If 1≤P<2--> y= -40x+40
If 2≤P<3--> y=-x/40+3
If 3≤P≤4--> y=-x/7+33/7

GLOBAL BRIDGE FUNCTIONAL PERFORMANCE SCORE	3.00

REMAINING FUNCTIONAL LIFE	12	YEARS

UNCERTAINTIES

Assessment uncertainty	±	10	years
Functional Evolution Uncertainty	±	10%	of remaining functional life

	FROM	MEAN	TO	
REMAINING FUNCTIONAL LIFE WITH UNCERTAINTY	0.80	12	23.20	YEARS

Appendix 11. Bridges for the study cases from highway A20 between Gouda and Rotterdam.

NAME	Number	Province	Municipality	Construction year	Nature	Objectsoort	Asbestos	Corridor/Economic importance	Cross angle	Cultural history	Current traffic intens	Description	Economic netw	Impact coeffi	EELI	Length	Load coeffi	Material	Spans	Object quali	Replacement value (K€)	Load class	Type of construction	Width
GOUDA																								
Groenebrug	38A-001-01	Zuid-Holland	Zuidplas	1981	Droog	Viaduct	Safe-non disti	KP Terbregseplein-KP Gouwe	88.9	Green	39700(4606)	Uneven-level crossroads - railway G	Orange		0.53	107.5	1	Concrete	6	2	3000-5000	60	Concrete-Beam	14.77
Groenebrug	38A-001-02	Zuid-Holland	Zuidplas	1937	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	100	Orange	X	Uneven-level crossroads - railway G	X	1	1.24	87.44	1	Concrete/steel	1	4	3000-5000	A	Concrete-Slab/Steel-arc	18.13
5e Tochtweg	38A-002-01	Zuid-Holland	Zuidplas	1978	Droog	Fixed bridge	Safe-non disti	KP Gouwe -KP Terbregseplein	78.5	Green	39700(4606)	Uneven-level crossroads national r	Orange	1	0.44	16.25	1	Concrete	1	3	1000-1500	60	Concrete-Slab	18.67
5e Tochtweg	38A-002-02	Zuid-Holland	Zuidplas	1981	Droog	Fixed bridge	Safe-non disti	KP Terbregseplein-KP Gouwe	65	Green	40100(6053)	Uneven-level crossroads national r	Orange	1	0.39	23.33	1	Concrete	1	3	1500-3000	60	Concrete-Slab	18.66
KW2	38A-146-01	Zuid-Holland	Zuidplas	2014	Droog	Viaduct	Asbestos safe	X	79.2	Not Judged	X	Uneven ground intersection nationa	X	X	0.16	82.91	X	Concrete	3	X	5000-10000	NEN-EN 1991-2	Concrete-Beam	31.36
Schielandweg	38A-122-01	Zuid-Holland	Zuidplas	1983	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	90	Green	90300(9610)	Uneven ground intersection nationa	Orange	1	0.39	53.21	1	Concrete	2	2	3000-5000	60	Concrete-Slab	20.08
Cortlandt	38A-114-02	Zuid-Holland	Zuidplas	1976	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	78.2	Yellow	52000(4963)	Uneven-level crossroads - Westring	Orange	1	0.49	56	1	Concrete	2	3	1500-3000	60	Concrete-Slab	10.01
Cortlandt	38A-114-03	Zuid-Holland	Zuidplas	1977	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein		Yellow	48400(6171)	Uneven-level crossroads - Westring	Orange	1	0.49	56	1	Concrete	2	4	1500-3000	60	Concrete-slab	14.11
Schollevaartsetocht	37F-131-01	Zuid-Holland	Capelle aan de	1979	Droog	Fixed bridge	Safe-non disti	KP Gouwe -KP Terbregseplein	100	Green	52000(4963)	Bridge over the Schollevaarts tour v	Orange	1	0.45	21.5	X	Concrete	2	3	1500-3000	60	Overcoupling-Plate/Fixed bridge-concrete-Beam	23.33
	37F-131-02	Zuid-Holland	Capelle aan de	1979	Droog	Fixed bridge	Safe-non disti	KP Terbregseplein-KP Gouwe	100	Green	48400(6171)	Bridge over the Schollevaarts tour v	Orange	1	0.44	21.5	X	Concrete	1	4	1500-3000	60	Overcoupling-Plate/Fixed bridge-concrete-Beam	23.33
Schollevaartse Dreef	37F-115-01	Zuid-Holland	Capelle aan de	1981	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	81.99	Green	52000(4936)	Uneven-level crossroads - Schollev	Orange	1	0.37	68.73	1	Concrete	2	4	3000-5000	60	Concrete-Beam	19
Bourguignon	37F-120	Zuid-Holland	Capelle aan de	1974	Droog	Viaduct																		
Bourguignon	37F-120-01	Zuid-Holland	Capelle aan de	1979	Droog	Fixed bridge	Safe-non disti	KP Gouwe -KP Terbregseplein	95.6	Green	52000(4963)	Bridge over the Schollevaarts tour v	Orange	1	0.45	21.5	1	Concrete	1	3	1500-3000	60	Overcoupling-Plate/Fixed bridge-concrete-Beam	23.33
Capelseweg	37F-002-02	Zuid-Holland	Capelle aan de	1974	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	91	Green	42900 (6181)	Uneven ground intersection nationa	Orange	1	0.46	84.86	1	Concrete	4	3	3000-5000	60	Concrete-beam	18.81
Capelseweg	37F-002-01	Zuid-Holland	Capelle aan de	1974	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	91	Green	45200 (4471)	Uneven ground intersection nationa	Orange	1	0.42	84.86	1	Concrete	4	3		60	Beam	18.81
Prins Alexanderlaan	37F-116-01	Zuid-Holland	Rotterdam	1968	Droog	Viaduct	Safe-non disti	KP Terbregseplein-KP Gouwe	97.38	Green	67600(6601)	Uneven-level crossroads - Prins Ale	Orange	1	0.51	90.08	1	Concrete	5	3	5000-10000	60	Concrete-beam	23
Prins Alexanderlaan	37F-116-02	Zuid-Holland	Rotterdam	1968	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	97.38	Green	70000(6166)	Uneven-level crossroads - Prins Ale	Orange	1	0.5	90.08	1	Concrete	5	4	5000-10000	60	Concrete-beam	23
Knooppunt Terbregseplein	37F-003-01	Zuid-Holland	Rotterdam	1971	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	44.44	Orange	29000(1201)	Uneven ground intersection nationa	Orange	1	0.44	122	1	Concrete	4	3	5000-10000	60	Concrete-Slab	18.36
Knooppunt Terbregseplein	37F-003-02	Zuid-Holland	Rotterdam	1971	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	44.44	Orange	30100(2932)	Uneven ground intersection nationa	Red	1	0.44	122	1	Concrete	4	3	5000-10000	60	Concrete-Slab	18.36
Knooppunt Terbregseplein	37F-003-03	Zuid-Holland	Rotterdam	1970	Droog	Viaduct	Safe-non disti	s-Gravendeel - KP Ridderkerk-Noord	88.5	Orange	42200(1912)	Uneven ground intersection nationa	Red	1	0.49	52.5	1	Concrete	2	3	3000-5000	60	Concrete-Beam	24.6
Knooppunt Terbregseplein	37F-003-04	Zuid-Holland	Rotterdam	1973	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	96	Orange	30100(2932)	Uneven ground intersection nationa	Red	1	0.48	52.5	1	Concrete	2	3	1500-3000	60	Concrete-Beam	18.05
Knooppunt Terbregseplein	37F-003-05	Zuid-Holland	Rotterdam	1973	Droog	Viaduct	Safe-non disti	s-Gravendeel - KP Ridderkerk-Noord	0	Orange	X	Uneven ground intersection nationa	Red	1	0.5	52.5	1	Concrete	2	2	1500-3000	60	Concrete-Beam	13.65
Knooppunt Terbregseplein	37F-003-06	Zuid-Holland	Rotterdam	1971	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	100	Orange	46700(4822)	Uneven ground intersection nationa	Red	1	0.44	219.61	1	Concrete	8	4	5000-10000	60	Concrete-kokerligger	14.1
Knooppunt Terbregseplein	37F-003-07	Zuid-Holland	Rotterdam	1971	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	100	Orange	68800(5882)	Uneven ground intersection nationa	Red		0.43	383.82	1	Concrete	12	4	10000-100000	60	Concrete-kokerligger	14.1
Knooppunt Terbregseplein	37F-003-08	Zuid-Holland	Rotterdam	1966	Droog	Viaduct	Safe-non disti	KP Ridderkerk-Noord-KP Terbregsepl	94.1	Orange	85400(7754)	Uneven ground intersection nationa	Red	1	0.46	53.22	1	Concrete	4	4	5000-10000	60	Concrete-Slab	48.66
Knooppunt Terbregseplein	37F-003-12	Zuid-Holland	Rotterdam	1973	Droog	Viaduct	Safe-non disti	KP Gouwe -KP Terbregseplein	96	Orange	29000(1201)	Uneven ground intersection nationa	Orange		0.5	52.5	1	Concrete	2	3	1500-3000	60	Concrete-Beam	18.05
Knooppunt Terbregseplein	37F-003-13	Zuid-Holland	Rotterdam	1966	Droog	Viaduct	Safe-non disti	KP Ridderkerk-Noord-KP Terbregsepl	88.9	Orange	96000(9661)	Uneven ground intersection nationa	Red	X	0.51	53.8	X	Concrete	4	3	3000-5000	60	Concrete-Slab	27.68
Knooppunt Terbregseplein	37F-003-14	Zuid-Holland	Rotterdam	1970	Droog	Viaduct	Veilig-nondes	KP Ridderkerk-Noord-KP Terbregsepl	100	Green	Not calculated	Uneven ground intersection nationa	Red		0.56	115.86	X	Concrete	1		5000-10000	60	Concrete-bream/Concrete	23.18
Knooppunt Terbregseplein	37F-003-15	Zuid-Holland	Rotterdam	1970	Droog	Fixed Bridge	Safe-non disti	KP Terbregseplein-KP Kleinpolderplei	100	Green	U	Uneven ground intersection nationa	X	X	0.42	7.7	X	Concrete	1		100-500	X	Concrete-Slab	4.25
Veilingviaduct	37F-102-01	Zuid-Holland	Rotterdam	1970	Droog	Viaduct	Safe-non disti	KP Terbregseplein-KP Kleinpolderplei	100	Green	76600(8303)	Uneven-level crossroads - railway li	Red	1	0.48	304.4	1	Concrete	9		10000-100000	60	Concrete-Beam	17
Veilingviaduct	37F-102-02	Zuid-Holland	Rotterdam	1970	Droog	Viaduct	Safe-non disti	KP Kleinpolderplein (L)- KP Terbregse	100	Green	76600(7540)	Uneven-level crossroads - railway li	Red	1	0.49	304.4	1	Concrete	9		10000-100001	60	Concrete-Beam	17
Veilingviaduct	37F-101-01	Zuid-Holland	Rotterdam	1976	Droog	Fixed bridge	Safe-non disti	KP Terbregseplein-KP Kleinpolderplei	76.53	Green	76600(8303)	Bridges in the national road over th	Red	1	0.48	205.6	1	Concrete	4		10000-100000	60	Fixed bridge-concrete-bea	16.85
Rotte	37F-101-02	Zuid-Holland	Rotterdam	1976	Droog	Fixed bridge	Safe-non disti	KP Kleinpolderplein (L)- KP Terbregse	76.53	Green	77600(7540)	Bridges in the national road over th	Red	1	0.43	188.6	1	Concrete	4		10000-100000	60	Fixed bridge-concrete-bea	16.85
Bergweg	37F-100-01	Zuid-Holland	Rotterdam	1966	Droog	Viaduct	Safe-non disti	KP Terbregseplein-KP Kleinpolderplei	100	Yellow	84800(8861)	Uneven-level crossroads - Bergweg	Red	1	0.53	596.51	1	Concrete	17	3	10000-100000	60	Concrete-slab/Concrete-b	18.58
Bergweg	37F-100-02	Zuid-Holland	Rotterdam	1966	Droog	Viaduct	Safe-non disti	KP Kleinpolderplein (L)-KP Terbregsep	100	Yellow	84900(8074)	Uneven-level crossroads - Bergweg	Red	1	0.53	596.51	1	Concrete	17	4	10000-100000	60	Concrete-beam/Concrete	18.58
Weg op palen 1	37F-109-01	Zuid-Holland	Rotterdam	1971	Droog	Viaduct	Safe-non disti	KP Terbregseplein-KP Kleinpolderplei	100	Green	84800(8861)	Road on piles in northern roadway/	Red	1	0.48	241	1	Concrete	9			60	Concrete-Road on piles w	28.37
Schieplein	37F-001-03	Zuid-Holland	Rotterdam	1970	Droog	Viaduct	Safe-non disti	KP Terbregseplein-KP Kleinpolderplei	100	Green	13900 (1071)	Uneven ground intersection nationa	Red		0.5	152.1	1	Concrete	3	3	5000-10000	60	Concrete-beam/Concrete	13
ROTTERDAM																								

[Blank on purpose]

Appendix 12. Questionnaire for the study cases delivered to asset managers.

Before anything, I would like to thank you for your time. I know the busy agendas you have, and I really appreciate if you can sacrifice some minutes to help me in the realisation of my master thesis. This is the last step to finish it and your input would be important for the final research. If you have any doubt while doing the questionnaire, you can contact me at: saulcuendias@gmail.com or directly call at 0034657305328. Furthermore, if you cannot complete the whole questionnaire, but just partially, something is better than nothing, so you can also send me your answers.

Thank you very much.

First, you will find a short explanation of the research and what I would need from you. Then, you can find the tables you need to fill up and, in the end, some general questions about your opinion of the methodology.

EXPLANATION

The Dutch infrastructure is getting older and the next decades will require great investments to renovate and replace the assets reaching their end of service life. Within this framework, a study ordered by RWS found out that almost 90% of the bridge replacements were done due to functional problems, not to technical. This means that the end of service life based on a typical design life of 60-80 years might not be fully correct and a lot of bridges might need to be replaced before or after those 60-80 years. Then, a methodology that help to study those functional problems and determine when the asset reaches the end of functional life could be an interesting tool to improve the decision-making and to better allocate the resources.

Here, a student from TU Delft, Yue Xie, introduced in 2017 a methodology called Performance Age. This methodology has as outcome the age of an asset (bridge) according to its functional performance based on a set of performance indicators.

This research aims to use the principles of the Performance Age and useful for the decision-making procedure. The methodology consists on the following steps:

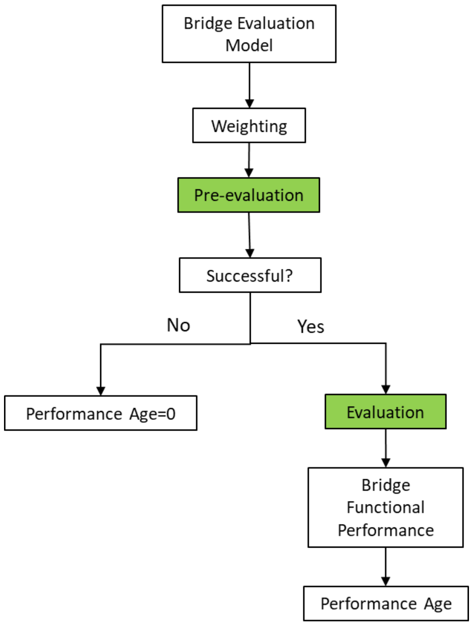


Figure 1. Performance Age methodology. In green, steps where asset managers' input is required.

First, the Hierarchy of Bridge Functional Criteria should be developed. It is a framework in which the important aspects that should be evaluated from the bridge are shown. In our case, it was developed by literature review, experts' assessment and the opinion of policy makers from the Ministry. The Hierarchy of Bridge Functional Criteria can be seen in Table and the definition of the performance indicators in the Appendix.

Table 1. Hierarchy of Bridge Functional Criteria.

GOAL CATEGORY	SUBCATEGORY	PERFORMANCE INDICATOR
Safety	Users	Safety to users
Accessibility	Traffic flow	Traffic volume carried
	Bridge physical features	Traffic load
		Bridge geometry
	Intervention	Maintenance hindrance
	Resilience to climate change	Resilience to extreme weather events
Society	Social hindrance	Aesthetics
Environment	Sustainability	Noise emissions
		Presence of polluting substances
		Landscape fragmentation

The second step, the weighting, is done to determine which is the relative importance of each performance indicator in the whole bridge performance. For this research, decision makers were considered the main input to determine the weights and they were interviews to retrieve the proper data. The Performance Age is a tool whose outcome will be basically used by them, so the introduction of their interests should be highly considered. They gave the weights and the outcome can be seen in Table .

Table 3. Weights for the Goal Categories and Performance Indicators according to policy makers of the Dutch Ministry of Infrastructure and Environment.

GOAL CATEGORY	Normalized Weight in % (extrapolated) (W)	SUBCATEGORY	PERFORMANCE INDICATOR	Weights per Goal Categories in % (w)
Safety	**8**	Users	Safety to users	**100**
Accessibility	**48**	Traffic flow	Traffic volume carried	**36**
		Bridge physical features	Load bearing capacity	**16**
			Bridge geometry	**16**
		Intervention	Maintenance hindrance	**16**
		Resilience to climate change	Resilience against extreme weather events	**16**
Society	**4**	Social hindrance	Aesthetics	**100**
Environment	**40**	Sustainability	Noise emissions	**30**
			Presence of polluting substances	**30**
			Fauna habitat fragmentation	**40**

The next step is bridge assessment. The assessment should be done by <u>asset managers</u> and I would kindly ask for your help to try the methodology out with real cases. I would like to apply the methodology to 5 bridges to see how it might work and to get feedback or comments by asset managers that could help to improve the methodology. In order to assess 5 bridges, the asset manager should have certain knowledge of the bridges and since I do not know with which bridges you might be more familiar with, you can choose 5 you know. If you cannot due 5, at this point a smaller number would be also useful.

The assessment can be done with a table I have developed with a scale that can be seen in the APPENDIX. There is one example table to show how the bridge assessment should be done and 5 other tables, one for each bridge.

With the answers given by the asset managers, I will be able to calculate the bridge functional performance by a set of equations in which the weights and the scores are put together.

Finally, the bridge functional performance will be translated in an approximate bridge remaining life.

APPENDIX

1. PERFORMANCE INDICATORS DEFINITIONS

Performance Indicator	Definition
Safety to users	*Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities.*
Traffic volume carried	*Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society.*
Load bearing capacity	*Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic.*
Bridge geometry	*Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service.*
Maintenance hindrance	*Whether and to what extent the bridge maintenance requirements influence in the bridge functional performance.*
Resilience to extreme weather events	*Whether the bridge performance is affected by floods or heavy storms.*
Aesthetics	*Whether the public is satisfied with the aesthetic appearance of the bridge.*
Noise emissions	*Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment.*
Presence of polluting substances	*Whether the bridge construction materials contain polluting materials that can cause a negative impact in the environment. The most common is the presence of asbestos in the bridge structure.*
Landscape fragmentation	*Whether the bridge causes hindrance in the connection between parts of the city or between fauna habitats.*

1. BRIDGE EVALUATION. **EXAMPLE**

BRIDGE or VIADUCT Nº n/5

Please, select a bridge from the road network under your responsibility. **The bridge or viaduct must be: FIXED, FROM HIGHWAY AND MADE OUT OF CONCRETE.**

BRIDGE/VIADUCT NAME: Groenebrug

ROAD: A20 Gouda-Rotterdam

In the table, highlight the condition state corresponding to each indicator for the bridge selected above. If you have any comment, write it down in the cell created for that purpose.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	COMMENTS
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.9 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.9 ≤ I/C ratio ≤ 0.95[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and	

		allows increase of the traffic dimensions.			the bridge becomes a bottleneck in the network.	
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	
Society	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	

2. BRIDGE EVALUATION

BRIDGE or VIADUCT Nº 1/5

Please, select a bridge from the road network under your responsibility. **The bridge or viaduct must be: FIXED, FROM HIGHWAY AND MADE OUT OF CONCRETE.**

BRIDGE/VIADUCT NAME:

ROAD:

In the table, highlight the condition state corresponding to each indicator for the bridge selected above. If you have any comment, write it down in the cell created for that purpose.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	COMMENTS
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.9 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.9 ≤ I/C ratio ≤ 0.95[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and	

		allows increase of the traffic dimensions.		above the bridge but does not create an important bottleneck in the network.	the bridge becomes a bottleneck in the network.	
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	
Society	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	
[1]: (XIE, 2017) [2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)						

BRIDGE or VIADUCT Nº 2/5

Please, select a bridge from the road network under your responsibility. **The bridge or viaduct must be: FIXED, FROM HIGHWAY AND MADE OUT OF CONCRETE.**

BRIDGE/VIADUCT NAME:

ROAD:

In the table, highlight the condition state corresponding to each indicator for the bridge selected above. If you have any comment, write it down in the cell created for that purpose.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	COMMENTS
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.9 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.9 ≤ I/C ratio ≤ 0.95[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and	

		allows increase of the traffic dimensions.			the bridge becomes a bottleneck in the network.	
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	
Society	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	

[1]: (XIE, 2017)

[2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)

BRIDGE or VIADUCT № 3/5

Please, select a bridge from the road network under your responsibility. **The bridge or viaduct must be: FIXED, FROM HIGHWAY AND MADE OUT OF CONCRETE.**

BRIDGE/VIADUCT NAME:

ROAD:

In the table, highlight the condition state corresponding to each indicator for the bridge selected above. If you have any comment, write it down in the cell created for that purpose.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	COMMENTS
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.9 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.9 ≤ I/C ratio ≤ 0.95[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and	

		allows increase of the traffic dimensions.			the bridge becomes a bottleneck in the network.	
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	
Society	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	
[1]: (XIE, 2017) [2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)						

BRIDGE or VIADUCT Nº 4/5

Please, select a bridge from the road network under your responsibility. **The bridge or viaduct must be: FIXED, FROM HIGHWAY AND MADE OUT OF CONCRETE.**

BRIDGE/VIADUCT NAME:

ROAD:

In the table, highlight the condition state corresponding to each indicator for the bridge selected above. If you have any comment, write it down in the cell created for that purpose.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	COMMENTS
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.9 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.9 ≤ I/C ratio ≤ 0.95[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and	

		allows increase of the traffic dimensions.			the bridge becomes a bottleneck in the network.	
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	
Society	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	
[1]: (XIE, 2017) [2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)						

BRIDGE or VIADUCT Nº 5/5

Please, select a bridge from the road network under your responsibility. **The bridge or viaduct must be: FIXED, FROM HIGHWAY AND MADE OUT OF CONCRETE.**

BRIDGE/VIADUCT NAME:

ROAD:

In the table, highlight the condition state corresponding to each indicator for the bridge selected above. If you have any comment, write it down in the cell created for that purpose.

	CONDITION / INDICATOR	PERFECT [Score=1] *"The most desirable bridge functional performance. The condition of the bridge corresponds to a new built bridge."*	GOOD [Score=2] *"The bridge functional performance is acceptable, but it is no longer as desired."*	FAIR [Score=3] *"The bridge does not fully meet the required functional performance, but it can still provide a fair service without unwanted consequences."*	POOR [Score=4] *"The bridge fails to meet the required functional performance and it causes severe consequences in the traffic and the environment."*	COMMENTS
Safety	**Safety to users**	The road on the bridge is safe to users (related to injuries and fatalities).	The road on the bridge is safe to users but there are traffic accidents with slight injuries.	The road on the bridge is not as safe to users as required and there are several traffic accidents with serious injuries.	The road on the bridge is not safe to users and there are several traffic accidents with fatalities.	
Accessibility	**Traffic volume carried**	The traffic flow on the bridge is smooth and accomplishes with the requirements. I/C ratio ≤ 0.8 [1]	The residual capacity does not fully meet the requirements which causes light congestion at peak hours. 0.80 ≤ I/C ratio ≤ 0.9 [1]	The residual capacity is slightly insufficient and causes some congestion during the day, with more intense traffic jams in peak hours. 0.9 ≤ I/C ratio ≤ 0.95[1]	The residual capacity is insufficient and causes serious congestion. I/C ratio ≥ 0.95[1]	
	Load bearing capacity	The bridge has capacity to carry the traffic loads and it allows the traffic load to increase, according to the design.	The bridge has just enough capacity to carry the traffic load.	The bridge load bearing capacity limits the traffic load and the traffic is restricted (load or speed, especially for trucks).	The traffic load is above the bridge load bearing capacity and there is a high probability of dangerous consequences.	
	Bridge geometry	The structure geometry is at design level with respect to height and width under and above the bridge and it	The structure geometry is adequate for current traffic with respect to bridge height and width under and above the bridge.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge but does not create an important bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width under and above the bridge, and	

		allows increase of the traffic dimensions.			the bridge becomes a bottleneck in the network.	
	Maintenance hindrance	The bridge does not require important maintenance works and they can be done with negligible traffic hindrance.	The bridge needs maintenance activities that will reduce the traffic capacity leading to not negligible traffic hindrance but still acceptable. It is translated into incidental complaints of road users and other stakeholders.	The bridge needs maintenance activities that will reduce the traffic capacity, leading to unacceptable congestion during peak hours or to traffic detouring out of the bridge. It is translated into frequent complaints of road users and other stakeholders.	The bridge needs maintenance works that require the closing of the road and a long detour for traffic out of the bridge. It is translated into claims or seriously damaged reputation.	
	Resilience to extreme weather events	The bridge performs perfectly against extreme weather events.	The bridge suffers light consequences of extreme weather events, but it does not affect the traffic flow or the safety.	The bridge is affected by extreme weather events, causing bottlenecks and safety reduction, but in an acceptable level.	The bridge is highly vulnerable to extreme events. It becomes a bottleneck and/or an unsafe road.	
Society	**Aesthetics**	The bridge perfectly fits in the environment according to the design.	The bridge fits in the environment but it is no longer as desired in the design.	The bridge does not fully fit in the environment as desired, but it is still acceptable.	The bridge does not fit in the environment and leads to an important number of complaints from citizens.	
Environment	**Noise emissions**	The noise emissions are totally acceptable and has enough residual space for noise increase. The noise emissions are more than 0.5 dB under the sound threshold for the road. [2]	The noise emissions are under the current limitations, but the residual space for noise increase is low. The noise emissions are between 0.5 and 0.0 dB under the sound threshold for the road. [2]	The noise emissions are over the current limitation, but it is still tolerable. [2]	The noise emissions exceed the limitation and are intolerable to people and the surrounding environment.[2]	
	Presence of polluting substances	The bridge does not contain any polluting substances.	The bridge contains polluting substances, but they are in isolated places and will not cause any harm.	The bridge contains polluting substances in accessible places that can have small consequences for the environment.	The bridge contains polluting substances that can cause a lot of negative consequences to the environment.	
	Landscape fragmentation	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, according to design.	The location and characteristics of the bridge are adequate to allow an adequate movement of people and fauna, but it is not at design level anymore.	The location and characteristics of the bridge are not the most adequate to ensure a proper movement of fauna and people.	The location and characteristics of the bridge impede the free movement of people and fauna, causing great hindrance.	
[1]: (XIE, 2017) [2]: (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)						

GENERAL QUESTIONS ABOUT THE METHODOLOGY

1. Do you think this methodology could help to make better decisions for the bridge replacements in the next decades?

2. Do you feel that the main aspects that influence the functional performance are included in the methodology?

3. What do you think about the scale and the definitions of the different scores?

4. Does it require a lot of time to fill up the table if you are familiar with the bridge?

5. Other comments or feedback.

6. Questions about the methodology you might have.

Thank you very much for your time, I really appreciate it. I would like to to wish you a very good day!

Saúl Cuendias González

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Appendix 13. Data Sources

1. SAFETY TO USERS

"Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities".

It has been found out that there are databases in which the incidents in the roads are recorded. This is an objective way to determine it, although the information is given in the road hectometre and that should be extrapolated to the bridge position. If the hectometres correspond, then the incident occurred on the bridge. Table 22 shows the information recorded in the A4. Unfortunately, for the road of study A20 the database was not obtained and then the bridges cannot be assessed according to this performance indicator.

Table 22. Database for incidents in the A4

Incident registration										
	Starting date	Starting time	Finishing date	Finishing Time	Road	Side	From Hectometer	To Hectometer	Accident	Description
ID	Startdatum	Starttijd	Einddatum	Eindtijd	Weg	Zijde	Hmp van	Hmp tot	Proces	Beschrijving
897830	28-03-2018	15:45:57	28-03-2018	16:01:01	A4	Re	21.2	-	Ongeval	pa op vl
897830	28-03-2018	15:45:57	28-03-2018	16:01:01	A4	Re	21.2	-	Ongeval	pa op vl
897830	28-03-2018	15:45:57	28-03-2018	16:01:01	A4	Re	21.2	-	Ongeval	pa op vl
896964	27-03-2018	15:46:19	27-03-2018	15:56:17	A4	Re	20.2	-	Pechgeval	Busje

2. TRAFFIC VOLUME CARRIED

"Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society".

The I/C values of the road network are monitored by Rijkwaterstaat so the bridge assessment should not be a problem. Figure 33 shows the I/C values of a sector of the A20 and the surroundings. The databases are found in excel sheets that contain a map of the road and the I/C values in different parts of the road during the morning peak hour and during the evening peak hour. This information could be used to score the bridge according to the scale. However, the information is not updated (from 2014) and you would need to decide whether the morning or evening data are adequate since they are extreme numbers and if they are, which one is better for the calculation.

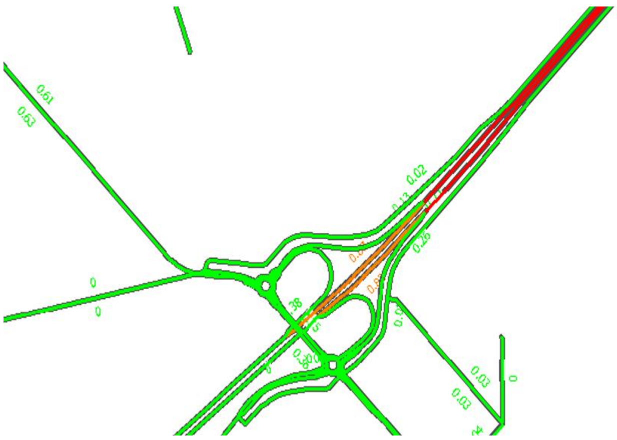

Figure 33.Morning I/C values from excel file: IC A20 Terbregseplein - kpt Gouda NRM2018 Basisjaar2014, 2014.

Although less precise, the I/C value can be also found in the Netwerkschapel (Rijkswaterstaat, 2017). In this case, the I/C value given is for the whole road. In the case of the A20, the I/C value in 2016 0.96 in both directions, with expectancies to be 0.97 (direction Gouda-Rotterdam) and 1.00 (direction Rotterdam-Gouda) in 2030 and 0.99 (lane Gouda-Rotterdam) and 1.00 (lane Rotterdam-Gouda) in 2040.

In order to assess the Traffic Volume Carried indicator, the I/C on the bridge should be determined. For the study cases, two different I/C values will be used:

1. If the road on the bridge is the A20, the I/C ratio is be retrieved from Netwerkschapel because it is the most recent data.
2. If the road on the bridge is over the A20, the I/C ratio is retrieved from the excel file (morning time) because it is the only available information.

NOTE: The I/C ratio of the roads under the bridge should be also used to assess the Bridge Geometry. They are used to know which the current condition of the other roads is. If they are at the maximum of their capacity (I/C>0.95) and there is no space for expanding due to the bridge geometry, the "Bridge Geometry" indicator will reflect the limitation and the bridge should be replaced.

3. <u>LOAD BEARING CAPACITY</u>

"Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic".

According to the information in DISK, all the bridges in the A20 between Gouda and Rotterdam are Load Class 60, which is above the current traffic weight threshold. Then, Load Bearing Capacity should not be a problem.

If more information is required, the group GPO-ICO from Rijkswaterstaat has done a research in which the load bearing capacity of bridges is studied in order to route heavy trucks in safe conditions. It was not possible to have access to that research. Anyway, for this research the Load Class 60 is enough to consider that the A20 has a perfect performance in the Load Bearing Capacity Indicator.

4. <u>BRIDGE GEOMETRY</u>

"Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service".

As defined by asset managers, the bridge dimensions are available. In this case, the access to DISK was not possible and a software called StreetSmart was used to get the measurements. This software allows a precise measurement of the height and width of the bridge, as well as the physical outside condition. Table 7 shows the measurements of the height and the width under and above the bridge.

The height dimensions can be used to assess the bridge because the maximum allowed height is currently 4 metres so if bridges are above that threshold, they should perform perfect. Furthermore, StreetSmart also allows to analyse the bridge deck and look for friction marks from truck's tops.

About the width, the road capacity should be considered. If the I/C ratio is at maximum acceptable levels, then the road will need a capacity increase. With the images, the extra space under or on the bridge can be seen and measured. Also, the bridge piles position can be detected. If there is enough space for increasing the capacity of the road without demolishing the bridge, then the bridge would have a perfect performance. To get more precise answers, traffic managers, who has more expertise on the required space for a road expansion, could be interviewed to make sure that the available width is enough.

5. MAINTENANCE HINDRANCE

"Whether and to what extent the bridge maintenance requirements influence in the bridge functional performance".

To determine the required maintenance indicator, there are two source of information that should be considered. First, the maintenance activities can be found on DISK. This will allow the user to find out what is the dimension of the maintenance activities. Second, the characteristics of the bridge, basically in terms of width or possible detour of the traffic on the other direction. This will allow the user to know what the influence of the maintenance activity on the traffic flow is. If there is enough space in the road shoulders to move the traffic, the impact will be lower than if there is no space, for example.

6. RESILIENCE TO EXTREME WEATHER EVENTS

"Whether the bridge performance is affected by floods or heavy storms".

The Netherlands, due to its low height compared to the sea level has high-risk of floods, and so does the road network. In order to ensure that the road network is safe and reliable, Rijkswaterstaat has made a study in which each bridge is analysed and the performance of the bridge under these extreme events is studied. However, in this research that information was not available. To properly evaluate the bridges, it is recommended to get that study.

An employee from the Afdeling Netwerkontwikkeling en Visie (Department of Network Development and Vision) from Rijkswaterstaat stated that the resilience to floods is not currently a problem because since the flood in 1953, a lot of dikes that protect this area have been built. However, in a few decades with the rising sea and the sinking land, the water management in the area might become a big challenge.

7. AESTHETICS

“Whether the public is satisfied with the aesthetic appearance of the bridge”.

In order to get more information about this topic, an employee from the Afdeling Netwerkontwikkeling en Visie (Department of Network Development and Vision) from Rijkswaterstaat was asked whether there is any problem about aesthetics in the A20. The answer was that currently, there is no aesthetic related problem in the A20. The aesthetic problem might happen more commonly in the countryside area in which the bridges are sometimes replaced by tunnels to reduce the visual hindrance on the natural environment. The A20 is in an urban area in which aesthetics are not considered. Then, in the assessment of bridges in the A20, the score will be “4-Perfect” in all the bridges for aesthetics.

8. NOISE EMISSIONS

“Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment”.

To get information about the noise emissions, employees from the department Bureau Sanering Verkeerslawaai (Remediation Traffic Noise Department) from Rijkswaterstaat were asked about monitored data for noise emissions. Several data bases were obtained. First, there are the called “contour maps”, in which the noise situation around motorways is shown. These “contour maps” are renewed every 5 years according to European directrices. The “contour maps” show the noise emissions in the road and the surroundings in the morning (Figure 34) and in the night (Figure 35). In these figures, it can be seen that the noise emissions on the whole A20, and therefore on the bridges, vary between 65 and 74 dB.

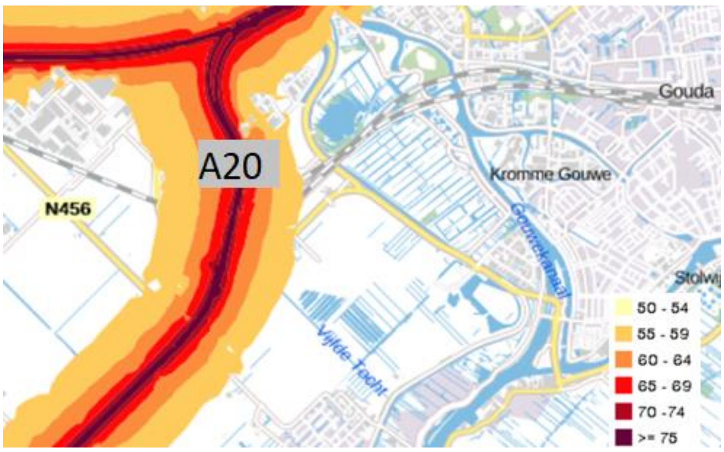

Figure 34. Noise contour A20 in the morning, 2016 (From https://www.rijkswaterstaat.nl/kaarten/geluidcontouren.aspx)

Figure 35. Noise contour A20 in the night, 2016 (From https://www.rijkswaterstaat.nl/kaarten/geluidcontouren.aspx)

Apart from the "contour maps", Rijkswaterstaat has over 60.000 virtual registration point along the whole network which are independent from the "contour maps". This data can be found in Noise Registration but the data can just be obtained from Rijkswaterstaat intranet.

Finally, the RIVM-Rijksinstituut voor Volksgezondheid en Milieu (National Institute for Health and Environment) validates the noise measurements from Rijkswaterstaat. In Figure 36, the measurements validated by RIVM in the A20 can be seen. However, there is just one measurement point, which is representative for the road. In that point, the noise emissions were above the threshold in of 69.6 dB in 2016 and in 2017.

Figure 36. Noise emissions in a reference point in A20 in Rotterdam in dB. GPM: Measured GPR: Calculated (From https://geluid.rivm.nl/app/index.php?type=r)

An expert from the RIVM was asked whether they think that the noise emissions data is suitable to evaluate the bridge performance. He thinks that it would not be a precise measure since the measuring points are not on the bridge, which has certain characteristics that require a different measurement procedure. For instance, an action plan was developed to find out how to measure the noise in the bridges (Movares Nederland B.V., 2010) but it is not considered for this research.

Anyway, in order to have an approximate value of the noise emissions, the "contour map" shows noise emissions between 65 and 74, whose mean value is 69.5 dB. That will be the assumed value for the whole A20. Bridges will be assessed considering a maximum noise emission of 69.6 dB as can be seen in Figure 36.

9. PRESENCE OF POLLUTING SUBSTANCES

> "Whether the bridge construction materials contain polluting materials that can cause a negative environmental impact".

The presence of asbestos can be found in DISK. For the case of the A20, there is not any bridge with asbestos problems (see Appendix 11).

Other dangerous substance might be the fine particles. In the Netherlands, there is a National Air Quality Cooperation Programme (NSL), that provides national, regional and local measures to meet the standards. The NSL data base is annually updated with information of the past year and an updated forecast of the coming years. The NSL has developed interactive maps (Interactive map) in which the different monitored substances and their levels can be seen. Figure 38 and Figure 37 show the interactive map. It can be seen that the fine particles are above the legal levels less than 30 days/year and the concentrations are the lowest measured (<35µg/m³). Then, the fine particles are below the legal levels in all the A20.

Figure 37. Fine particles concentrations in the A20 and surroundings. (From: https://www.nsl-monitoring.nl/viewer/)

Figure 38. Number of days/year in with a certain concentration of fine particles (From https://www.nsl-monitoring.nl/viewer/)

10. LANDSCAPE FRAGMENTATION

“Whether the bridge allows the proper fauna habitat connection between the lands divided by the road according to the regulations”.

In order to get more information about this topic, an employee from the Afdeling Netwerkontwikkeling en Visie (Department of Network Development and Vision) from Rijkswaterstaat was asked whether there is any problem about aesthetics in the A20. Similarly to the aesthetics, the urban nature of the A20 leads to no landscape fragmentation. Furthermore, it does not cause serious hindrance to the towns in the surroundings. The specialist stated that there is not any problem in this indicator in the A20.