Quantifying the Performance Age of Highway Bridges

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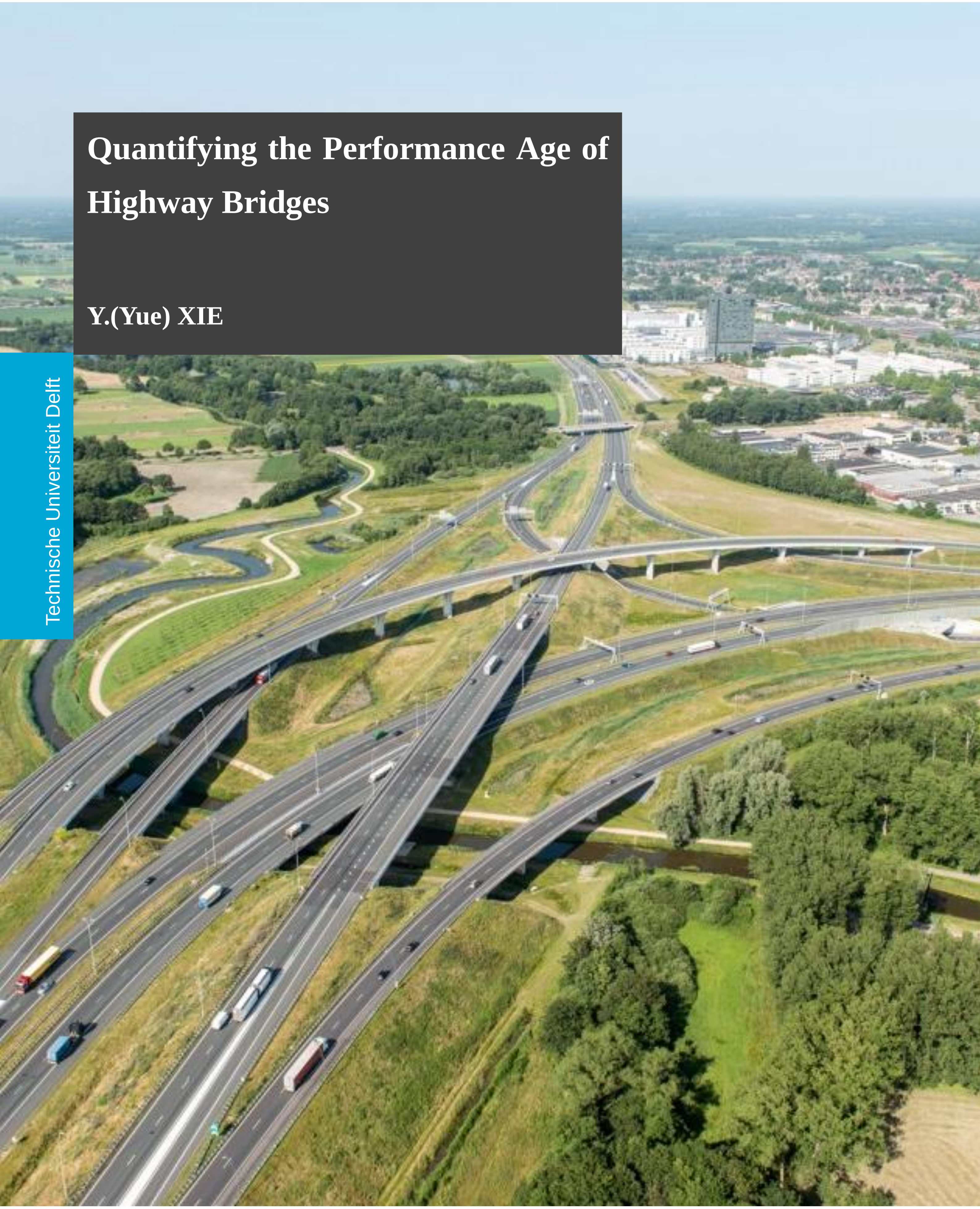

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Challenge the future

Master Thesis

Quantifying the Performance Age of Highway Bridges

By

Y.(Yue) XIE

in partial fulfilment of the requirements for the degree of

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Preface

The research is conducted as my thesis of MSc. Construction Management and Engineering in the faculty of Civil Engineering and Geoscience at Delft University of Technology, collaborating with Rijkswaterstaat, the Dutch Ministry of Infrastructure and Environment.

This research started in January 2017, which lasted for 8 months in total. The topic and scope was determined after discussing with supervisors at TU Delft and RWS. It could never be done without the guidance and support from my graduation committee members. I would like to thank Marcel, for enhancing my understanding of the societal value of this research and all the valuable feedbacks, Daan, for providing me sufficient time to discuss on my questions and very helpful feedbacks on my report whenever I need, Jafar, for introducing me the efficient and effective quantification method and the principles behind it, Jaap, for giving me an opportunity to carry out my research at RWS and organizing the workshop and everything. I really appreciate that all of you always encouraged me to execute my research in the way I expected and let me hold on my own idea. This experience has not only enabled me to conduct an academic research independently, but also made me a more persevering person.

In addition, I would also like to thank my colleagues at RWS office. Thank you all for helping me to overcome the language barrier and all the useful suggestions throughout the whole research period. I would especially thank the experts who participated the workshop in 20th June 2017. Thank you for your time and corporation. This research would not go further without your help.

Lastly, I would like to thank my family, and friends who always supported me and offered me help whenever I needed throughout the research period and my entire master study.

Y.(Yue) XIE

Delft, August 2017

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Executive Summary

With the enormous growth of population after World War Ⅱ, the Netherlands has experienced a golden era of post-war reconstruction. According to the statistics, the highway bridges construction concentrated in the 1960s and 1970s (CBS, 2016). It is discovered by Rijkswaterstaat (Dutch Ministry of Infrastructure and Environment) that the average service lifetime of demolished bridges is 80.2 years, which implies that most of the bridges ought to be replaced in the following decades. In reality, the majority of bridges were demolished as there were changes on functional requirements. To be more specific, out of 219 projects, 88,9% of them were demolished due to functional problems whereas 11,1% due to technical problems (Rijkswaterstaat Grote Projecten en Onderhoud, 2016b). In infrastructure asset management, Life Cycle Management makes significant improvements to the asset management field, which enables asset managers to optimize the value of the infrastructure over its whole life cycle (Hertogh & Bakker, 2016). Life Cycle Management contains three aspects: Life Cycle Performance, Life Cycle Cost, and Life Cycle Risk. In practice, replacement decisions are heavily relied on the experience of decision-makers. In addition, the parameters that support the decisions are mainly economic-driven. For example, the Economic End of Life Indicator (EELI) is used in Rijkswaterstaat to show whether a bridge is profitable to be maintained or not. It is defined as the ratio between (Bakker, Roebers, & Knoops, 2016):

- The life-cycle cost of maintaining a structure and replacing in a statistically expected replacement year
- The life-cycle cost of direct replacement and subsequent maintenance.

When applying EELI into making the replacement decision, decision makers compare the value of the ratio to 1. If the value is less than 1, then it is still profitable to keep maintaining the object. On the contrast, if the value exceeds than 1, then maintaining the object become meaningless considering the cost and benefits. In this case, it makes sense to assess the functional aspects to evaluate whether replacement may be more beneficial. However, a solid decision should take parameters based on performance into consideration as well. The problem statement of this research is:

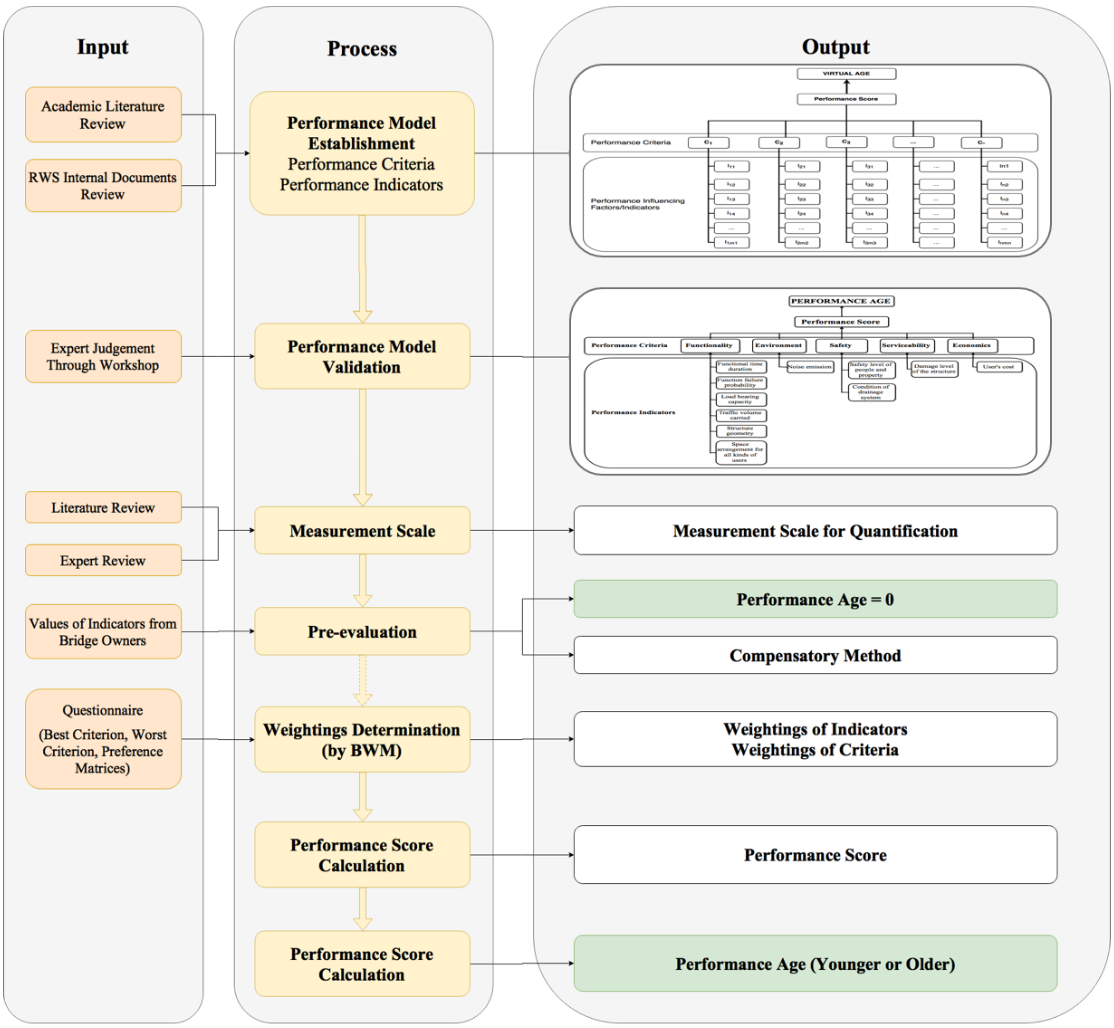
"Observations show that the highway bridge replacement decisions lack of life cycle performance basis."

In order to solve the observed problem, and to improve the efficiency and accuracy of the decisions, the objective of this research is to seek more support based on Life Cycle Performance. The main research question is formulated:

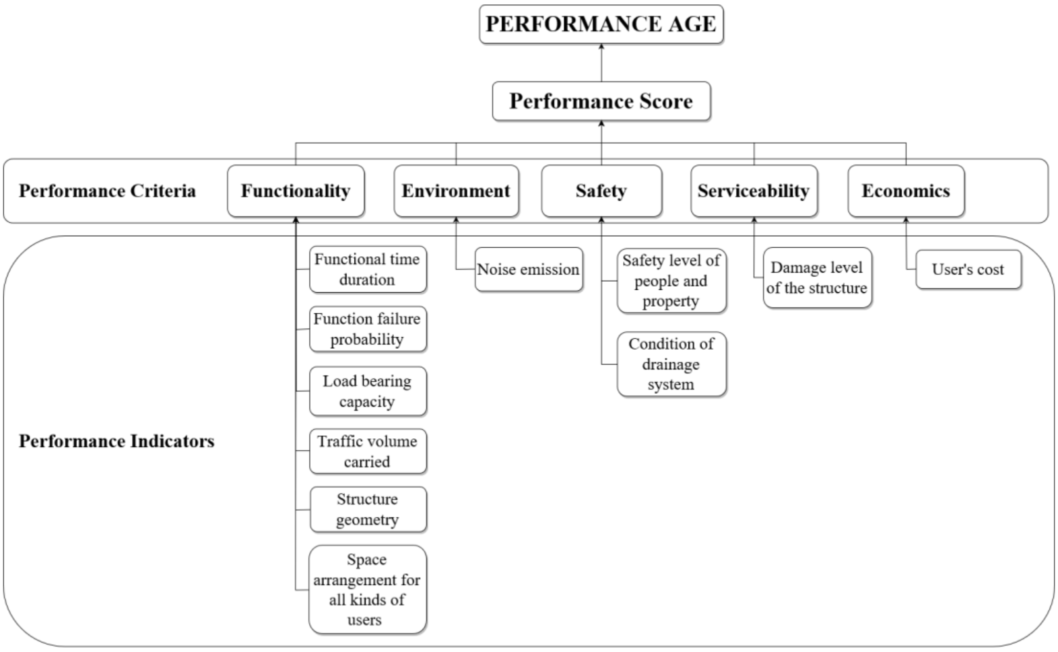
"How can the long-term parameter "Performance Age" based on life cycle performance improve replacement decisions only based on economic parameters of highway bridges?"

In order to carry out this study, a new concept "Performance Age" introduced in this research. Performance Age is the age of bridges that calculated based on its performance. Even if a bridge is already very old, it can still be regarded as a young bridge if it performs well. The research was conducted following the procedure in the figure below step by step. This procedure is regarded as a generic skeleton of quantifying the Performance Age of highway bridges with flexibilities. The concept of this procedure can be applied in the quantification of similar assets or industries.

The procedure starts with performance model establishment, as the quantification of Performance Age is considered as a Multi-Criteria Decision-Making problem, which is influenced by multi factors and interests of different stakeholders. An extensive literature review and a comprehensive RWS internal document analysis were conducted in this step. The outcome of this step is a multi-layer performance model, which includes: (1) top layer – performance age and performance score, (2) middle layer – performance criteria, (3) bottom layer – performance indicators.



With the performance model derived from academic literature and RWS internal documents, the next step is to validate the model and selecting the key performance indicators. This step aims to narrow the performance scope down to the practical level according to the preference of RWS. It was carried out through a problem-scoping workshop with contribution of expert judgement. The result is shown in the figure below, which contains 5 performance criteria and 11 performance indicators.



After the validated model is obtained, precise definition of measuring these indicators in this model is the next step. This step was expected to the contribution from experts who attended the problem-scoping workshop. However, in the practical implementation, it was done by proposing a measurement scale, and reviewed by experts. The outcome of this step is a measurement scale for indicators.

Bridge owners were asked to give values for each indicator to carry out the pre-evaluation step. This step applied the conjunctive screening theory, which requires all the indicators to meet the minimum requirements in order to tell if the bridge is already at its end of life. The bridges that were filtered out in this step were estimated to be at their end of life and require replacement as soon as possible. In the contrary, the ones that passed this filter will be delivered to the next steps that applies compensatory method.

In order to implementing compensatory method, which aims to obtain a weighted average performance score in this research. Best Worst Method (BWM) was chosen in this research. Comparing to other existing MCDM methods, BWM requires less comparison data and keeps the comparisons more consistent, thus its results are more reliable. The data was gathered through questionnaires. The data processing was carried out by a new MS Excel template developed by the author. The outcome of this step are the weightings of performance criteria and indicators.

Thereafter, the following step is to calculate the performance score, which only requires the outcome of the previous two steps. The performance score will be obtained by multiplying the weightings and scores as there is only one response. Actually in the proposed calculation step in Chapter 4, it requires contribution from a group of bridge owners.

The final step deals with the interpretation from performance score to performance age. It follows the calculation method proposed in Chapter 4 and the outcome will be an exact number of years, which implies whether the bridge is younger or older than its real age. In addition, the suggested replacement year is part of the outcome as well.

Through operating the whole process, the answer to the main research question is achieved, which includes three improvements:

- *Performance Age contains considerations on criteria and indicators from different perspectives and various interests of stakeholders, the result is more comprehensive and easier to be accepted by stakeholders.*
- *Performance Age provides a numerical prediction on the end of life of bridges in a time scale, the result is more direct and accurate.*
- *Different replacement strategies can be made based on the combinations of Performance Age and EELI, which are shown in the following table.*

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 reached the end of Performance Age	Do not replace the bridge and remain current maintenance strategies till one of the parameters reaches its limitation

Due to the limitation of the accuracy measurement scale definition of indicators, it is highly recommended that RWS can conduct a comprehensive investigation in making a precise measurement scale expressed in as much quantified description as possible. Apart from that, it is suggested that future research can focus on the relation between deterioration rate and Performance Age. In addition, expanding the decision-making to the network level is worthy to explore as well.

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CHAPTER ONE

INTRODUCTION

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1. Introduction

1.1 Introduction to Research Topic

The Netherlands has suffered heavily in the disastrous Second World War, during which the majority of the infrastructure was destroyed. Due to the rapid population growth after war, there was a great need for everything: more agriculture, factories, infrastructure and living spaces. The infrastructure projects built in the reconstruction period still serve as the skeleton of the country nowadays. However, with deterioration and degradation, they will meet the end of their service life in the following decades, requiring much effort in renovation and replacement. This brings asset managers a big challenge that they have to maintain assets properly and adapt them to future function upgrades within limited budget. With the complexity of the infrastructure network, implementing management strategies from a multi-perspective view, is of vital importance for a sustainable and competitive society.

ISO 55000 defines Asset Management as the "coordinated activity of an organisation to realize value from assets" (ISO 55000, 2013), which aims to achieve the organisational objectives by maintaining the balance between costs, risks, and performance. In traditional asset management, most asset managers just limit their focus on short-term management strategies that are applied in improving the performance and lowering the costs and risks of assets at the same time. However, many changes exist throughout the whole lifespan of assets, which contains different stages including design, construction, operation and disposal. Changes in one stage might lead to huge consequences in the balance of these three aspects in other stages. This requires the management strategies to be adaptable in a dynamic environment. In addition, the fact that many infrastructure assets come to the end of their technical or functional lifespan also stimulates the development of asset management with a life-cycle consideration. Hence, in order to fulfil the continuously changes from societal, political, economic and environmental domains, it is of necessity for the asset owners and assets managers to apply life-cycle management strategies in infrastructure assets.

Life Cycle Management (LCM) makes significant improvement to the asset management field, which enables asset managers to optimize the value of the infrastructure over its life cycle (Hertogh & Bakker, 2016). Ideally, LCM strategies should be implemented throughout the whole life cycle of assets, which starts from initiative stage, followed by the design and construction stages, and eventually the operation and disposal stages. During all these stages, asset managers are pursuing the best balance in three aspects of assets: performance, cost and risks. (Fuchs, I., Bakker, & Mante, 2014). Figure 1 shows how Life Cycle Performance (LCP), Life Cycle Cost

(LCC) and Life Cycle Risks (LCR) are overlapping and interacting with each other in a dynamic environment with developing demands.

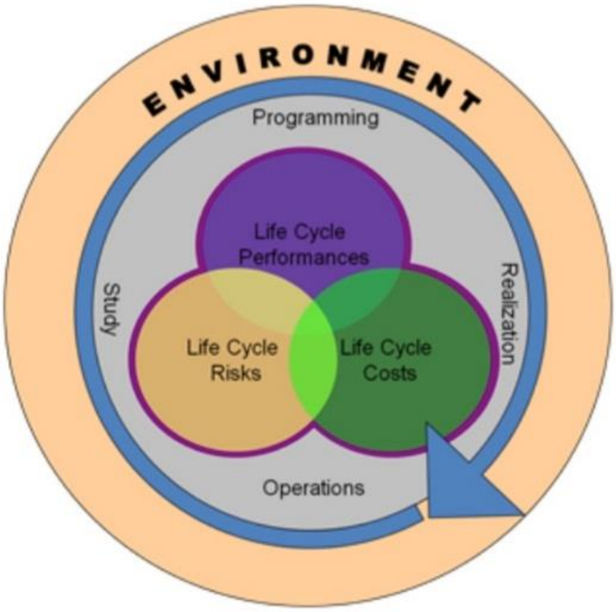

Figure 1 Three Aspects of LCM in a Dynamic Environment (Fuchs, I., Bakker, & Mante, 2014)

LCC is the analysis of cost spent in acquirement (including design and construction), operation, maintenance and disposal of assets. With the target of optimizing the value of assets within a limited budget, LCC is expected to identify all relevant costs happened in the life cycle and apply controlling strategies to ensure these costs in a reasonable range. (Hastings, 2015). In LCC, all the influencing factors are expressed in cost with time value. LCR management is the identification, assessment, prioritization and mitigation of risks. By identifying and analysing risks, the efficiency of project management process will be improved and the resources can be used more effectively (Banaitiene, 2012). Infrastructure performance is the degree to which the value of the infrastructure meets the expectations of all the stakeholders, who have different preferences. They may have diverse manners to assess performance according to peculiar indicators that reflect the requirements from their own perspective (National Research Council, 1995). The performance of infrastructure measures how effectively the objective is achieving its performance demands required by all the stakeholders. The progress of asset management strategies implementation can be easily reflected by performance assessment. It is also helpful to facilitate effective communications with stakeholders by demonstrating performance against requirements (PIARC, 2009). LCP is a rapidly emergent field in infrastructure asset management. However, in comparison with LCC and LCR analysis which all the indicators could be translated to one parameter, LCP is far more complex as it is hard to normalise indicators that are evaluated in different scales. Moreover, rather than performance measures which are location- and/or situation-specific, performance overall should be measured to reflect the objectives of all stakeholders (National Research Council, 1995), which increase its complexity.

Infrastructure ages over years, both technically and functionally, and at a certain moment structures need to be demolished or replaced, i.e. "end of life". The decision when an asset is at its end-of-life, is a human decision, affected by many rational and less rational considerations. Rijkswaterstaat (hereafter indicated as RWS), the executive agency of the Ministry of Infrastructure and the Environment, as asset manager of many aging structures, aims to quantify the replacements needs for structures in the coming decades. One parameter they have introduced is called the EELI (Economic End of Life Indicator) to reflect economic grounds to what extent the maintenance of an aging structure is still financially viable to a 1 to 1 replacement (Bakker, Roebers, & Knoops, 2016). In their Data Informatie Systeem Kunstwerken (Data Information System Structures, DISK), which they use for collecting data to support the management of structures, the risk analysis is also well-established in RAMSSHEEP framework (Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economic, Politics). Yet, as mentioned above, LCM is not limited in cost and risk but should also have performance basis in order to make the replacement decisions more accurate. Therefore, in order to find a parameter that quantifies the performance, this research aims to develop a quantification method that depends on quantitative data as much as possible.

1.2 Problem Statement

With the enormous growth of the economy and population in the Netherlands after the Second World War, the demand of urban development increased dramatically. The Netherlands has one of the densest road network in the world. The total length of the road in the Netherlands exceeded 139,000 km in 2016, which includes 5,340 km highway and most of them are managed by RWS (CBS, 2016). The network of highways became more complex and the number of structures (assets), like bridges, viaducts and tunnels, has increased as well (Verlaan & Schoenmaker, 2013). Nowadays, there are 1,023 viaducts over roadways, 1,816 viaducts in roadways, 58 movable bridges and 728 fixed bridges in the highway network. Statistics shows the bridge construction concentrated heavily in the 1960s and 1970s (Figure 2). In general, the average service life of bridges which were constructed in those periods is commonly believed to be between 60 to 80 years, thus the majority of bridges in the Netherlands will reach the end of their service life in the coming 50 years, requiring huge investments in replacement.

Infrastructures are built and operated to fulfil the basic requirements of the society.

However, those requirements are various and complicated as different stakeholders, both individuals and groups, have demands for that infrastructure should meet from their own perspective. These stakeholders are from different levels, including local, state, national, and international levels. They all make their own judgements on if the performance of the infrastructure asset has met their expectations (National Research Council, 1995). Therefore, apart from the complex of diverse social objectives, the multiplicity of stakeholders, including users and those who are affected by the asset system.

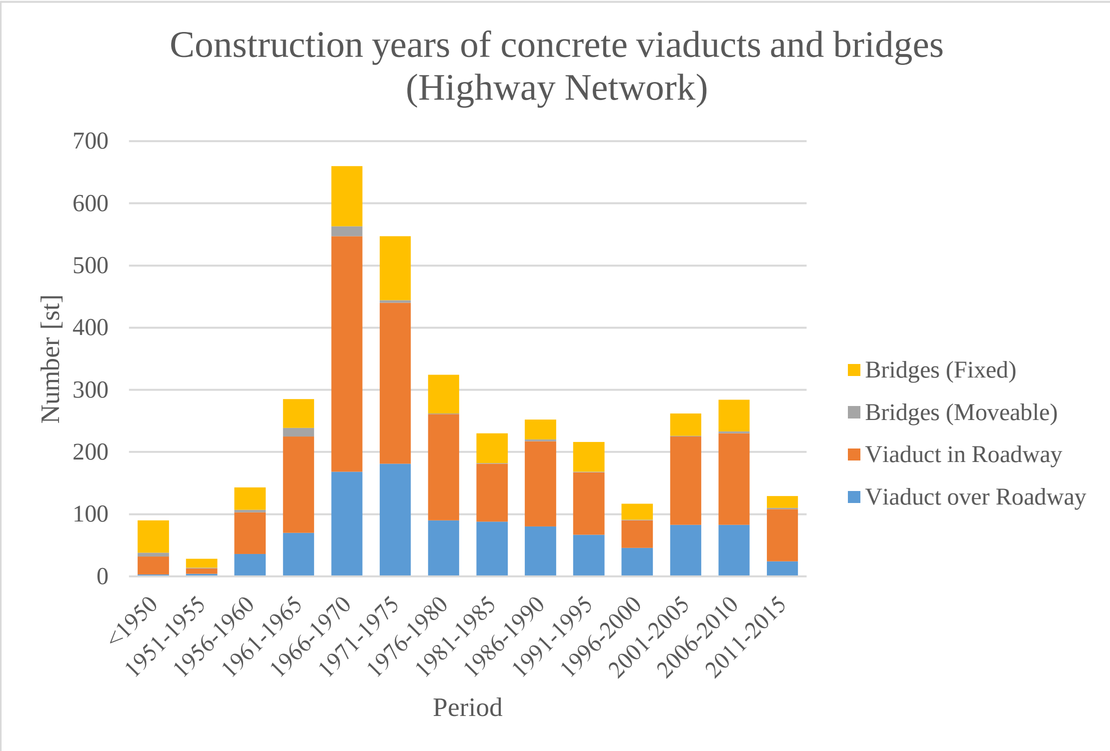

Figure 2 Construction year of concrete viaducts and bridges (Highway Network)

In asset management throughout the whole life cycle, maintenance strategies are designed and carried out to enable assets meet their required performance level. As a typical aging and deteriorating civil infrastructure, bridges need management which involves multiple-stage and multiple-discipline considerations. In addition, bridge management is supposed to be dynamic, flexible, and is used over a long period and to cover bridges within a large region. In the roadway network, when the management actions are not able to fulfil the requirements of performance and functionality of a bridge, the only way to keep the serviceability of the roadway network would be replacing the bridge. To be more specific, typical reasons of bridge replacement could be: urban development, function changes and upgrades, high maintenance costs and uncertainties, damage of superstructure, damage of substructure, insufficient load bearing capacity, improvement work, countermeasure against seismicity, and damage due to disasters, etc. In addition, from the experience of demolished bridges, only one in nine bridges was being demolished due to technical reasons. To be more specific, out of 219 projects, 88,9% of them were demolished due to functional problems whereas 11,1% due to technical problems (Rijkswaterstaat Grote Projecten en Onderhoud, 2016b). However, in the bridge replacement decision-making process, the majority of decisive parameters and indicators are economically driven and based on risk analysis. It would be more efficient and accurate if there are more life cycle performance-based parameters that support the decision-making.

Based on the abovementioned problem summary a problem statement is formulated:

“Observations show that the highway bridge replacement decisions lack of life cycle performance basis."

1.3 Research Question

As the majority of bridges would reach their end of service life in the next 50 years, many replacement decisions need be made. In order to help RWS with the replacement decision for bridges in and over highway network and the life cycle management of bridges, there is a huge necessity to figure out long-term parameters of bridges. Current long-term parameters are mainly economically or risk driven, such as EELI, which is already applied in assessing the service life of bridges and assisting the optimization process. This parameter was developed by RWS as a parameter for the “end of life” of objects. It is defined as the ratio between (Bakker, Roebers, & Knoops, 2016):

- The life-cycle cost of maintaining a structure and replacing in a statistically expected replacement year
- The life-cycle cost of direct replacement and subsequent maintenance.

EELI is a simple, powerful tool to assess the economical end of life for structures. When applying EELI into making the replacement decision, decision makers compare the value of the ratio to 1. If the value is less than 1, then it is still profitable to keep maintaining the object. On the contrast, if the value exceeds than 1, then maintaining the object become meaningless considering the cost and benefits. In this case, it makes sense to assess the functional aspects to evaluate whether replacement may be more beneficial. Concluding from the research situation discussed above, it is still not sufficient to make the replacement decision with consideration only from economic and risk viewpoints. Hence, replacement decisions require more considerations based on the performance. For broadening performance-based criteria, RWS has developed the RAMSSHEEP concept, but practical indicators for quantification of these aspects in the performance evaluation procedure still need more exploration.

Thus, the objective of this research is to develop a new life cycle parameter that measures the performance of bridges on object level but with network-thinking, which considers the functionality of bridges and their compliance in the highway system. In order to carry out this research that improves the accuracy of the decision-making, a so-called performance parameter "Performance Age" is introduced, in which all the criteria are composed into a single scale.

Based on current problems and research situation, the research question of this research is:

"How can the long-term parameter "Performance Age" based on life cycle performance improve replacement decisions only based on economic parameters of highway bridges?"

Based on the main research question and objectives, the corresponding sub-questions are listed below:

(1) What are the important long-term life cycle performance criteria and indicators of bridges?
(2) What are the key long-term life cycle performance indicators within each criterion?
(3) How are these indicators be measured and quantified in a normalised and comparable scale?
(4) How are these indicators converted to one parameter "Performance Age"?
(5) What is the difference between "Performance Age" and economic parameter?
(6) How can these differences improve the decision making?

1.4 Research Design

1.4.1 Research Scope

This part will limit this research into a certain scope, within which the research carried out. The research scope describes the certain boundaries in which the research problem to be solve should fit (Simon & Goes, 2013). There are four limiting conditions for this research to meet: 1) the targeted bridges are highway fixed concrete bridges; 2) this research is helping with the decisions only on project level, not on network level; 3) only the replacement decision is under consideration, not renovation or any others; 4) the research is only focused on the performance of bridges while risk and cost of them will not be considered.

Highway Fixed Concrete Bridge (including viaducts)

This research is focused on the fixed concrete bridges (including viaducts) in and over the highway network in the Netherlands. The choice is based on the interest of RWS for whom this research is being conducted. Highway bridges are critical road structures which are devised to enable the traffic travel over or underneath obstacles. In most cases, there is no pedestrian path as the users of highway bridges barely contain pedestrians. Instead, they are usually intended to allow the vehicles, such as passenger cars or trucks, to safely cross over or under the obstacle. Highway system is the backbone of the whole country, and bridges are vital components of the highway system. A bridge in poor condition or one that has inadequate functional capacities can cause a reduction in the operating capacity of the highway system. Moreover, poor performance often leads to moderate to severe negative influences on economics and environment, both locally and regionally, such as loss of productive time due to congestions and detours, more fuel consumption, and increased greenhouse gas emissions (Federal Highway Administration, 2014a). With the growing inventory of highway bridges, the demand of making appropriate and accurate maintenance and replacement decisions also grew. In addition, as demonstrated in Figure 2, the greatest part of highway bridges are fixed concrete ones, thus this study is focused on this kind of bridges.

At the outset of its work, it was acknowledged that focusing only on highway fixed concrete bridge would ignore other important transport modes. But limiting the scope to the highway fixed concrete bridge sector was practical, which made it possible to assemble a group of experienced practitioners to discuss and propose performance indicators for their sector.

Object level

Decision-making in highway project management is performed at two levels: the object level and network level. At the object level, a particular highway object is considered so that the optimal maintenance and rehabilitation options are selected for the object, whereas at the network level, the projects that will produce the maximum system-wide benefit are selected (Yi, 1990). It was decided to focus on bridge performance on the object level. This decision was taken because this research functions as the fundamental step from performance point of view for RWS. In this stage, this research is developed and tested for single bridges, thus it is only focused on object level. However, the network-thinking should also be held in mind as the bridge might be the bottleneck of the local or regional highway network. The performance of bridge network and replacement priority decisions will be interested to explore in the following phases of this topic.

Bridge Replacement Decisions

There are many types of decisions that can be made in object level, such as repairing, strengthening, rehabilitation, modernization, replacement, etc. Repairing aims to put the bridge into good shape or working order again by reconditioning, renovating, restoring, and correcting. However, bridge repairing concerns rather the damages of elements than the overall structure, thus it is not under consideration in this research. Strengthening is applied to increase load-carrying capacity by adding more material, additional components, and so on. This kind of decision is also not considered due to the same reason as that of repairing decisions. Rehabilitation means to restore and renew the bridge to make it suitable to requirements and put it back to good condition. Modernization in the maintenance phase usually refers to upgrading of the bridge, such as widening the bridge deck due to new traffic flow arrangement. Replacement means to substitute. Replacing a whole bridge is considered as the last resort in the process of maintaining the existing infrastructure. It is a drastic measure and possibly the costliest. Rehabilitation, modernization and replacement concern mostly the whole bridge structure. However, with the objective of predicting the end of life of the whole bridge, this research is only focused on the bridge replacement decisions.

Life Cycle Performance of Bridges

Bridge performance reflects how bridges behave under internal and external factors that that they face every day, such as the traffic volume they need to carry, rain and strong wind, freeze-thaw cycles, temperature changes, etc. Design and construction of bridges, the type and age of materials, and maintenance records have huge influences in performance as well. It is the combination of these factors – unique for each individual bridge – that governs performance of that bridge (Federal Highway Administration, 2014b). As clearly mentioned in the research introduction section, this research is conducted for the asset manager RWS, who has already developed economic-driven parameter EELI and risk analysis system. This research is focused on the life cycle performance part of bridges, which aims to fill the knowledge gap of RWS on bridge replacement decision-making. In addition to RWS's interest, it is widely acknowledged that the performance of bridges is hard to quantify as it is influenced by many soft indicators. The level of understanding of how and why bridges perform the way they do and how to improve bridge performance can be enhanced (Federal Highway Administration, 2014b). Considering these points made above, it is reasonable to limit this study on the life cycle performance of bridge.

1.4.2 Research Approach

In this part, a theoretical model is firstly introduced, which is regarded as the basis of approaching the final target of this research. Thereafter, the specific research approach is illustrated step by step, including the ways to set up the theoretical model, to quantify this model and to analyse the targeted parameter.

Theoretical Model

In reality, the performance assessment of bridges is a typical multi-objective decision-making process because it is determined by multiple factors, such as structure condition, safety, maintenance cost, which are involved in the assessment process (Yi, 1990). Thus, in order to design a methodology to assess the bridge performance, this research is carried out following the pattern of solving Multi-Criteria Decision-Making (MCDM) problems because it is mostly applicable to provide a systematic approach and to identify and quantify decision-maker and stakeholder considerations about various factors. The most common way to solve a MCDM problem is to build a model which contains all the factors that influence the target. To support the replacement decision-making process, it is essential to gather the performance criteria that decision-makers rely on. Then the inventory of influencing factors that measures those performance criteria should be figured out, refer to performance indicators in this research. Hence, a hierarchy model (Figure 3) that includes categorised performance indicators is the most suitable model to solve the question in this research.

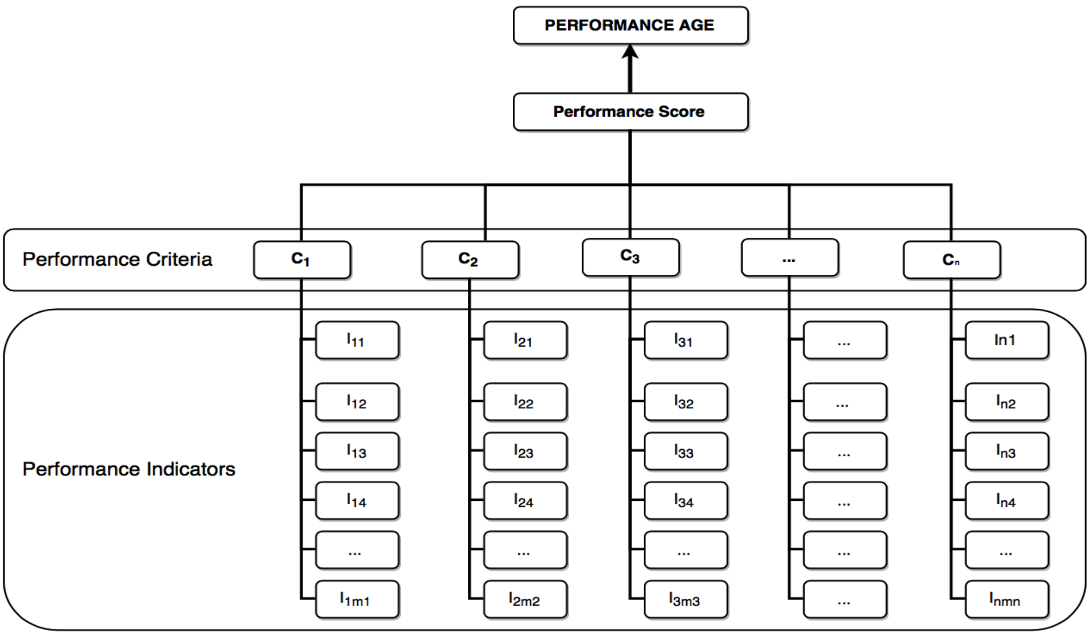

Figure 3 Theoretical performance criteria/indicators model

Research Phases

Based on the research sub-questions, this research can be divided into three phases (Figure 4), which should be carried out consecutively.

The first phase is to set up the performance criteria/indicators model. Performance criteria will be collected from academic literature and RWS internal documents. However, as there are not many document assessing bridge performance, the targeted documents will mostly be design documents. With the result of analysing these documents, the design requirements should be interpreted into performance criteria that influence the replacement decision. Similarly, performance indicators are also collected from academic literature and RWS internal documents, which will be summed up into a indicators inventory.

The second phase is to quantify the model. It is compulsory to figure out the measurement of performance indicators as they serve as the basis of the model. After that, performance score should be calculated through a MCDM method. It is ought to be translated into Performance Age this phase. Then the whole quantification methodology is complete, which will be tested in three existing bridges to check its feasibility.

The last phase is to analyse this new parameter. This is done by compare the results from Performance Age and the economic parameter EELI. Recommendations to the decision-maker and the following researches will be given in this phase.

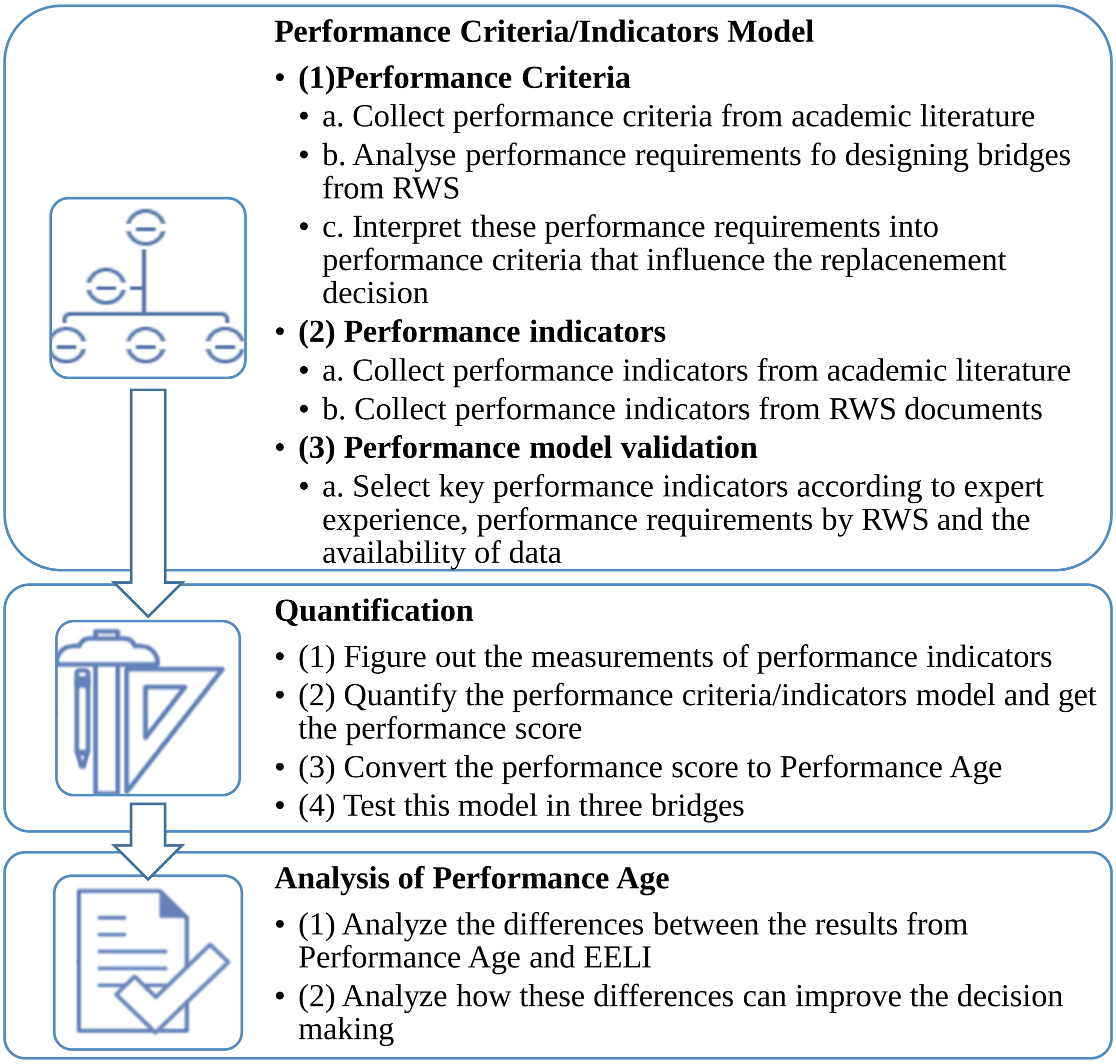

Figure 4 Research Steps

1.4.3 Research Methodology

In this section, the research methodology executed in this research is elaborated in detail. To begin with, a general review of the methods applied in each step is illustrated in Figure 5. After that, how these methods are specifically carried out in this research is explained.

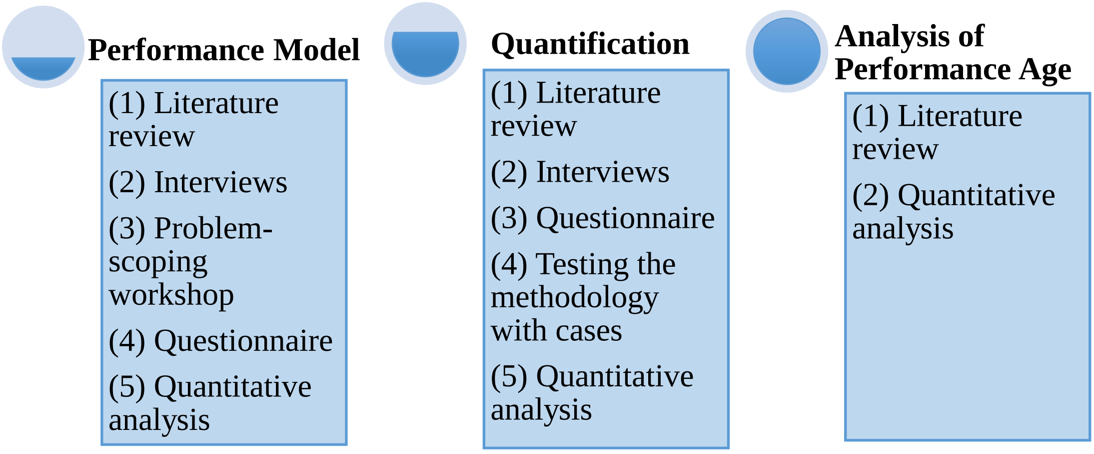

Figure 5 Research Methodology

Literature Review

A literature review is a comprehensive survey carried out in a limited range of sources, including books, academic articles, and any other documents relevant to the research issue. As a result, an extracted description and evaluation of these sources will be provided for this particular problem under research (Fink, 2005). It is the first step to get a comprehensive understanding about the current research on the evaluation of bridge performance. The performance criteria and indicators which are collected for setting up the performance model mentioned before will be achieved through this methodology. Both academic literature and internal documents of RWS will be analysed. In addition, the MCDM method used to quantify the performance model is supposed to be accomplished through literature study as well. Thus, literature study is one of the most important and basic approaches in this research and it will go through the whole research process.

Interviews

Interview is a qualitative research tool. It is intended to explore opinions and perspectives of respondents on specific issues by intensively talking with them. (Boyce & Neale, 2006). Interviews with experts in RWS will be carried out, aiming to know about the needs and concerns of RWS, in order to figure out the importance of performance criteria and key performance indicators.

Problem-scoping Workshop

Problem-solving workshops involve different parties which are invited to attend intensive and face-to-face discussions. And it aims to deliver an analysis of the problem and provide potential solutions that are feasible (Fisher, 2004). In this research, the problem to be solved in the workshop is actually to narrow down the scope of the performance model. Thus it is more precise to refer it as a problem-scoping workshop. After the performance model is set up through literature study, it should be validated by experts, and these experts should select key performance indicators as well. An problem-scoping workshop is the best way to combine the judgements from experts in a short time period.

Questionnaire

A questionnaire consists of a series of questions and other prompts in order to gather information and data from respondents. The questionnaire for selecting key performance indicators includes scaling questions – respondents are asked to rank the importance and relevance of indicators on a given scale with different values. Apart from scaling questions, the questionnaire for BWM also includes multiple choice questions – respondents are required to choose the best criterion/indicator and the worst criterion/indicator from a set of criteria/indicators.

Quantitative Analysis

Quantitative analysis investigates statistics sources by mathematical or computational tools and provide observable results (Given, 2008). In this research, the advantages and disadvantages of Performance Age will be analysed based on the results of case studies. the difference and similarities between “Performance Age” and EELI would be firstly analysed. Besides, the improvements that “Performance Age” brings to the decision-making process are also analysed based on quantitative results.

Testing the Methodology with Cases

In this research, both quantitative and qualitative data of three existing bridges are gathered to test the effectiveness of the quantification methodology. This helps to illustrate both the process and outcome of the methodology directly as this part completely operates the methodology step by step.

1.4.4 Report Structure

As can be found in Figure 6, the report is split up to 6 chapters. Chapter 1 gives a brief introduction to the research topic and defines the scope. Thereafter, in Chapter 2, a life cycle performance model of highway bridges is set up through extensive literature review and document analysis, which includes different performance criteria that influence the bridge condition. In this chapter, the sub-question 1 is answered. After that, a workshop was carried out to validate this model, this will be illustrated in Chapter 3. In this section, some key indicators are chosen, which answers the second sub-question. Chapter 1 to Chapter 3 are the outcome of the first research phase. Chapter 4 illustrates how the performance indicators are being measured and how the “Performance Age” should be calculated by MCDM method. The strengths and drawbacks of each method are also analysed in this part. Thus, the answer for both sub-question 3 and 4 can be found in this chapter. In Chapter 5, three bridges are tested in order to verify this methodology. The results of the quantification are analysed as well and how this parameter can improve the decision-making process is explained in this part. Chapter 4 and chapter 5 are the outcome of the second research phase. In the end, Chapter 6 highlights the research limitations and will conclude each research findings to eventually answer the main research question and provide recommendations to RWS, and the further research. This is the outcome of the last research phase. The relations between research sub-questions, research approach, and report structure are illustrated in Figure 6.

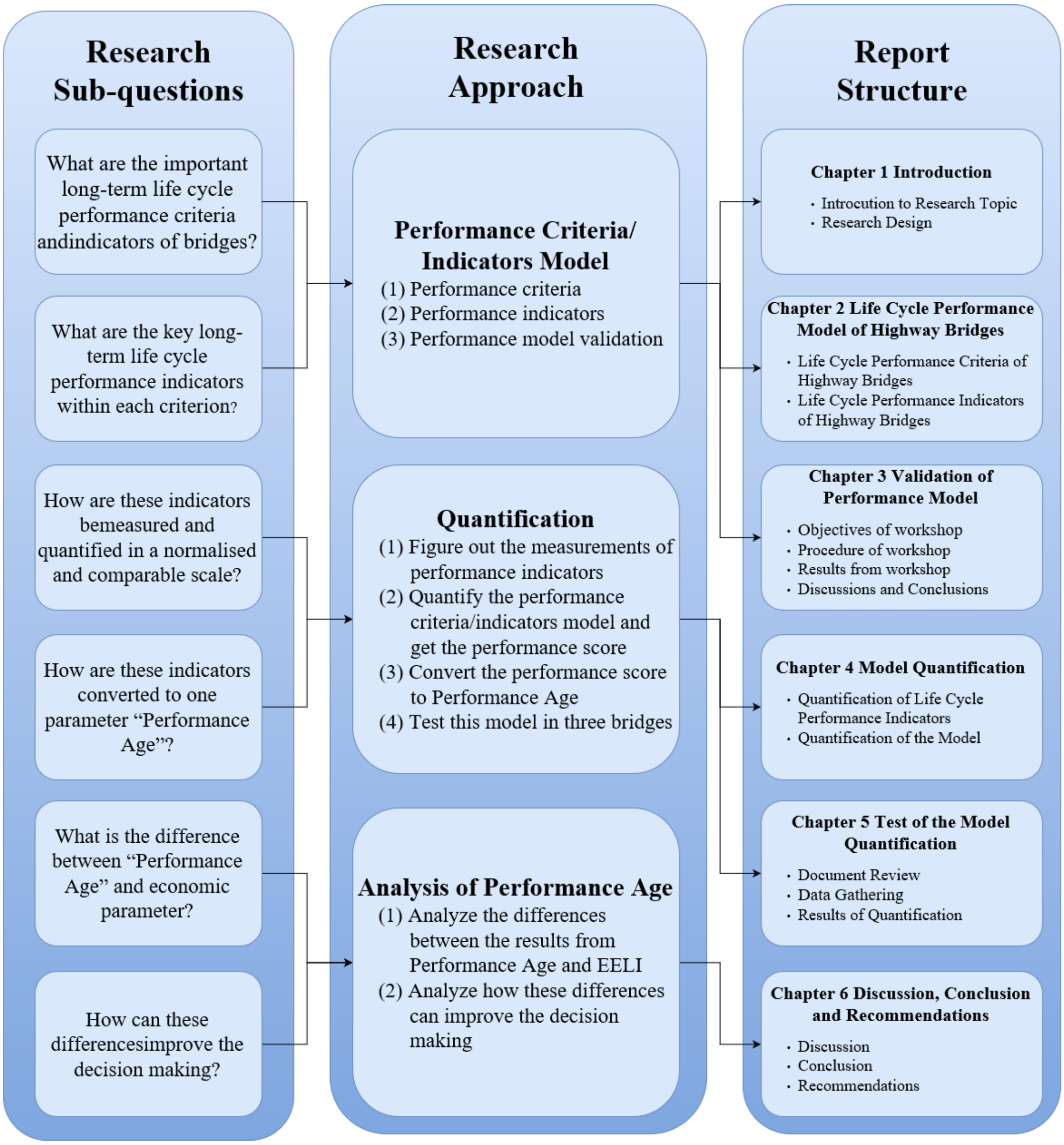

Figure 6 Report Structure

CHAPTER TWO

LIFE CYCLE PERFORMANCE MODEL OF HIGHWAY BRIDGES

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2. Life Cycle Performance Model of Highway Bridges

2.1 Introduction

In this chapter, an extensive literature review and document analysis are conducted in order to set up the life cycle performance framework of highway bridges, which is based on performance criteria and indicators of highway bridge. Firstly, the starting points and the logic of literature review are clarified in the introduction. Thereafter, the performance criteria and performance indicators of highway bridges are collected and analysed in section 2.2 and section 2.3 separately. However, in both sections, academic literature is firstly reviewed to gain a comprehensive understanding on the criteria and indicators that measure the performance of highway bridges. After that, the relevant documents from RWS are analysed in order to take the interests of RWS into consideration and enable this research to solve practical problems. The important criteria and indicators which are often considered in the existing literature and RWS documents are listed and explained, among which the relatively more important criteria will be chosen. Lastly, conclusions based on the analysis of performance criteria and indicators are made in the end of each section. which will be the input of Chapter 3. Based on an academic literature review and RWS document analysis, the research is believed to be more convincible to improve the effectiveness of the measuring tools that RWS is currently using.

2.1.1 Starting points of the literature review and document analysis

The first starting point of collecting performance criteria and indicators is based on the reasons of replacing bridges. In bridge replacement decision-making process, it is essential to know what happened to the bridge that leads to severe consequences, and under which circumstances that maintenance actions are not able to keep the bridge in service. Besides, when the bridge has different kinds of defects or functional failures. However, not all of them will lead to a replacement decision. Hence, it is necessary to grasp the defects or failures that make the bridge reach its end of life.

(Hyman, 1983) stated that estimates of bridge replacement needs are usually based on structurally deficiency or functionally obsolete. If repairs for superstructure or substructure are urgent or if the bridge is not able to carry loads and it is hard to be restored, then structurally deficiency occurred. A functionally obsolete bridge has a narrow deck, low vertical clearance, or poor alignment relative to the roadway. With the development of society, the cost-benefit is also taken into consideration when making the replacement decisions. (Klanker, Klatter, & Bakker, 2016) defined three scenarios that the bridge reaches its end of life: 1) structural reliability can no longer be guaranteed, 2) regular maintenance is insufficient to meet availability and reliability requirements, 3) the cost of necessary actions to sustain the structure are much higher than regular maintenance or replacement of the structure. All the maintenance actions are applied so that the overall performance of the structure can be maintained at a satisfying level. Structurally deficiency is mainly due to the deterioration of bridges. Bridge deterioration could bring negative influence to functional performance, for instance, lower comfort level of road user, inferior structural reliability, and higher maintenance cost (Pan, Lin, & Pan, 2009). Repairing or strengthening actions are chosen and carried out according to the severity of deterioration and its consequences. However, with a limited budget for all the bridges in one specific region, decision-makers have to think about such renovations carefully as they will spare the funds for building new bridges. (Miyamoto, Kawamura, & Nakamura, 2000). When the bridge is too costly to maintain, decision of replacing this bridge would be probably made. In addition, (van Noortwijk & Klatter, 2004) stated that the majority of bridges that were not replaced because of technical problems, but changes in functions or economical demands. Based on the viewpoints listed above, the functional changes and budget limitations take more important position in nowadays bridge replacement decisions.

The second starting point is the interests of different stakeholders. As mentioned in Chapter 1.4.2, bridge replacement decision is not only influenced by a wide range of changes in physical environment but also the interests of different stakeholders, such as the bridge owner, bridge manager and users, etc. It is also of importance to carry out the literature review and document analysis from this viewpoint. The stakeholders are basically divided into four groups: private users of bridges, commercial users of bridges, bridge service providers and policy sector. Different stakeholders have their own demands and priority of bridge performance. Both private and commercial bridge users have requirements from aspects such as comfort, safety, mobility, accessibility and etc. These demands reflect that the functionality of the bridge plays an important role in the bridge performance as bridges are constructed to provide the service to these users after all. On the other hand, all the bridge service providers including owners, investors, managers, operators, etc. should cooperate with the policy sector in order to provide efficient bridges for the users. However, bridge service providers consider more about the serviceability of the bridge, including the structural safety and reliability. Cost is also of importance to them as they need to produce the greatest benefit using the limited budget. The policy sector has more concerns on the network level, such as if the bridge functions well for the regional development. They need to make sure that the bridges should not be the bottleneck of the local area. With the analysis of different stakeholder interests, it is easier to address the criteria and indicators that contribute to the performance of bridges.

2.1.2 Outline of the considered literature and RWS documents

Based on the starting points of literature review mentioned in the previous section, the outline of considered literature and the reasons of choosing these literatures will also be explained in this section. Even though the next two sections focus on performance criteria and indicators separately as they are in different layers in the performance model, the logics of reviewing literature for both are the same.

First of all, EUROCODE (European Committee for Standardization, 2005) is analysed to figure out the most general performance criteria and indicators, as all the bridges in the Netherlands should firstly follow international guidelines. Besides, the Performance Indicators Database of an international research project COST TU 1406 Action (European Cooperation in Science and Technology, 2016), which focus on highway bridge performance evaluation is also analysed. Thereafter, literature which study the local and regional (in the Netherlands) performance evaluation system of highway bridges are analysed to achieve more precise criteria and indicators, e.g., (Klatter, van Noortwijk, & Vrisou van Eck, 2002). After that, apart from the research already done on bridges in the Netherlands, it is also helpful to broaden the literature review scope to some similar studies in other countries, e.g. (Federal Highway Administration, 2014a). If there are already mature and well-established performance evaluation systems for highway bridges in other countries, then these could be excellent references when designing the tailor-made system for highway bridges in the Netherlands. Then, it is also possible to refer to performance criteria and indicators of some similar infrastructure assets such as roads to enrich the performance model, e.g. (Haas, Felio, Lounis, & Falls, 2009). Lastly, as bridge is part of the highway network, it is necessary to have systematic thinking in measuring the bridge performance, e.g. (David T. Hartgen, 2013). Then literature about the performance of the whole system could also be analysed to help setting up the performance framework.

Regarding the RWS documents analysis part, the document *Basisspecificatie Vaste Brug (Basic specifications Fixed Bridge)* is firstly analysed in order to derive the most basic criteria and indicators of highway bridges. Then other documents mentioned in *Basisspecificatie Vaste Brug* are analysed in order to gain a more comprehensive understanding of these criteria and indicators, including *Richtlijn Ontwerp Kunstwerken (ROK) (Directive Design Structures)*, (Rijkswaterstaat Grote Projecten en Onderhoud, 2015), *Richtlijn Beoordelen Kunstwerken (RBK) (Directive Judgement Structures)* (Rijkswaterstaat, Richtlijnen Beoordeling Kunstwerken 1.1, 2013), etc.

With the consideration of bridge replacement reasons, the *document Sloopoorzaken Bruggen en Viaducten in en over Rijkswegen (Demolition of Bridges and Viaducts in and over National Roads)* (Rijkswaterstaat Grote Projecten en Onderhoud, 2016b) is analysed. Also, some supporting documents about similar infrastructure assets such as roads are analysed to improve the lists *Handboek Wegontwerp – Basiscriteria (Handbook Road Deign – Baisc Criteria)* (CROW, 2002).

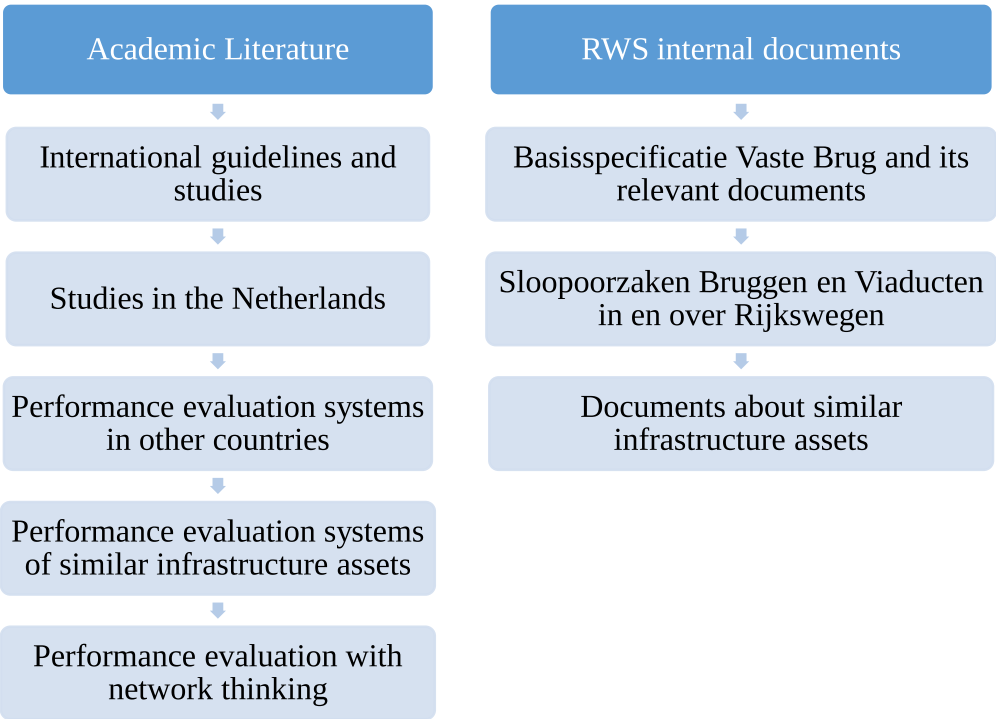

Figure 7 Literature review and document analysis logic

However, the majority of the analysed RWS documents are used for designing bridges, in which the requirements have critical impact in the construction phase. It might not be appropriate to apply some of those criteria and indicators in evaluating the performance of existing bridges directly. Thus it should be acknowledged that there is limitation that the interpretation of these criteria and indicators will need adjustments if other studies would like to apply them.

2.2 Life Cycle Performance Criteria of Highway Bridges

2.2.1 Life Cycle Performance Criteria from Literature

Performance criteria are the aspects that performance is evaluated, which are used as the basis for gathering information on the performance of the object. These are the fundamental input to a wide range of decision-making processes in infrastructure management. Different ways are used to measure bridge performance from various perspectives, and they usually involve comparison of current level of performance against some set of established standards.

In EUROCODE, the structural safety, durability and serviceability are stressed to assess the performance of bridges. (Hida, et al., 2010) pointed out that European highway agencies have three main objectives: 1) bridges should ensure the safety of all kinds of users, 2) bridges should meet the expectations on serviceability, 3) the capital investment should be optimized as much as possible.

A research project on an European basis such as COST TU 1406 Action are looking for solutions of performance evaluation of bridges, of which results contribute to this study. COST TU 1406 Action is aimed at setting up quality specifications for roadway bridges, which are on basis of well-grounded indicators. These indicators should be reasonable and acceptable on a European basis (Casas, 2016). In COST TU1406 Action, performance indicators are classified into three aspects: 1) technical indicators – express mechanical and technical behaviours, 2) sustainable indicators - environmental based indicators, 3) other indicators – economic and social driven.

This research aims to improve the bridge management in the Netherlands, thus research papers which focus on local and regional performance evaluation system of highway bridges are analysed. Reliability, Availability, Maintainability and Safety (RAMS) is defined as aspects in a performance assessment system (CENELEC, 2012). In addition to RAMS, RWS has developed a more complete concept of bridge performance aspects – RAMSSHEEP- where each criterion is defined as follows (Rijkswaterstaat, 2012):

- Reliability—indicates the failure probability of a system in which its functions cannot be fulfilled;
- Availability—indicates the time duration in which the system is functional and its functions can be fulfilled;
- Maintainability—the ease in which the system can be maintained over time;
- Safety—the absence of human injuries during using or maintaining the system;
- Security—a safe system with respect to vandalism, terrorism and human errors;
- Health—the objective argument of good health with respect to the physical, mental and societal views;
- Environment—influence of the system on its direct physical environment;
- Economics—a serious reflection in terms of costs versus benefits (direct and indirect) to provide more insight for an economical responsible choice;
- Politics—a rational decision on all the previous aspects.

In other countries, there are some existing performance evaluation systems of highway bridges, which can be good references when customizing the system for the Netherlands. For example, in USA, the highway management agency applies

Sufficiency Rating procedure to gather condition data of bridges and calculate their performance in order to acquire a numeric value that indicate the sufficiency degree to which the bridge can remain in service. It is split up into four aspects: structural adequacy and safety, serviceability and functional obsolescence, essentiality for public use, and special reductions (Tokdemir, Ayvalik, & Mohammadi, 2000). Another example would be the Australian bridge performance management system, in which the following aspects are focused (Austroads, 2009):

- Functionality—minimization of traffic delays
- Safety—safe for intended use
- Aesthetics—maintenance of an acceptable appearance
- Sustainability—no backlog of repairs, and the workload remains at a manageable level
- Economic—maintenance is based upon lifecycle cost analysis

When looking into performance management of similar infrastructure assets such as road networks, (Talvitie, 1999) pointed out that performance criteria include accessibility and mobility, traffic safety, equity and community, road program development, which can also be applied into the performance management of bridges.

Followed the reviewing logic, Table 1 provides the highly mentioned performance criteria and their distribution in literature (Appendix A.1 provides more information). The literature listed in this table is not only limited to those referred in the previous paragraphs. All the comprehensively explained and analysed separately based on reviewed literature in order to determine the critical criteria.

Availability

According to the Directive EN 50126-1 (1999), availability refers to the ability that a structure is able to perform required functions for a certain amount of time in a specific time period, assuming that all external conditions are not changeable (CENELEC, 1999). A structure will be unavailable due to planned maintenance or unplanned maintenance, which means availability is the supplement of unavailability (Wagner & van Gelder, 2013). In the COST TU1406 Action performance indicators database, the availability is mentioned as the robustness of the object, which confirmed the explanation of availability above. (Klatter, van Noortwijk, & Vrisou van Eck, 2002) proposed a criterion called accessibility that deals with the primary functions of the structure, which actually refers to availability if it is described in a quantitative way. (Hugo & Nuno, 2016) defines availability as a criterion which measures the total operating time of a bridge or a system portfolio. The findings show that availability is one of the most critical criteria of bridge performance.

Table 1 List of performance criteria from academic literature

Criteria	Short description	References
Availability	A theoretical rate of time of which a bridge is able to fulfil its function	(European Cooperation in Science and Technology, 2016) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Wagner & van Gelder, 2013) (Hugo & Nuno, 2016)
Reliability	The failure probability of a bridge occurring over a specified time interval	(Wagner & van Gelder, 2013) (Hugo & Nuno, 2016) (Hartgen, Fields, & San Jose, 2013)
Sustainability	The natural environment should be protected while enhancing the performance of bridges	(Hartgen, Fields, & San Jose, 2013)
Health	The objective argument of good health with respect to physical, mental and societal views, mainly refers to the health of inspection personnel	(Wagner & van Gelder, 2013)
Environment	the influence of the bridge on its direct physical environment	(European Cooperation in Science and Technology, 2016) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Wagner & van Gelder, 2013) (Dette & Sigrist, 2011) (Hartgen, Fields, & San Jose, 2013)
Maintainability	The ease to prevent the bridge from functional failing and to reduce the time to repair the bridge due to functional failure	(Wagner & van Gelder, 2013) (Hartgen, Fields, & San Jose, 2013)
Safety (to users)	The safety of the users (drivers, passengers) should be ensured	(European Committee for Standardization, 2005) (European Cooperation in Science and Technology, 2016) (Wagner & van Gelder, 2013) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Hartgen, Fields, & San Jose, 2013) (Federal Highway Administration, 2014a)
Aesthetics	The appearance of the object should comply with the Directives as well as the urban landscape	(Klatter, van Noortwijk, & Vrisou van Eck, 2002)
Functionality	Fulfilling the primary functions of bridges: carry loads, provide connections and space for users	(Wagner & van Gelder, 2013) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a) (Hugo & Nuno, 2016) (Humplick & Paterson, 1994)
Security	Whether the security system with respect to vandalism, terrorism and human errors is performing well	(Klatter, van Noortwijk, & Vrisou van Eck, 2002)
Economics	The economic benefit considering only indirect costs	(European Cooperation in Science and Technology, 2016) (Wagner & van Gelder, 2013) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a) (Hugo & Nuno, 2016) (Hartgen, Fields, & San Jose, 2013)
Politics	A rational decision on all the previous aspects	(Wagner & van Gelder, 2013)
Serviceability	The structural serviceability concerns about the technical performance	(European Committee for Standardization, 2005) (European Cooperation in Science and Technology, 2016) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a) (Hugo & Nuno, 2016) (Humplick & Paterson, 1994) (Hartgen, Fields, & San Jose, 2013)
Durability	A durable structure shall meet the requirements of serviceability, strength and stability throughout its intended working life	(European Committee for Standardization, 2005) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a) (Hugo & Nuno, 2016)
Comfort level	To what degree the users of the provided services are satisfied	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Humplick & Paterson, 1994)
Social & Culture	The heritage value of bridges, and the influence to people with social concerns	(Dette & Sigrist, 2011)

Reliability

Reliability is defined as the likelihood that failures occurred to the structure throughout a specified time period (Stipanovic Oslakovic, Hoj, & Klanker, 2016). The more likely a structure fails, the lower the reliability is. In other words, reliability is the supplement of unreliability (Wagner & van Gelder, 2013). Reliability describes the ability of a structure to meet identified demands (Hugo & Nuno, 2016). (Hartgen, Fields, & San Jose, 2013) mentioned the reliability of the whole system, which aims to improving efficiency of the surface transportation system. This criterion also applies to bridges as they are the critical components in the highway system, thus they also should be reliable enough. Hence, reliability is also a critical criterion.

Sustainability

The sustainability refers to environmental sustainability in most research papers, such as the one stated in (Hartgen, Fields, & San Jose, 2013), which implies protecting the natural environment while enhancing the performance of bridges. Thus it is reasonable to merge this criterion into the criteria "environment".

Health

In the health aspect, the workers of the bridge is expected to be in good health condition both physically and mentally (Wagner & van Gelder, 2013). It mainly refers to the health of inspection personnel, which is of great importance to the bridge maintenance. If the current way of inspection do harms to the health of inspection personnel, another inspection method should be found. However, it is not really relevant to the end of life of bridges, thus it is not that important. It is expected that the experts give the judgement if this criterion should play an important role in the determining performance age.

Environment

Regarding the environmental performance, (Wagner & van Gelder, 2013) regards it as the impact of the bridge to the physical environment that surrounds it. It is more specifically expressed in (Klatter, van Noortwijk, & Vrisou van Eck, 2002) that the environmental performance is mainly determined by the noise emission of the traffic. (European Cooperation in Science and Technology, 2016) measures the environmental performance by CO_2 foot-print and some other indicators. (Dette & Sigrist, 2011) also mentions environmental aspects such as greenhouse gas emission, resource consumption, waste generation, etc. Though those measurements are more suitable for construction phase, they can have positive or negative impacts on the operation phase, which also need consideration. As mentioned in the analysis of sustainability, (Hartgen, Fields, & San Jose, 2013) proposed environmental sustainability that actually concerns about environmental performance. With these evidences, the environmental performance is regarded as an important criterion.

Maintainability

The maintainability indicated if the bridge is easy to maintain and requires less time to be repaired if failures happen (Wagner & van Gelder, 2013). Maintainability is mentioned as the bridge condition in (Hartgen, Fields, & San Jose, 2013), which measures if the bridge is in a good state to be repaired. These evidence indicates that maintainability is important as it has a great influence on the functionality of bridges.

Safety (to users)

Almost in all documents and research papers, safety is a criterion which is highly mentioned. Some of the papers emphasize the structural safety such as EUROCODE and COST TU 1406 research, which is obviously critical to the object. However, more typical articles address the safety to users that not directly related to structural safety. For example, (Wagner & van Gelder, 2013) states that safety is the occurrence of human injuries in using and maintaining the bridge. (Klatter, van Noortwijk, & Vrisou van Eck, 2002) specifically pointed out that safety is related to the users in traffic actions. Then the significant reduction in fatalities and injuries can partly reflect the safety level to users (Hartgen, Fields, & San Jose, 2013). Therefore, the safety is defined as the safety to users including drivers and passengers. However, (Federal Highway Administration, 2014a) classified user safety as a part of the functionality. In this research, the safety is considered to be an independent criteria but not a part of functionality. This is determined by the definition of functionality in this study, which will be illustrated in the following analysis on functionality. But in any cases, safety is one of the most criteria that needs to be ensured, which will heavily influence the bridge replacement decisions.

Aesthetics

(Klatter, van Noortwijk, & Vrisou van Eck, 2002) mentioned aesthetics as the external design of the structure which needs to fit in the urban landscape. It is important concerning the social value of bridges, while the decision-maker would probably not replace a bridge if its appearance is not maintaining well. Hence, it is reasonable not to regard this as a decisive criterion but it can be an indicator of functionality.

Functionality

Functionality refers to the user’s benefit and it covers the indicators from aspects including availability, reliability, and maintainability. Sometimes the user safety is also partly included within this criterion. As explained in (Humplick & Paterson, 1994), functionality implies whether the performance of bridge meets its expected efficiency and whether the objectives of stakeholders are met. However, it is interesting that (Dette & Sigrist, 2011) divided the functionality of bridges into three domains including structural safety, structural serviceability and durability, which contain more technical considerations. In order to ensure the performance model can be operated as efficiently as expected, the performance criteria should be independent to each other. If there are sub-criteria such as safety in criterion functionality, the operation of the model will have a longer procedure. Hence, in this research, the functionality only refers that the bridge should meet its primary functions, including providing enough load carrying capacity, the connections and the space for users, while the safety and technical concerns are excluded. With the same concern and also the discussions about criteria availability, reliability and maintainability, which mainly concern if the bridge can function well, it is reasonable to merge these three criteria into functionality (degrade them to indicators).

Security

It is only mentioned in the RAMSSHEEP framework in the literature and is defined as whether the security system regarding vandalism, terrorism and human mistakes is performing well. (Klatter, van Noortwijk, & Vrisou van Eck, 2002) stated that the security can be merged into criterion “economics. Thus it is better to regard it as an indicator while not a separate criteria.

Economics

Basically, economics consists of two main aspects. The first part is direct costs, which comprises all costs throughout the whole life cycle of the bridge (Dette & Sigrist, 2011). This part is usually reflected by life cycle cost analysis that the owners need to consider. Another part is the indirect cost for users such as accident costs and detour and delay costs. In addition, the potential economic benefit that the bridge will bring to the regional development can be also considered in the second part. The economic performance measures the benefits versus the costs to provide more rational consideration for the replacement decision. It is supposed to be considered as an important criterion. However, the argument is that RWS is already applying EELI to assess the first part of the economic performance of bridges, which is based on life cycle cost analysis. Hence, only the second part of economic performance – indirect cost – is taken into consideration in this research.

Politics

In the Netherlands, for the medium term (2028) the main political goals concerning infrastructures is to keep the competitiveness of the Netherlands by strengthening spatial and economic infrastructure, increasing the accessibility and providing a safe environment for people for live with considerations of the nature at the same time (Stipanovic Oslakovic, Hoj, & Klanker, 2016). However, the politics criterion is only mentioned in the RAMSSHEEP framework in the literature which refers to a rational decision over all the other aspects. Actually, it concerns more about the bridge replacement on network level while not on project level, thus it is not that important in this study.

Serviceability

EUROCODE 2 (European Committee for Standardization, 2005) describes a bridge performs well in serviceability if it is managed to satisfy its intended use and service life. In order to measure the serviceability of bridge, maintenance actions, environmental conditions and their influences are taken into account. In COST TU 1406 Action Performance Indicators Database, serviceability is mentioned to be measured in respect to reliability of bridges. In other papers, serviceability are more concerns about the structural condition of the bridges. The structural serviceability is verified by indicators such as stresses in concrete and steel, crack widths, deflections and vibrations, etc. (Dette & Sigrist, 2011). As the bridge structural condition cannot be neglected when evaluating the bridge performance and making the replacement decision, this criterion is considered as a part of the performance framework to reflect the technical performance of bridges.

Durability

A durable structure should meet the expectations on serviceability, strength and stability in its service life. In addition, it should not cause significant loss or unexpected maintenance investments (European Committee for Standardization, 2005).Considering this definition, it can be merged into serviceability while not be a separate criteria.

Comfort level

The comfort level implies whether the users of the bridge is satisfied with it or not. It is mainly decided by the quality of bridge surface, which means if there are many bumps or obstacles on the bridge, then the traffic users will hardly have satisfying experience in using this bridge (Klatter, van Noortwijk, & Vrisou van Eck, 2002). Also, (Humplick & Paterson, 1994) proposed that bridge performance should measure the degree to which the users are satisfied with the provided services. Therefore, the comfort level of users could be an indicator within the social & cultural criterion discussed below.

Social & Cultural

Social and cultural performance concerns the design and heritage value of bridges (Dette & Sigrist, 2011), as well as other aspects which consider the influence of bridge performance to people and society. With the raising awareness of social and cultural performance, this criterion should be considered in the bridge replacement decision making.

In conclusion, environment, safety (to users), functionality, economics, serviceability, social & cultural are important criteria based on the analysis above. Availability, sustainability, reliability, maintainability, aesthetics, security, durability, comfort level are degraded into indicators within the six main criteria, while health and politics are suggested to be neglected in the targeted performance model.

2.2.2 Life Cycle Performance Criteria from RWS Documents

In order to see which performance criteria of highway bridges are used in practice in the Netherlands, the documents from RWS are analysed. The document *Basisspecificatie Vaste Brug (Basic Specifications Fixed Bridge)* is firstly analysed to figure out the functional requirements. This document classifies the most basic functions of bridges in the following three aspects:

- Carry loads: the bridge should be able to carry the loads required by [*Richtlijn Ontwerp Kunstwerken (ROK)*] (Directive Design Structures) and [*Richtlijn Beoordelen Kunstwerken (RBK)*] (Directive Judgement Structures), which are two directives for designing bridges. Carry loads are loads such as mobile loads (vertical and horizontal), load of the pavement, loads of components, and loads from different environmental issues (wind, snow, temperature).
- Provide space over the bridge: on the bridge, there should be sufficient space for the connection. Also, the bridge should provide enough space for all kinds of users. The bridge and all relevant components should align well with roads, such as road pavement, vehicle barrier, lights, traffic signs, traffic related support structures and other components, such as acoustic barriers, cables and pipes, space for maintenance, etc.
- Provide space under the bridge: the bridge should provide enough space for traffic which goes underneath the bridge. Also, the bridge should provide enough space for all kinds of users and all its accessories, such as road pavement, vehicle barrier, lights, traffic signs, traffic related support structures and other components, such as acoustic barriers, cables and pipes, space for maintenance, and so on. (Rijnen, 2016)

Other requirements of designing a bridge are also mentioned in *Basisspecificatie Vaste*

Brug, which can be considered as performance criteria:

- Availability: the time that the object functions in a sufficient level.
- Reliability: the object should function well and there are no fixed obstacles for the usage of different arranged space.
- Sustainability: the requirements of deterioration and damage prevention strategy.
- Ergonomics: ergonomics requirements in respect to the accessibility for inspection and maintenance.
- Health: in respect to capabilities for inspection and maintenance. The vulnerable points in maintaining the existing structures should be warned in the beginning.
- Environment: the noise emission of expansion joint should be in limited level.
- Maintenance: the object should be able to be inspected and maintained safely.
- Demolition Difficulty: it should be able to be demolished with less damages to the surroundings.
- Future Stability: there should be space for future development in this bridge
- Safety: the safety of the users should be ensured in many aspects.
- Aesthetic: the appearance of the object should comply with the Directives as well as the urban landscape.

As can be seen in the list above, the requirements of designing a bridge are not strictly following the RAMSSHEEP framework proposed by RWS. In order to better interpret these design requirements to the performance criteria that influence the replacement decisions, more relevant documents that discussed about this framework are analysed.

Objectbeheerregime Kunstwerken HWN (Object Management Regime Structures HWN) states that the requirements that a bridge needs to fulfil are categorized into RAMSSHEEP aspects, However, some of them are combined into a broader one (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a). For example, reliability, availability and maintainability are combined into functionality as they are focused on whether the object can fulfil its functions or not. The safety also addresses the user safety of the network. Security, health and environment are combined as the preconditions which enable a bridge to fulfil its functions. The economics aspect is determined by life cycle costs and politics aspects are considered as the reputation of RWS in the public and in political purpose. This document also addresses that safety and functionality are the main targets and thus determine the intended functionality of the infrastructure assets. The requirements for various functions of objects within the infrastructure network are translated into standards and guidelines that ultimately form the basis for long-term management and maintenance measures. In addition, different kinds of structures in highway network are functioning essentially the same even though the technical appearance of various structures are different to a large extent. This conclusion proof that some performance criteria and indicators from similar infrastructure assets can be partly applied to measure the bridge performance.

Hence, some of the criteria that influence the performance of the road mentioned in *Handboek Wegontwerp – Basiscriteria (Handbook Road Deign – Basic Criteria)* (CROW, 2002) could also be the ones for bridge. In this document, the criterion safety is emphasized again, which can be one of the most important life cycle performance criteria of bridges. The safety of bridge is affected by the capacity of the bridge, the intensity and density of traffic, the speed of vehicles, visibility, and the degree of integration to the network.

When it comes to the details of bridges, *Standaarddetails voor Betonnen Bruggen (Standard Details for Concrete Bridges)* provides the specific requirements of bridge components, including rainwater drainage system, vehicle barriers and handrails, shutters, grids, curb edges, etc. Requirements form different components are based on functionality, constraints, internal and external interfaces and feature demands. The aspects the requirements are classified into including the appearance (aesthetics), management and maintenance (maintainability), safety and health, availability/reliability, future stability (Rijkswaterstaat Dienst Infrastructuur, 2009).

Richtlijnen Ontwerpen Kunstwerken 1.3 (Directive Design Structures 1.3) illustrates a set of requirements for the design and implementation of new structures (Rijkswaterstaat Grote Projecten en Onderhoud, 2015). It also applied to new component of existing structures if there are replacement or extensions of these components. *Richtlijnen Beoordeling Kunstwerken 1.1 (Directive Assessment Structures 1.1)* contains guidelines and additional requirements for the assessment of existing structures in main roads and main waterways. It is intended to be used in assessing the constructive safety and usefulness of existing structures (Rijkswaterstaat, 2013). Both the directives emphasize the structural reliability and safety from technical perspective.

The summary of the performance criteria mentioned in RWS documents are listed in Table 2, more information regarding this table is given in Appendix A.2. From the analysis above, it can be concluded that functionality, environment, safety and economics are addressed again as the most important criteria in evaluating the performance of highway bridges. However, the serviceability and social & cultural is not mentioned in RWS documents. It is due to the limitations of this documents analysis which were acknowledged in section 2.1.2.

Table 2 List of performance criteria from RWS documents

Criteria	Short description	References
Availability	The time that the object functions in a sufficient level	(Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Reliability	The object should function well and there is no fixed obstacles for the usage of different arranged space	(Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2015) (Rijkswaterstaat, Richtlijnen Beoordeling Kunstwerken 1.1, 2013)
Sustainability	The requirements of deterioration and damage prevention strategy	(Rijnen, 2016)
Ergonomics	Ergonomics requirements in respect to the accessibility for inspection and maintenance	(Rijnen, 2016)
Health	In respect to capabilities for inspection and maintenance. The vulnerable points in maintaining the existing structures should be warned in the beginning	(Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Environment	The influence of the bridge to the physical environment	(Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Maintainability	The object should be able to be inspected and maintained safely	(Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Demolition Difficulty	The level of damage to the physical environment of the bridge if it should be demolished	(Rijnen, 2016)
Future Stability	There should be space for future development in the bridge	(Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Safety (to users)	The safety of the users (drivers, passengers) should be ensured	(Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (CROW, 2002) (Rijkswaterstaat Dienst Infrastructuur, 2009) (Rijkswaterstaat Grote Projecten en Onderhoud, 2015) (Rijkswaterstaat, Richtlijnen Beoordeling Kunstwerken 1.1, 2013)
Aesthetics	The appearance of the object should comply with the Directives as well as the urban landscape	(Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Functionality	Fulfilling the primary functions of the bridge	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (CROW, 2002)
Security	Whether the security system with respect to vandalism, terrorism and human errors is performing well	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Economics	The cost versus benefits	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)
Politics	A rational decision on all the previous aspects	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)

2.2.3 Conclusion on Performance Criteria

There are some mismatches between the results from academic literature and RWS internal documents, which could be found by comparing Table 1 and Table 2. Here are some discussions on these mismatches.

Regarding the reliability, it is defined as the object should function well and there is no fixed obstacles for usage of different arranged space in documents. The former part of the definition is in consistency with the findings in literature, while the latter part of it could be an indicator which concerns about the reliability of the space arrangement within functionality, as it is one of the three primary functions of bridges.

Sustainability provides bridges the requirements of deterioration and damage prevention strategy, which is actually part of the maintainability, thus it would be considered when assessing the maintainability while it would not be a separate criteria in this study. The ergonomics and health are also concerning about the feasibility of inspection and maintenance. Hence, they would also not be at the criteria level.

Demolition difficulty refers to the level of damage to physical environment of the bridge if it should be demolished, which can be concerned in the environment part as it is the influence of the bridge to the physical environment.

Future stability in documents means that there should be space for future development in the bridge, which will obviously considered in the space arrangement reliability part discussed above. Thus it is reasonable not to regard it as an independent criteria.

The economics part is focused on the cost versus benefits in documents, while referring to the discussion in the literature review part on economics, it is more clear that the economics part should concentrate on the indirect cost and economic development.

Based on the results of both reviewing academic literature and RWS documents, the distribution of performance criteria is shown in Appendix A.3.

With consideration of the distribution and discussions above, it can be concluded that the performance criteria of highway bridges which contains most of the concerns are functionality, environment, safety, serviceability, economics, and social & cultural. The model contains the performance criteria layer is illustrated in Figure X and the definitions of these six criteria are shown in the following table 3.

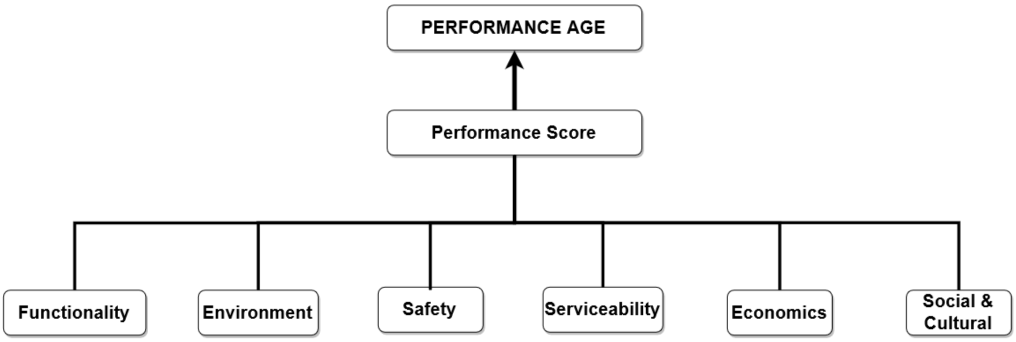

Figure 8 Performance model of highway bridges including performance criteria layer

Table 3 Description of the selected performance criteria

Functionality	The bridge should fulfil its primary functions (carry loads, provide connections and provide reasonable space)
Environment	The influence of the bridge to the physical environment
Safety	The safety of the users (drivers, passengers) should be ensured
Serviceability	The structure should be stable enough to ensure the service
Economics	The cost versus benefits
Social & Cultural	The influence of bridge to people and society

2.3 Life Cycle Performance Indicators of Highway Bridges

2.3.1 Life Cycle Performance Indicators from Literature

In order to make all the performance criteria measurable that demonstrate how effectively a bridge performs, sets of performance indicators within each criterion should be figured out. Performance indicators are measurable values that demonstrate how effectively a bridge is achieving its performance objectives in this factor. They are categorized into subsets within different criteria in accordance to their influence on the bridge performance. The indicators should, by its definition, capture the deterioration and degradation that lead to unplanned maintenance or reduce the remaining service life of bridges (Strauss, et al., 2016).

This section also follows the literature review logic mentioned in section 2.1.2. Apart from literature that contains structured system for performance evaluation, literature with separate indicators can also contribute to this performance model. It also should be mentioned that there are different statements in different literature but they basically refer to the same indicator. The interpretation of the indicators are based on the viewpoints in literature and also the author's understanding, thus there will be limitations in this study again. A general overview of performance indicators is illustrated in the following two paragraphs. Thereafter, the list of indicators is given in Table 4. More discussions on these indicators will be carried out according to the categories they are classified into. In addition, the reasons of the classification will be explained.

Performance indicators should be directly relevant to minimize the consequence of deterioration. In EUROCODE, there are different kinds of factors that affect the service life of bridges, such as thickness of the concrete cover, material quality, and the completeness of components, which reflect damage level of the structure and current conditions of materials (European Committee for Standardization, 2005). Apart from these internal factors, some external factors will lead to structural deterioration. For instance, aging of materials, changing environment, heavy traffic which affects the load bearing capacity. It is observed that the most critical factors which influences the bridge performance is the age and the average daily traffic (Caner, Yanmaz, Avsar, & Yilmaz, 2008). Due to those factors mentioned above, bridge capacities are required to be measured periodically to ensure the bridge safety (Cai & Shahawy, 2004). These factors mentioned above can be interpreted to performance indicators such as damage level of the structure, current conditions of materials, load bearing capacity, etc.

A lot of performance indicators can be found in the US Sufficiency Rating system. For example, in evaluating the functionality which includes user safety and service, indicators such as structure geometry, vertical clearance, traffic volumes are applied (Federal Highway Administration, 2014a). Other literature also mentioned these functional indicators, but expressed in different way, such as: width of deck, vertical clearance, alignment degree relative to the roadway (Hyman, 1983), truck traffic carried (Saito & Sinha, 1990), length of the structure, truck traffic volume (Beng & Matsumoto, 2012), traffic congestion, accident data, freight movement across the structure (Friedland, Ghasemi, & Chase, 2007), etc. (Klatter, van Noortwijk, & Vrisou van Eck, 2002) listed indicators such as the condition of guard rail which refers to the condition of protection components in safety domain, and aesthetics demands which means the degree of integration in the functionality domain. Another performance indicator “resilience” refers to the ability that a bridge returns to its normal condition after an extreme event (Dong & Frangopol, 2016), which includes human-made attacks (e.g. explosions), as well as natural disasters (e.g. floods, earthquakes) (Bai, Burkett, & Nash, 2006).

Table 4 List of Performance Indicators from Academic Literature

Indicators	Description	References
Functional time duration	The rate of time of which a system is able to fulfil its function	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Wagner & van Gelder, 2013) (Hugo & Nuno, 2016)
Function failure probability	The failure probability of a bridge in which its functions cannot be fulfilled	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Wagner & van Gelder, 2013)
Ease to maintain functions	The ease in which the bridge can be maintained over time	(European Cooperation in Science and Technology, 2016) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Wagner & van Gelder, 2013) (Federal Highway Administration, 2014a)
Aesthetic appearance	Whether the public satisfy with the aesthetic appearance of the bridge	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Dette & Sigrist, 2011)
Load bearing capacity	Whether the load bearing capacity can still fulfil the requirements of design and development, mainly focus on truck traffic movement (percentage of trucks)	(European Committee for Standardization, 2005) (European Cooperation in Science and Technology, 2016) (Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Dette & Sigrist, 2011),etc.
Traffic volume carried	Whether the bridge can carry the required traffic volume as required with the development of society	(European Cooperation in Science and Technology, 2016) (Federal Highway Administration, 2014a) (Hugo & Nuno, 2016) (Humplick & Paterson, 1994), etc.
Structure geometry	Concerns the width of deck, vertical and horizontal clearance, skew and alignment degree relative to the roadway	(Federal Highway Administration, 2014a)
Noise emission of expansion joints	Whether the noise emission is acceptable	(European Cooperation in Science and Technology, 2016) (Klatter, van Noortwijk, & Vrisou van Eck, 2002)
Greenhouse gas emission	The greenhouse gas emission during its life cycle	(European Cooperation in Science and Technology, 2016) (Dette & Sigrist, 2011)
Negative influence to the natural environment	The damage caused by the bridge to the natural environment considering wildlife	(Wagner & van Gelder, 2013) (David T. Hartgen, 2013)
Safety level of people and property	Whether the fatalities and injuries rate fulfil the relevant requirements	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Wagner & van Gelder, 2013) (Federal Highway Administration, 2014a) (David T. Hartgen, 2013)
Influence of extreme events	Influence of terrorist attack as well as man-made and natural disasters	(Bai, Burkett, & Nash, 2006)
Damage level of the structure	Is the damage or defects and their consequences of the bridge serious	(European Committee for Standardization, 2005) (European Cooperation in Science and Technology, 2016) (Dette & Sigrist, 2011) (Hugo & Nuno, 2016) (Federal Highway Administration,

		2014a)
Prevent deterioration mechanism	Whether the prevent deterioration mechanism is appropriate and functional for the bridge	(European Committee for Standardization, 2005) (European Cooperation in Science and Technology, 2016) (Federal Highway Administration, 2014a)
Current conditions of materials	The deterioration degree of bridge materials in different components	(European Committee for Standardization, 2005) (European Cooperation in Science and Technology, 2016) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a)
Settlement and shifting of slope paving	Settlement of mechanically stabilized earth wall Loss of protective materials and sloughing of backfill	(Federal Highway Administration, 2014a)
Utilities under structures	Corrosion of straps and hangars	(Federal Highway Administration, 2014a)
Life cycle cost	Whether the bridge is profitable with current maintenance	(European Cooperation in Science and Technology, 2016) (Wagner & van Gelder, 2013) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a) (Hugo & Nuno, 2016)
User’s cost	Including accident costs and detour and delay costs	(Wagner & van Gelder, 2013) (Dette & Sigrist, 2011) (Federal Highway Administration, 2014a)
Contribution to regional economic development	Whether and to what extent does the bridge stimulate or hinder the regional economic development	(David T. Hartgen, 2013)
Comfort level	To what degree the users are satisfied with the provided services	(Klatter, van Noortwijk, & Vrisou van Eck, 2002) (Humplick & Paterson, 1994)
Cultural value	The heritage value of bridges, and the influence to people with social concerns	(Dette & Sigrist, 2011)

All the indicators listed above are clustered into different groups according to their relations to the selected criteria. However, not all of them are considered in the performance model. That is because there are some overlapping effects or influences between some of these indicators. In order to avoid this situation, some of the indicators will be neglected. On the other hand, some indicators are combined to improve the efficiency of model operation. The reasons of all these situations mentioned above are explained for each indicator within each criterion.

Functionality

- Functional time duration: this indicator is the result of degrading availability which has been discussed in the section 2.2.1 (availability), thus it should be a critical indicator to functionality. A bridge will not be available due to planned and unplanned maintenance (Klatter, van Noortwijk, & Vrisou van Eck, 2002). It can be expressed by (Wagner & van Gelder, 2013):

  $$A = 1 - U = 1 - (U_{unpl} + U_{pl})$$

  where U_{unpl}=unavailability due to unplanned maintenance;
  and U_{pl}=unavailability due to planned maintenance.

- Function failure probability: this indicator refers to the reliability of bridges, which implies the likelihood of failures. The bridge is more reliable if there is less failures. Therefore it is critical to assess the performance of bridges and it can be expressed by (Wagner & van Gelder, 2013):

  $$R(x) = 1 - F(x)$$

  where $R(x)$=function of reliability;
  and $F(x)$=function of cumulative probability of failure.
- Ease to maintain functions: it is another way to express the maintainability, which indicates if it is easy to prevent this bridge from functional failure and the time to repair the bridge if the failures happened. Hence, it should be within functionality, and it can be assessed by the parameter Mean Time To Repair (MTTR) (Wagner & van Gelder, 2013).
- Aesthetics appearance: this indicator mainly refers to the aesthetic requirements which focus on the external appearance of the bridge. The colour and shape of the bridge are the most critical factors that measure this indicator (Klatter, van Noortwijk, & Vrisou van Eck, 2002). Another important point is that bridges are often located directly in the urban space or are seen as prestigious landmarks (Dette & Sigrist, 2011). Even though this research is focused on highway bridges, the aesthetics appearance is also of importance to the functionality.
- Load bearing capacity: this indicator is mentioned in literature in different ways. For example, (Hugo & Nuno, 2016) stated one of the performance characteristics

is delivery, thus the bridge should provide available capacity. (Federal Highway Administration, 2014a) mentioned one of the failure mode of vulnerability of bridges is overload, which implies that the bridge should be able to carry the required load to meet the satisfying performance level. This indicator is also mentioned in COST TU 1406 Action Performance Indicators Database as one of the most primary indicators of bridge performance (European Cooperation in Science and Technology, 2016). Therefore, it is very important and should obviously be included in the performance model.

- Traffic volume carried: highway bridges should be able to carry the required traffic volume in this area, which is mainly about the truck weights and frequencies (Federal Highway Administration, 2014a). It can be reflected by assessing it the number of lanes fulfil the need of usage. This indicator should be considered as an important one.
- Structure geometry: to assess the structure geometry, these factors are considered (Federal Highway Administration, 2014a): 1) width of deck – whether the width of deck; 2) vertical and horizontal clearance – whether the bridge offers enough space for the traffic that goes underneath it; 3) skew – whether the bridge is in good alignment with the connecting roadway.

In conclusion, these indicators are considered in the performance model: functional time duration, function failure probability, ease to maintain functions, aesthetics appearance, load bearing capacity, traffic volume carried, and structure geometry.

Environment

- Noise emission: it is mentioned in (Klatter, van Noortwijk, & Vrisou van Eck, 2002) that the environmental quality is decided by the noise emission of traffic. Main factors include the status of the pavement, expansion joints, and road surface. It is also mentioned in (European Cooperation in Science and Technology, 2016), where this indicator stress the noise emission of expansion joints. Therefore, it is necessary to keep this indicator.
- Greenhouse gas emission: energy usage of bridges and related greenhouse gas emission have raised a huge concern globally (Asif, Muneer, & Kelly, 2007). Environmental performance is therefore acting as an important role in assessing the overall performance of bridges (Tam, Tam, & Zeng, 2002). (Dette & Sigrist, 2011) also mentioned greenhouse gas emission as one life-cycle indicator for the environmental performance. In fact, the greenhouse gas emission is a critical environmental performance indicator in the construction phase of bridges. For the existing bridges, greenhouse gas are mainly produced by the cars which are not that relevant to the bridge itself.

- Negative influence to the natural environment: (David T. Hartgen, 2013) proposed the environmental sustainability which aims to enhance performance while protecting the natural environment. This indicator can be reflected by the bridge's negative influence to the natural environment. The natural environment can be damaged by the bridge construction in many ways. For instance, the wildlife that once thrived in the area can no longer live or survive there. Thus it is necessary to check whether the negative influence to the natural environment still meet the requirements in the design phase.

Based on the discussion above, the noise emission and the negative influence to the natural environment are considered as performance indicators under environment.

Safety

- Safety level of people and property: this indicator mentions the extent of physical risk when users are using the bridge facilities (Humplick & Paterson, 1994). It should be paid with extreme high attention as safety is always the prior concern.
- Influence of extreme disasters: there are two main sources of extreme disasters: man-made events such as explosions and natural disasters, for instance, floods and earthquakes (Bai, Burkett, & Nash, 2006). As the extreme disasters cause unplanned maintenance or replacement of components or even the whole bridge, the influence of them are actually counted in the indicator "ease to maintain functions", thus it does not have to be counted again here.

Therefore, safety level of people and property should be included in the performance model of highway bridges.

Serviceability

- Damage level of the structure: (Dette & Sigrist, 2011) proposed that the performance in terms of 'serviceability' is usually verified by indicators such as stresses in concrete and steel, crack widths, deflections and vibrations, which all reflect the damage level of the structure. It is also regarded as the basic indicator from the technical viewpoint in (European Committee for Standardization, 2005) and (European Cooperation in Science and Technology, 2016). Moreover, it can be found that different types of damages are the majority part of inspection report. Therefore, this indicator plays an important role in evaluating the serviceability.
- Prevent deterioration mechanism: preventive maintenance mechanism is mainly designed to prevent the deterioration of the structure itself. Considering the huge influence of deterioration to the bridge, this indicator should be included.
- Current condition of materials: the as-built material qualities and current conditions is one of the influencing factors of the structural serviceability (Federal

Highway Administration, 2014a). In this research, the current condition of materials would have a significant influence on the assessment of serviceability while the as-built material qualities act as the supporting factors of current condition of materials. Hence, this indicator should be included.

- Settlement and shifting of slope paving: (Federal Highway Administration, 2014a) listed this indicator and it refers to the settlement of mechanically stabilized earth wall, loss of protective materials and sloughing of backfill. However, as the three indicators discussed above are decided to be included in the performance model, this indicator can be deleted as it is actually reflected in those three indicators.
- Utilities under structures: it is also mentioned in (Federal Highway Administration, 2014a) as the degree of corrosion of straps and hangars, which is reflected by the damage level of the structure and current condition of materials. Thus it can be excluded as there is no necessity to repeat calculating the influence of indicators.

To conclude the analysis above, the damage level of the structure, prevent deterioration mechanism and current condition of materials are taken into account when setting up the performance model.

Economics

- Life cycle cost: even though this indicator is mentioned very frequently in literature, it is not considered in this research. This viewpoint has been discussed in section 2.2.1 economics.
- User's cost: the user's cost refers to the indirect cost caused by the bridge. In contrast to the owner costs, the definition of the indirect user costs by different authors shows not much consistency as they assess it from different viewpoints. For example, (Patidar, 2007) consider the indirect cost as the result of traffic accidents and delays in monetary terms, while (Lounis & Daigle, 2010) assign these aspects to social performance, which take the time loss due to reduced speed into account. With the consideration of performance evaluation, user's cost can be assessed by the accidents cost an detour and delay costs.
- Contribution to regional economic development: bridge structures interact with their surroundings in various ways. The functioning as traffic route, the structural capacity and the actual condition are the dominant for the bridge meet the mobility demands of the society. The regional economic could be positively developed with the bridge construction by providing much more communication and increasing the efficiency of transportation between the connecting areas. On the other hand, the bridge might service as a bottleneck of network between these areas if it already cannot meet the required capacity, which will hinder the regional economic development. Thus, the contribution to the regional economic

development can also be regarded as an economic performance indicator.

Hence, the two indicators – user's cost and contribution to regional economic development are considered in the performance model.

Social & Cultural

- Comfort level: this indicator deals with the degree to which the users are satisfied with the services provided by the bridge (Humplick & Paterson, 1994). It is used to express an extra user quality.
- Heritage value: historic bridges can constitute a part of the cultural heritage and hence, preservation can become an important part (Dette & Sigrist, 2011). As some of highway bridges are in international or national monument lists, they cannot be replaced even though they have really bad performance. Hence, this indicator should not be neglected.

It can be concluded that both comfort level and heritage value should be in the model.

2.3.2 Life Cycle Performance Indicators from RWS Documents

In addition to these indicators derived from academic research papers, there are also many indicators in RWS documents. This document analysis also follows the logic introduced in section 2.1.2.

In *Basisspecificatie Vaste Brug*, the requirements within each aspect can be translated into performance indicators. The functionality criterion is firstly looked into. As discussed in previous sections, the requirements from availability, reliability and maintainability aspects are suggested to be merged into functionality. There are three indicators for availability: 1) the time duration that the whole object fulfils its function; 2) the time duration that bridge components fulfil their functions; 3) the traffic which goes underneath the bridge should be ensured during construction. 1) & 2) can be concluded as the time duration that the bridge system fulfils its function, which is an important indicator. However, this research concerns existing bridge, thus 3) can be neglected. For reliability, the reliability of the space arrangement for different kinds of usages should be ensured. The requirement that the object should offer space for possible cable and pipes in the future listed in the future stability part can also be included in this indicator. Another requirement is that the bridge should be constructed reliable in compliance with the required reliability level from ROK and RBK. Again, that is not for existing bridges, so it is of no necessity to consider. Regarding maintenance, there should be safe and acceptable maintenance methods and inspection path. The components of the system with a lifetime that is less than 100 years should also be easily inspected, maintainable and replaceable. This implies the ease of maintaining its functions. Another indicator is that the anti-graffiti protection system, which mainly contributes to maintain the appearance of the bridge. However, it is already considered when assessing the aesthetic appearance, which includes the degree of integration with the urban landscape.

Within the environment criterion, only the noise emission of expansion joints is mentioned and it should be in a limited level. However, another indicator demolition difficulty can also be regarded as an indicator in this domain as it measures about the level of damage to the physical environment of the bridge if it should be demolished.

Regarding the safety to users, first of all, the object should not endanger the safety of people and property, this can be reflected by the statistic numbers about fatalities and injuries. Another indicator can be derived is the visibility, which includes the sightlines and illumination condition of the bridge. The bridge should offer good sightlines for users to see the space and the route and avoid space with poor light. Apart from that, the protection components such as security screens and handrails should be in good condition to ensure the safety. In addition, the precipitation drainage system should function well and not contain any danger to road safety, as the road is slippery if the drainage pipe is clogged, which will be dangerous for the traffic.

Apart from *Basisspecificatie Vaste Brug*, indicators can be derived from the requirements in other documents. For example, in *Objectbeheerregime Kunstwerken HWN*, one basic function of the bridge is connecting the traffic, which means moving the traffic from location from A to B. From this basic requirement, one can think about if the bridge still able to carry the traffic loadings, which could be the performance indicators in the functionality aspect. Another example could be the indicator connection maintenance that evaluates if the bridge fits in the urban development. This indicator also implies if the bridge is the bottleneck for this local network. In other words, the bridge should have enough capacity, which reflects in the load bearing capacity and number of lanes in structure geometry. Life cycle cost is also mentioned in this document as the indicator reflects the economics part. However, as discussed before, it is not being considered in this research.

Handboek Wegontwerp – Basiscriteria mentioned load bearing capacity. And the requirements about defining the location and making the drivers possible to choose the route in the network in document *Objectbeheerregime Kunstwerken HWN* confirm the indicator visibility.

The performance indicators derived from RWS design documents for bridges are listed in Table 6. These indicators are the influencing factors of different performance criteria of bridges used at RWS. In addition to this list of performance indicators, findings from individual document can be seen in Appendix A.5.

2.3.3 Conclusion on Performance Indicators

Based on the results of both reviewing academic literature and RWS documents, the distribution of performance indicators is shown in Appendix A.6. With consideration of the distribution and discussion above, the performance model of highway bridges that contains both the performance criteria layer and performance indicators layer is illustrated in Figure 8 and the descriptions are shown in the following Table 7.

Table 5 List of Performance Indicators from RWS Documents

Indicators	Description	References
Functional time duration	The time duration in which the bridge is functional and its functions can be fulfilled	(Rijnen, 2016)
Function failure probability	The failure probability of a bridge in which its functions cannot be fulfilled	(Rijnen, 2016)
Space arrangement for all kinds of users	The bridge should provide reliable space arrangement for users also for possible future development	(Rijnen, 2016)
Ease to maintain its function	The ease in which the bridge can be maintained over time	(Rijnen, 2016)
Aesthetic appearance	Whether the public satisfy with the aesthetic appearance of the bridge	(Rijnen, 2016) (CROW, 2002) (Rijkswaterstaat Dienst Infrastructuur, 2009)
Load bearing capacity	Whether the load bearing capacity can still fulfil the requirements of design and development	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (CROW, 2002)
Traffic volume carried	Whether the bridge can carry the required traffic volume as required with the development of society	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (CROW, 2002)
Connection maintenance	Whether the bridge can still maintain its connection function according to the urban development	(Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (CROW, 2002)
Noise emission of expansion joints	Whether the noise emission of expansion joints is acceptable by the environment	(Rijnen, 2016)
Demolition difficulty	The level of damage to the physical environment of the bridge if it should be demolished	(Rijnen, 2016)
Safety level of people and property	Whether the fatalities and injuries rate fulfil the relevant requirements	(Rijnen, 2016)
Visibility	Whether the bridge provides good sightlines and illumination condition for users	(Rijnen, 2016) (Rijkswaterstaat Grote Projecten en Onderhoud, 2016a) (CROW, 2002)
Condition of security screens and handrails	Whether the protection system is in good condition	(Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009) (Rijkswaterstaat Grote Projecten en Onderhoud, 2015) (Rijkswaterstaat, Richtlijnen Beoordeling Kunstwerken 1.1, 2013)
Condition of drainage system	Whether the drainage system is in good condition	(Rijnen, 2016) (Rijkswaterstaat Dienst Infrastructuur, 2009) (Rijkswaterstaat Grote Projecten en Onderhoud, 2015) (Rijkswaterstaat, Richtlijnen Beoordeling Kunstwerken 1.1, 2013)
Life cycle cost	Whether the bridge is profitable with current maintenance	(Rijkswaterstaat Grote Projecten en Onderhoud, 2016a)

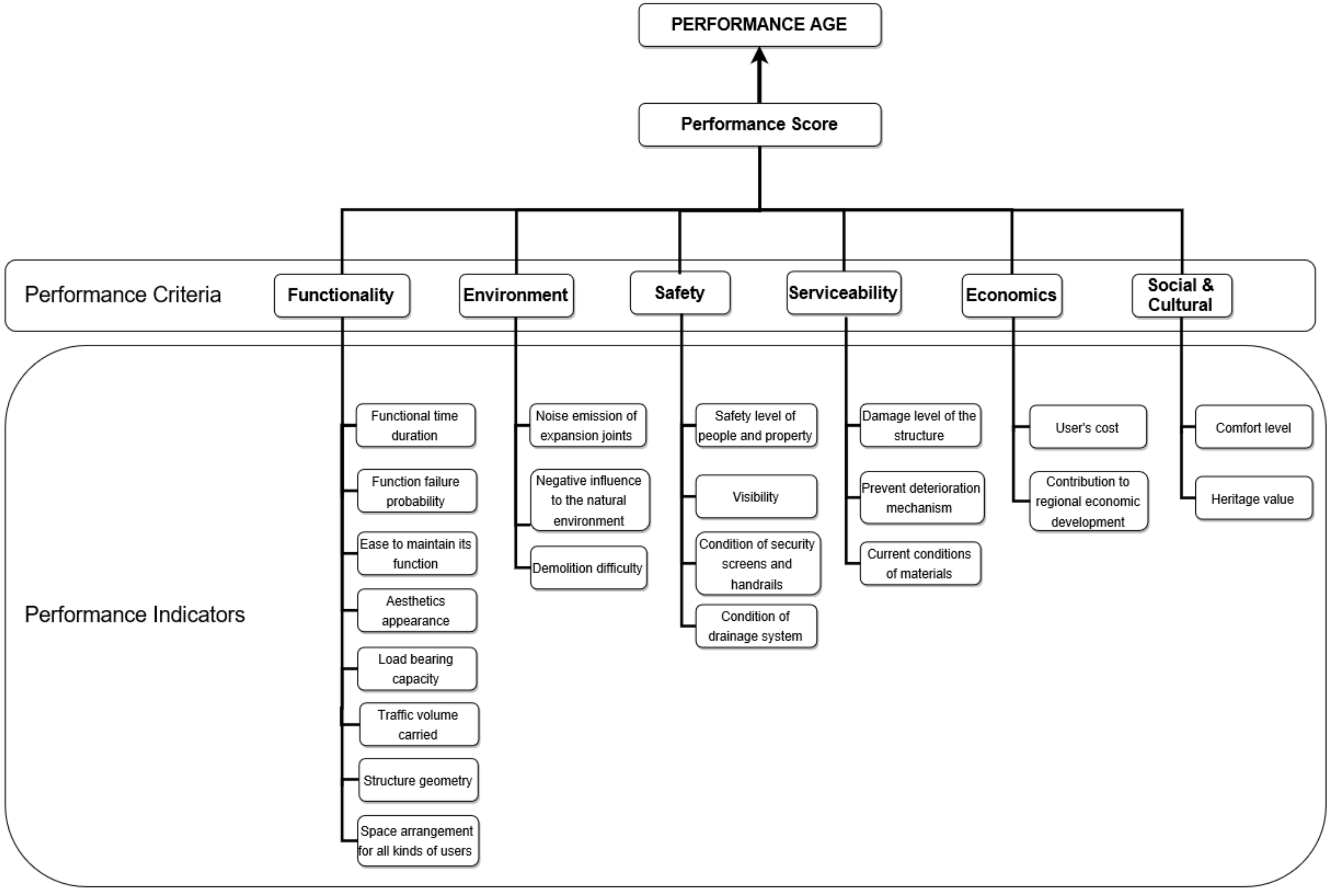

Figure 9 Performance model of highway bridges including criteria and indicators layers

Table 6 Description of performance model of highway bridges including criteria and indicators layers

Criteria	Definition	Indicators	Description
Functionality	The bridge should fulfil its primary functions (carry loads, provide connections and provide reasonable space)	Functional time duration	The time duration in which the bridge is functional and its functions can be fulfilled
		Function failure probability	The failure probability of a bridge in which its functions cannot be fulfilled
		Ease to maintain its function	The ease in which the bridge can be maintained over time
		Aesthetic appearance	Whether the public satisfy with the aesthetic appearance of the bridge
		Load bearing capacity	Whether the load bearing capacity can still fulfill the requirements of design and development
		Traffic volume carried	Whether the bridge have enough capacity to carry the traffic, reflected by the number of lanes
		Structure geometry	Physical characteristics concern the width of deck, vertical and horizontal clearance, skew and alignment degree relative to the roadway
		Space arrangement for all kinds of users	The bridge should provide reliable space arrangement for users also for possible future development
Environment	The influence of the bridge to the physical environment	Noise emission of expansion joints	Whether the noise emission of expansion joints is acceptable by the environment
		Negative influence to the natural environment	The damage caused by the bridge to the natural environment considering wildlife
		Demolition difficulty	The level of damage to the physical environment of the bridge if it should be demolished
Safety	The safety of the users (drivers, passengers) should be ensured	Safety level of people and property	Whether the fatalities and injuries rate fulfill the relevant requirements
		Visibility	Whether the bridge provides good sightlines and illumination condition for users
		Condition of security screens and handrails	Whether the protection system is in good condition
		Condition of drainage system	Whether the drainage system is in good condition
Serviceability	The structure is still stable enough to ensure the service	Damage level of the structure	Is the damage or defects and their consequences of the bridge serious
		Prevent deterioration mechanism	Whether the prevent deterioration mechanism is appropriate and functional for the bridge
		Current conditions of materials	The deterioration degree of bridge materials in different components
Economics	The costs versus benefits	User's cost	The indirect cost of the bridge in terms of economic and social influence
		Contribution to regional economic development	Whether and to what extent does the bridge stimulate or hinder the regional economic development
Social & Cultural	The influence of bridge to people and society	Comfort level	To what degree the users are satisfied with the provided services
		Heritage value	The heritage value of bridges, and the influence to people with social concerns

CHAPTER THREE

PERFORMANCE MODEL VALIDATION & INDICATORS SELECTION

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3. Performance Model Validation & Indicators Selection

Introduction

This chapter describes how the performance model is validated and how the key performance indicators are selected. Thus sub-question 2 will be answered in this chapter. The validation and selection process were carried out by a two-hour problem-scoping workshop on 20th June, 2017. In this chapter, the objectives of the workshop are illustrated firstly, followed by the workshop procedure which is split into two sections. Thereafter, the outcome of the workshop, including the irrelevant performance indicators, the key performance indicators, and the performance model after validation and selection are depicted. Lastly, discussions and arguments occurred during the workshop are recorded.

3.1 Objectives of the workshop

A problem-scoping workshop is chosen as the method to realize the validation and selection goal. First of all, there are mismatches between the findings from literature and RWS documents, while the documents did not explain the reasons behind it. Consulting experts who are working in this organisation will help understanding these mismatches. Secondly, there is no performance evaluation system or indicators inventory for highway bridges in the Netherlands in the existing literature, thus the primary performance model in Chapter 2 requires validation according to the expert's experience in order to make the model more precise. Last but not least, for the purpose of conducting this research in a limited time period, it is suggested to select a limited number of performance indicators to show how this quantification methodology works and test the effectiveness of it. And as the precise measurements of these indicators are not available in literature, it is also expected a normalised measurement scale can be provided by the experts through discussion in the workshop. Based on these points listed above, a problem-scoping workshop which lasted for two hours was organized. Nine experts who are from different departments in RWS participated this workshop.

According to the reasons listed above, the main objectives would be as following:

1) Validate the performance model in order to remove the performance indicators which are irrelevant to performance age
2) Select the performance indicators which RWS concerns as the key ones
3) Discuss and provide the precise definition of the measurement scale of performance indicators
4) Where I can achieve the information and data of these selected indicators

These objectives 1 and 2 will be achieved based on a survey carried out among the experts. These nine participants consist of experts with knowledge in one or more performance criteria. Objective 3 and 4 are expected to achieved through the discussions in the workshop.

The participants and their expertise field is shown in Table 7.

Table 7 List of Experts

Name	Expertise field
Expert 1	End of Life/Performance
Expert 2	End of Life/Performance
Expert 3	System Engineering/Highway Bridges
Expert 4	Asset Management
Expert 5	Risk Management
Expert 6	Traffic Management
Expert 7	LCC/Cost Benefit Analysis
Expert 8	Durability/Environment
Expert 9	Highway Bridges/Safety

3.2 Procedure of workshop

Based on the four objectives listed above, the workshop is divided into two sections. The first part is focused on objective 1 and 2, whereas object 3 and 4 will be achieved in the second part. The workshop is designed to follow the following schedule:

11:00 – 11:10 Section 1 -- Introduction of participants
11:10 – 11:20 Section 1 -- A short presentation on this study
11:20 – 11:40 Section 1 – Fill in the workshop questionnaire
11:40 – 12:10 Lunch (Calculate the survey result and list the selected indicators for the following discussion)
12:10 – 13:00 Section 2 -- Discussion over the measurements of selected indicators

Section 1 begins with the introduction of all the experts. Thereafter, a brief introduction to the research topic is given to enhance the experts' understanding on this study, including the reasons of carrying out the research, the research approach, how the performance model was achieved and how it would be quantified. The objectives of the workshop are also specifically explained in this section. After this, the survey to select key performance indicators is conducted. In this step, all the experts are asked to fill out a questionnaire which requires them to classify the indicators to five categories according to their relevance in a Likert scale (one of the answer is shown as an example in Appendix B). The definition of the scale is shown below (Wade, 2006):

5 – Dominant

4 – Important

3 – Neutral

2 – Not important

1 – Not relevant

The relevance score will be calculated by Equation (1):

$$Relevance\ Score = \sum N_e \times V_r$$

Where,

N_e is the number of experts who choose these relevance level,

V_r is the relevance value Defined in the Likert scale above.

As there are 9 experts in total, thus the highest score an indicator can get would be 45. In this research, we set 30 as the threshold whether the indicator is a key indicator or not, which implies two thirds of the experts think they are at the dominant position.

The questionnaire will give the result of irrelevant performance indicators at the same time. In fact, it is hard to set a threshold for the irrelevant indicators. This is because that the Likert scale contains four options which imply the indicator is relevant to performance age but in different level, while only one option which states the indicator is not relevant. Then if we divide the five options into two categories, relevant and irrelevant, then the chances of choosing relevant and irrelevant will be 0.8 and 0.2 separately. Therefore, it is reasonable to say that one indicator is irrelevant if more than 2 (9*0.2=1.8 rounded to 2) experts think it is not relevant. During the lunch time, the results of the questionnaire will be calculated and the selected indicators will be discussed in the next section.

In section 2, experts will be divided into small groups to have discussions over the selected indicators that they are in their expertise field. The measurement of functional time duration is given as an example of the expected outcome format.

Likert scale	Likert definition	Precise definition	
5	Extremely good (desirable condition)	95% of the time in a time interval (one year), the bridge is available	Acceptable
4	Good	90% of the time in a time interval (one year), the bridge is available	
3	Average	85% of the time in a time interval (one year), the bridge is available	
			Cut-off Value
2	Poor	80% of the time in a time interval (one year), the bridge is available	Unacceptable
1	Extremely poor	75% of the time in a time interval (one year), the bridge is available	

Figure 10 Measurement Scale Example Given in the Workshop

3.3 Result of workshop

With the limitation of time, the overall result of the workshop is given in Table 8.

Table 8 Overall Result of Workshop

Steps	Results
11:00 – 11:10 Introduction of participants	As scheduled
11:10 – 11:20 A short presentation on this study	As scheduled
11:20 – 11:40 Fill in the workshop questionnaire	Delayed
11:40 – 12:10 Lunch	Delayed
12:10 – 13:00 Discussion over the measurements of selected indicators	Homework

The expected procedure got delayed since the questionnaire session. This is because that all the indicators in Table 6 were asked to be explained one by one to avoid confusion and misunderstanding. In addition, many discussions and questions on this list of indicators that were not expected will be elaborated in the following paragraphs. The overall scores of indicators are illustrated in Table 9, which implies that there are 11 key performance indicators (in green) and 2 irrelevant ones (in red).

As shown in Table 9, demolition difficulty is considered as an irrelevant indicator. Demolition is to deconstruct the targeted structure systematically without unplanned potential energy release (Barsottelli & Arci, 2013). Demolition process of highway bridges requires a combined investment of much engineering analysis, accurate machine operation, and a reasonable budget. In fact, the demolition process requires much more engineering analysis than that for initial construction. The highway network in the area where a bridge is demolished might loss its primary function – providing connections and accessibility. In addition, the waste from demolition will cause more or less unwanted consequence to the surrounding physical environment. However, some experts addressed that the target of this study is to develop a quantification methodology for Performance Age. Decision-makers will take the demolition difficulty into consideration when they choose whether to replace the bridge or not. But whether the difficulty of demolishing a bridge would not have influence on Performance Age itself. Hence, demolition difficulty should be removed from this model.

Another irrelevant indicator is heritage value. There are international list and national list of monuments and structures with high heritage value. Even though not many highway bridges are included in those lists, the heritage value is also under consideration when determining whether to replace a bridge or not. In fact, the heritage value is a benchmark that decides if the asset manager can replace this bridge or not. In other words, if the bridge is a monument, then it cannot be replaced even though it is unacceptable in every criteria, which brings both the asset manager and regulators a dilemma. Therefore, heritage value of highway bridges is out of the indicators list in this research as it does not influence the performance age, neither.

The indicator “noise emission of expansion joints” should be changed to “noise emission” as there are more components in bridges that will produce noise. Thus noise emission should be limited to that of expansion joints even though they are the main sources of noise. This change was approved by all the experts.

Some experts pointed out that safety should be prior than any other criteria and it cannot be compensated by others. Only when the safety requirements are fulfilled, other criteria will be on the stage. However, other experts consider that it gets the priority during the design and maintenance but it can be compensated when assessing the Performance Age. That is because Performance Age is focused on comparing current safety level to the desirable level, which is the same as how other criteria are assessed. Hence, safety is still kept at the same level as other criteria.

Within safety, the criteria “condition of drainage system” is regarded as a key indicator with consideration of climatic influences to highway bridges. The percentage of rainy days is really high in the Netherlands, hence the performance requirements of drainage system would be more strict. It might not be an important indicator in other countries or areas.

Table 9 Result of Workshop Questionnaire

Scales / Indicators	Dominant	Important	Neutral	Not important	Not relevant	Score
	5	4	3	2	1	
Functional time duration	5	4	0	0	0	41
Function failure probability	6	2	1	0	0	41
Ease to maintain its function	2	2	2	2	1	29
Aesthetic appearance	0	1	6	1	1	25
Load bearing capacity	4	5	0	0	0	40
Traffic volume carried	2	5	1	1	0	35
Structure geometry	1	6	1	0	1	33
Space arrangement for all kinds of users	1	3	4	1	0	31
Noise emission	0	6	3	0	0	33
Negative influence to the natural environment	0	3	2	4	0	26
Demolition difficulty	0	2	2	2	3	21
Safety level of people and property	6	2	1	0	0	41
Visibility	1	4	2	1	1	30

Condition of security screens and handrails	2	2	3	1	1	30
Condition of drainage system	1	3	4	1	0	31
Damage level of the structure	2	3	2	1	1	31
Prevent deterioration mechanism	0	4	3	1	1	28
Current conditions of materials	0	5	2	1	1	29
User's cost	1	4	3	1	0	32
Contribution to regional economic development	1	4	2	1	1	30
Comfort level	0	2	5	1	1	26
Heritage value	0	2	2	0	5	19

As there is no time left for the discussion part, all the participated experts were asked to fill in a form which contains the reference definition of the measurement scale. They are expected to fill in this form according to the reference (by changing the red words into precise value of the indicator) in order to normalise the measurements for different indicators. However, they are also free to give their own proposed definition. The result of this homework is given in Chapter 4, section 4.1.

Table 10 Measurement Scale (Homework from Workshop)

Score	Level	Reference Definition	Your Proposed Definition
5	Extremely good	This is the most desirable performance: The condition of the bridge designed with a lifespan of 80 years	
4	Good	The performance of bridge is sufficient to fulfil the current requirements. Future (expected) changing performance requirements can only be achieved by adjusting the object.	
3	Average	The performance of bridge is on an acceptable level, but the it is no longer what you would like now. It does not create any bottleneck or limitation regarding the relevant criteria in current use.	
2	Poor	Fails to meet the agreed performance (object specific or policy) regarding the criteria, but it is not urgent to replace it as it does not have unwanted consequence.	
1	Extremely poor	Fails to meet the agreed performance and it leads to unwanted consequence.	

3.4 Discussions and Conclusion

Thinking about why the result did not turned to be what it was supposed to be, there are two main reasons contributed to it. The first one is that the author did not prepare a time period for the questions and discussions on the listed indicators. Even though it is written down in the workshop invitation email that the experts should at least read Figure 9 and Table 6 before the workshop, the effectiveness of this request was not as expected at all. Hence, it is recommended to give at least 20 minutes for this part in the workshop design. The second reason is that the calculation of the questionnaire result should be shortened under the circumstance when delays happen. However, the questionnaire was designed before the workshop without expectations of delays. And it is in hard copy, thus it takes more time to count the numbers. An online questionnaire is recommended if similar workshop should be carried out. In addition, it is suggested not to arrange workshop when lunch time is included. The workshop in this study had to be scheduled from 11:00 to 13:00 as there was no other options.

According to the result, the performance model after validation and selection is shown in Figure 9. As can be seen, the criteria "Social & Cultural" is not in this model as all the indicators within this criteria are not considered as key ones. Key indicators are: functional time duration, function failure probability, load bearing capacity, traffic volume carried, structure geometry, space arrangements for all kinds of users, noise emission, safety level of people and property, condition of drainage system, damage level of the structure, and user's cost. This model will be applied in the quantification process, which is the input of Chapter 4.

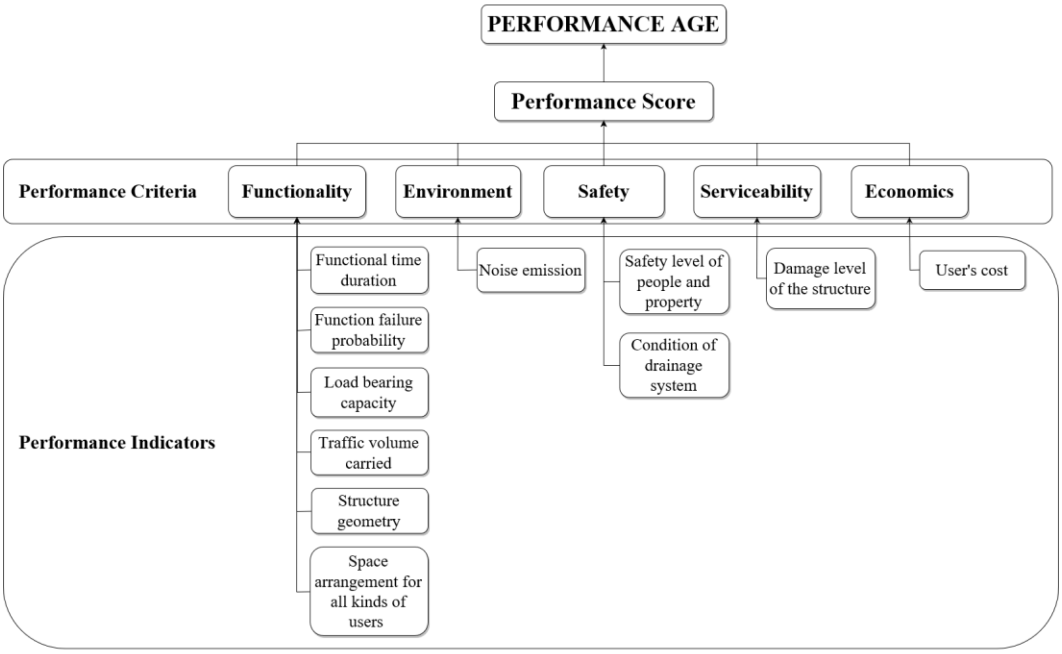

Figure 11 Validated Performance Model

CHAPTER FOUR

QUANTIFICATION METHODOLOGY

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4. Quantification Methodology

Introduction

Based on the performance criteria/indicators model which is obtained from the literature review, document analysis in Chapter 2, expert's validation and indicators selection in Chapter 3, this chapter is focused on the methodology which is applied in quantifying the model. The measurement scale of performance indicators is discussed in the first section. In this section, an overview about the measurements of performance indicators is firstly given, followed by the approach to determine the precise definition of measurements for all the key performance indicators in this research. Thereafter the result is given. After that, the second part illustrates the method used for quantifying the performance model step by step. In this part, the requirements of the quantification method are firstly explained in order to show the reason of choosing this method. Next, the underlying theory, Multi-Criteria Decision-Making theory, is introduced, followed by the chosen method, conjunctive screening and Best-Worst-Method. The inputs, outcomes, data collection and data processing are presented. A Microsoft Excel Program based on Visual Basic for Applications is designed to operate the calculation of the methodology, which enables us to operate all the calculations within several steps in one platform. In the end, the last part presents the results of quantification.

4.1 Measurement Scales of Life Cycle Performance Indicators

In this part, the quantification process of performance indicators will be discussed. In the performance model, all the indicators can be basically divided into two categories: quantitative and qualitative. Quantitative indicators could be expressed in a pure number, an index, ratio or a percentage expressed in specific term, whereas Likert scales and thresholds are commonly used to quantify soft qualitative indicators. One typical example of expressing quantitative indicators could be found in (Haas, Felio, Lounis, & Falls, 2009), where the "mobility and speed" (can be regarded as accessibility) is assessed by delays, congestion rate, average travel speed, closures and detours. And the indicator "safety level of people and property" is measure by injury/fatality rate. Another example is that the reliability of a bridge can be assessed by a percentage, which refers to the likelihood of failure (van Noortwijk & Klatter, 2004). However, indicators such as the "comfort level of users" which can be reflected by the road smoothness, could be measured in Likert scale.

In order to ensure all the indicators are measurable and comparable, all of them should be normalized, which means they should be expressed in the same scale in the end. In addition, the majority of the measurements for performance indicators are expressed in scores, the time-based measurements are barely found. Thus, it is more convenient and efficient if a performance score is firstly calculated and then translated into a performance age.

In the US Federal Sufficiency Rating system, indicators within technical and functional aspects are expressed in Likert scale 1~9 (N) and 0~9 separately, which provides a typical example of normalizing the scores of different indicators. In the technical aspect, it is expressed by the severity level of problems, e.g. 6 – satisfactory condition (structural elements show some minor deterioration). In the functional aspect, it is assessed by comparing the current condition to the different types of requirements, such as desirable requirement, minimum requirement (Federal Highway Administration, 2014a).

Similar to the US Federal Sufficiency Rating System, in this research, Likert scale measurement could be suitable to assess the qualitative indicators directly, while the measurements for evaluating quantitative indicators can be converted to Likert scale (i.e. 1~5) by Equation (2):

$$S = \frac{Current\ conditon}{Perfect\ condition} \times 5$$

Where,
Current condition is the current status of the bridge,
Perfect condition is the desirable condition of a new bridge (design life is 80 years) at the same location.

As mentioned in section 3.3, the precise definition of measurement scales was left as an assignment to experts. However, the assignment did not work as effective as expected. There are three main reasons:

1) Experts gave the feedback that the definitions of some indicators are not precise or clear enough to them, thus it is hard for them to figure out the best way to assess these indicators. Some responses are still vague and not able to be applied in measuring the indicators. For example, one expert provided the definition for functional time duration measurement as following:
   5 – extremely good (the value is 98-100% of the initial value)
   4 – good (the value is 95-98% of the initial value)
   3 – average (the value is 90-95% of the initial value)
   2 – poor (the value is lower than 90% of the initial value)
   1 – extremely poor (the value is lower than 90% of the initial value)
   From this example, it is still hard to measure the functional time duration as the

"initial value" is not clear. In addition, there is no difference between the definitions of "poor" and "extremely poor".

2) Different experts have various opinions on these indicators, which increases the difficulties of formalising the measurement scale. For instance, one expert thought that there are overlaps between different indicators. He pointed out that "structure geometry", "space arrangement for all kinds of users" have overlapped areas with "functional time duration". This makes it hard to give the precise definition.
3) It is hard to get proper responses only through emails. As mentioned before, this task was left as a homework to experts as the time was so limited in the workshop. However, as experts were asked to fill in a MS Excel spread sheet which was designed to collect the definitions, and it was sent through email, it is quite understandable that they paid less attention to the spread sheet. In addition, the majority of this group of experts were not available due to summer vacation, which increases the difficulties in determining the definitions of measurement scale. This problem leads to limitations of the data collection process as well.

Therefore, the author proposed the definition of the measurement scales for all the key performance indicators. This measurement scale is applied to get the evaluation scores from bridge owner. The original proposal is provided in Appendix C. The references of defining the scale are given below:

- Functional Time Duration
  As it is hard to give a specific percentage or ratio of the functional time in an exact time interval, the indicator becomes easier to be measured if it is assessed by its influences or consequences to the bridge. According to the definition that functional time is opposite to dysfunctional time which is caused by planned and unplanned maintenance, the measurement is determined by the degree of the disruption to the bridge operation.
- Function Failure Probability
  According to its definition, then the measurement of this indicator can be expressed by the functional reliability of the bridge.
- Load Bearing Capacity
  According to its definition -- the bridge should be able to carry the required load to meet the satisfying performance level, this indicator is expressed as if the bridge can carry the traffic, especially truck traffic.
- Traffic Volume Carried
  This indicator is expressed by I/C ratio (Intensity/Capacity).
  The I/C ratio is the ratio between intensity and capacity on a road, road or multiple consecutive road sections. Each roadmap has a certain maximum capacity, which is the number of units of vehicles that can travel over a roadmap in a given period. The intensity is the number of units of vehicles that pass at a

certain point in a certain period. Simply put, the ratio of how congestion-sensitive is the intended portion. If the intensity is divided by the capacity, a certain number will be released. The number thus indicates the degree of congestion. For this purpose, the I / C ratio is usually determined in the busiest rush hours or during all hours of a peak period.

In general, it can be said that at an I / C ratio of:

- 0.7 or less there will be no or little congestion
- 0.7 - 0.9 the section will have congestion at certain times, for example during peak hours
- 0.9 or higher, structural file formation will occur.

In document *NETWERKSCHAKEL A12 beheersgrens – Knooppunt Oudenrijn* (Rijkswaterstaat, 2016), it is defined that:

I/C ratio: with an I/C value above 0.9 limited residual capacity.

With an I/C ratio <=0,8 is sufficient capacity

Desired value: 0,85

- Structure Geometry

  According to the influencing factors of this indicator, then the measurement scale is expressed by the sufficient degree of width of deck, vertical and horizontal clearance, and skew.
- Space arrangement for all kinds of users

  As it is defined that the bridge should provide reliable space arrangement for users also for possible future development. The level of reasonable space arrangement is used to measure this indicator.
- Noise emission

  This indicator is also measured by its influence and difficulty to maintain it or make it back to its desired situation.
- Safety level of people and property (fatalities & injuries/accidents)

  As this indicator is mainly measured by the fatalities and injuries rate, when determining the measurement scale, the rate is used to reflect the safety level.
- Condition of drainage system

  The condition of drainage system is reflected by the reliability of all the elements in the system.
- Damage level of the structure

  The measurement of this indicator refers to the rating system that the US is using now. However, there are some adjustments according to the local condition and the range of the scale.
- User's cost

  As is described, this indicator concerns about the detour and delay costs, thus this is also applied to measure it directly.

In order to improve the proposed measurement scale, it has been checked by an expert from this academic field. The main points that should be improved are as follows:

- Function failure probability should be better reflected as a 'likelihood' of something occurring instead, this is more to the nature of the word 'probability'.
- The scale of the drainage system condition is not clear enough and should be improved.
- The "critical users" and "limitations" mentioned in the scale should be more clear.

In addition, the proposed measurement scale has also been checked by one expert from RWS as it is ought to be practical and it is used for RWS cases. There are some main comments pointed out by the expert:

- Functional time duration is only a problem when people are in a traffic jam or a time consuming detour for considerable time per year. This should be clear when making the measurement scale.
- Function failure probability is related to the expected amount of moments of traffic hindrance, in contrast to the previous, related to the total time, which should be covered in the scale.
- The scale of structure geometry and the drainage system is not clear enough and should be improved.
- The scale on damage should be limited to the main structure and things exceeding the regular maintenance.

In the evaluation process, the bridge owner can also give alternative measurement ways to assess the bridge performance as feedback.

Based on the procedure above, the final definition of the scales is listed in Table 11.

Table 11 Measurement Scales of Indicators

Indicators	Meets the future desired requirement (5)	Meets the current desired requirement (4)	Sufficient (3)	Slightly insufficient (2)	Extremely poor (1)
Functional time duration	Hardly any hindrance due to planned and unplanned maintenance (robust) with traffic increase.	Hardly any hindrance due to planned and unplanned maintenance, leading to negligible user delay cost compared to the regular road maintenance.	Planned or unplanned maintenance leads to undesired, not negligible yearly user delay, leading to incidental but acceptable complaints of road users or other stakeholders.	Planned or unplanned maintenance leads to not negligible user delay cost and frequent complaints of road users.	Planned or unplanned maintenance leads to claims or seriously damaged reputation.
Function failure probability	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low and not expected to grow in the next decades.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is moderate, leading to incidental but acceptable complaints of road users or other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is moderate. It leads to frequent complaints of road users and other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is high. It leads to claims of road users and other stakeholders or seriously damaged reputation.
Load bearing capacity	Load bearing capacity fulfills the requirements even with foreseeable traffic increase.	Load bearing capacity completely fulfills the requirements of current traffic.	Load bearing capacity almost fulfills the requirements of current traffic and does not limit the traffic.	Load bearing capacity is not sufficient and the traffic is limited (loading or speed, especially truck traffic) in an unacceptable level.	Load bearing capacity fails to carry the traffic and have high probability of dangerous consequences.
Traffic volume carried	There is sufficient residual capacity for the future traffic increase I/C ratio (Intensity/Capacity) <=0.8	The residual capacity meets the current requirements I/C ratio ∊ (0.8,0.85]	The residual capacity does not fully meet the current requirements but is still sufficient to carry current traffic volume, I/C ratio ∊ (0.85,0.9].	The residual capacity is slightly insufficient but will not cause any serious congestion, I/C ratio ∊ (0.9,0.95].	The residual capacity is insufficient and will any serious congestion, I/C ratio >0.95.
Structure geometry	The structure geometry is at design level with respect to bridge height and width below and above, and sufficiently flexible for traffic increase.	The structure geometry is sufficient for current traffic with respect to bridge height and with below and above.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, but does not create an unacceptable bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, and creates an unacceptable bottleneck in the network, leading to complaints.	The bridge is the bottleneck of the surrounding network (with respect to vertical clearance/width of deck), and it causes potential safety hazard (with respect to skew).

Space arrangement for all kinds of users	The bridge provides reliable space arrangement for all users also for possible future development.	The bridge provides reliable space arrangement for all users.	The bridge provides reliable space arrangement only for critical users (including users who contribute to the main traffic flow, inspections, and emergency services).	The bridge does not provide reliable space arrangement for critical users.	The bridge has hindrance for critical users in using spaces.
Noise emission	The noise emission is totally acceptable and can fulfill the requirements in the foreseeable future without control measures.	The noise emission is under current limitation (required for environment permit) but requires control measures to meet the future requirements.	The noise emission is over the current limitation but it is still tolerable (no control measures).	The noise emission exceeds the limitation and some measures should be taken to control it but has no urgency	The noise emission is intolerable to people and the surrounding environment, which requires urgent measures.
Safety level of people and property	Road configuration (fatalities and injuries percentage) is safe to users with traffic increase.	Road configuration (fatalities and injuries percentage) is currently at a safe level to users.	Road configuration (fatalities and injuries percentage) is safe enough to users with minor prevention measures.	Road configuration (fatalities and injuries percentage) is safe enough to users with a lot of prevention measures.	Road configuration (fatalities and injuries percentage) is not safe enough to users.
Condition of drainage system	Drainage system has the required draining ability and operates without problems, even when subject to scenarios of climate change regarding the next 20 years.	The drainage system has the required draining ability and operates without problems currently.	The drainage system does not have the required draining ability and operates with problems, resulting in minor additional maintenance cost and/or yet controllable risks for road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in minor additional maintenance cost and/or incidental uncontrollable risks or road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in major additional maintenance cost and/or uncontrollable risks for road users due to deformations or aquaplaning.
Damage level of the structure	The main structure is in perfect condition and no other cost than regular maintenance are expected in the next 20 years.	The main structure of the bridge is still in good condition. No specific maintenance problems, other than the regular periodic maintenance as expected for any other bridge.	The main structure of the bridge shows problems that exceed the regular maintenance expectations and needs minor investments to maintain the needed safety and risk level.	The main structure does not meet the current safety requirements and needs major investments to reach the needed safety and risk level.	The structure is unsafe due to damages and/or the main structure needs major investments to reach the needed safety and risk level, and will also need increasing major expenses in the future.
User's cost	Traffic users cost the same when detour happen.	Low extra cost when detour and delay happen.	Reasonable extra cost when detour and delay happen.	Slightly unacceptable extra cost when detour and delay happen.	Unacceptable extra cost when detour and delay happen.

4.2 Quantification Methods of the Model

4.2.1 Requirements for Quantification Method

In order to select the appropriate quantification method, the requirements for the method should be listed. There are two basic requirements for this target method.

First of all, as mentioned in Chapter 1, life cycle performance of highway bridges is influenced by a wide variety of criteria and indicators, as well as different stakeholders' interests. Thus a Multi-Criteria Decision-Making method is chosen to solve this problem. Usually for an evaluation problem, compensatory MCDM methods are applied to achieve a weighted average score for the assessed object. Compensatory methods assumes that the criterion with poor performance is able to be compensated with other criterion with good performance (Rezaei, Nispeling, Sarkis, & Tavasszy, 2016). However, in reality, there are some minimum requirements for criteria which they have to meet, especially for the crucial criteria. Therefore, it is more reliable to have a pre-evaluation phase before the compensatory evaluation phase. In the pre-evaluation stage, it is assumed that the performance criteria cannot compensate each other and they should meet minimum requirements separately. In this way, it is easy to figure out the vulnerable performance aspects of the bridge. Hence, applying non-compensatory in this phase is more appropriate. After ensuring that the bridge has met the minimum requirements, the compensatory method will be applied to get a weighted average value of the bridge's performance.

Secondly, in order to achieve a result as reliable as possible, the chosen method should provide high consistency between inputs and outputs as the data collection for evaluating the bridge performance is a tough process, which requires efforts from different departments. Hence, out of many popular MDCM methods such as Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), and Weighted Product Model (WPM), etc., the Best Worst Method (BWM) is chosen in this research. Comparing to other existing MCDM methods, BWM requires less comparison data and keeps the comparisons more consistent, thus its results are more reliable (Rezaei, 2015). The detailed process and the its operation of the performance criteria/indicators model will be shown in the following sections.

4.2.2 Multi-Criteria Decision-Making

Decisions have to be made in every aspect of life. Choices are made based on the decision maker's preference and evaluation. Multi-Criteria Decision-Making theory is an important division of decision-making theory system (Rezaei, 2015). According to (Belton & Stewart, 2002), various types of MCDM methods are applied in different fields and clustered into three groups: (1) value measurement models, which are usually applied to choose the best alternative and refers to Multi-Attribute Value theory, (2) goal models, which functions as screening out alternatives that do not meet the requirements, (3) outranking models, which usually used to rank options.

Apparently, this study is to solve a typical Multi-Attribute Decision-Making (MADM) problem. MADM methods deal with problems that involve impacts from diverse perspectives and are influenced by multiple criteria (Mianabadi, van de Giesen, Mostert, & Sheikhmohammady, 2012). MADM methods help the decision makers to choose the best alternative that fits their demands. The most popular method is Analytical Hierarchy Process (AHP) introduced by (Saaty, 2000). It is applied in a wide range of fields as it is able to handle both qualitative and quantitative data. However, it has drawbacks at the same time, one of which is the great demand of pairwise comparison numbers. Those numbers are decided by experts, which is the main reason of (Kilincci & Onal, 2011). Moreover, AHP requires a large number of data. The method chosen in this research should maximize the advantages and minimize the drawbacks of such pairwise comparison MADM method as much as possible.

4.2.3 Proposed Quantification Procedure

Based on the requirements of the method, a two-phase methodology is proposed, which is given in Figure 12. In the first stage, the values of indicators are put into a pre-evaluation function. If the function equals 0, then it means this bridge already fails to meet its requirements and reaches its end of service life. Then the performance age of the bridge is 0. On the other hand, if the function equals to 1, then it goes to the compensatory quantification. This function will be explained in details in section 4.2.4. When the bridge meets all of its requirements, BWM is used to determine the weightings of different performance criteria and indicators. Performance score is the weighted average value of all the indicators. After that, performance score will be translated to performance age. The approach to this is elaborated specifically in section 4.2.5. In the following sections, the procedure of quantifying criteria is used to explain the quantification methodology, because these steps for criteria and indicators are exactly the same.

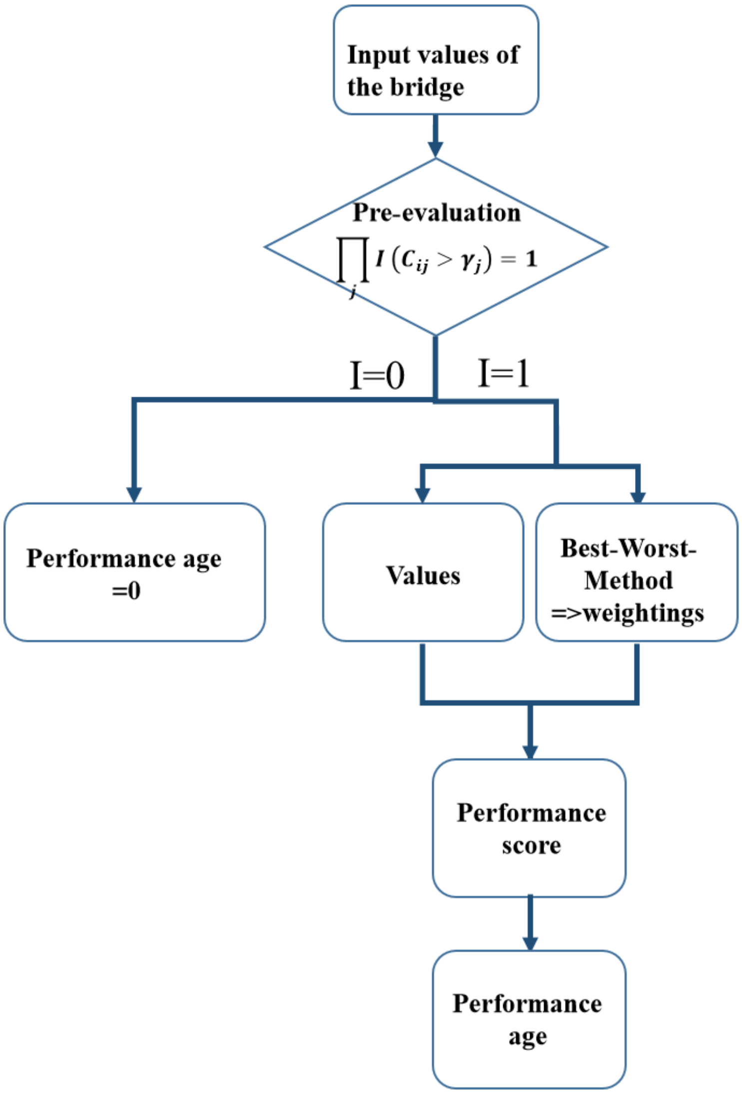

Figure 12 Quantification Procedure

4.2.4 Pre-evaluation Phase (Conjunctive Screening)

In order to check if the bridge meets the minimum requirements, screening theory is applied in the pre-evaluation phase. Basically, screening theory aims to filter out the unqualified alternatives, and there are three types of screening methods, including conjunctive screening, disjunctive screening, and lexicographic screening (Hwang & Yoon, 1981). In conjunctive screening, a bridge is acceptable if the bridge meets or exceeds the minimum requirements of each criterion/indicator. Similarly, disjunctive screening requires a bridge at least meets or exceeds the minimum requirements of one criterion/indicator. Criteria are ranked according to their importance when applying lexicographic screening method (de Boer, Labro, & Morlacchi, 2001). In order to fulfil the requirements of the quantification methodology, conjunctive screening method is selected in this research to judge if the bridge has met the minimum requirements.

The first step is to decide the cut-off value of criteria and indicators. For each criterion, there are two general scenarios of their performance: unacceptable and acceptable. The threshold value between these two scenarios is called cut-off value. According to the measurement scale proposed in section 4.1, if the score of one criterion is more than 2, then it is in an acceptable situation, otherwise it is unacceptable. Thus in this case, the cut-off value for all the criteria is 2. It has to be pointed out that the cut-off value is dependent on the measurement scale. If the criteria are evaluated in different scale, or if they are evaluated in the same scale but the threshold values are different, then the cut-off value can be different in these cases. For example, if the criterion functionality is acceptable only when its value is more than 3, while that of environment is 2, then the cut-off values of these two criteria are 3 and 2 respectively.

After the cut-off values are determined, the two general scenarios are coded as 0 (unacceptable) and 1 (acceptable) in order to calculate the pre-evaluation function more conveniently. The pre-evaluation function is the product of the coded values of all the criteria. There will be two cases of the function. One is that it equals to 1, which means all of the coded values are 1, thus the bridge is acceptable in all criteria. Another is that it equals to 0, which means there are at least one criterion that failed to meet its requirement, thus the bridge is unacceptable and the rest of its life (performance age) is 0. The pre-evaluation function is expressed in Equation (3), and the basis of the function is given in Table 13

$$\prod_{j} \boldsymbol{I}\left(\boldsymbol{C_j} > \boldsymbol{\gamma_j}\right) = \mathbf{1}$$

where,
C_j is the real value of the indicator,
γ_j is the cut-off value in this criteria/indicator

Table 12 Basis of Pre-evaluation Function

Criteria	Levels	Coded Values	Cut-off Value (γ_m)
Functionality	Unacceptable	0	2
	Acceptable	1	
Environment	Unacceptable	0	2
	Acceptable	1	
Safety	Unacceptable	0	2
	Acceptable	1	
Serviceability	Unacceptable	0	2
	Acceptable	1	
Economics	Unacceptable	0	2
	Acceptable	1	

An example of the pre-evaluation function result is shown in the Table 14. The pre-evaluation function of Bridge A is 1, which means it has passed the minimum performance requirements and requires more precise assessment. Whereas the result 0 of bridge B means its performance age will be 0, and the coded value shows that it has serious problems in safety.

Table 13 Example of Pre-evaluation Function Result

Project	Criteria					Screening Function I
	Functionality	Environment	Safety	Serviceability	Economics	
Bridge A	1	1	1	1	1	1
Bridge B	1	1	0	1	1	0

4.2.5 Best-Worst Method

When the bridge has passed the pre-evaluation, it comes to the second phase where compensatory MCDM method is applied. In this study, Best-Worst-Method is chosen to quantify the model due to its two aforementioned advantages. Best-Worst Method is a new method proposed to solve MCDM problems. For explicit and detailed explanation of BWM, (Rezaei, 2015) is referred. This method relieves the problems of comparisons that other methods encountered. In other words, the BWM needs less comparison data due to which there are less issues with the inconsistency that are experienced by pairwise comparison (Rezaei, 2015). Compared to the most popular pairwise comparison MCDM method AHP, BWM helps decision makers to relieve the stress of giving the accurate preference strength, which is almost the main source of inconsistency.

The steps of application of BWM in this study are shown in Figure 13 and the details are described below:

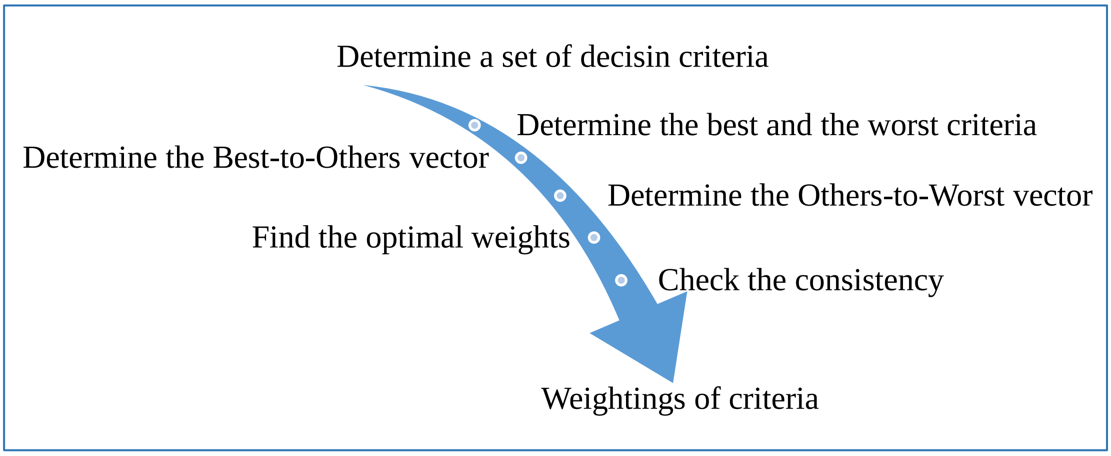

Figure 13 BWM steps

Step 1

Determine a set of decision criteria $\{c_1, c_2, \ldots, c_n\}$ that should be used to arrive at the performance score. In this study, this set of decision criteria is the result of the model validation workshop, which is:
{Functionality (c_1), Environment (c_2), Safety (c_3), Serviceability (c_4), Economics (c_5)}

Step 2

Determine the best (most desirable, most important) and the worst (least desirable, least important) criteria. The best and worst criteria should be determined by decision-makers. In this research, this step is carried out by a questionnaire filled in by experts. The questionnaire will be illustrated in section 4.2.8. There is no comparison to be made in this step.

Step 3

Determine the preference of the best criterion over all the other criteria in scale 1~5. It has to be pointed out that other scales are also applicable to determine the preference, such as 1~9, 1~100. Scale 1~5 is chosen in this study to relieve the expert's stress of choosing the accurate preference number.
The definition of 1~5 preference scale is:

Table 14 Preference Scale

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

The Best-to-Others vector is achieved in this step: $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$

Step 4

Determine the preference of all the criteria over the worst criterion in scale 1~5.
The Others-to-Worst vector is achieved in this step: $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$
Step 3 and step 4 are also carried out by the questionnaire illustrated in section 4.2.8.

Step 5

This step is aiming to find the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$
The optimal weight for the criteria is the one where, for each pair of $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. To satisfy these conditions for all j, we should find a solution where the maximum absolute difference $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized.

It can be transferred to a linear programing problem:

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

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

$$\sum_j w_j = 1$$

$w_j \geq 0$, for all j

The optimal weights vector for the five performance criteria will be obtained in this step: $W = (w_1^*, w_2^*, \ldots, w_n^*)$ and ξ^*. The calculation is solved by an excel template developed by the author. The application of the template is elaborated in section 4.2.9 step by step. Due to the limitation of excel, $\xi^{L*}$is obtained with adjustment to the original linear programming problem. This will be explained in section 4.2.9 as well.

Step 6

Check the consistency. $Consistency\ Ratio = \frac{\xi^*}{Consistency\ Index}$

These maximum values are used as consistency index.

Table 15 Consistency Index of BWM

a_{BW}	1	2	3	4	5
Consistency index(max ξ^*)	0.00	0.44	1.00	1.63	2.30

By doing the BWM to obtain the weights vectors for indicators within each criterion. The optimal weights vector for performance indicators within each criterion will be achieved in this step. When there is only one indicator under the criterion, then the weight of the indicator will be 1 automatically. In this study, the weights vectors of indicators would be:

6 indicators in c_1: $W_1 = (w_{11}, w_{12}, \ldots, w_{16})$

1 indicator in c_2: $W_2 = (w_{21})=(1)$

1 indicators in c_3: $W_3 = (w_{31})=(1)$

2 indicators in c_4: $W_4 = (w_{41}, w_{42})$

1 indicator in c_5: $W_5 = (w_{51})=(1)$

4.2.6 Performance Score Calculation

Step 1

Determine the measurement set. As proposed in section 4.1, the measurement set: $E = (e_1, e_2, e_3, e_4, e_5)$ = (Extremely good, Good, Average, Poor, Extremely poor), which reflects in the score set $F = (f_1, f_2, f_3, f_4, f_5)^T = (5,4,3,2,1)^T$

Step 2

Get opinions from a group of experts
e.g. within c_1, the measurement matrix is below:

$$R_1 = \begin{bmatrix} r_{11} r_{12} r_{13} r_{14} r_{15} \\ r_{21} r_{22} r_{23} r_{24} r_{25} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ r_{61} r_{62} r_{63} r_{64} r_{65} \end{bmatrix}$$

where r_{11} implies the percentage of experts who think the indicator is in extremely good situation (score 5), r_{12} implies the percentage of experts who think the indicator is in good condition (score 4), etc.
Similar measurement matrices could be done for other criteria. R_2, R_3, R_4, R_5.

Step 3

Calculate the performance score.
Weighted experts' judgement percentage matrix of c_1 would be:

$$P_1 = W_1 \times R_1 = [w_{11} \quad w_{12} \quad \cdots \quad w_{16}] \times \begin{bmatrix} r_{11} r_{12} r_{13} r_{14} r_{15} \\ r_{21} r_{22} r_{23} r_{24} r_{25} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ r_{61} r_{62} r_{63} r_{64} r_{65} \end{bmatrix} = [p_{11} \quad p_{12} \quad \cdots \quad p_{15}]$$

Similarly, P_2, P_3, P_4, P_5 can be calculated.
Thereafter, the fuzzy weighted average score of c_1 can be calculated by:

$$Z_1 = P_1 \times F = [p_{11} \quad p_{12} \quad \cdots \quad p_{15}] \times \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix} = score\ of\ criterion\ 1$$

Similarly, scores of other criteria could be calculated, then the set of criteria scores would be: $Z = (Z_1, Z_2, \ldots, Z_5)^T$
The final score would be

$$\mathrm{S} = \mathrm{W} \times \mathrm{Z} = [w_1 \quad w_2 \quad \cdots \quad w_5] \times \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_5 \end{bmatrix} = Performance\ Score$$

4.2.7 Interpretation from Performance Score to Performance Age

Once the performance score is obtained, the next step would be translating performance score to performance age, which implies the rest of life of the bridge.

As the perfect condition in this study is the desirable condition of a new bridge (design life is 80 years) at the same location aforementioned in section 4.1, Performance age can be calculated through the following equation:

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

It is noticeable that this formula is based on the assumption that the performance decrease of bridges are in linear relation with the time increase.

An example of the calculation is given below:

Suppose:
The existing bridge was built in 1950
Performance Score is 3 out of 5 (current condition out of perfect condition)

Then:
The actual age is 2017-1950=67 years
The residual life of this bridge is [(3-2)/(5-2)] * 80=26,7 years ≈ 27 years
Performance age is 80-27=53 years
The replacement year is 2017+27=2044

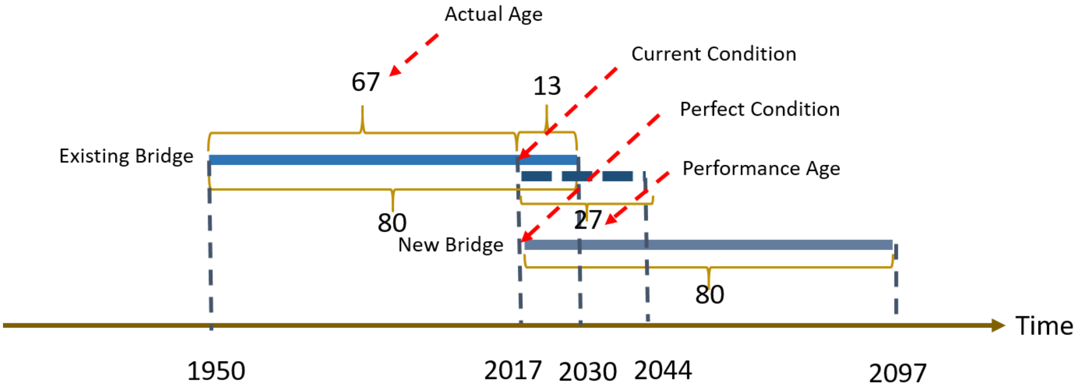

Figure 14 Example of Translation from Performance Score to Performance Age

4.2.8 Data Collection and Preliminary Preparation

Data collection refers to the process of gathering required data systematically. The bridge performance of different indicators is determined in consultation with RWS. Collecting performance data has several limitations, such as time limitation. In addition, the data is collected from different data sources, which enlarges its limitation (Humplick & Paterson, 1994).

As there is no existing secondary data for this research nowadays, questionnaires are used to collect the primary data. In order to enhance the validity of the data, all the questionnaires were filled in in a short period of time (one week).

There are four questions that need to be answered by the respondents in the questionnaire. However, 31 questions with logic behind are designed in the questionnaire as there are 20 (5*4) scenarios when choosing the best and worst criterion. The detailed design of the questionnaire is provided in Appendix D.1, and a guidance to fill in the questionnaire is given in Appendix D.2 in order to ensure the correctness of the answers. An example of answer is presented step by step to explicitly demonstrate the principle of the questionnaire.

Firstly, a brief background information of the research and the objective of the questionnaire are given in the introduction part (Figure 15).

Performance age of highway bridges

As the asset manager for highway fixed concrete briges, you would have different considerations when you make the replacement decisions. The following criteria are considered to evaluate the performance of bridges in order to make the replacement decisions more accurate. The definition of these criteria as as follows:
Functionality: Fulfilling the primary functions of the bridge and also the network (carry loads, provide connections and provide space)
Environment: The influence of the bridge to the physical environment
Safety: safety to users and the network
Serviceability: The structure is still stable enough to ensure the service
Economics: the costs versus benefits

Figure 15 BWM Questionnaire Introduction

After reading the background information, the respondent is supposed to make the choice for the most important criterion. In this example, functionality is chosen (Figure 16).

1. Which criterion do you think is the most important one *

- (●) Functionality
- ( ) Environment
- ( ) Safety
- ( ) Serviceability
- ( ) Economics

Figure 16 BWM Questionnaire Question 1

Thereafter, the respondent is required to choose the least important criterion. The second question will jump out without the option of functionality which was already chosen as the most important one. In this example, environment is selected as the worst criterion (Figure 17).

2. Which criterion do you think is the least important one *

- (●) Environmnet
- ( ) Safety
- ( ) Serviceability
- ( ) Economics

Figure 17 BWM Questionnaire Question 2

After that, the third and fourth questions will jump out automatically according to the choices of question 1 and 2. In question 3, respondents are asked to give numbers to indicate the preference of the most important criterion over the other criteria (Figure 18). The tips in this question remind the respondents of the meaning of preference numbers.

7. You have chosen Functionality as the MOST IMPORTANT criterion. Could you please indicate your 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. * [Please input number between 1 and 5]

	Environment	Safety	Serviceability	Economics
Functionality	5	2	4	3

Tips:Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

Figure 18 BWM Questionnaire Question 3

Finally, in the fourth question, respondents should fill in the preference numbers of the other criteria over the least important criterion. In order to keep the data in a good consistency, the best criterion (functionality in this example) is intentionally excluded in this question (Figure 19).

8. You have chosen Environment as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion * [Please input number between 1 and 5]

	Environment
Safety	4
Serviceability	2
Economics	1

Tips:Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

Figure 19 BWM Questionnaire Question 4

All the four questions are compulsory to be filled in. And similar questionnaires of indicators within each criterion are also conducted to obtain the input of BWM.

4.3 Data Processing

In the existing literature, Microsoft Excel is used to proceed the results from questionnaire conducted to obtain the input of BWM. The Add-in application Solver in MS Excel is applied to solve the liner programming problem by Simplex Method. Some limitations of the existing tool are: 1) when using Solver to do the calculation, it cannot be applied for multiple times automatically in one excel sheet. In this case, if there are many respondents to the questionnaire, then it will cause a lot of labour work as the results should be put into Solver manually, which reduces the efficiency of the methodology, 2) there is a risk that people make mistakes when they type in the numbers manually. If only one excel template is reused again and again, the mistakes in the input are extremely hard to find as the former input will be invisible. 3) five criteria will lead to 20 scenarios when respondents are choosing the best and worst criteria. Then the constraints in the template should be changed again and again as they are different for different scenarios. Based on the limitations of existing calculation tool listed above, a new template is developed to improve the efficiency and accuracy of the quantification process. MS Excel is chosen to realize the calculation as it is still the mostly common-used data processing software and it will be the easiest one for the users. The new template designed based on MS Excel Visual Basic for Application is able to combine all the phases of the methodology in one platform.

4.3.1 Data Processing in the Pre-evaluation Phase

Following the aforementioned principles of this phase in section 4.2.4, the data processing in this phase is basically a YES/NO question, thus it is designed based on IF-THEN syntax. The interface design is given in Figure 20. There will be two types of result. One is that the pre-evaluation function I equals to 0 which means performance age is 0, and the other is that I equals to 1 which means the assessment should go to the compensatory method phase. When clicking the "Function" button, the outcome of this process will be printed automatically. Examples of these two types of results are provided in Figure 21 and Figure 22. The code is provided in Appendix E.1.

Criteria	**Value**	**Cut-off value**	**Coded value**
Functionality			
Environment			
Safety			
Serviceability			
Economics			
			Function
Performance age			
	Input		
	Output		

Figure 20 Data Processing Pre-evaluation Phase Interface

When not all the values are more than the cut-off values, then the Function I = 0, the Performance Age = 0 is obtained.

Criteria	Value	Cut-off value	Coded value
Functionality	5	2	1
Environment	4	2	1
Safety	2	2	0
Serviceability	3	2	1
Economics	3	2	1
			Function
Performance age			0
	Input		
	Output		

Figure 21 Data Processing Pre-evaluation Phase Result Case 1

When all the values are more than the cut-off values, then the Function I = 1, the Performance Age prints "Compensatory method", and a Userform "BWMINPUT" (explained in section 4.3.2) will pop up automatically.

Criteria	Value	Cut-off value	Coded value
Functionality	5	2	1
Environment	4	2	1
Safety	3	2	1
Serviceability	3	2	1
Economics	3	2	1
			Function
Performance age			Compensatory method
	Input		
	Output		

Figure 22 Data Processing Pre-evaluation Phase Result Case 2

4.3.2 BWM Data Processing

In the case where pre-evaluation function I = 1, the data for the compensatory method phase requires processing. As aforementioned in the last section, a Userform "BWMINPUT" will jump out to input the results from BWM questionnaire into this templet. The interface of the Userform is shown in Figure 23, and an example of the filling results (refers to the numbers in the questionnaire example in section 4.2.8) is provided in Figure 24. The inputs will be arranged in order in a form (also provided in Figure 24). In this way, it is easy to find if there is any mistake made in the input and to locate the mistakes, which reduces the second limitation mentioned before in the beginning of section 4.3.

For every input column, all the options are inserted. Users only need to select while not type in the numbers. When clicking the "Submit" button, one response of the questionnaire will be recoded. When clicking the "Close" button, the input process will end. The code of the Userform is provided in Appendix E.2.

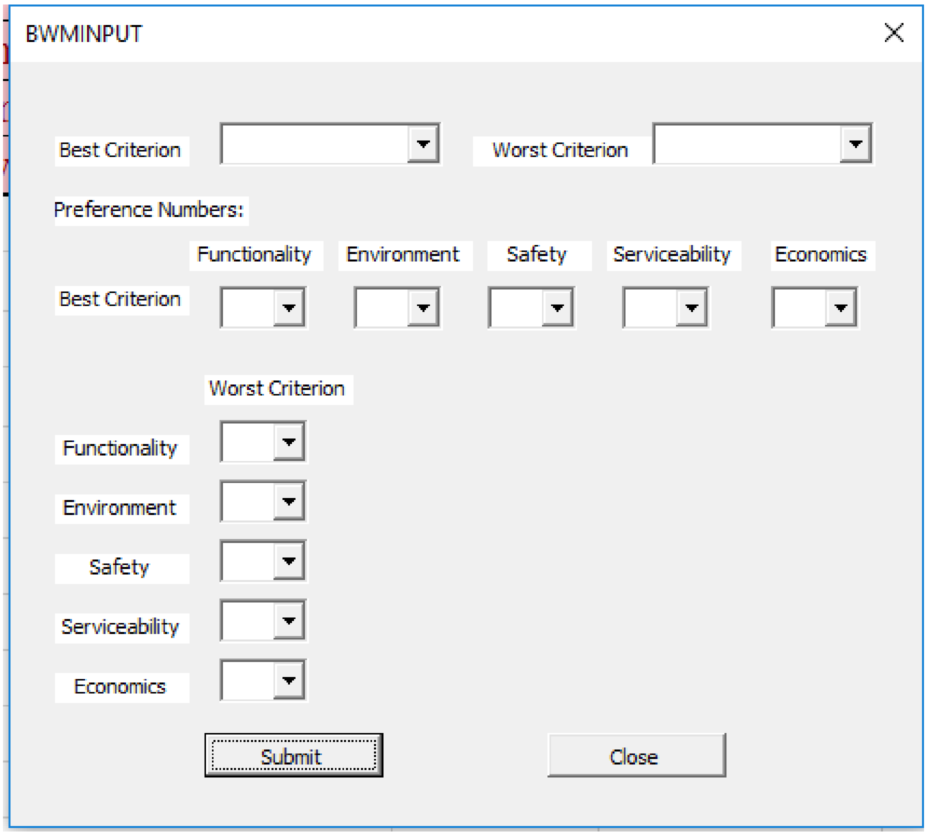

Figure 23 BWM Data Processing Userform Interface

After finishing the input of BWM, as there are 20 scenarios which have different constraints, a "Sort" button is designed to classify them. This design will reduce the third limitation. The interface of the sorting is shown in Figure 25 (only includes the scenarios in which functionality is chosen as the best criterion). The code of this button is given in Appendix E.3. One result example is given in Figure 26.

Then, clicking the "Calculate" button, the calculation process will run automatically, this function calls the inserted Solver, and it reduces the first limitation. In order to apply Solver for multiple times automatically, all the relevant inputs and constraints for one response of the questionnaire are settled in one row. The constraints columns which contain 0 in red are designed to ensure the constraint formula are typed in correctly. An result example is shown in Figure 27, where the final outcome (weights of criteria) is shown on the top. The code is provided in Appendix E.4.

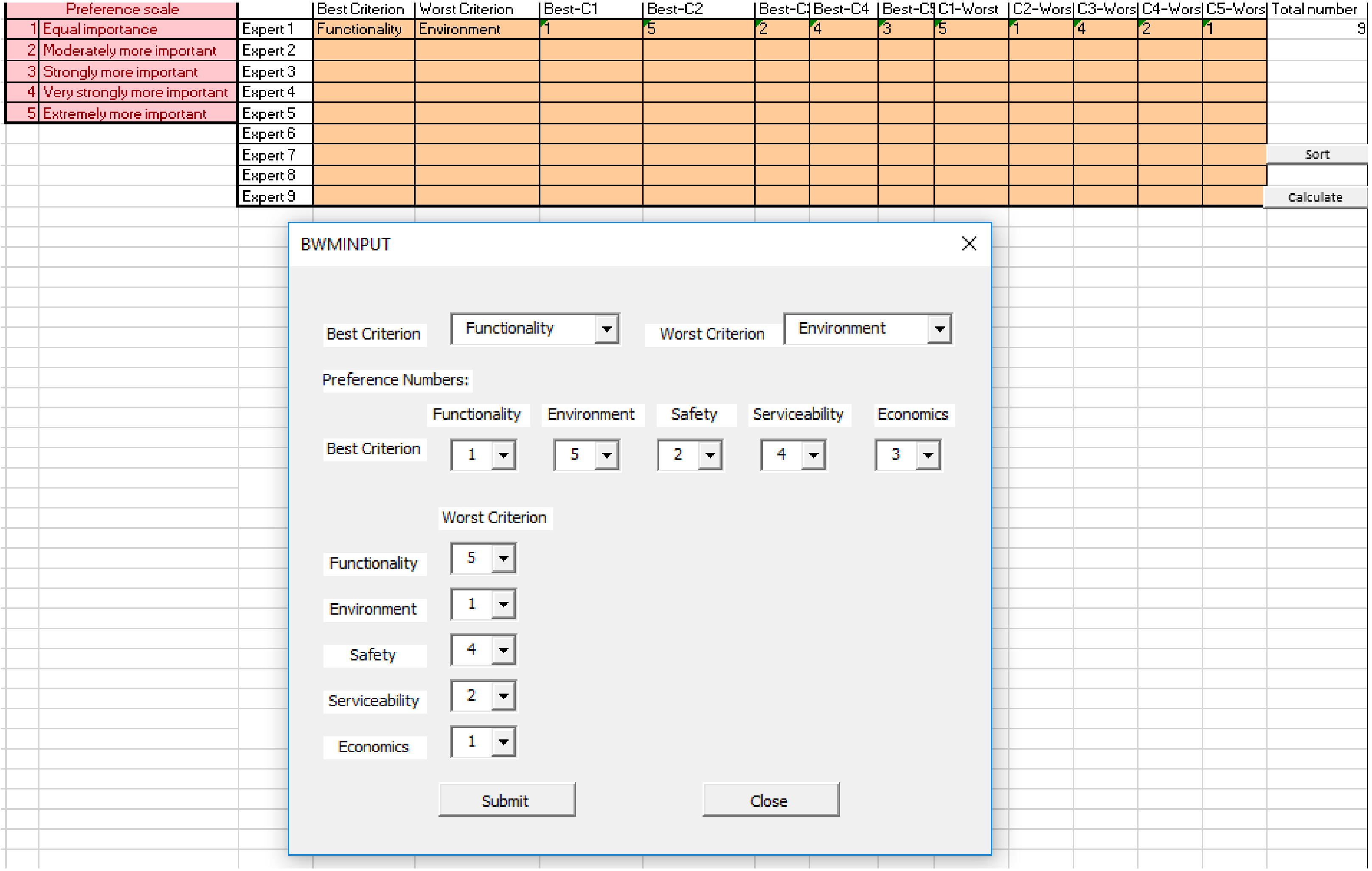

Figure 24 BWM Data Processing Userform Result Example

Scenario 1	Best Criterion	Worst Criterion											
	Functionality	Environment	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)
Scenario 2	Best Criterion	Worst Criterion											
	Functionality	Safety	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)
Scenario 3	Best Criterion	Worst Criterion											
	Functionality	Serviceability	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)
Scenario 4	Best Criterion	Worst Criterion											
	Functionality	Economics	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)

Scenario 1	Best Criterion	Worst Criterion											
	Functionality	Environment	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Worst	C2-Worst	C3-Worst	C4-Worst	C5-Worst	v
	Functionality	Environment	1	5	2	4	3	5	1	4	2	1	
Scenario 2	Best Criterion	Worst Criterion											
	Functionality	Safety	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Worst	C2-Worst	C3-Worst	C4-Worst	C5-Worst	v
	Functionality	Safety	1	2	5	4	3	5	3	1	2	1	
Scenario 3	Best Criterion	Worst Criterion											
	Functionality	Serviceability	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Worst	C2-Worst	C3-Worst	C4-Worst	C5-Worst	v
	Functionality	Serviceability	1	2	4	5	3	5	3	2	1	3	
Scenario 4	Best Criterion	Worst Criterion											
	Functionality	Economics	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Worst	C2-Worst	C3-Worst	C4-Worst	C5-Worst	v
	Functionality	Economics	1	2	4	3	5	5	3	2	3	1	

Figure 25 BWM Data Processing Sorting Interface
Figure 26 BWM Data Processing Sorting Result Example

Weighting	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)
Sum	1,6926404	0,786417	0,562119	0,47015	0,48867
Average	0,4231601	0,196604	0,14053	0,11754	0,12217

Scenario 1	Best Criterion	Worst Criterion																	1	Constraints																			
	Functionality	Environment	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)	Ksi*	sum	Inequation 1 (Positive)					Inequation 1 (Negative)					Inequation 2 (Positive)					Inequation 2 (Negative)				
	Functionality	Environment	1	5	2	4	3	5	1	4	2	1	0,4299	0,0748	0,243	0,1215	0,1308	0,0561	1	0	0,0561	-0,0561	-0,0561	0,0374	0	-0,0561	0,0561	0,0561	-0,0374	0,05607	0	-0,0561	-0,028	0,0561	-0,0561	0	0,0561	0,028	-0,0561
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Scenario 2	Best Criterion	Worst Criterion																		Constraints																			
	Functionality	Safety	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)	Ksi*	sum	Inequation 1 (Positive)					Inequation 1 (Negative)					Inequation 2 (Positive)					Inequation 2 (Negative)				
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Functionality	Safety	1	2	5	4	3	5	3	1	2	1	0,4312	0,2385	0,0826	0,1193	0,1284	0,0459	1	0	-0,0459	0,0183	-0,0459	0,0459	0	0,0459	-0,0183	0,0459	-0,0459	0,01835	-0,0092	0	-0,0459	0,0459	-0,0183	0,0092	0	0,0459	-0,0459
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Scenario 3	Best Criterion	Worst Criterion																		Constraints																			
	Functionality	Serviceability	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)	Ksi*	sum	Inequation 1 (Positive)					Inequation 1 (Negative)					Inequation 2 (Positive)					Inequation 2 (Negative)				
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Functionality	Serviceability	1	2	4	5	3	5	3	2	1	3	0,4158	0,2366	0,1183	0,0717	0,1577	0,0573	1	0	-0,0573	-0,0573	0,0573	-0,0573	0	0,0573	0,0573	-0,0573	0,0573	0,05735	0,0215	-0,0251	0	-0,0573	-0,0573	-0,0215	0,0251	0	0,0573
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Scenario 4	Best Criterion	Worst Criterion																		Constraints																			
	Functionality	Economics	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Wors	C2-Wors	C3-Wors	C4-Wors	C5-Wors	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)	Ksi*	sum	Inequation 1 (Positive)					Inequation 1 (Negative)					Inequation 2 (Positive)					Inequation 2 (Negative)				
																			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Functionality	Economics	1	2	4	3	5	5	3	2	3	1	0,4158	0,2366	0,1183	0,1577	0,0717	0,0573	1	0	-0,0573	-0,0573	-0,0573	0,0573	0	0,0573	0,0573	0,0573	-0,0573	0,05735	0,0215	-0,0251	-0,0573	0	-0,0573	-0,0215	0,0251	0,0573	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 27 BWM Data Processing Final Outcome Result Example

4.3.3 Data Processing for Performance Score Calculation

When the weightings of indicators and criteria are obtained, the next step is to calculate the performance score. It starts with the lower layer – calculating the score of criteria through indicators, and followed by calculating the overall score through criteria. The calculation follows the steps illustrated in section 4.2.6. The example of calculating functionality score is given in Figure 28. As can be seen in the left part of this figure, the measurement matrix of functionality is the input, which comes from the assessment of different indicators from bridge owners. In the right part, the weightings of indicators are listed, which are from the results of BWM calculation. By multiplying these two matrices, weighted measurement matrix is obtained. The performance score in functionality could be easily obtained by multiplying it with the evaluation scale. And the result will be shown automatically if the input areas are filled in correctly. The overall performance score calculation process is shown in the next section in order to illustrate the process of translation from score to age more clearly.

Functionality	r11	r12	r13	r14	r15
	r21	r22	r23	r24	r25
	r31	r32	r33	r34	r35
	r41	r42	r43	r44	r45
	r51	r52	r53	r54	r55
	r61	r62	r63	r64	r65

Weightings of indicators	w11	w12	w13	w14	w15	w16
Weighted measurement matrix	p11	p12	p13	p14	p15	
	0	0	0	0	0	
Evaluation scale	f1	5		Score of C1	0	
	f2	4				
	f3	3			Input	
	f4	2			Output	
	f5	1				

Figure 28 Example of Performance Score Calculation

4.3.4 Data Processing for the Score to Age Translation

The final step of the quantification process is to interpret performance score into performance age. It is calculated through the formula illustrated in section 4.2.7. Thus the calculation in this step would be done just by inputting the formula in the performance age result cell. The interface of this step is provided in Figure 29. Through the whole quantification process, decision makers can obtain the result Performance Age from this cell directly.

Score of C1		Weightings of criteria	w1	w2	w3	w4	w5
Score of C2							
Score of C3							
Score of C4		Overall Score	0		Performance Age		
Score of C5							

Figure 29 Process of Score to Age Translation

4.3.5 Limitations of the Data Processing Template

In the BWM Data Processing part, all the constraints for different scenarios should be set manually, which is not hard but just copy-paste work. This is because the limitation of Visual Basic CallSolver syntax. In this syntax, only a specific cell or a range of cells can be quoted while it cannot do calculation between cells. Thus all the calculation formula inserted in the constraint cells should be typed in manually. In order to reduce this limitation, more advanced platform should be used to develop a template or software for the application of BWM when the sample size is quite big.

4.4 Quantification Result

This section depicts the quantification result. In fact, part of the complete quantification process requires values from specified projects, including the pre-evaluation step and the final score and age calculation. Hence, in this chapter, only the quantification result of applying BWM method is illustrated, whereas other parts will be shown in the next chapter, which tested this model with three specific bridges in the Netherlands.

Regarding the BWM part, which provides the model the weightings of criteria and indicators, it is a generic step which can be applied in measuring the performance of highway bridges as all of them follow the same performance measurement model.

The response to the questionnaire for giving weightings to performance criteria is shown in Figure 30. The questionnaire was handed out to the 9 experts who has attended the problem-scoping workshop, 8 of them delivered answers. However, there is one response which is not proper as the respondent chose “Functionality” as the most important indicator, “Environment” as the least important indicator and give the preference number of “Functionality” over “Environment” as 1, which means they are equally important. This is a contradiction, thus this response should not be included in calculation. As can be found in the result figure, “Functionality” is considered as the Best Criterion mostly, while “Economics” is usually regarded as the Worst Criterion.

	Best Criterion	Worst Criterion	Best-C1	Best-C2	Best-C3	Best-C4	Best-C5	C1-Worst	C2-Worst	C3-Worst	C4-Worst	C5-Worst
Expert 1	Functionality	Economics	1	3	1	3	3	3	1	3	1	1
Expert 2	Functionality	Serviceability	1	3	5	4	4	4	2	5	1	4
Expert 3	Functionality	Economics	1	5	1	5	5	5	1	5	1	1
Expert 4	Functionality	Environment	1	5	2	3	4	5	1	4	3	4
Expert 5	Functionality	Serviceability	1	4	2	5	3	5	2	5	1	3
Expert 6	Safety	Economics	1	3	1	2	2	5	1	2	3	1
Expert 7	Safety	Economics	2	3	1	3	4	3	2	4	2	1
Expert 8												
Expert 9												

Figure 30 Response to Questionnaire for Criteria

By operating the calculation program, the weightings of the 5 criteria calculated from the each response are provided in Table 16. The consistency ratios are given in this table as well. It can be seen that the outcome of each result are in good consistency with the input as the consistency ratios are quite low. The overall result of the weightings of performance criteria is given in Figure 31, from which we can see that functionality takes the dominant position in determining the performance age.

Table 16 Results of Performance Criteria

	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)	ξ	Consistency index	Consistency ratio
Response 1	0.3968	0.0581	0.2516	0.1677	0.1258	0.1065	2.30	0.0463
Response 2	0.4421	0.2105	0.1263	0.0632	0.1579	0.1895	1.63	0.1163
Response 3	0.4065	0.1220	0.2439	0.0650	0.1626	0.0813	2.30	0.0353
Response 4	0.0333	0.1111	0.3333	0.1111	0.1111	0	1.00	0
Response 5	0.3846	0.0769	0.3846	0.0769	0.0769	0	2.30	0
Response 6	0.3529	0.1176	0.2647	0.1765	0.0882	0.0882	0.44	0.2005
Response 7	0.2206	0.1471	0.3971	0.1471	0.0882	0.0441	1.63	0.0271

Weightings	w(C1)	w(C2)	w(C3)	w(C4)	w(C5)	Sum
Sum	2,537	0,843	2,002	0,808	0,811	7,000
Average	0,362	0,120	0,286	0,115	0,116	1,000

Figure 31 Weightings of Performance Criteria

In the indicators layer of the model, the process of achieving the weightings of criteria is also applied to indicators. As can be seen in the validated performance model, only the criteria "Functionality" and "Safety" have more than one indicators, while there is only one indicator within other criteria respectively. Hence, the process is only required to carry out for indicators within "Functionality" and "Safety". Unfortunately, only three responses were obtained due to the time limitation. However, it is still acceptable as the results are only used for illustrating the quantification process and the results show consistency to some extent, especially for the indicators in "Safety". The responses to the questionnaire for giving weightings to performance indicators are given in Figure 32 (in functionality) and Figure 34 (in safety). The results are shown in Figure 33 and Figure 35 respectively. From the consistency ratio calculation tables (Table 17 and Table 18), the outcomes of each response are in good consistency with their inputs as the consistency ratios are less than 0.1, which is quite low.

	Best Indicator	Worst Indicator	Best-I1	Best-I2	Best-I3	Best-I4	Best-I5	Best-I6	I1-Worst	I2-Worst	I3-Worst	I4-Worst	I5-Worst	I6-Worst
Expert 1	Load bearing capacity	Space arrangement for all kinds of users	2	2	1	2	4	5	3	3	5	4	4	1
Expert 2	Functional time duration	Space arrangement for all kinds of users	1	1	2	3	4	4	4	5	4	4	3	1
Expert 3	Function failure probability	Structure geometry	2	1	2	3	5	4	4	5	5	4	1	2
Expert 4														
Expert 5														
Expert 6														
Expert 7														
Expert 8														
Expert 9														

Figure 32 Responses to Questionnaire for Indicators in Functionality

Table 17 Results of Performance Indicators in Functionality

	w(I1)	w(I2)	w(I3)	w(I4)	w(I5)	w(I6)	ξ	Consistency index	Consistency ratio
Response 1	0.1884	0.1884	0.2971	0.1884	0.0942	0.0435	0.0797	2.30	0.0347
Response 2	0.2667	0.3143	0.1713	0.1143	0.0857	0.0476	0.0762	1.63	0.0467

Response 3	0.1975	0.3241	0.1975	0.1316	0.0506	0.0987	0.0709	2.30	0.0308

Weightings	w(I1)	w(I2)	w(I3)	w(I4)	w(I5)	w(I6)	Sum
Sum	0,653	0,827	0,665	0,434	0,239	0,183	3,000
Average	0,218	0,276	0,222	0,145	0,080	0,061	1,000

Figure 33 Weightings of Indicators in Functionality

	Best Indicator	Worst Indicator	Best-I1	Best-I2	I1-Worst	I2-Worst
Expert 1	Safety level of people and property	Condition of drainage system	1	4	4	1
Expert 2	Safety level of people and property	Condition of drainage system	1	5	5	1
Expert 3	Safety level of people and property	Condition of drainage system	1	5	5	1
Expert 4						
Expert 5						
Expert 6						
Expert 7						
Expert 8						
Expert 9						

Figure 34 Responses to Questionnaire for Indicators in Safety

Table 18 Results of Performance Indicators in Safety

	w(I1)	w(I2)	ξ	Consistency index	Consistency ratio
Response 1	0.8000	0.2000	0	1.63	0
Response 2	0.8333	0.1667	0	2.30	0
Response 3	0.8333	0.1667	0	2.30	0

Weightings	w(I1)	w(I2)	Sum
Sum	2,467	0,533	3,000
Average	0,822	0,178	1,000

Figure 35 Weightings of Indicators in Safety

CHAPTER FIVE

TEST THE QUANTIFICATION METHODOLOGY WITH CASES

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5. Test the Quantification Methodology with Cases

Introduction

In order to illustrate the proposed methodology more directly, an application of it in the real world will be discussed in this chapter. In addition, by implementing the application, there will be a better insight into the feasibility and efficiency of the quantification method. According to the quantification process proposed in Chapter 4, there will be three different kinds of outcomes: 1) performance age equals to 0 as it did not pass the pre-evaluation phase, 2) performance age is shorter than the theoretical service lifetime, which means the bridge is older than it is supposed to be, 3) performance age is longer than its theoretical service lifetime, which means the bridge is younger than it is supposed to be. Hence, three bridges are chosen to carry out the test. This chapters begins with the cases information, which gives a brief introduction to the chosen bridges. After that, the data of the chosen bridges required to operate the proposed methodology is gathered from bridge owners. The results of test are illustrated thereafter. Finally, discussions over the results will be presented.

5.1 Cases Information

In this part, three highway bridges/viaducts are chosen to carry out the testing. In fact, these bridges should be chosen randomly. However, in order to show how the quantification methodology works and all the possible results, the bridge selection is based on these rules: (1) the bridge is located in an area where there is potential of urban development (preferably Randstad area); (2) the bridge is estimated to be demolished in 20 years; (3) the three bridges have different EELI, including the one which is less than 1, as well as the one which is more than 1 (in order to show how can "Performance Age" can improve decisions made based on EELI). Among the possible bridges listed in Appendix C, the following three bridges which locate in three different areas are chosen to do the case study for quantification methodology verification.

5.1.1 Project 1 Boonervliet Noord Brug

This bridge Boonervliet Noord locates in the western Rotterdam, the second largest city in the Netherlands. As the biggest harbour in Europe, there is still great demand of urban development in this area. This bridge was constructed in 1939 and it was designed to provide service for the local transportation for 80 years, which means it should be demolished in 2 years theoretically. However, it is estimated that it will reach its end of life in the year 2035 from technical perspective. In addition, the EELI for this bridge is 0.7, which is approaching 1. In other words, this bridge should also be demolished soon from economic perspective. Hence, it is interesting to see if the same conclusion will be achieved from performance perspective. The picture of this bridge and basic background information of it can be seen in Figure 36 and Table 19.

Figure 36 Project 1 Boonervliet Noord Brug

Table 19 Background Information of Boonervliet Noord Brug

Code	37B-110-02
Name	Boonervliet noord: Noordelijke brug over de Boonervliet (the northern bridge over river Boonervliet)
Administrator	RWS WNZ/WNZ District Noord
Municipality	Midden-Delftland
Province	Zuid-Holland
National Road	A20
Construction Year	1939
Object Type	Fixed Bridge (Concrete, Cantilever beam)
Network	HWN-Dry
Object Size (m)	Length: 114.42 Width: 10.2
Cultural & Historical Importance	Green
Economic Network Category	Green (B): ‘Medium’ intensities and importance with the spatial economic policy
Object status	In use
Corridor/Economic Importance	KP Kethelplein – Maassluis (L)/
Current Traffic Intensity	Total 31100 per year (weekday), wherein truck traffic 4452
Last IHA	01/05/2016
Object Quality (Risk Level)	4
Load Class	A
End of Life	Theoretical: 2019 Technical: 2035
EELI	0.7
Replacement Value (k€)	3000-5000

5.1.2 Project 2 Bieslandsebrug

This bridge Bieslandsebrug locates in the eastern Delft, one of the small cities in Randstad. As a knowledge-based city and the connection part between The Hague and Rotterdam, the urban development is of necessity in this area. Moreover, this bridge locates in National way A13, which is one of the most busiest highway in the Netherlands. This bridge was constructed in 1933 and it was designed to provide service for the local transportation for 80 years, which means it should have been demolished already theoretically. From the technical viewpoint, it is estimated that it will reach its end of life in the year 2031. In addition, the EELI for this bridge is 0.84, which is approaching 1. In other words, this bridge should also be demolished soon from economic perspective. However, it is interesting to check if the bridge also gets support from performance perspective for not being demolished after the theoretical end of life. The picture of this bridge and basic background information of it can be seen in Figure 37 and Table 20.

Figure 37 Project 2 Bieslandsebrug

Table 20 Background Information of Bieslandsebrug

Code	37E-126-01
Name	Bieslandsebrug: Brug over de Bieslandse Molensloot (bridge over Bieslandse Molensloot)
Administrator	RWS WNZ/WNZ District Noord
Municipality	Delft
Province	Zuid-Holland
National Road	A13
Construction Year	1933 (1934 in inspection report)
Object Type	Fixed Bridge (Concrete, Slab)
Network	HWN-Dry

Object Size (m)	Length: 33.3 Width: 37.2
Cultural & Historical Importance	Green
Economic Network Category	Orange (C): high intensities and great importance with the spatial economic policy
Object status	In use
Corridor/Economic Importance	Delft-Zuid – KP Ypenburg (L)
Current Traffic Intensity	Total 80800 per year (weekday), wherein truck traffic 7945
Last IHA	01/10/2014
Object Quality (Risk Level)	4
Load Class	60
End of Life	Theoretical: 2013 Technical: 2031
EELI	0.84
Replacement Value (k€)	3000-5000

5.1.3 Project 3 Groenebrug Oost

Groenebrug Oost locates near Gouda in Randstad area. This bridge was constructed in 1937 and it was designed to provide service for the local transportation for 80 years, which means it should be demolished in this year. Moreover, its technical life also ends in one year. In addition, the EELI for this bridge is 1.2, which is already more than 1. In other words, this bridge has been replaced already because it is not worthy to spend a huge amount of budget to maintain it. Hence, it is verified if this bridge should be replaced soon using performance age. The picture of this bridge and basic background information of it can be seen in Figure 38 and Table 21.

Figure 38 Project 3 Groenebrug Oost Viaduct

Table 21 Background Information of Groenebrug Oost Viaduct

Code	38A-001-02
Name	Groenebrug oost: Hoofdoverspanning van het oostelijk viaduct (Ongelijkvloerse kruising rijksweg – spoorlijn Gouda-Den Haag)
Administrator	RWS WNZ/WNZ District Noord
Municipality	Zuidplas
Province	Zuid-Holland
Construction Year	1937
Object Type	Viaduct (Concrete, loadings carried by slab) Viaduct (Steel, loadings carried by arch)
Network	HWN-Dry
Object Size (m)	Concrete Slab *2: length: 8.3 width: 18.13 Steel Arch: length: 70.84 width: 17.87
Cultural & Historical Importance	Orange
Object status	In use
Corridor/Economic Importance	KP Gouwe – KP Terbregseplein (L)/
Current Traffic Intensity	
Last IHA	01/04/2017
Object Quality (Risk Level)	4
Load Class	A
End of Life	Theoretical: 2017 Technical: 2018
EELI	1.2
Replacement Value (k€)	3000-5000

5.2 Data Gathering

The data is gathered by interviewing three experts and asking them to fill in the evaluation form, see Table 20 in the next page. According to the discussion in section 4.1, this measurement scale is proposed based on literature and reviewed by two experts, which is a compromised scale with many qualitative statements. However, in reality, there will be two types of data that can be applied to describe indicators: quantitative data and qualitative data. In order to strengthen the measurement result, bridge owners can provide alternative measurement ways which apply quantitative data if possible. If not, then bridge owners are asked to colour the statements which are closest to the condition of these bridges. When there are quantitative measurements, the exact numbers are asked to be provided as well. The coloured (yellow) area in Table 22 is just to give the bridge owners an example of how to finish this form. The results of the forms for three bridges are attached in Appendix G.

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Table 22 Measurement Table for Bridges

Indicators	Meets the future desired requirement (5)	Meets the current desired requirement (4)	Sufficient (3)	Slightly insufficient (2)	Completely insufficient (1)
Functional time duration	Hardly any hindrance due to planned and unplanned maintenance (robust) with traffic increase.	Hardly any hindrance due to planned and unplanned maintenance, leading to negligible user delay cost compared to the regular road maintenance.	Planned or unplanned maintenance leads to undesired, not negligible yearly user delay, leading to incidental but acceptable complaints of road users or other stakeholders.	Planned or unplanned maintenance leads to not negligible user delay cost and frequent complaints of road users.	Planned or unplanned maintenance leads to claims or seriously damaged reputation.
Alternative measurement					
Function failure probability	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low and not expected to grow in the next decades.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is moderate, leading to incidental but acceptable complaints of road users or other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is moderate. It leads to frequent complaints of road users and other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is high. It leads to claims of road users and other stakeholders or seriously damaged reputation.
Alternative measurement					
Load bearing capacity	Load bearing capacity fulfills the requirements even with foreseeable traffic increase.	Load bearing capacity completely fulfills the requirements of current traffic.	Load bearing capacity almost fulfills the requirements of current traffic and does not limit the traffic.	Load bearing capacity is not sufficient and the traffic is limited (loading or speed, especially truck traffic) in an unacceptable level.	Load bearing capacity fails to carry the traffic and have high probability of dangerous consequences.
Alternative measurement					
Traffic volume carried	There is sufficient residual capacity for the future traffic increase I/C ratio (Intensity/Capacity) <=0.8	The residual capacity meets the current requirements I/C ratio ∈ (0.8,0.85]	The residual capacity does not fully meet the current requirements but is still sufficient to carry current traffic volume I/C ratio ∈ (0.85,0.9]	The residual capacity is slightly insufficient but will not cause any serious congestion I/C ratio ∈ (0.9,0.95]	The residual capacity is insufficient and will any serious congestion I/C ratio >0.95
Alternative measurement					
Structure geometry	The structure geometry is at design level with respect to bridge height and width below and above, and sufficiently flexible for traffic increase.	The structure geometry is sufficient for current traffic with respect to bridge height and with below and above.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, but does not create an unacceptable bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, and creates an unacceptable bottleneck in the network, leading to complaints.	The bridge is the bottleneck of the surrounding network (with respect to vertical clearance/width of deck), and it causes potential safety hazard (with respect to skew).
Alternative measurement					
Space arrangement for all kinds of users	The bridge provides reliable space arrangement for all users also for possible future development.	The bridge provides reliable space arrangement for all users.	The bridge provides reliable space arrangement only for critical users (including users who contribute to the main traffic flow, inspections, and emergency services).	The bridge does not provide reliable space arrangement for critical users.	The bridge has hindrance for critical users in using spaces.
Alternative measurement					

Noise emission	The noise emission is totally acceptable and can fulfill the requirements in the foreseeable future without control measures.	The noise emission is under current limitation (required for environment permit) but requires control measures to meet the future requirements.	The noise emission is over the current limitation but it is still tolerable (no control measures).	The noise emission exceeds the limitation and some measures should be taken to control it but has no urgency	The noise emission is intolerable to people and the surrounding environment, which requires urgent measures.
Alternative measurement					
Safety level of people and property	Road configuration (fatalities and injuries percentage) is safe to users with traffic increase.	Road configuration (fatalities and injuries percentage) is currently at a safe level to users.	Road configuration (fatalities and injuries percentage) is safe enough to users with minor prevention measures.	Road configuration (fatalities and injuries percentage) is safe enough to users with a lot of prevention measures.	Road configuration (fatalities and injuries percentage) is not safe enough to users.
Alternative measurement					
Condition of drainage system	Drainage system has the required draining ability and operates without problems, even when subject to scenarios of climate change regarding the next 20 years.	The drainage system has the required draining ability and operates without problems currently.	The drainage system does not have the required draining ability and operates with problems, resulting in minor additional maintenance cost and/or yet controllable risks for road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in minor additional maintenance cost and/or incidental uncontrollable risks or road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in major additional maintenance cost and/or uncontrollable risks for road users due to deformations or aquaplaning.
Alternative measurement					
Damage level of the structure	The main structure is in perfect condition and no other cost than regular maintenance are expected in the next 20 years.	The main structure of the bridge is still in good condition. No specific maintenance problems, other than the regular periodic maintenance as expected for any other bridge.	The main structure of the bridge shows problems that exceed the regular maintenance expectations and needs minor investments to maintain the needed safety and risk level.	The main structure does not meet the current safety requirements and needs major investments to reach the needed safety and risk level.	The structure is unsafe due to damages and/or the main structure needs major investments to reach the needed safety and risk level, and will also need increasing major expenses in the future.
Alternative measurement					
User's cost	Traffic users cost the same when detour happen.	Low extra cost when detour and delay happen.	Reasonable extra cost when detour and delay happen.	Slightly unacceptable extra cost when detour and delay happen.	Unacceptable extra cost when detour and delay happen.
Alternative measurement					

5.3 Results of Test

The form designed for gathering data is expected to be filled in by a group of bridge owners. However, due to limited time and corporation, it was only filled in by one bridge owner. Thus in this research, these numbers collected are only used to illustrate the process of the methodology, while not to support the decisions on these three bridges in practice. The results for three bridges are illustrated and analysed in this section separately. The Groenebrug Oost is estimated at the end of its service life already, while Boonervliet Noord Brug and Bieslandsebrug are younger than their real age, which are estimated to be replaced in year 2054 and 2050 respectively.

Project 1 Boonervliet Noord Brug

The scores of performance indicators are given by one expert and it is shown in Table 23. The original result form is attached in Appendix G.

Table 23 Pre-evaluation Result of Boonervliet Noord Brug

Indicators	Scores	Coded value
Functional time duration	3	1
Function failure probability	3	1
Load bearing capacity	4	1
Traffic volume carried	4	1
Structure geometry	4	1
Space arrangement for all kinds of users	3	1
Noise emission	3	1
Safety level of people and property	4	1
Condition of drainage system	3	1
Damage level of the structure	3	1
User's cost	3	1
Pre-evaluation Function		1

As given in the table above, the scores of all the indicators are more than 2, which means they are higher than the cut-off value. Thus all the coded value for these indicators are 1, then the pre-evaluation function equals to 1 obviously. It can be concluded that this bridge is still in an acceptable condition.

Having passed the pre-evaluation, the measurement went to the stage where compensatory method is applied. The result is shown in Table 44, from which we can tell the overall performance score is 3.396. It indicates that the performance age is 37 years and it is suggested to be replaced in year 2054. The scores in different criteria are given in the table as well. In order to show the vulnerable criteria more directly,

Figure 39 gives the distribution of performance score. Safety has the best performance out of the five criteria and there is not much difference among all these criteria.

Table 24 Final Result of Boonervliet Noord Brug

Score of Functionality	3.453
Score of Environment	3
Score of Safety	3.822
Score of Serviceability	3
Score of Economics	3
Performance Score	3.396
Residual Life	37
Performance Age	43
Estimated Replacement Year	2054

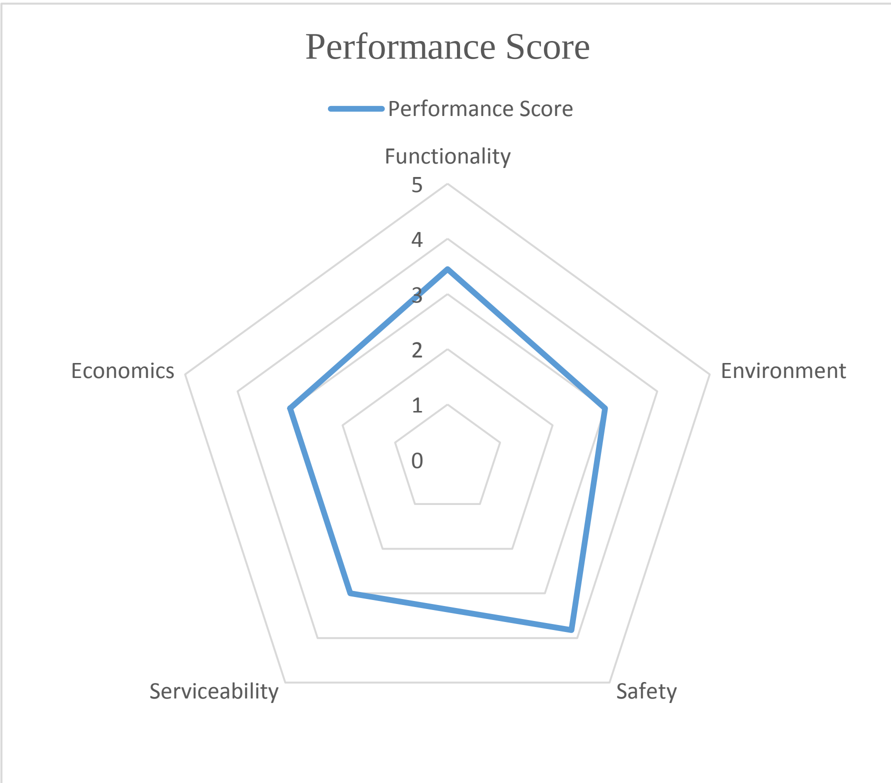

Figure 39 Performance Score Distribution of Boonervliet Noord Brug

Project 2 Bieslandsebrug

Table 25 provides the pre-evaluation result of this bridge. Similar to the result of Boonervliet Noord Brug, the scores of indicators are higher than one, thus the coded value of them are 1 and the pre-evaluation function equals to 1. This bridge also passed the pre-evaluation.

Table 25 Pre-evaluation Result of Bieslandsebrug

Indicators	Scores	Coded value
Functional time duration	3	1
Function failure probability	3	1
Load bearing capacity	3	1
Traffic volume carried	4	1
Structure geometry	3	1
Space arrangement for all kinds of users	4	1
Noise emission	4	1
Safety level of people and property	3	1
Condition of drainage system	3	1
Damage level of the structure	3	1
User's cost	3	1
Pre-evaluation Function		1

From the data gathered above, the final result of Bieslandsebrug calculated by the quantification methodology is given in Table 26. The result implies that the bridge is younger than its real age and it is suggested to be replaced in year 2050.

Table 26 Final Result of Bieslandsebrug

Score of Functionality	3.212
Score of Environment	4
Score of Safety	3.178
Score of Serviceability	3
Score of Economics	3
Performance Score	3.245
Residual Life	33
Performance Age	47
Estimated Replacement Year	2050

The distribution of performance score is depicted in Figure 40, which indicates that this bridge has good performance in environment, whereas the other four criteria have almost same level of performance.

Project 3 Groenebrug Oost

The pre-evaluation result of this bridge is shown in Table 27. As can be seen in this table, the indicators "structure geometry" and "damage level of the structure" obtained 2 and the coded value turned to be 0, which stopped this bridge to get into the next phase. In fact, this bridge ought to be widened according to the local spatial development. However, due to technical problems in the bridge itself, it cannot be widened or it is not worthy to be widened. In conclusion, the performance age of this bridge is 0 and it is suggested to be replaced as soon as possible.

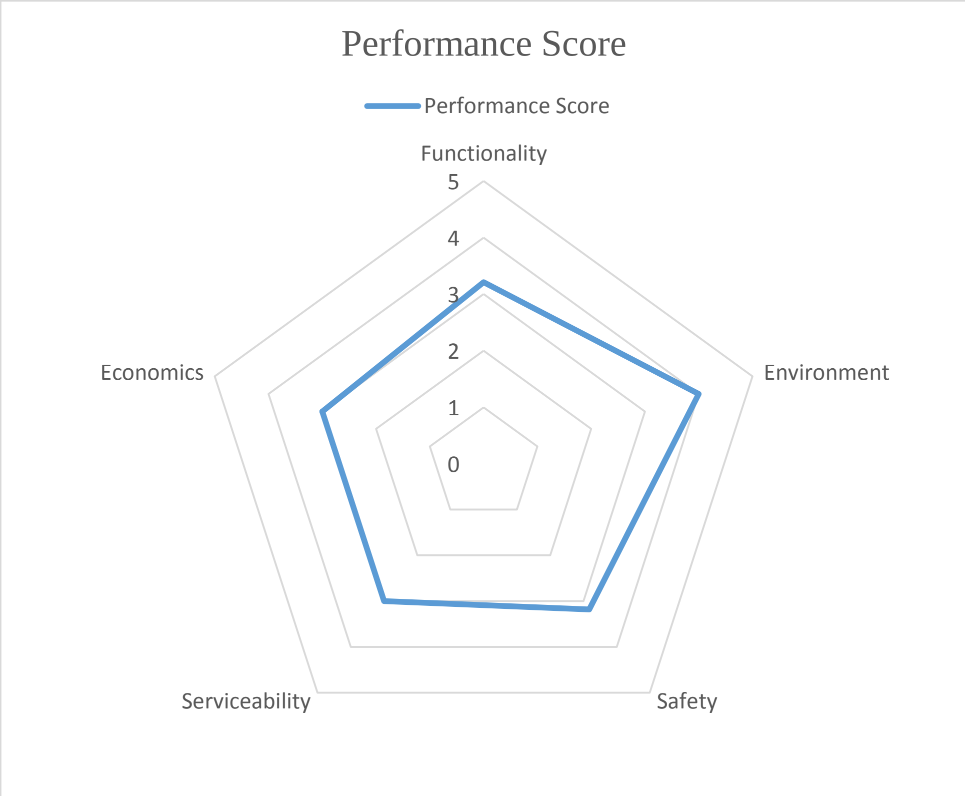

Figure 40 Performance Score Distribution of Bieslandsebrug

Table 27 Pre-evaluation Result of Groenebrug Oost

Indicators	Scores	Coded value
Functional time duration	3	1
Function failure probability	3	1
Load bearing capacity	3	1
Traffic volume carried	5	1
Structure geometry	2	0
Space arrangement for all kinds of users	3	1
Noise emission	4	1
Safety level of people and property	3	1
Condition of drainage system	4	1
Damage level of the structure	2	0
User’s cost	3	1
Pre-evaluation Function		0

5.4 Discussion

From the results of running the proposed methodology in three typical cases, it can be seen that there are some differences between the parameters which are in use and Performance Age. The comparison is shown in Table 28. In this comparison table, the EELI based on Performance Age is calculated by EELI calculation form which is used by RWS currently. The detailed calculation can be found in Appendix H.

Table 28 Comparison of Performance Age

	Project 1	Project 2	Project 3
Technical replacement year	2035	2031	2018
EELI based on Technical replacement year	0.7	0.84	1.2
Replacement year based on Performance Age	2054	2050	2017
EELI based on Performance Age	0.61	0.58	1.12

Regarding the comparison between technical replacement year and replacement year base on performance age, the results keep in consistency, which shows the project 1 and project 2 are still in good service condition from performance perspective. However, the replacement years based on Performance Age are longer than those based on technical estimations. For the project 3, the results from both ways are almost the same as the bridge is already the bottleneck of the local network and it is urgent to take some actions on it.

When comparing the EELI calculated based on technical replacement year and performance age, the results show consistency as well. For project 1, EELI based on technical replacement year is 0.7, which is higher than the result based on Performance Age. This implies that the bridge is more profitable when taking the performance evaluation into account while not only technical considerations. The results of project 2 again proof that EELI based on Performance Age is lower than that based on technical replacement year, which will actually postpone the replacement decision. In other words, the later the replacement year is, the lower EELI is when EELI is lower than 1. On the contrast, when EELI is higher than 1, the earlier the replacement year is, the lower EELI is, which can be discovered from the results of project 3. However, this finding is only based on the tested three bridges. It should be tested in more samples before using it as a generic rule.

In conclusion, in these three cases, even though the result of Performance Age is not fully consistent with the technical replacement year, it still matches the real-world practice. In addition, both EELI and Performance Age contribute to consistent results, and Performance Age gives more numerical indication of the exact replacement year. The replacement decisions can be improved in this way. Moreover, EELI can also be improved if calculated based on Performance Age. Last but not least, based on the combination of EELI and Performance Age, different replacement decisions (provided in Table 29) and strategies can be made. When EELI is higher than 1, there will be three scenarios: 1) the residual life is already 0, then this bridge should be replaced as soon as possible, because both parameters indicate that it is not worthy to keep maintaining the bridge, 2) the residual life is less than its theoretical rest service life, then the asset manager could spare the money on current maintenance to other investments and replace it when it reaches the end of Performance Age. This is because EELI already shows it is not worthy to keep maintaining it but Performance Age would prefer keeping the bridge functioning, 3) the residual life is more than its theoretical rest service life, then contradictory happens between these two parameters, which requires judgements from other parameters. When EELI is lower than 1, three scenarios lead to different strategies as well: 1) the residual life is already 0, which is in conflict with EELI result, then other parameters should be looked into, 2) the residual life is less than theoretical rest service life, then more money should be invested on maintenance even though this action will have bad influence on EELI, there is still buffer zone for before EELI suggests to replace this bridge. The bridge should also be replaced when it reaches the end of Performance Age, 3) the residual life is longer than theoretical rest service life, then do nothing and just keep the current maintenance strategies.

Table 29 Replacement Strategies based on Combination of EELI and Performance Age

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

CHAPTER SIX

CONCLUSIONS, DISCUSSIONS, RECOMMENDATIONS

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6. Conclusions, Discussions, and Recommendations

Introduction

In this chapter, the conclusions, discussions and recommendations will be elaborated. Conclusions explain how the research objective can be satisfied and end with the answer to the main research question. Thereafter, the challenges that were confronted during implementing the research and the limitations to the proposed methodology are discussed. Lastly, recommendations for RWS and future research are listed separately.

6.1 Conclusions

To meet the main objective of this research, which is to find more performance-based support to improve the replacement decision of highway bridges, the parameter Performance Age was introduced and the methodology to quantify it was proposed. The proposed methodology is able to deliver on this objective. Figure 41 provides the procedure of operating the proposed methodology. The input, process, and output of each step in the methodology are illustrated in this figure separately. The connections between them are depicted as well. The procedure starts with establishing a performance model (Figure 9). All the criteria and indicators in this model were investigated in detail on the basis of literature review and document analysis. In this research, a performance score was calculated as the intermediary of quantifying Performance Age. A group of experts were invited to validate this model and the complete quantification process was tested in three real-world projects.

However, the proposed procedure is just the main skeleton of realizing the quantification goal. Even though it is designed to help with replacement decisions by RWS, it still keeps its generic characteristic and is open to different flexibilities. Firstly, the performance model in this research was designed for RWS and only focused on the highway fixed bridges, thus part of the input which influences the model establishment can be flexible in other cases. In addition, validation and selection phase contains flexibilities such as the number of attending experts. The workshop can also be replaced by a survey with a clear target if it is more convenient and efficient to achieve the goal. Secondly, the model data collecting stage contains many flexibilities. For example, the strategy of carrying out the data collection could be different. Instead of asking bridge owners to fill in measurement forms, intensive interviews could be another feasible way. Last but not least, regarding the data processing tool, it can be developed by other software and/or other coding languages instead of MS Excel template and Visual Basic.

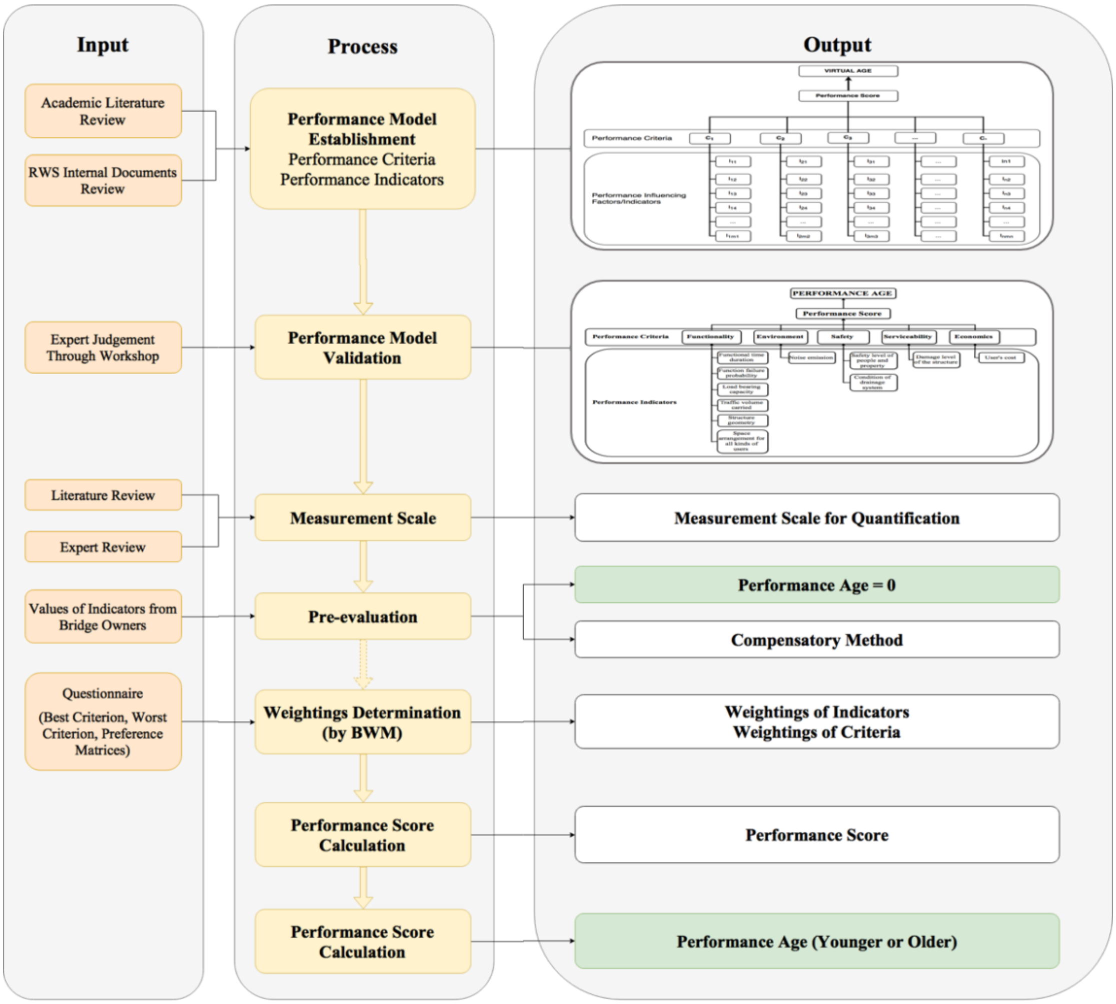

Figure 41 Quantification Methodology of Performance Age

Apart from the high flexibility, the which is the most widely-used platform in office. This will increase the efficiency of making the replacement decisions and it is much easier for people to understand how the procedure and calculation work.

Through operating the whole process, the answer to the main research question ***"How can the long-term parameter "Performance Age" based on life cycle performance improve replacement decisions only based on economic parameters of highway bridges?"*** would be the three main improvements:

- ➢ *Performance Age contains considerations on criteria and indicators from different perspectives and various interests of stakeholders, the result is more comprehensive and easier to be accepted by stakeholders.*

  As the main question is solved following the pattern of solving MCDM problems, the performance model includes considerations from diverse viewpoints, the result would be an overall one. In addition, various interests of different stakeholders, both in individuals and groups, the performance model enables multi actors to play in the decision-making platform. Thus, the decisions made with support of

Performance Age will be easier to be accepted by different stakeholders.

- *Performance Age provides a numerical prediction on the end of life of bridges in a time scale ,then the result is more direct and accurate.*

  There will be three types of results by running this methodology: (1) Performance Age is 0 (at its end of life), (2) Performance Age is longer than its theoretical rest lifetime, (younger than its real age), (3) Performance Age is shorter than its theoretical rest lifetime, (older than its real age). These three types of result deliver the asset manager direct information about whether the bridge should be replaced or not. Moreover, the prediction on the rest lifetime provides the asset manager more accurate suggestions on when to replace the bridge.
- *Different replacement strategies can be made based on the combinations of Performance Age and EELI.*

6.2 Challenges and Limitations

Several challenges need to be overcome in building performance metrics for highway bridges. Not surprisingly, this research was confronted with these challenges.

Typically it was always challenging to deal with the time. For instance, when collecting the responses to the questionnaire designed for determining the weightings of performance indicators, only the responses in one week were collected. The response rate was quite low, which might lead to inaccuracy of this quantification result. It is believed that the challenge of limited time can be solved by doing intensive interviews with targeted respondents while not through online questionnaire.

Another challenge is the low corporation degree of the bridge owners. When collecting the values of indicators from bridge owners, it was super hard as some relevant bridge owners are on their summer vacation, therefore only data from one bridge owner was gathered. This contributed to delay of the schedule of this research. However, this challenge was not excepted but sort of unavoidable and has to be accepted as this research was carried out in a specified time period.

Apart from these challenges, there are also limitations to the proposed methodology.

- It is was hard to derive precise definition of the criteria and indicators in the performance model as the descriptions of them are so vague in existing literature. This led to confusion to experts in the problems-coping workshop.
- Most of the indicators were measured by qualified statements while not quantified numbers. In fact, it was a compromised way to cope with the failure in collecting the measurements from experts. This weakened the accuracy of the methodology.
- When collecting the data for measuring the performance of the three chosen bridges, only response from one bridge owner was obtained. This makes the evaluation subjective to some extent. However, it has to be admitted that that is the most reliable data that could be achieved at that moment. This limitation led to

inaccuracy of the final assessment and it can be improved if there are contributions from more bridge owners.

- From the result of the testing cases, limited accuracy can be found in the measurement scale part, when values of criteria/indicators equal to 2 or 1, then Performance Age is already 0. This also means the starting score of calculating the rest lifetime (0 year) will be 2 as it is the break-even point. If it is more than 2 then it is acceptable. However, if the bridge passed the pre-evaluation phase, there will only be scores 3, 4, and 5 on all the indicators, which means no matter how the scores distribute, the overall score after multiplying weightings will equal to 3 or be more than 3. In other words, the starting residual lifetime would not be 0 year while [(3-2)/(5-2)]*80=26.7≈27 years. Hence, there will be a blank score range (2,3) when determining performance score.
- When interpreting the performance score to Performance Age, the relation between them were assumed to be linear. However, in reality, the relation should be decided by the deterioration rate of the bridge, which usually is non-linear.

6.3 Recommendations

In this section, recommendations for RWS and future research will be elaborated based on the aforementioned limitations so that the quantification methodology can be improved in the future. This section is divided into two parts. Firstly the recommendations for RWS are listed, followed by those for future research.

6.3.1 Recommendations for Asset Manager (RWS)

Based on the limitations, further work could be of vital importance if asset manager (RWS) is to adopt Performance Age metric to a serious degree. It is recommended that the following actions should be resolved before they are able to do so.

- ➢ As there is no structured working procedure of evaluating the performance of highway bridges, it is strongly recommended to build up a comprehensive checklist of the performance criteria and indicators that influence performance.
- ➢ In order to overcome this challenge, some real-world case studies on how the decision-makers made the replacement decisions are suggested to be conducted, which will enhance the understandings of criteria and indicators.
- ➢ It is highly recommended to conduct problem-scoping workshops for different types of bridges as the key performance indicators can differ from type to type, area to area, etc.
- ➢ It is strongly recommended to derive the definition of measurement scale from the existing database, as well as the experience of experts. In this research, this step was not able to be carried out that far but it will make the quantification much more objective.
- ➢ EELI is calculated based on the technical year of bridges, which is determined by

the estimation of experts. In order to improve the accuracy of EELI, it is strongly recommended to use Performance Age as the basis of EELI calculation.

- It is highly suggested to implement the evaluation procedure in a specified time interval so that the condition of the bridge could be monitored. And the information for making decisions will be updated.
- It is strongly recommended to include the Performance Age in DISK system, thus the Performance Age will be more direct and visualized for RWS.
- It is recommended that RWS should organize workshops to make the decision-makers aware about the performance indicators that can be derived from academic literature, while not only make decisions based on existing practice.

6.3.2 Recommendations for Future Research

Recommendations for future research are given in this part. These recommendations are based on the limitations discussed in section 6.2. If there are more research on the following tracks, the accuracy of the methodology will be increased, and the efficiency of the decision-making process can be improved.

Improving the accuracy of the proposed methodology

As discussed in the previous limitation section, the accuracy of the measurement scale is not satisfying enough as it uses only 3, 4, and 5 to represent 80 years, which is in fact quite vague. This is the nature of quantifying soft indicators but it could be improved by defining a more refined measurement scale, such as 1-9, and give as precise as possible definition of each value in the scale. Therefore the accuracy can be improved.

Another track to improve the accuracy would be looking into the relation between the performance decreasing speed and deterioration. This will help with the interpretation from performance score to Performance Age, and to develop a more accurate long-term performance-based parameter.

Expanding the methodology into a network level

This research limited the scope in the replacement decisions on object level. However, in reality, asset manager are always required to make the bridge replacement decisions with considerations of its influence to the network, local, regional, or even national. For instance, replacing a bridge requires the asset manager to spare money from construction of new bridges in this area. In this case, the asset manager will have to think about the priority of these decisions. Therefore, it will be worthy to explore more on network level.

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Appendices

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Appendices

Appendix A: Document Analysis & Literature Study

Appendix A.1: List of performance criteria in separate academic research papers

NO	Literature	Performance Criteria
1	Name: EN 1992 EUROCODE 2: Design of Concrete Structures – Part 2: Concrete Bridges – Design and detailing rules Author: European Committee for Standardization Year: 2005 Type: Guideline	Apart from structural safety, serviceability and durability are also addressed as criteria of bridge performance. - Serviceability: the required protection of the structure is established by considering its intended use, service life, maintenance program and actions. The possible significance of direct and indirect actions, environmental conditions and consequential effects are also considered. - Durability: A durable structure shall meet the requirements of serviceability, strength and stability throughout its intended working life, without significant loss of utility or excessive unforeseen maintenance.
2	Name: COST TU1406 Action Performance Indicators Database Author: European Cooperation in Science and Technology TU1406 Action Working Group 1 Year: 2016 Type: Report	This report addressed a general description of life-cycle bridge performance indicators, how they are assessed (e.g. visual inspection, non-destructive tests and monitoring systems), with what frequency, what values are generally obtained and, finally, some general recommendations. The criteria applied in this research are as follows: - Safety: the load factor, the reliability index to ULS - Serviceability: the condition index, the reliability index to SLS - Availability: robustness - Costs: the total LCC, values related to durability aspects - Environmental efficiency: CO_2 foot-print
3	Name: Bridge management in the Netherlands; prioritization based on network performance Author: H.E. Klatter, J.M. van Noortwijk, N. Vrisou van Eck Year: 2002 Type: Conference Proceedings	- Accessibility: accessibility relates to the primary function of the structure for traffic. Quantitatively this implies availability. A structure can be not available during maintenance activities or due to failure of installations. - Traffic safety: traffic safety comprises user safety directly related to traffic actions. - Environmental quality: the environmental quality in the definition used is determined by the noise production of the traffic using the structure. - Comfort: comfort is used to express an extra user quality. - Aesthetics: aesthetics is determined by the external design of the structure.
4	Name: Applying RAMSSHEEP analysis for risk-driven maintenance Author: W. Wagner, P.H.A.J.M van Gelder Year: 2013 Type: Conference Proceedings	The criteria that is applied in analysing the bridges in the Netherlands are RAMSSHEEP: - Reliability: the failure probability of a system in which its functions cannot be fulfilled - Availability: the time duration in which the system is functional and its functions can be fulfilled - Maintainability: the ease in which the system can be maintained over time - Safety: the absence of human injuries during using or maintaining the system - Security: a safe system with respect to vandalism, terrorism and human errors - Health: the objective argument of good health with respect to the physical, mental and societal views - Environment: influence of the system on its direct physical environment - Economics: a serious reflection in terms of cost versus benefits (as well as direct and indirect) to provide more insight for

		an economical responsible choice - Politics: a rational decision on all the previous aspects
5	Name: Performance indicators for concrete bridges Author: Grischa Dette, Viktor Sigrist Year: 2011 Type: Conference Proceedings	This paper mainly describes the performance indicators for concrete bridges in Germany and applied its framework in a case study of a bridge in Hamburg. The proposed criteria and indicators are as follows: - Proper functioning: structural safety, structural serviceability, durability - Economy: owner's cost, user's cost/social cost - Society & Culture: aesthetics, preservation, other social aspects - Environment: greenhouse gas emission, resource consumption, waste generation
6	Name: Long-term Bridge Performance High Priority Bridge Performance Issues Author: US Department of Transportation, Federal Highway Administration Year: 2014 Type: Report	This paper illustrates the bridge assessment framework in US. The bridge performance is evaluated in the following four aspects: - Structural condition: durability and serviceability (including fatigue) - Functionality: user safety and service - Costs: State transportation department and users - Structural integrity: safety and stability in failure modes
7	Name: A framework for evaluating the performance of infrastructure assets. Application to the life-cycle of road and railway bridges Author: Patrício Hugo, Almeida Nuno Year: 2013 Type: Conference Proceedings	The main criteria and indicators are: - Delivery: available capacity, required capacity - Condition (durability): remaining life-span - Availability: % of agreed availability, % availability - Life cycle costs: preventive maintenance, corrective maintenance, renewal - Reliability: probability of failure, level of service
8	Name: Framework of performance indicators for managing road infrastructure and pavements Author: Frannie Humplick, William D. O. Paterson Year: 1994 Type: Conference Proceedings	The set of indicators for the bridge performance should measure the following: - Whether operational, sectorial, and policy objectives are being met - Whether user demands are being met and to what degree the users of the provided services are satisfies - Whether the service providers are performing as efficiently as expected - Whether the actions desired by policy makers (e.g., regulators) are being carried out and whether policy makers' actions are creating bottlenecks for service producers.
9	Name: 20th Annual Report on the Performance of State Highway Systems Author: David T. Hartgen, M. Gregory Fields and Elizabeth San Jose Year: 2013 Type: Report	This report measures the bridge performance in 6 different domains: - Safety: significant reduction in fatalities and injuries - Infrastructure condition: maintain highway infrastructure ...in a state of good repair - System reliability: improve efficiency of the surface transportation system - Freight movement and economic vitality: improve national freight network, strengthen rural communities... and support regional economic development - Environmental sustainability: enhance performance while protecting ...natural environment - Reduced project delivery delays: ...eliminate delays in project development

Appendix A.2: List of performance criteria in RWS documents

NO	Name	Performance Criteria
1	Basisspecificatie Vaste Brug	Availability: life time requirements for bridge object and its components. The availability of other traffic during the construction should also be ensured. Reliability: the object should provide the minimum required space and also should be constructed reliable with the requirements listed in ROB and RBK. Sustainability: the object should have protection system so that the structure can last till its required lifetime. Ergonomics: not really important, but some specific project will have requirements in this aspect in respect to the accessibility for inspection and maintenance. Health: not that important but some specific project have requirements in this aspect. The vulnerable points or where the deficiency will mostly happen in the operation and maintenance phase should be warned in the beginning. Environmental Nuisance: the noise emission of the bridge should be under control. Maintenance: the bridge should be easy and safe to inspect and maintain Demolition Difficulty: the bridge should have as less as possible influence to its environment during demolition. Future Stability: there should be some space left for future changes or development in the bridge Safety: the safety of users including drivers and passengers should be ensured Aesthetics: the appearance of the bridge should fulfil its specific requirements
2	Objectbeheerregime Kunstwerken HWN (inclusief OBR samenvatting)	Another important point in this document is that the requirements that a bridge needs to fulfil are categorized into RAMSSHEEP aspects. However, some of them are combined into a broader ones and their definitions are as follows: Reliability + Availability + Maintainability: fulfilling the primary function of the networks. It also is described as the operation of networks or network availability. Safety: user safety of the network. Security + Health + Environment: preconditions which make it possible to fulfil its primary functions. Economics: life cycle costs Politics: the image or reputation of RWS, both in the public and in political and administrative purposes.
3	Handboek Wegontwerp – Basiscriteria	The basic criteria of road design, road category and the specific design for each type of road are explained. The criteria for elements and some other topics are also discussed in this document. As bridges are also part of the roadway system, thus some criteria could be borrowed to the bridge performance evaluation with systematic consideration. Safety is emphasized in this document.
4	Standaarddetails voor Betonnen Bruggen	In each chapter, a separate part of concrete bridge is dealt with and the requirements of each component are listed. These requirements can be divided into functional requirements, constraints, internal and external interfaces and feature requirements. The requirements are classified into different aspects: appearance, management and maintenance, safety and health, availability/reliability, future stability. This document can provide the information about how to assess the performance indicators and their thresholds.
5	Richtlijnen Ontwerpen Kunstwerken 1.3	Almost all the additional requirements of bridges mentioned in this document are from technical perspective, which are not so important to evaluate the functionality or serviceability of the bridge from performance perspective. But it can provide references when quantifying the relevant indicators.
6	Rijchtlijnen Beoordeling Kunstwerken 1.1	Similar to ROK, RBK is a guideline for assessing existing structure safety and serviceability from technical perspective, which can be a reference documents when quantifying the relevant indicators.

Appendix A.3: Distribution of performance criteria

Criteria	Documents						Typical literature								
	Basisspecificatie	OBR Kunstwerken HWN	Handboek Wegontwerp - Basiscriteria	Standaarddetails voor Betonnen Bruggen	Richtlijnen Ontwerpen Kunstwerken 1.3	Richtlijn Beoordeling Kunstwerken 1.1	(European Committee for Standardization)	(COST TU1406 Action WG1)	(Klatter, van Noortwijk, & Vrisou van Eck, 2002)	(W. Wagner, P.H.A.J.M van Gelder)	(Grischa Dette, Viktor Sigrist)	(US Department of Transportation)	(Patrício Hugo, Almeida Nuno)	(Frannie Humplick, William D. O. Paterson)	(David T. Hartgen, M. Gregory Fields and Elizabeth San Jose)
Availability	√			√				√	√	√			√		
Reliability	√				√	√				√			√		√
Sustainability	√														
Ergonomics	√														
Health	√	√		√						√					
Environment	√	√						√	√	√	√				√
Maintainability	√			√						√					√
Demolition Difficulty	√														
Future stability	√			√											
Safety (to users)	√	√	√	√	√	√	√	√	√	√	√	√			√
Aesthetics	√			√					√						
Functionality		√	√						√		√	√	√	√	
Security		√								√					
Economics		√						√		√	√	√	√		√
Politics		√								√					
Serviceability							√	√			√	√	√	√	√
Durability							√				√	√	√		
Comfort									√					√	
Social & Culture											√				

Appendix A.4: List of performance indicators in separate academic research papers

NO	Literature	Performance Indicators
1	Name: EN 1992 EUROCODE 2: Design of Concrete Structures – Part 2: Concrete Bridges – Design and detailing rules Author: European Committee for Standardization Year: 2005 Type: Guideline	In order to provide bridge a sufficient life, the following actions could be taken, which can also be considered as indicators to assess the bridge condition: - Density, quality, and thickness of concrete cover (for corrosion protection of steel bars) - Crack control (for corrosion protection of steel bars) - Stress limitation (for concrete and steel bars) - Appropriate detailing of the reinforcement - Appropriate detailing of the bridge to limit external attacks (waterproofing layer, waterspouts, sufficient cross and longitudinal slope) - Taking into account the evolution of material properties during the prescripted lifetime of the bridge: concrete (shrinkage, creep), pre-stressing (stress relaxation, pre-stress loss) - Precautions and recommendations to avoid alkali-aggregate reaction in concrete and delayed ettringite formation (internal surface attack) (type of aggregate, temperature of the concrete) - Avoidance of abrasion and erosion with coated macadam - Checking of the fatigue behavior of pre-stressed tendons when concrete is in tension under frequent live loads (particularly pre-stressed structures)
2	Name: COST TU1406 Action Performance Indicators Database Author: European Cooperation in Science and Technology TU1406 Action Working Group 1 Year: 2016 Type: Report	However, those indicators are concentrated on technical deterioration of bridges, and there are 385 indicators even in the clustered database. So only a small part of the indicators could be the performance indicators that the thesis is looking for, such as level of damage, material conditions, load-bearing capacity, noise, vegetation level, the impact of the bridge availability on the network availability, traffic restriction, traffic volume, and traffic loading.
3	Name: Bridge management in the Netherlands; prioritization based on network performance Author: H.E. Klatter, J.M. van Noortwijk, N. Vrisou van Eck Year: 2002 Type: Conference Proceedings	- Accessibility: The quality of the structure directly related to the traffic is also included in this objective. Indicators are structural reliability, load carrying capacity, user safety (not directly related to traffic safety) and durability. - Traffic safety: The condition of the road surface and guard rail are the most relevant components. - Environmental quality: The condition of the road surface, pavement and joints, is the dominant factor. - Comfort: This aspect is also determined by the quality of the road surface. - Aesthetics: The most relevant items for maintenance are the color and the shape of the visible surface.
4	Name: Performance indicators for concrete bridges Author: Grischa Dette, Viktor Sigrist Year: 2011	- Proper functioning (structural safety): is usually verified by two alternative types of performance indicators: by the relation of the design resistance to the corresponding sectional force or alternatively by the reliability index β - Proper functioning (structural serviceability): is usually verified by indicators such as stresses in concrete and steel, crack widths, deflections and vibrations — each of which being calculated for service loads

	Type: Conference Proceedings	- Proper functioning (durability): mentions performance indicators such as carbonation depth, or chloride content - Economy (owner's cost): comprise all costs in connection with the design, construction, inspection, maintenance and decommissioning of the asset - Economy (user's cost/social cost): there is still argument in this aspect - Society & Culture (aesthetics): The indicator relative time of unsatisfactory appearance (RTUA) is defined as the fraction of the service lifetime in which the condition of the concrete surface is below a certain aesthetic threshold and thus the appearance is impaired. - Society & Culture (preservation): 'preservation of heritage' The performance indicator average availability (Aav) describes the average ratio of actual traffic capacity to the design capacity - Society & Culture (other social aspect): 'prestige' / 'acceptable risks to society' - Environment (greenhouse gas emission): CO2 equivalent emissions (kg) - Environment (resource consumption): primary energy consumption (J) - Environment (waste generation): landfill (m3) - Environment (others): such as eutrophication which is assessed by PO4 equivalent (kg)
5	Name: Long-term Bridge Performance High Priority Bridge Performance Issues Author: US Department of Transportation, Federal Highway Administration Year: 2014 Type: Report	- The performance of any single bridge or element of a bridge is dependent on multiple factors, many of which are closely linked. They include the original design parameters and specifications (bridge type, materials, geometries, load capacities); the initial quality of materials and quality of the as-built construction; varying conditions of climate, air quality, and soil properties; and corrosion and other deterioration processes. Other factors influencing performance include traffic volumes, counts and weights of truck loads, truck live load impacts, and damage sustained as a result of scour, seismic events, wind, etc. A final critical factor influencing performance is the type, timing, and effectiveness of preventive maintenance, of minor and major rehabilitation actions, and ultimately of replacement actions applied to the bridge.
6	Name: A framework for evaluating the performance of infrastructure assets. Application to the life-cycle of road and railway bridges Author: Patrício Hugo, Almeida Nuno Year: 2013 Type: Conference Proceedings	- Delivery: available capacity, required capacity - Condition (durability): remaining life-span - Availability: % of agreed availability, % availability - Life cycle costs: preventive maintenance, corrective maintenance, renewal - Reliability: probability of failure, level of service
7	Name: Framework of performance indicators for managing road infrastructure and pavements Author: Frannie Humplick, William D. O. Paterson Year: 1994 Type: Conference Proceedings	Service quality: The service quality indicators reflect the user's perspective, which can be measured in two ways. The first of these is in terms of the end product to the user-for example, whether the user actually receives the services desired and whether there has been an alteration, cessation, or total loss of service. - Functionality: network density, road-space availability, road-space sustainability, Utilization: vehicle travel, traffic density, passenger travel, freight travel

Appendix A.5: List of performance indicators in RWS documents

NO	Document & Introduction	Performance Indicators
1	Basisspecificatie Vaste Brug	- Technical lifetime (object): The bridge should fulfil its functions for at least 100 years. (This requirement applies to new construction, while the requirements for existing structures should be in accordance with RBK.) - Technical lifetime (component): The technical life of different structural components should fulfil their functions for a period of years. At least the expansion joints should meet the requirements in ROK/RTD 1007-2, and bearings should sustain for 25 years. (Perhaps in some specific projects, there are components with special lifetime requirements.) - Availability for crossing traffic during realization: There should be a minimal space to ensure that the existing traffic can still go smoothly (during construction when there are some temporary structures, the ships can still go through it). (This requirement only applies to existing connections. Specific project must also meet this requirement.) - Reliability for space profile: The object should facilitate compliance with the required usability from ROK and/or RBK (Minimum required space). (In the review of the Profile of free space, the deformations caused by captured loads in the ROK should be taken into account.) - Reliability for construction: The object should be constructed reliable in compliance with the required reliability level from ROK and RBK (follow the directives). (ROK applies to new construction, RBK applies to rehabilitation and usage.) - Prevent deterioration mechanisms: (Degradation mechanisms that can shorten the remaining life of components in the system must be prevented or remedied in accordance with the ROK, RTD1002 requirement 8.8.(9) T/m(11) and RTD 1009). (ROK, RTD 1002 requirement 8.8 (9) t/m (11) relates to the hydrophobic. RTD 1009: 'Richtlijn ontwerp van asfalt wegverhardingen op betonnen en stalen brugdekken' relates to the pavement construction. The density of the concrete and the concrete cover also play a role in preventing degradation mechanism.) - Prevent damage of steel components: Degradation mechanisms which shorten the residual life of steel components should be avoided. (In ROK various standards and guidelines have been incorporated with the preservation of steel components. In annex 8, a variety of requirements regarding the preservation of steel components are represented. Applying these standards in consultation with RWS Knowledge Centre of Conservation.) - Ergonomics: Specific project can be asked for requirements in this aspect. (Perhaps ergonomics requirements of specific project are set regarding to the maintenance in accordance with RTD 1003 with respect to the accessibility for inspection and maintenance.) - Health: Specific project can be asked for requirements in this aspect. (Perhaps health requirements of specific project are set regarding to maintenance, in accordance with RTD 1003 such as ventilation capabilities for inspection and maintenance in box girders. In case of reconstruction, asbestos in the reconstruction of existing structures should be warned) - Noise emission of expansion joints: Expansion joints should be silent in accordance with the RTD 1007-3 Noise requirements expansion joints. (Verification is based on detection by testing the noise emission of expansion joints (see RTD 1007-1) to the noise requirement (RTD 1007-3). Check with noise measurements after realization is applicable only if there is reasonable doubt to the noise emission of an expansion joint.) - Maintenance, method of maintaining: The object is inspected and maintained in a safe and acceptable way during the lifetime. (Once RTD 1003 (Ontwerp can inspectie- en onderhoudsvoorzieningen van vaste bruggen) is ready, the system should comply with this Directive. This Directive is also aiming at making possible safe maintenance ways.)

		- Inspection paths: The bridge should offer inspection paths in both side of the bridge, which are at least 500mm wide and [NTB] mm high, behind the barriers and along with the passing road. (There should be space for safe inspection of the system on and under the bridge/viaduct. Exceptions are possible underpasses where vehicle barriers are applied in the form of integrated barriers. Traffic measures should be taken in order to take inspection safely in such a situation.) - Maintenance components with a lifespan shorter than 100 years: Components of the system with a lifetime which is less than 100 years should be easily inspected, maintainable and replaceable. (Once RTD 1003 (Ontwerp can inspectie- en onderhoudsvoorzieningen van vaste bruggen) is ready, the system should comply with this Directive. This Directive is also aiming at making possible safe maintenance ways. The degree of availability of roads during inspection and/or maintenance requirements may be included in the system Road.) - Vandal resistance (graffiti): All the graffiti-accessible concrete surfaces of the object should be equipped with anti-graffiti protection. (Under-accessible surfaces are those surfaces which are accessible without tools from ground level. This requirement is further filled in consultation with the manager of the object.) - Demolition difficulty: The object should be able to be demolished within the available space in a safe way with minimal disruption to local residents and without damage to third party. (Specific project can be made. If unacceptable risks are estimated to be there, the contractor may be asked to submit a demolition plan. Herein the chosen solution can be motivated according to the requirement.) - Future cables and pipelines: The object should offer space for possible cable and pipes in the future. Because of this, there should be space available in each glancing side with a minimum diameter of 90 mm. (Here one can think of a tube, pipe or a gutter.) - Safe use: The use of the object should not endanger the safety of people and property. (A higher-level requirement may be included in the requirements in Weginfrasysteem.) - Sightlines: The system should provide sightlines for visitors, allowing them to see the space and the route. (Requirements particularly for space under bridge.) - Illumination: The system should avoid poor light space. (Requirements particularly for space under bridge.) - Security screens: The system should provide safety screens on both sides, according to RTD 1022. (Application of security screens is on the basis of risk assessment with the manager.) - Precipitation drainages: The drainage of precipitation and under the object should not contain any danger to road safety. The object should drain the precipitation according to RTD 1008. (Once RTD 1008 (Directive design of precipitation drainage of roads and works) is completed, the object must comply with this Directive. Possible projects specifically impose additional requirements on the connection between sewer and infiltration facility.) - Handrails: The object should have separation in the location of different levels according to the Bouwbesluit (Building Regulations). (Separation often takes place by means of handrail or fence. Requirements (height, distance between bars and so on) are resulted from Bouwbesluit. Perhaps they are used between the bridge decks.) - Aesthetic demands: The system must comply with the requirements of the Aesthetic Program of Requirements (EPvE). (Requirements regarding external appearance is another reason of the object construction. Standards and guidelines often include requirements for materials, workmanship and detailing in which a choice must be made from quality class, a workmanship for performance tolerances. As these requirements affect construction costs, they should be specified and they form the basis of testing and acceptance during the contract management.)

2	Objectbeheerregime Kunstwerken HWN (inclusief OBR samenvatting)	The basic functions of HWN structures are also defined in this document. All these basic functions are aiming to fulfil public interest and to create favourable conditions for usages. The possible translation of these functions to performance indicator is assumed in the brackets, and the translation can be expanded. - Connecting the traffic: move traffic from location A to location B. (Is the structure still able to carry the traffic loads, traffic volume, etc.?) - Making driving traffic possible: stimulate (in decent behaviour) and correct (by small incidents) to road traffic in the area and remain the free space between location A and B. (Is there still sufficient space for all kinds of users, including the drivers and also the passengers?) - Defining the location: enable the road/bridge users know about where they are in the road/bridge they are using. (Is there good sightline in the bridge?) - Making it possible to navigate: enable the road/bridge users to choose the route in the network. (Are the signs in the bridge still there? Is there security system for preventing vandalism and how is it functioning?) - Providing caring facilities: offer opportunities for traffics that needs care for themselves. (What is the security system condition currently? Are all the protection facilities still strong enough?) - Maintaining connections: keep other connections available other than this structure, such as wildlife, waterways, railways and recreational traffic. (Is the bridge not providing the available space for other connections as designed?)
3	Handboek Wegontwerp – Basiscriteria .	In this document, some of the indicators that influence the traffic safety for the road, which could also be the ones for bridge. - Capacity: the maximum number of vehicles that can pass a lane or bridge at a time point under certain circumstances. - Intensity: the number of vehicles per unit of time passes through a cross-section, expressed as vehicles per hour, or 24 hours. - Speed: the average speed of all vehicles on a bridge, expressed in kilometres per hour. - Density: the number of vehicles per unit of length on a bridge road, expressed in vehicles per kilometre. - Degree of integration: the relation between the bridge and the urban landscape. - Visibility: to see something from a distance, especially in some circumstances such as fog, darkness, which can be applied in assessing long bridges.
4	Standaarddetails voor Betonnen Bruggen	This document can provide the information about how to assess the performance indicators and their thresholds.
5	Richtlijnen Ontwerpen Kunstwerken 1.3	Almost all the additional requirements of bridges mentioned in this document are from technical perspective, which are not so important to evaluate the functionality or serviceability of the bridge from performance perspective. But it can provide references when quantifying the relevant indicators.
6	Rijchtlijnen Beoordeling Kunstwerken 1.1	Similar to ROK, RBK is a guideline for assessing existing structure safety and serviceability from technical perspective, which can be a reference documents when quantifying the relevant indicators.

Appendix A.6 Distribution of performance indicators

Indicators		Academic literature										Documents					
		(European Committee for Standardization,	(European Cooperation in	(Klatter, van Noortwijk & Vrisou	(Wagner & van Gelder, 2013)	(Dette & Sigrist, 2011)	(Federal Highway Administration,	(Hugo & Nuno, 2016)	(Humplick & Paterson, 1994)	(David T. Hartgen, 2013)	(Bai, Burkett, & Nash, 2006)	(Rijnen, 2016)	(Rijkswaterstaat Grote Projecten en	(Rijkswaterstaat, Richtlijnen	(Rijkswaterstaat Grote Projecten en	(Rijkswaterstaat Dienst Infrastructuur	(CROW, 2002)
Functionality	Functional time duration			√	√			√				√					
	Function failure probability			√	√							√					
	Ease to maintain its function		√	√	√		√					√					
	Aesthetics appearance			√		√						√				√	√
	Load bearing capacity	√	√	√		√		√	√	√		√			√		√
	Traffic volume carried		√				√	√	√						√		√
	Structure geometry						√										
	Space arrangement for all kinds of users											√					
	Connection maintenance											√			√		√
Environment	Noise emission of expansion joints		√	√								√					
	Greenhouse gas emission		√			√							√				
	Negative influence to the natural environment				√					√							
	Demolition difficulty											√					
Safety	Safety level of people and property			√	√		√			√		√		√			√
	Influence of extreme events										√						
	Visibility											√			√		√
	Condition of security screens and handrails											√	√	√		√	
	Condition of drainage system											√	√	√		√	
Serviceability	Damage level of the structure	√	√			√	√	√									
	Prevent deterioration mechanism	√	√				√										
	Current conditions of materials	√				√	√										
	Settlement and shifting of slope paving						√										
	Utilities under structures						√										
Economics	Life cycle cost		√		√	√	√	√							√		
	User's cost				√	√	√										
	Contribution to regional economic development									√							√
Social & Cultural	Comfort level			√					√								
	Heritage value					√											

Appendix B: An Example Answer of the Questionnaire in Workshop

Criteria	Definition	Indicators	Description	Dominant	Important	Neutral	Not important	Not relevant
Functionality	The bridge should fulfil its primary functions (carry loads, provide connections and provide reasonable space)	Functional time duration	The time duration in which the bridge is functional and its functions can be fulfilled		√			
		Function failure probability	The failure probability of a bridge in which its functions cannot be fulfilled		√			
		Ease to maintain its function	The ease in which the bridge can be maintained over time				√	
		Aesthetic appearance	Whether the public satisfy with the aesthetic appearance of the bridge			√		
		Load bearing capacity	Whether the load bearing capacity can still fulfill the requirements of design and development	√				
		Traffic volume carried	Whether the bridge have enough capacity to carry the traffic, reflected by the number of lanes		√			
		Structure geometry	Physical characteristics concern the width of deck, vertical and horizontal clearance, skew and alignment degree relative to the roadway		√			
		Space arrangement for all kinds of users	The bridge should provide reliable space arrangement for users also for possible future development				√	
Environment	The influence of the bridge to the physical environment	Noise emission of expansion joints	Whether the noise emission of expansion joints is acceptable by the environment			√		
		Negative influence to the natural environment	The damage caused by the bridge to the natural environment considering wildlife				√	
		Demolition difficulty	The level of damage to the physical environment of the bridge if it should be demolished					√

Safety	The safety of the users (drivers, passengers) should be ensured	Safety level of people and property	Whether the fatalities and injuries rate fulfill the relevant requirements	√				
		Visibility	Whether the bridge provides good sightlines and illumination condition for users					√
		Condition of security screens and handrails	Whether the protection system is in good condition					√
		Condition of drainage system	Whether the drainage system is in good condition			√		
Serviceability	The structure is still stable enough to ensure the service	Damage level of the structure	Is the damage or defects and their consequences of the bridge serious					√
		Prevent deterioration mechanism	Whether the prevent deterioration mechanism is appropriate and functional for the bridge					√
		Current conditions of materials	The deterioration degree of bridge materials in different components					√
Economics	The costs versus benefits	User's cost	The indirect cost of the bridge in terms of economic and social influence		√			
		Contribution to regional economic development	Whether and to what extent does the bridge stimulate or hinder the regional economic development		√			
Social & Cultural	The influence of bridge to people and society	Comfort level	To what degree the users are satisfied with the provided services			√		
		Heritage value	The heritage value of bridges, and the influence to people with social concerns					√

Appendix C: Original Proposal of Measurement Scale for Performance Indicators

Indicators	Meets the future desired requirement (5)	Meets the current desired requirement (4)	Sufficient (3)	Slightly insufficient (2)	Extra insufficient (1)
Functional time duration	Hardly any hindrance due to planned and unplanned maintenance (robust) with traffic increase	Hardly any hindrance due to planned and unplanned maintenance	Hindrance but acceptable	Unacceptable hindrance but without secondary consequence	Serious hindrance and lead to serious consequence
Function failure probability	There is no failure, the bridge is fully reliable	The probability of functional failure is extremely low	The probability of functional failure will be extremely low with extra prevention measures	The probability of functional failure is under the acceptable level but will not lead to serious consequence currently	The probability of functional failure is high and will lead to serious consequence
Load bearing capacity	Load bearing capacity fulfills the requirements with foreseeable traffic increase	Load bearing capacity fulfills the requirements of current traffic	Load bearing capacity almost fulfills the requirements of current traffic with acceptable limitations	Load bearing capacity is not sufficient and the traffic is limited (loading or speed, especially truck traffic) in an unacceptable level	Load bearing capacity fails to carry the traffic and have high probability of dangerous consequence
Traffic volume carried	There is sufficient residual capacity for the future traffic increase I/C ratio<=0.8	The residual capacity meets the current requirements I/C ratio $\in$ (0.8,0.85]	The residual capacity does not fully meet the current requirements but is still sufficient to carry current traffic volume I/C ratio $\in$ (0.85,0.9]	The residual capacity is slightly insufficient but will not cause any serious congestion I/C ratio $\in$ (0.9,0.95]	The residual capacity is insufficient and will any serious congestion I/C ratio >0.95
Structure geometry	The structure geometry can fulfill the requirements in the foreseeable future	The structure geometry fulfills the current requirements and it functions well	The structure geometry does not fully fulfill the current requirements but it can still serve the network	Structure fails to meet the current requirements but did not cause hindrance to the network	The bridge is the bottleneck of the surrounding network (vertical clearance/width of deck), or it causes potential safety hazard (skew)
Space arrangement for all kinds of users	The bridge provides reliable space arrangement for users also for possible future development	The bridge provides reliable space arrangement for users	The bridge provides reliable space arrangement only for critical users	The bridge does not provide reliable space arrangement for users	The bridge provide hindrance for users in using spaces

Noise emission	The noise emission is totally acceptable and can fulfill the requirements in the foreseeable future without control measures	The noise emission is under current limitation but requires control measures to meet the future requirements	The noise emission is over the current limitation but it is still tolerable (no control measures)	The noise emission exceeds the limitation and Some measures should be taken to control it but not in urgent	The noise emission is intolerable to people and the surrounding environment, which requires urgent measures
Safety level of people and property	Road configuration (fatalities and injuries percentage) is safe to users with traffic increase	Road configuration (fatalities and injuries percentage) is safe to users currently	Road configuration (fatalities and injuries percentage) is safe enough to users with minor prevention measures	Road configuration (fatalities and injuries percentage) is safe enough to users with a lot of prevention measures	Road configuration (fatalities and injuries percentage) is not safe enough to users
Condition of drainage system	All elements in the system meet the intervention standards for safe operation over the next 10 years	Most elements in the system meet the intervention standards for safe operation over the next 10 years	Some of elements in the system do not meet the intervention standards for safe operation over the next 10 years but the system does not cause damages currently	The system does not meet the intervention standards for safe operation over the next 10 years and raise threat to user's safety	The system does not meet the intervention standards for safe operation over the next 10 years and caused unexpected danger to user's safety
Damage level of the structure	There is no damages in the structure	Some minor defects in non-critical structural elements due to deterioration	Some minor defects in critical structural elements but they are still robust to maintain the serviceability of the structure	Defects (cracks, spalling, etc.) happened to structural elements, and they require in-time maintenance	Serious deterioration happened to critical elements
User's cost	Traffic users cost the same when detour happen,	Low extra cost when detour and delay happen	Reasonable extra cost when detour and delay happen	Slightly unacceptable extra cost when detour and delay happen	Unacceptable extra cost when detour and delay happen

Appendix D: Best Worst Method Questionnaire

Appendix D.1: Questionnaire for Ranking Performance Criteria

Performance age of highway fixed concrete bridges

As the asset manager for highway fixed concrete badges, you would have different considerations when you make the replacement decisions. The following criteria are considered to evaluate the performance of bridges in order to make the replacement decisions more accurate. The definition of these criteria as following:
Functionality: Fulfilling the primary functions of the bridge and also the network (provide loads, provide connections and provide space)
Environment: The influence of the bridge to the physical environment
Safety: safety to users and the network
Serviceability: The structure is still stable enough to ensure the service
Economics: the costs versus benefits

1. Which criterion do you think is the most important one
○ Functionality
○ Environment
○ Safety
○ Serviceability
○ Economics

2. Which criterion do you think is the least important one (base on Question 1 chosen “Functionality”)
○ Environment
○ Safety
○ Serviceability
○ Economics

3. Which criterion do you think is the least important one (base on Question 1 chosen “Environment”)
○ Functionality
○ Safety
○ Serviceability
○ Economics

4. Which criterion do you think is the least important one (base on Question 1 chosen “Safety”)
○ Functionality
○ Environment
○ Serviceability
○ Economics

5. Which criterion do you think is the least important one (base on Question 1 chosen “Serviceability”)
○ Functionality
○ Environment
○ Safety
○ Economics

6. Which criterion do you think is the least important one (base on Question 1 chosen “Economics”)
○ Functionality
○ Environment
○ Safety
○ Serviceability

7. You have chosen Functionality as the MOST IMPORTANT criterion. Could you please indicate your 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. (base on Question 1 chosen “Functionality”)

	Environment	Safety	Serviceability	Economics
Functionality				

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important

4: Very strongly more important
5: Extremely more important

8. You have chosen Environment as the LEAST IMPORTANT crite v rion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 2 chosen “Environment”)

	Environment
Safety	
Serviceability	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

9. You have chosen Safety as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 2 chosen “Safety”)

	Safety
Environment	
Serviceability	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

10. You have chosen Serviceability as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 2 chosen “Serviceability”)

	Serviceability
Environment	
Safety	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

11. You have chosen Economics as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 2 chosen “Economics”)

	Economics
Environment	
Safety	
Serviceability	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance

2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

12. You have chosen Environment as the MOST IMPORTANT criterion. Could you please indicate your 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. (base on Question 1 chosen “Environment”)

	Functionality	Safety	Serviceability	Economics
Environment				

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

13. You have chosen Functionality as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 3 chosen “Functionality”)

	Functionality
Safety	
Serviceability	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

14. You have chosen Safety as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 3 chosen “Safety”)

	Safety
Functionality	
Serviceability	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

15. You have chosen Serviceability as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 3 chosen “Serviceability”)

	Serviceability
Functionality	
Safety	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important

3: Strongly more important
4: Very strongly more important
5: Extremely more important

16. You have chosen Economics as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 3 chosen “Economics”)

	Economics
Functionality	
Safety	
Serviceability	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

17. You have chosen Safety as the MOST IMPORTANT criterion. Could you please indicate your 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 (base on Question 1 chosen “Safety”)

	Functionality	Environment	Serviceability	Economics
Safety				

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

18. You have chosen Functionality as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 4 chosen “Functionality”)

	Functionality
Safety	
Serviceability	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

19. You have chosen Environment as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 4 chosen “Environment”)

	Environment
Functionality	
Serviceability	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important

5: Extremely more important

20. You have chosen Serviceability as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 4 chosen "Serviceability")

	Serviceability
Functionality	
Environment	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

21. You have chosen Economics as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 4 chosen "Economics")

	Economics
Functionality	
Environment	
Serviceability	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

22. You have chosen Serviceability as the MOST IMPORTANT criterion. Could you please indicate your 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. (base on Question 1 chosen "Serviceability")

	Functionality	Environment	Safety	Economics
Serviceability				

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

23. You have chosen Functionality as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 5 chosen "Functionality")

	Functionality
Environment	
Safety	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important

5: Extremely more important

24. You have chosen Environment as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 5 chosen “Environment”)

	Environment
Functionality	
Safety	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

25. You have chosen Safety as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 5 chosen “Safety”)

	Safety
Functionality	
Environment	
Economics	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

26. You have chosen Economics as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 5 chosen “Economics”)

	Economics
Functionality	
Environment	
Safety	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

27. You have chosen Economics as the MOST IMPORTANT criterion. Could you please indicate your 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. (base on Question 1 chosen “Economics”)

	Functionality	Environment	Safety	Serviceability
Economics				

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

28. You have chosen Functionality as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 6 chosen "Functionality")

	Functionality
Environment	
Safety	
Serviceability	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

29. You have chosen Environment as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 6 chosen "Environment")

	Environment
Functionality	
Safety	
Serviceability	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

30. You have chosen Safety as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 6 chosen "Safety")

	Safety
Functionality	
Environment	
Serviceability	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

31. You have chosen Serviceability as the LEAST IMPORTANT criterion. Could you please indicate your preference of other criteria over this criterion. Use a number between 1 and 5 to show the preference of the other criteria over the LEAST IMPORTANT criterion (base on Question 6 chosen "Serviceability")

	Serviceability
Functionality	
Environment	
Safety	

Hint：Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

Appendix D.2: Guidance to the Questionnaire for Ranking Performance Criteria

Goal: Determining the weightings of different criteria in order to evaluate the performance of bridges

Method: Best-Worst-Method

Criteria: Functionality, Environment, Safety, Serviceability, Economics

Step 1: choose the best criterion (THE MOST IMPORTANT CRITERION)

e.g. **Functionality** is chosen as the most important criterion

Step 2: choose the worst criterion (The LEAST IMPORTANT CRITERION)

e.g. **Economics** is chosen as the least important criterion

Step 3: Now use a number between 1 and 5 to show the preference of your

MOST IMPORTANT criterion over the other criteria (first line in the following table). E.g.

MOST IMPORTANT CRITERION	Functionality	Environment	Safety	Serviceability	Economics
Functionality	**1**	**3**	**4**	**4**	**5**

This number is not asked in the questionnaire as it is 1 automatically, other numbers in this row should be bigger than 1

It is fine if there are two same numbers in this

The largest number in this row should be this one (best over worst)

Step 4: Now use a number between 1 and 5 to show the preference of

the criteria (first column in the following table) over the LEAST IMPORTANT criterion. E.g.

LEAST IMPORTANT CRITERION	**Economics**
Functionality	**5**
Environment	**2**
Safety	**4**
Serviceability	**2**
Economics	**1**

This number is not asked in the questionnaire as it is 1 automatically, other numbers in this column

This number is not in the questionnaire because it is already given in the former

The result of the questionnaire would be the weightings of the five criteria.

W (Functionality)	W (Environment)	W (Safety)	W (Serviceability)	W (Economics)	Sum
					1

Appendix D.3: Questionnaire for Ranking Performance Indicators

Performance Age Indicators

As the asset manager for highway fixed concrete bridges, you would have different considerations when you make the replacement decisions. According to the workshop result, the performance indicators are clustered into different groups. This questionnaire is designed to give weightings of different indicators.

There are 6 performance indicators in the functionality aspect. The definition of these indicators as following:

Functional time duration: the time duration in which the bridge is functional and its functions can be fulfilled

Functional failure probability: the failure probability of a bridge in which its functions cannot be fulfilled

Load bearing capacity: whether the load bearing capacity can still fulfil the requirements of design and development

Traffic volume carried: whether the bridge have enough capacity to carry the traffic, reflected by the number of lanes

Structure geometry: physical characteristics concern the width of deck, vertical and horizontal clearance, skew and alignment degree relative to the roadway

Space arrangement for all kinds of users: the bridge should provide reliable space arrangement for users also for possible future development

There are two indicators in the safety aspect, and their definitions are as following:

Safety level of people and property: whether the fatalities and injuries rate fulfil the relevant requirements

Condition of drainage system: whether the drainage system is in good condition

1. In the Safety aspect, which criterion do you think is more important?

○ Safety level of people and property
○ Condition of drainage system

2. You have chosen "Safety level of people and property" as the more important indicator. Could you please indicate your preference of this indicator over the other one. Use a number between 1 and 5 to show the preference. (based on Question 1 chosen “Safety level of people and property”)

	Condition of drainage system
Safety level of people and property	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

3. You have chosen "Condition of drainage system" as the more important indicator. Could you please indicate your preference of this indicator over the other one. Use a number between 1 and 5 to show the preference. (based on Question 1 chosen “Condition of drainage system”)

	Safety level of people and property
Condition of drainage system	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

4. In the Functionality aspect, which indicator do you think is the most important one
○ Functional time duration
○ Function failure probability
○ Load bearing capacity
○ Traffic volume carried
○ Structure geometry
○ Space arrangement for all kinds of users

5. In the Functionality aspect, which indicator do you think is the least important one (based on Question 4 chosen "Functional time duration")
○ Function failure probability
○ Load bearing capacity
○ Traffic volume carried
○ Structure geometry
○ Space arrangement for all kinds of users

6. In the Functionality aspect, which indicator do you think is the least important one (based on Question 4 chosen "Function failure probability")
○ Functional time duration
○ Load bearing capacity
○ Traffic volume carried
○ Structure geometry
○ Space arrangement for all kinds of users

7. In the Functionality aspect, which indicator do you think is the least important one (based on Question 4 chosen "Traffic volume carried")
○ Functional time duration
○ Function failure probability
○ Traffic volume carried
○ Structure geometry
○ Space arrangement for all kinds of users

8. In the Functionality aspect, which indicator do you think is the least important one (based on Question 4 chosen "Load bearing capacity")
○ Functional time duration
○ Function failure probability
○ Load bearing capacity
○ Structure geometry
○ Space arrangement for all kinds of users

9. In the Functionality aspect, which indicator do you think is the least important one (based on Question 4 chosen "Structure geometry")
○ Functional time duration
○ Function failure probability
○ Load bearing capacity
○ Traffic volume carried
○ Space arrangement for all kinds of users

10. In the Functionality aspect, which indicator do you think is the least important one (based on Question 4 chosen "Space arrangement for all kinds of users")
○ Functional time duration
○ Function failure probability
○ Load bearing capacity
○ Traffic volume carried
○ Structure geometry

11. You have chosen "Functional time duration" as the MOST IMPORTANT indicator. Could you please indicate your preference of this indicator over other indicators. Use a number between 1 and 5 to show the preference of the MOST IMPORTANT indicator over other indicators. (based on Question 4 chosen "Functional time duration")

	Functional failure probability	Load bearing capacity	Traffic volume	Structure geometry	Space arrangement for all kinds of users

			carried		
Functional time duration					

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

12. You have chosen "Functional failure probability" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Functional failure probability
Load bearing capacity	
Traffic volume carried	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

13. You have chosen "Load bearing capacity" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Load bearing capacity
Functional failure probability	
Traffic volume carried	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

14. You have chosen "Traffic volume carried" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Traffic volume carried
Functional failure probability	
Load bearing capacity	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

15. You have chosen "Structure geometry" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Structure geometry
Functional failure probability	
Load bearing capacity	
Traffic volume carried	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

16. You have chosen "Space arrangement for all kinds of users" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Space arrangement for all kinds of users
Functional failure probability	
Load bearing capacity	
Traffic volume carried	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

17. You have chosen "Functional failure probability" as the MOST IMPORTANT indicator. Could you please indicate your preference of this indicator over other indicators. Use a number between 1 and 5 to show the preference of the MOST IMPORTANT indicator over other indicators.

	Functional time duration	Load bearing capacity	Traffic volume carried	Structure geometry	Space arrangement for all kinds of users
Functional failure probability					

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

18. You have chosen "Function time duration" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Function time duration
Load bearing capacity	
Traffic volume carried	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important

3: Strongly more important
4: Very strongly more important
5: Extremely more important

19. You have chosen "Load bearing capacity" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Load bearing capacity
Function time duration	
Traffic volume carried	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

20. You have chosen "Traffic volume carried" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Traffic volume carried
Function time duration	
Load bearing capacity	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

21. You have chosen "Structure geometry" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Structure geometry
Function time duration	
Load bearing capacity	
Traffic volume carried	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

22. You have chosen "Space arrangement for all kinds of users" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Space arrangement for all kinds of users
Function time duration	
Load bearing capacity	
Traffic volume carried	

Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

23. You have chosen "Load bearing capacity" as the MOST IMPORTANT indicator. Could you please indicate your preference of this indicator over other indicators. Use a number between 1 and 5 to show the preference of the MOST IMPORTANT indicator over other indicators.

	Functional time duration	Functional failure probability	Traffic volume carried	Structure geometry	Space arrangement for all kinds of users
Load bearing capacity					

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

24. You have chosen "Function time duration" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Function time duration
Functional failure probability	
Traffic volume carried	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

25. You have chosen "Functional failure probability" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Functional failure probability
Function time duration	
Traffic volume carried	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

26. You have chosen "Traffic volume carried" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Traffic volume carried

Function time duration	
Functional failure probability	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

27. You have chosen "Structure geometry" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Structure geometry
Function time duration	
Functional failure probability	
Traffic volume carried	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

28. You have chosen "Space arrangement for all kinds of users" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Space arrangement for all kinds of users
Function time duration	
Functional failure probability	
Traffic volume carried	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

29. You have chosen "Traffic volume carried" as the MOST IMPORTANT indicator. Could you please indicate your preference of this indicator over other indicators. Use a number between 1 and 5 to show the preference of the MOST IMPORTANT indicator over other indicators.

	Functional time duration	Functional failure probability	Load bearing capacity	Structure geometry	Space arrangement for all kinds of users
Traffic volume carried					

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

30. You have chosen "Function time duration" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Function time duration
Functional failure probability	
Load bearing capacity	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

31. You have chosen "Functional failure probability" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Functional failure probability
Function time duration	
Load bearing capacity	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

32. You have chosen "Load bearing capacity" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Load bearing capacity
Function time duration	
Functional failure probability	
Structure geometry	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

33. You have chosen "Structure geometry" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Structure geometry
Function time duration	
Functional failure probability	
Load bearing capacity	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important

3: Strongly more important
4: Very strongly more important
5: Extremely more important

34. You have chosen "Space arrangement for all kinds of users" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Space arrangement for all kinds of users
Function time duration	
Functional failure probability	
Load bearing capacity	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

35. You have chosen "Structure geometry" as the MOST IMPORTANT indicator. Could you please indicate your preference of this indicator over other indicators. Use a number between 1 and 5 to show the preference of the MOST IMPORTANT indicator over other indicators.

	Functional time duration	Functional failure probability	Load bearing capacity	Traffic volume carried	Space arrangement for all kinds of users
Structure geometry					

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

36. You have chosen "Function time duration" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Function time duration
Functional failure probability	
Load bearing capacity	
Traffic volume carried	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

37. You have chosen "Functional failure probability" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Functional failure probability
Function time duration	
Load bearing capacity	
Traffic volume carried	

Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

38. You have chosen "Load bearing capacity" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Load bearing capacity
Function time duration	
Functional failure probability	
Traffic volume carried	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

39. You have chosen "Traffic volume carried" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Traffic volume carried
Function time duration	
Functional failure probability	
Load bearing capacity	
Space arrangement for all kinds of users	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

40. You have chosen "Space arrangement for all kinds of users" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Space arrangement for all kinds of users
Function time duration	
Functional failure probability	
Load bearing capacity	
Traffic volume carried	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

41. You have chosen "Space arrangement for all kinds of users" as the MOST IMPORTANT indicator. Could you please indicate your preference of this indicator over other indicators. Use a number between 1 and 5 to show the preference of the MOST IMPORTANT indicator over other indicators.

	Functional time duration	Functional failure probability	Load bearing capacity	Traffic volume carried	Structure geometry
Space arrangement for all kinds of users					

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

42. You have chosen "Function time duration" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Function time duration
Functional failure probability	
Load bearing capacity	
Traffic volume carried	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

43. You have chosen "Functional failure probability" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Functional failure probability
Function time duration	
Load bearing capacity	
Traffic volume carried	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

44. You have chosen "Load bearing capacity" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Load bearing capacity
Function time duration	
Functional failure probability	
Traffic volume carried	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important

5: Extremely more important

45. You have chosen "Traffic volume carried" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Traffic volume carried
Function time duration	
Functional failure probability	
Load bearing capacity	
Structure geometry	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

46. You have chosen "Structure geometry" as the LEAST IMPORTANT indicator. Could you please indicate your preference of other indicators over this indicator. Use a number between 1 and 5 to show the preference of other indicators over the LEASE IMPORTANT indicator.

	Structure geometry
Function time duration	
Functional failure probability	
Load bearing capacity	
Traffic volume carried	

Hint: Definition of 1 to 5 measurement scale:
1: Equal importance
2: Moderately more important
3: Strongly more important
4: Very strongly more important
5: Extremely more important

Appendix E: Best Worst Method Data Processing Code

Appendix E.1: Code of "Function Button"

```
Sub test1()
Dim i As Integer
For i = 2 To 6
    If Cells(i, 2) > Cells(i, 3) Then
    Cells(i, 4) = 1
    Else
    Cells(i, 4) = 0
    End If
Next i

Dim f As Integer
f = 1
For i = 2 To 6
f = f * Cells(i, 4)
Next i
    If f = 0 Then
    Cells(8, 4) = 0
    Else
    Cells(8, 4) = "Compensatory method"
    End If
If Cells(8, 4) = "Compensatory method" Then
BWM.Show
End If
End Sub
```

Appendix E.2: Code of Userform

```
Private Sub submit_Click()
Dim ssheet As Worksheet
Set ssheet = ThisWorkbook.Sheets("Sheet1")
nr = ssheet.Cells(Rows.Count, 10).End(xlUp).Row + 1
ssheet.Cells(nr, 9) = Me.cmbbestcriterion
ssheet.Cells(nr, 10) = Me.cmbworstcriterion
ssheet.Cells(nr, 11) = Me.bestc1
ssheet.Cells(nr, 12) = Me.bestc2
ssheet.Cells(nr, 13) = Me.bestc3
ssheet.Cells(nr, 14) = Me.bestc4
ssheet.Cells(nr, 15) = Me.bestc5
ssheet.Cells(nr, 16) = Me.c1worst
ssheet.Cells(nr, 17) = Me.c2worst
ssheet.Cells(nr, 18) = Me.c3worst
ssheet.Cells(nr, 19) = Me.c4worst
ssheet.Cells(nr, 20) = Me.c5worst
End Sub

Private Sub cls_Click()
Unload Me
End Sub
```

Appendix E.3: Code of “Sort Button”

```
Sub sort()
Dim i As Integer
For i = 2 To 10
If Range("$i$" & i) = "Functionality" And Range("$j$" & i) = "Environment" Then
Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 5 & ":$ah$" & i + 5)
Else
    If Range("$i$" & i) = "Functionality" And Range("$j$" & i) = "Safety" Then
    Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 17 & ":$ah$" & i + 17)
    Else
        If Range("$i$" & i) = "Functionality" And Range("$j$" & i) = "Serviceability" Then
        Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 29 & ":$ah$" & i + 29)
        Else
            If Range("$i$" & i) = "Functionality" And Range("$j$" & i) = "Economics" Then
            Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 41 & ":$ah$" & i + 41)
            Else
                If Range("$i$" & i) = "Environment" And Range("$j$" & i) = "Functionality" Then
                Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 53 & ":$ah$" & i + 53)
                Else
                    If Range("$i$" & i) = "Environment" And Range("$j$" & i) = "Safety" Then
                    Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 65 & ":$ah$" & i + 65)
                    Else
                        If Range("$i$" & i) = "Environment" And Range("$j$" & i) = "Serviceability" Then
                        Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 77 & ":$ah$" & i + 77)
                        Else
                            If Range("$i$" & i) = "Environment" And Range("$j$" & i) = "Economics" Then
                            Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 89 & ":$ah$" & i +
89)
                            Else
                                If Range("$i$" & i) = "Safety" And Range("$j$" & i) = "Functionality" Then
                                Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 101 & ":$ah$"
& i + 101)
                                Else
                                   If Range("$i$" & i) = "Safety" And Range("$j$" & i) = "Environment" Then
                                    Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 113 &
":$ah$" & i + 113)
                                    Else
                                        If Range("$i$" & i) = "Safety" And Range("$j$" & i) = "Serviceability"
Then
                                        Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i + 125
& ":$ah$" & i + 125)
                                        Else
                                            If Range("$i$" & i) = "Safety" And Range("$j$" & i) = "Economics"
Then
                                            Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$" & i +
137 & ":$ah$" & i + 137)
                                            Else
                                                If Range("$i$" & i) = "Serviceability" And Range("$j$" & i) =
"Functionality" Then
                                                Range("$i$" & i & ":$t$" & i).Copy Destination:=Range("$w$"
& i + 149 & ":$ah$" & i + 149)
                                                Else
                                                    If Range("$i$" & i) = "Serviceability" And Range("$j$" & i)
= "Environment" Then
                                                    Range("$i$" & i & ":$t$" & i).Copy
Destination:=Range("$w$" & i + 161 & ":$ah$" & i + 161)
                                                    Else
                                                        If Range("$i$" & i) = "Serviceability" And
Range("$j$" & i) = "Safety" Then
                                                        Range("$i$" & i & ":$t$" & i).Copy
Destination:=Range("$w$" & i + 173 & ":$ah$" & i + 173)
                                                        Else
                                                            If Range("$i$" & i) = "Serviceability" And
Range("$j$" & i) = "Economics" Then
                                                            Range("$i$" & i & ":$t$" & i).Copy
Destination:=Range("$w$" & i + 185 & ":$ah$" & i + 185)
```

```
Else
    If Range("$i$" & i) = "Economics" And
Range("$j$" & i) = "Functionality" Then
    Range("$i$" & i & ":$t$" & i).Copy
Destination:=Range("$w$" & i + 197 & ":$ah$" & i + 197)
    Else
        If Range("$i$" & i) = "Economics" And
Range("$j$" & i) = "Environment" Then
        Range("$i$" & i & ":$t$" & i).Copy
Destination:=Range("$w$" & i + 209 & ":$ah$" & i + 209)
        Else
            If Range("$i$" & i) = "Economics"
And Range("$j$" & i) = "Safety" Then
            Range("$i$" & i & ":$t$" &
i).Copy Destination:=Range("$w$" & i + 221 & ":$ah$" & i + 221)
            Else
                If Range("$i$" & i) =
"Economics" And Range("$j$" & i) = "Economics" Then
                Range("$i$" & i & ":$t$" &
i).Copy Destination:=Range("$w$" & i + 233 & ":$ah$" & i + 233)
                Else
                End If
            End If
        End If
    End If
Else
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
Next i
End Sub
```

Appendix E.4: Code of "Calculate Button"

```
Sub test2()
Dim a As Integer
For a = 7 To 15
solverreset
solverok setcell:="$an$" & a, maxminval:=2, bychange:="$ai$" & a & ":$an$" & a
solveradd cellref:="$ao$" & a, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & a & ":$bi$" & a, relation:=1, formulatext:="$an$" & a
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next a

Dim b As Integer
For b = 19 To 27
solverreset
solverok setcell:="$an$" & b, maxminval:=2, bychange:="$ai$" & b & ":$an$" & b
solveradd cellref:="$ao$" & b, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & b & ":$bi$" & b, relation:=1, formulatext:="$an$" & b
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next b

Dim c As Integer
For c = 31 To 39
solverreset
solverok setcell:="$an$" & c, maxminval:=2, bychange:="$ai$" & c & ":$an$" & c
solveradd cellref:="$ao$" & c, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & c & ":$bi$" & c, relation:=1, formulatext:="$an$" & c
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next c

Dim d As Integer
For d = 43 To 51
solverreset
solverok setcell:="$an$" & d, maxminval:=2, bychange:="$ai$" & d & ":$an$" & d
solveradd cellref:="$ao$" & d, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & d & ":$bi$" & d, relation:=1, formulatext:="$an$" & d
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next d
```

```
Dim e As Integer
For e = 55 To 63
solverreset
solverok setcell:="$an$" & e, maxminval:=2, bychange:="$ai$" & e & ":$an$" & e
solveradd cellref:="$ao$" & e, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & e & ":$bi$" & e, relation:=1, formulatext:="$an$" & e
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next e

Dim f As Integer
For f = 67 To 75
solverreset
solverok setcell:="$an$" & f, maxminval:=2, bychange:="$ai$" & f & ":$an$" & f
solveradd cellref:="$ao$" & f, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & f & ":$bi$" & f, relation:=1, formulatext:="$an$" & f
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next f

Dim g As Integer
For g = 79 To 87
solverreset
solverok setcell:="$an$" & g, maxminval:=2, bychange:="$ai$" & g & ":$an$" & g
solveradd cellref:="$ao$" & g, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & g & ":$bi$" & g, relation:=1, formulatext:="$an$" & g
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next g

Dim h As Integer
For h = 91 To 99
solverreset
solverok setcell:="$an$" & h, maxminval:=2, bychange:="$ai$" & h & ":$an$" & h
solveradd cellref:="$ao$" & h, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & h & ":$bi$" & h, relation:=1, formulatext:="$an$" & h
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next h
```

```
Dim i As Integer
For i = 103 To 111
solverreset
solverok setcell:="$an$" & i, maxminval:=2, bychange:="$ai$" & i & ":$an$" & i
solveradd cellref:="$ao$" & i, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & i & ":$bi$" & i, relation:=1, formulatext:="$an$" & i
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next i

Dim j As Integer
For j = 115 To 123
solverreset
solverok setcell:="$an$" & j, maxminval:=2, bychange:="$ai$" & j & ":$an$" & j
solveradd cellref:="$ao$" & j, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & j & ":$bi$" & j, relation:=1, formulatext:="$an$" & j
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next j

Dim k As Integer
For k = 127 To 135
solverreset
solverok setcell:="$an$" & k, maxminval:=2, bychange:="$ai$" & k & ":$an$" & k
solveradd cellref:="$ao$" & k, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & k & ":$bi$" & k, relation:=1, formulatext:="$an$" & k
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next k

Dim l As Integer
For l = 139 To 147
solverreset
solverok setcell:="$an$" & l, maxminval:=2, bychange:="$ai$" & l & ":$an$" & l
solveradd cellref:="$ao$" & l, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & l & ":$bi$" & l, relation:=1, formulatext:="$an$" & l
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next l
```

```
Dim m As Integer
For m = 151 To 159
solverreset
solverok setcell:="$an$" & m, maxminval:=2, bychange:="$ai$" & m & ":$an$" & m
solveradd cellref:="$ao$" & m, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & m & ":$bi$" & m, relation:=1, formulatext:="$an$" & m
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next m

Dim n As Integer
For n = 163 To 171
solverreset
solverok setcell:="$an$" & n, maxminval:=2, bychange:="$ai$" & n & ":$an$" & n
solveradd cellref:="$ao$" & n, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & n & ":$bi$" & n, relation:=1, formulatext:="$an$" & n
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next n

Dim o As Integer
For o = 175 To 183
solverreset
solverok setcell:="$an$" & o, maxminval:=2, bychange:="$ai$" & o & ":$an$" & o
solveradd cellref:="$ao$" & o, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & o & ":$bi$" & o, relation:=1, formulatext:="$an$" & o
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next o

Dim p As Integer
For p = 187 To 195
solverreset
solverok setcell:="$an$" & p, maxminval:=2, bychange:="$ai$" & p & ":$an$" & p
solveradd cellref:="$ao$" & p, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & p & ":$bi$" & p, relation:=1, formulatext:="$an$" & p
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next p
```

```
Dim q As Integer
For q = 199 To 207
solverreset
solverok setcell:="$an$" & q, maxminval:=2, bychange:="$ai$" & q & ":$an$" & q
solveradd cellref:="$ao$" & q, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & q & ":$bi$" & q, relation:=1, formulatext:="$an$" & q
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next q

Dim r As Integer
For r = 211 To 219
solverreset
solverok setcell:="$an$" & r, maxminval:=2, bychange:="$ai$" & r & ":$an$" & r
solveradd cellref:="$ao$" & r, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & r & ":$bi$" & r, relation:=1, formulatext:="$an$" & r
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next r

Dim s As Integer
For s = 223 To 231
solverreset
solverok setcell:="$an$" & s, maxminval:=2, bychange:="$ai$" & s & ":$an$" & s
solveradd cellref:="$ao$" & s, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & s & ":$bi$" & s, relation:=1, formulatext:="$an$" & s
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next s

Dim t As Integer
For t = 235 To 243
solverreset
solverok setcell:="$an$" & t, maxminval:=2, bychange:="$ai$" & t & ":$an$" & t
solveradd cellref:="$ao$" & t, relation:=2, formulatext:="$ao$5"
solveradd cellref:="$ap$" & t & ":$bi$" & t, relation:=1, formulatext:="$an$" & t
SolverOptions AssumeLinear:=True, AssumeNonNeg:=True
solversolve userfinish:=True
Next t
End Sub
```

Appendix F: List of Possible Bridges for Case Study

Network	Code	Name	Location	National way	Construction year	Length	Width	Type
HWN	37E-126-01	Bieslandsebrug	Brug over de Bieslandse Molensloot	A13	1933	33.3	37.2	Brug (Beton klein)
HWN	37E-126-02	Bieslandsebrug gemaal	Gemaal Bieslandsche-Molensloot	A13	1934			Gemalen
HWN	37E-301-01	Hoftunnel	Onderdoorgang onder de rijksweg in de Hofweg	A13	1938	35.6	7	Onderdoorgangen
HWN	37E-132-01	Karitaatbrug	Brug over de Kariaat-Molensloot	A13	1938	36	5.17	Duikers
HWN	37E-200-01	Onderdoorgang Baanweg	Onderdoorgang onder de rijksweg in de Baanweg	A13	1952	182.48	12	Onderdoorgangen
HWN	37E-302-01	Overschie	Viaduct in de rijksweg over de Zestienhovensekade	A13	1936	313.11	22.3	Viaducten (in RW)
HWN	37E-138-01	Tempelbrug	Brug in de rijksweg over de Molentocht	A13	1927	36.6		Duikers
HWN	37E-104-01	Vorkbrug	Brug over de Oude Laanmolensloot	A13	1928	29.21	6.8	Duikers
HWN	37E-317-01	Zestienhovense duiker	Duiker in de rijksweg nabij Zestienhoven	A13	1933	36.62	3.2	Duikers
HWN	37E-137-01	Zwethbrug	Brug in de rijksweg over de Zweth	A13	1930	54.37		Brug (Beton klein)
HWN	37E-136-01	Zwethtunnel	Onderdoorgang onder de rijksweg in de Zwethkade	A13	1930	35.72	4	Onderdoorgangen
HWN	38A-124-01	2e Tocht	Duiker in de 2e Tocht	A20	1956	69	7	Duikers
HWN	37B-110-01	Boonervliet	Zuidelijke brug over de Boonervliet	A20	1939	114.42	9.5	Brug (Beton klein)
HWN	37B-110-02	Boonervliet noord	Noordelijke brug over de Boonervliet	A20	1939	114.42	10.2	Brug (Beton klein)
HWN	37B-119-01	Duiker Aalkeettocht	Duiker onder de rijksweg in de Aalkeettocht	A20	1938	33	4.5	Duikers
HWN	38A-001-02	Groenebrug oost	Hoofdoverspanning van het oostelijk viaduct	A20	1937	87.44		Brug (Beton & Staal)
HWN	37B-106-01	Lierwatertje	Duiker onder de rijksweg in het Lierwatertje	A20	1935	23.1	3.7	Duikers
HWN	37B-104-01	Westgaag	Duiker onder de rijksweg in de Westgaag	A20	1937	54.43	5.2	Duikers

Appendix G: Scores of Testing Bridges

Bridge Code: 37B-110-02 Boonervliet Noord

Indicators	Meets the future desired requirement (5)	Meets the current desired requirement (4)	Sufficient (3)	Slightly insufficient (2)	Completely insufficient (1)
Functional time duration	Hardly any hindrance due to planned and unplanned maintenance (robust) with traffic increase.	Hardly any hindrance due to planned and unplanned maintenance, leading to negligible user delay cost compared to the regular road maintenance.	Planned or unplanned maintenance leads to undesired, not negligible yearly user delay, leading to incidental but acceptable complaints of road users or other stakeholders.	Planned or unplanned maintenance leads to not negligible user delay cost and frequent complaints of road users.	Planned or unplanned maintenance leads to claims or seriously damaged reputation.
Function failure probability	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low and not expected to grow in the next decades.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is moderate, leading to incidental but acceptable complaints of road users or other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is moderate. It leads to frequent complaints of road users and other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is high. It leads to claims of road users and other stakeholders or seriously damaged reputation.
Load bearing capacity	Load bearing capacity fulfills the requirements even with foreseeable traffic increase.	Load bearing capacity completely fulfills the requirements of current traffic.	Load bearing capacity almost fulfills the requirements of current traffic and does not limit the traffic.	Load bearing capacity is not sufficient and the traffic is limited (loading or speed, especially truck traffic) in an unacceptable level.	Load bearing capacity fails to carry the traffic and have high probability of dangerous consequences.
Traffic volume carried	There is sufficient residual capacity for the future traffic increase I/C ratio (Intensity/Capacity) <=0.8	The residual capacity meets the current requirements I/C ratio $\in$ (0.8,0.85]	The residual capacity does not fully meet the current requirements but is still sufficient to carry current traffic volume I/C ratio $\in$ (0.85,0.9]	The residual capacity is slightly insufficient but will not cause any serious congestion I/C ratio $\in$ (0.9,0.95]	The residual capacity is insufficient and will any serious congestion I/C ratio >0.95
Structure geometry	The structure geometry is at design level with respect to bridge height and width below and above, and sufficiently flexible for traffic increase.	The structure geometry is sufficient for current traffic with respect to bridge height and with below and above.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, but does not create an unacceptable bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, and creates an unacceptable bottleneck in the network, leading to complaints.	The bridge is the bottleneck of the surrounding network (with respect to vertical clearance/width of deck), and it causes potential safety hazard (with respect to skew).
Space arrangement for all kinds of users	The bridge provides reliable space arrangement for all users also for possible future development.	The bridge provides reliable space arrangement for all users.	The bridge provides reliable space arrangement only for critical users (including users who contribute to the main traffic flow, inspections, and emergency services).	The bridge does not provide reliable space arrangement for critical users.	The bridge has hindrance for critical users in using spaces.
Noise emission	The noise emission is totally acceptable and can fulfill the requirements in the foreseeable future without control measures.	The noise emission is under current limitation (required for environment permit) but requires control measures to meet the future requirements.	The noise emission is over the current limitation but it is still tolerable (no control measures).	The noise emission exceeds the limitation and some measures should be taken to control it but has no urgency	The noise emission is intolerable to people and the surrounding environment, which requires urgent measures.
Safety level of people and property	Road configuration (fatalities and injuries percentage) is safe to users with traffic increase.	Road configuration (fatalities and injuries percentage) is currently at a safe level to users.	Road configuration (fatalities and injuries percentage) is safe enough to users with minor prevention measures.	Road configuration (fatalities and injuries percentage) is safe enough to users with a lot of prevention measures.	Road configuration (fatalities and injuries percentage) is not safe enough to users.
Condition of drainage system	Drainage system has the required draining ability and operates without problems, even when subject to scenarios of climate change regarding the next 20 years.	The drainage system has the required draining ability and operates without problems currently.	The drainage system does not have the required draining ability and operates with problems, resulting in minor additional maintenance cost and/or yet controllable risks for road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in minor additional maintenance cost and/or incidental uncontrollable risks or road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in major additional maintenance cost and/or uncontrollable risks for road users due to deformations or aquaplaning.
Damage level of the structure	The main structure is in perfect condition and no other cost than regular maintenance are expected in the next 20 years.	The main structure of the bridge is still in good condition. No specific maintenance problems, other than the regular periodic maintenance as expected for any other bridge.	The main structure of the bridge shows problems that exceed the regular maintenance expectations and needs minor investments to maintain the needed safety and risk level.	The main structure does not meet the current safety requirements and needs major investments to reach the needed safety and risk level.	The structure is unsafe due to damages and/or the main structure needs major investments to reach the needed safety and risk level, and will also need increasing major expenses in the future.
User's cost	Traffic users cost the same when detour happen.	Low extra cost when detour and delay happen.	Reasonable extra cost when detour and delay happen.	Slightly unacceptable extra cost when detour and delay happen.	Unacceptable extra cost when detour and delay happen.

Bridge Code: 37E-126-01 Bieslandsebrug

Indicators	Meets the future desired requirement (5)	Meets the current desired requirement (4)	Sufficient (3)	Slightly insufficient (2)	Completely insufficient (1)
Functional time duration	Hardly any hindrance due to planned and unplanned maintenance (robust) with traffic increase.	Hardly any hindrance due to planned and unplanned maintenance, leading to negligible user delay cost compared to the regular road maintenance.	Planned or unplanned maintenance leads to undesired, not negligible yearly user delay, leading to incidental but acceptable complaints of road users or other stakeholders.	Planned or unplanned maintenance leads to not negligible user delay cost and frequent complaints of road users.	Planned or unplanned maintenance leads to claims or seriously damaged reputation.
Function failure probability	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low and not expected to grow in the next decades.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is moderate, leading to incidental but acceptable complaints of road users or other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is moderate. It leads to frequent complaints of road users and other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is high. It leads to claims of road users and other stakeholders or seriously damaged reputation.
Load bearing capacity	Load bearing capacity fulfills the requirements even with foreseeable traffic increase.	Load bearing capacity completely fulfills the requirements of current traffic.	Load bearing capacity almost fulfills the requirements of current traffic and does not limit the traffic.	Load bearing capacity is not sufficient and the traffic is limited (loading or speed, especially truck traffic) in an unacceptable level.	Load bearing capacity fails to carry the traffic and have high probability of dangerous consequences.
Traffic volume carried	There is sufficient residual capacity for the future traffic increase I/C ratio (Intensity/Capacity) <=0.8	The residual capacity meets the current requirements I/C ratio ∈ (0.8,0.85]	The residual capacity does not fully meet the current requirements but is still sufficient to carry current traffic volume I/C ratio ∈ (0.85,0.9]	The residual capacity is slightly insufficient but will not cause any serious congestion I/C ratio ∈ (0.9,0.95]	The residual capacity is insufficient and will any serious congestion I/C ratio >0.95
Structure geometry	The structure geometry is at design level with respect to bridge height and width below and above, and sufficiently flexible for traffic increase.	The structure geometry is sufficient for current traffic with respect to bridge height and with below and above.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, but does not create an unacceptable bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, and creates an unacceptable bottleneck in the network, leading to complaints.	The bridge is the bottleneck of the surrounding network (with respect to vertical clearance/width of deck), and it causes potential safety hazard (with respect to skew).
Space arrangement for all kinds of users	The bridge provides reliable space arrangement for all users also for possible future development.	The bridge provides reliable space arrangement for all users.	The bridge provides reliable space arrangement only for critical users (including users who contribute to the main traffic flow, inspections, and emergency services).	The bridge does not provide reliable space arrangement for critical users.	The bridge has hindrance for critical users in using spaces.
Noise emission	The noise emission is totally acceptable and can fulfill the requirements in the foreseeable future without control measures.	The noise emission is under current limitation (required for environment permit) but requires control measures to meet the future requirements.	The noise emission is over the current limitation but it is still tolerable (no control measures).	The noise emission exceeds the limitation and some measures should be taken to control it but has no urgency	The noise emission is intolerable to people and the surrounding environment, which requires urgent measures.
Safety level of people and property	Road configuration (fatalities and injuries percentage) is safe to users with traffic increase.	Road configuration (fatalities and injuries percentage) is currently at a safe level to users.	Road configuration (fatalities and injuries percentage) is safe enough to users with minor prevention measures.	Road configuration (fatalities and injuries percentage) is safe enough to users with a lot of prevention measures.	Road configuration (fatalities and injuries percentage) is not safe enough to users.
Condition of drainage system	Drainage system has the required draining ability and operates without problems, even when subject to scenarios of climate change regarding the next 20 years.	The drainage system has the required draining ability and operates without problems currently.	The drainage system does not have the required draining ability and operates with problems, resulting in minor additional maintenance cost and/or yet controllable risks for road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in minor additional maintenance cost and/or incidental uncontrollable risks or road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in major additional maintenance cost and/or uncontrollable risks for road users due to deformations or aquaplaning.
Damage level of the structure	The main structure is in perfect condition and no other cost than regular maintenance are expected in the next 20 years.	The main structure of the bridge is still in good condition. No specific maintenance problems, other than the regular periodic maintenance as expected for any other bridge.	The main structure of the bridge shows problems that exceed the regular maintenance expectations and needs minor investments to maintain the needed safety and risk level.	The main structure does not meet the current safety requirements and needs major investments to reach the needed safety and risk level.	The structure is unsafe due to damages and/or the main structure needs major investments to reach the needed safety and risk level, and will also need increasing major expenses in the future.
User's cost	Traffic users cost the same when detour happen.	Low extra cost when detour and delay happen.	Reasonable extra cost when detour and delay happen.	Slightly unacceptable extra cost when detour and delay happen.	Unacceptable extra cost when detour and delay happen.

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Indicators	Meets the future desired requirement (5)	Meets the current desired requirement (4)	Sufficient (3)	Slightly insufficient (2)	Completely insufficient (1)
Functional time duration	Hardly any hindrance due to planned and unplanned maintenance (robust) with traffic increase.	Hardly any hindrance due to planned and unplanned maintenance, leading to negligible user delay cost compared to the regular road maintenance.	Planned or unplanned maintenance leads to undesired, not negligible yearly user delay, leading to incidental but acceptable complaints of road users or other stakeholders.	Planned or unplanned maintenance leads to not negligible user delay cost and frequent complaints of road users.	Planned or unplanned maintenance leads to claims or seriously damaged reputation.
Function failure probability	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low and not expected to grow in the next decades.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is low.	The likelihood that traffic disruptions occur due to planned or unplanned maintenance is moderate, leading to incidental but acceptable complaints of road users or other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is moderate. It leads to frequent complaints of road users and other stakeholders.	The likelihood that traffic disruptions with hindrance occur due to planned or unplanned maintenance is high. It leads to claims of road users and other stakeholders or seriously damaged reputation.
Load bearing capacity	Load bearing capacity fulfills the requirements even with foreseeable traffic increase.	Load bearing capacity completely fulfills the requirements of current traffic.	Load bearing capacity almost fulfills the requirements of current traffic and does not limit the traffic.	Load bearing capacity is not sufficient and the traffic is limited (loading or speed, especially truck traffic) in an unacceptable level.	Load bearing capacity fails to carry the traffic and have high probability of dangerous consequences.
Traffic volume carried	There is sufficient residual capacity for the future traffic increase I/C ratio (Intensity/Capacity) <=0.8	The residual capacity meets the current requirements I/C ratio ∈ (0.8,0.85]	The residual capacity does not fully meet the current requirements but is still sufficient to carry current traffic volume I/C ratio ∈ (0.85,0.9]	The residual capacity is slightly insufficient but will not cause any serious congestion I/C ratio ∈ (0.9,0.95]	The residual capacity is insufficient and will any serious congestion I/C ratio >0.95
Structure geometry	The structure geometry is at design level with respect to bridge height and width below and above, and sufficiently flexible for traffic increase.	The structure geometry is sufficient for current traffic with respect to bridge height and with below and above.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, but does not create an unacceptable bottleneck in the network.	The structure geometry is insufficient for some traffic with respect to bridge height and width below and above, and creates an unacceptable bottleneck in the network, leading to complaints.	The bridge is the bottleneck of the surrounding network (with respect to vertical clearance/width of deck), and it causes potential safety hazard (with respect to skew).
Space arrangement for all kinds of users	The bridge provides reliable space arrangement for all users also for possible future development.	The bridge provides reliable space arrangement for all users.	The bridge provides reliable space arrangement only for critical users (including users who contribute to the main traffic flow, inspections, and emergency services).	The bridge does not provide reliable space arrangement for critical users.	The bridge has hindrance for critical users in using spaces.
Noise emission	The noise emission is totally acceptable and can fulfill the requirements in the foreseeable future without control measures.	The noise emission is under current limitation (required for environment permit) but requires control measures to meet the future requirements.	The noise emission is over the current limitation but it is still tolerable (no control measures).	The noise emission exceeds the limitation and some measures should be taken to control it but has no urgency	The noise emission is intolerable to people and the surrounding environment, which requires urgent measures.
Safety level of people and property	Road configuration (fatalities and injuries percentage) is safe to users with traffic increase.	Road configuration (fatalities and injuries percentage) is currently at a safe level to users.	Road configuration (fatalities and injuries percentage) is safe enough to users with minor prevention measures.	Road configuration (fatalities and injuries percentage) is safe enough to users with a lot of prevention measures.	Road configuration (fatalities and injuries percentage) is not safe enough to users.
Condition of drainage system	Drainage system has the required draining ability and operates without problems, even when subject to scenarios of climate change regarding the next 20 years.	The drainage system has the required draining ability and operates without problems currently.	The drainage system does not have the required draining ability and operates with problems, resulting in minor additional maintenance cost and/or yet controllable risks for road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in minor additional maintenance cost and/or incidental uncontrollable risks or road users due to deformations or aquaplaning.	The drainage system does not have the required draining ability and operates with problems, and cannot be easily adjusted by regular maintenance, resulting in major additional maintenance cost and/or uncontrollable risks for road users due to deformations or aquaplaning.
Damage level of the structure	The main structure is in perfect condition and no other cost than regular maintenance are expected in the next 20 years.	The main structure of the bridge is still in good condition. No specific maintenance problems, other than the regular periodic maintenance as expected for any other bridge.	The main structure of the bridge shows problems that exceed the regular maintenance expectations and needs minor investments to maintain the needed safety and risk level.	The main structure does not meet the current safety requirements and needs major investments to reach the needed safety and risk level.	The structure is unsafe due to damages and/or the main structure needs major investments to reach the needed safety and risk level, and will also need increasing major expenses in the future.
User's cost	Traffic users cost the same when detour happen.	Low extra cost when detour and delay happen.	Reasonable extra cost when detour and delay happen.	Slightly unacceptable extra cost when detour and delay happen.	Unacceptable extra cost when detour and delay happen.

Appendix H: EELI based on Performance Age

Bridge 1

EINDE LEVENSDUUR INDICATOR												
Huidig jaar:		2017										
Disconto voet:		2,50%		Disconto factor		0,975609756			(berekend veld, hoeft geen attiibuut te zijn in DISK)			
IHP bestaand												
Vervangings maatregel	verv. Interval	eenheidsprijs	hoeveelheid	Laatste jaar	Theoretisch eerstvolgend jaar	Activiteit prijs	Adviesjaar	Uiterste jaar	referentie jaar eerstvolgende maatregel	Contante waarde		Contante waarde vervroegd vervangen
Vervangen viaduct	80	4000	1000	1939	2019		2054		2054	€ 1.862.622,43		€ 4.644.167,21
Aanbregen beschermlaag						€ 5.000,00	2019		2019	€ 4.759,07		€ -
Aanbregen HWA-systeem						€ 29.000,00	2017		2017	€ 29.000,00		€ -
Vervangen geleiderail	25	383	120	2013	2038		2038		2038	€ 59.408,15		€ 53.820,85
Herstellen betonschade onderzijde Rijdek	30	16	1170	2013	2043		2043		2043	€ 18.826,52		€ 17.055,90
Vervangen houten meerpalen	30	6700	80	1939	1969		2027		2027	€ 800.222,63		€ 488.352,62
Vervangen Remmingwerk	30	2140	80	1939	1969		2027		2027	€ 255.593,50		€ 155.981,28
Conserveren staalwerk	20	205	12	1939	1959		2019		2019	€ 6.007,93		€ 3.852,08
Herstellen betonschade schampkant	25	56	120	2013	2038		2038		2038	€ 8.686,31		€ 7.869,37
Herstellen betonschade steunpunt	30	8532	10	2013	2043		2043		2043	€ 85.805,48		€ 77.735,53
Vervangen deklaag	9	35	940	2013	2022		2028		2028	€ 125.831,07		€ 132.201,27
Vervangen hele constr	18	76	940	1939	1957		2017		2017	€ 199.089,22		€ 127.649,22
Vervangen constructie	35	1608,42	22	2013	2048		2048		2048	€ 28.443,44		€ 25.768,36
Vervangen onderdelen	10	689,48	22	2013	2023		2023		2023	€ 59.779,28		€ 54.157,08
										€ 3.544.075,03		€ 5.788.610,76
						Waarde vervangingsindicator						0,61224967

Bridge 2

EINDE LEVENSDUUR INDICATOR											
Huidig jaar:		2017									
Disconto voet:		2,50%		Disconto factor		0,9756098			(berekend veld, hoeft geen attiibuut te zijn in DISK)		
IHP bestaand											
Vervangings maatregel	verv. Interval	eenheidsprijs	hoeveelheid	Laatste jaar	Theoretisch eerstvolgend jaar	Activiteit prijs	Adviesjaar	Uiterste jaar	referentie jaar eerstvolgende maatregel	Contante waarde	Contante waarde vervroegd vervangen
Vervangen viaduct	80	4000	1000	1933	2013		2050		2050	€ 2.055.986,65	€ 4.644.167,21
Herstel damwand en deksloof						€ 18.000,00	2015		2015	€ 18.911,25	€ -
Vervangen geleiderail, type VLP	25	241,5	150	2008	2033		2033		2033	€ 52.977,78	€ 42.420,81
Conserveren stalen onderdelen	20	162	40	1965	1985		2018		2018	€ 16.221,40	€ 10.146,94
Herstellen betonschade onderzijde rijdek	30	16	1250	2010	2040		2018		2018	€ 37.289,87	€ 18.222,11
Herstellen betonschade bovenzijde rijdek	18	8,5	1200	1965	1983		2017		2017	€ 28.425,39	€ 18.225,39
Herstellen betonschade	30	27	100	1965	1995		2026		2026	€ 4.131,75	€ 2.459,99
Conserveren opleggingen	20	680	80	1965	1985		2017		2017	€ 139.584,15	€ 85.184,15
Herstellen betonscahde schampkant	25	56	110	2010	2035		2035		2035	€ 8.574,69	€ 7.213,59
Herstellen betonschade steunpunt	30	8532	6	1965	1995		2026		2026	€ 78.337,91	€ 46.641,32
Vervangen deklaag	9	35	1200	2009	2018		2024		2024	€ 177.311,43	€ 168.767,58
Vervangen hele constr.	18	83	1200	1965	1983		2017		2017	€ 277.565,60	€ 177.965,60
Vervangen voegovergang type 4.1.a	5	494	74	2009	2014		2017		2017	€ 314.742,57	€ 278.186,57
										€ 3.210.060,44	€ 5.499.601,25
						Waarde vervangingsindicator					0,58368967

Bridge 3

EINDE LEVENSDUUR INDICATOR												
Huidig jaar:		2017										
Disconto voet:		2,50%		Disconto factor		0,975609756			(berekend veld, hoeft geen attiibuut te zijn in DISK)			
IHP bestaand												
Vervangings maatregel	verv. Interval	eenheids prijs	hoeveel heid	Laatste jaar	Theoretisch eerstvolgen d jaar	Activiteit prijs	Adviesjaar	Uiterste jaar	referentie jaar eerstvolgende maatregel	Contante waarde		Contante waarde vervroegd vervangen
Vervangen viaduct	80	4000	1000	1937	2017		2017		2017	€ 4.644.167,21		€ 4.644.167,21
Herstellen staalconstructue						€ 5.000,00	2017		2017	€ 5.000,00		€ -
Aanbrengen kerende constructie (fietspad)						€ 10.000,00	2017		2017	€ 10.000,00		€ -
Vervangen geleiderail, type VLP	25	269,22	196	2015	2040		2040		2040	€ 64.920,47		€ 61.792,24
Herstellen betonschade bovenzijde rijvloer	19	5,29	1180	1937	1956		2027		2027	€ 13.022,05		€ 10.427,12
Herstellen betonschade bovenzijde rijvloer	30	5,29	350	1937	1967		2017		2017	€ 3.538,41		€ 1.686,91
Conserveren staalconstructie bovenbouw	18	182	2600	1937	1955		2017		2017	€ 1.318.715,28		€ 845.515,28
Conserven staalconstructie onderbouw	18	110	2230	1937	1955		2022		2022	€ 604.205,29		€ 438.302,83
Herstellen betonschades onderzijde rijvloer	30	2,49	1800	1937	1967		2017		2017	€ 8.565,58		€ 4.083,58
Conserveren leunning staal	18	49	144	1937	1955		2017		2017	€ 19.663,68		€ 12.607,68
Conserveren oplegging staal	18	164	25	1937	1955		2017		2017	€ 11.425,89		€ 7.325,89
Herstellen betonschade schampkant	25	28,26	200	1937	1962		2022		2022	€ 10.845,51		€ 6.618,70
Herstellen betonschade steunpunt	30	1350,71	2	1937	1967		2017		2017	€ 5.162,70		€ 2.461,28
Klein onderhoud landhoofd	30	1103,66	2	1937	1967		2022		2022	€ 3.728,47		€ 2.011,10
Vervangen hoofdwegennet	15	71	350	1937	1952		2017		2017	€ 80.281,86		€ 55.431,86
Vervangen deklaag rijbaanbreed 1500m2	9	68,56	1180	2015	2024		2024		2024	€ 341.538,97		€ 325.081,71
Vervangen hele constructie rijbaanbreed 1500m2	19	88,46	1180	2015	2034		2034		2034	€ 183.190,75		€ 174.363,60
Vervangen constructie (enkelvoudig)	35	1608,42	36	2011	2046		2046		2046	€ 48.900,10		€ 42.166,40
Vervangen onderdelen (enkelvoudig)	10	689,48	36	1990	2000		2015		2015	€ 119.184,95		€ 88.620,67
										€ 7.496.057,19		€ 6.722.664,08
						Waarde vervangingsindicator						1,115042653