ASSET DETERIORATION
Determining Probabilistic Maintenance Intervals

C.J.A. ter Berg

TU Delft

Author

Name	C.J.A. (Coen) ter Berg
Student number	4107942
Email	coenterberg@gmail.com

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University	TU Delft
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Committee

Chairman	Prof.dr.ir. A.R.M. (Rogier) Wolfert Faculty of Civil Engineering and Geosciences
Supervisor	Ir. M. (Martine) van den Boomen MBA Faculty of Civil Engineering and Geosciences
Supervisor	Dr. M.T.J. (Matthijs) Spaan Faculty of Electrical Engineering, Mathematics and Computer Science
External supervisor	S. (Sander) Sasburg Municipality of Amsterdam

TU Delft

Gemeente Amsterdam

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Acknowledgements

This thesis once started at the 8th floor of Weesperstraat 8 in Amsterdam, headquarters of the civil constructions team of the municipality of Amsterdam. In a meeting with several employees responsible for the management of civil works I introduced myself and experienced trouble illustrating the urge of my research on probabilistic intervals for bridge maintenance. Research is about discovering the unknown and it soon became obvious that I wasn't even familiar with the knowns at this stage. It was the beginning of a journey full of interviews with a variety of people across the Netherlands. As a graduate intern it is good to be naïve, but it is naïve to be good, I thought for a long time.

During an interview in the final phase of my research I had the opportunity to confront a senior inspector with the way maintenance predictions are generated in the construction industry. It was the first time during the research I had the chance to criticize and convince someone in the field with my own findings. While being insecure about my findings, my presumptions were actually confirmed. This stage marked the development of my attitude as a critical expert in the field of work of my thesis.

I can now tell that gaining knowledge has been a lot easier than producing it. I went through all the standard setbacks and thresholds every student is being warned for. Knowledge has been produced in this thesis that reveals a piece of conservativity at a particular aspect in the construction industry. Although my thesis doubts the work of the people that helped me the most, I would like to express my sincere gratitude for their transparency and willingness to cooperate. This research would not have been possible without the contribution of VolkerInfra, Antea Group, IV-Infra, Royal Haskoning DHV and the municipalities of Haarlem, Rotterdam and Amsterdam.

A special thanks is given to Amsterdam's asset manager Sander Sasburg and his team of civil constructions at the municipality of Amsterdam. Thanks for having me as an intern and the network I had access to, illustrated in the list of companies above. I enjoy and respect the passion by which your team performs the task to manage technical complexities in a public environment. The task of managing infrastructure is essential but seems without gratitude. It's one of these things the environment 'takes for granted', not seeing the world behind, earlier resulting in complaints instead of recognition.

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Coen ter Berg
Delft, February 2018

Figure 1 Special thanks to Peter Joosten for a tour along bascule bridges in Amsterdam

Executive summary

The challenge in the infrastructure industry has shifted from funding new infrastructure to funding the repairing, rehabilitating and replacing of existing infrastructure. This challenge is accompanied with a lot of uncertainties regarding the deterioration process of physical infrastructure assets. Deterioration can be modelled with the use of data, but the parameters involved that predict the physical behavior of infrastructure assets are mostly an assumption and not known with certainty. Useful data to predict the process appears to be rare and are costly to generate.

The mentioned problem derogates the reliability of both short and long term asset planning (LTAP). This thesis screens the problem to maintenance planning on bridges in an urban environment. The municipality of Amsterdam facilitated the research and is a perfect example of a public infrastructure owner using deterministic values for maintenance intervals that do not generate a reliable estimate for maintenance costs. Uncertainties like differences in the use of bridges are not taken account, aspects that exert a difference in the deterioration pace. A new method to quantify uncertainties regarding the deterioration process of bridges in an urban environment has been developed in this thesis where expert judgement will be applied. The outcome answers the main research question:

How can ***Expert Judgement*** *be deployed to develop a* ***probabilistic maintenance interval*** *for* ***maintenance activities on bridges*** *in a* ***dynamic urban environment*** *in order to improve the* ***reliability*** *of* ***long term asset planning*** *in the absence of hard data?*

This thesis describes the development of the COTA method which quantifies expertise regarding the Condition Over Time Assessment of infrastructure assets. Three sub-questions are answered in order to develop a questionnaire with the goal to gain more insight in the deterioration process, the practices in maintenance and the way infrastructure condition is measured. Along the answering of these questions, data have been acquired after a thorough search through companies and municipalities in the Netherlands. The questionnaire has been used in the application of expert judgement.

The first sub-question distinguished the deteriorating factors that are present in different significance at different bridges. Deteriorating factors such as chemical processes and steel fatigue are assumed to be present everywhere. The focus is on the use of bridges in an urban environment. Bridges do vary by their characteristics but also by their use which indicates the relevance of maintenance activities with different intervals for different bridges. The quantification of the impact of uncertainties might be fed back to a developed classification of bridges which is based on the differences between use and design. The method to do this is not elaborated upon in-depth and earns more research.

Second, the practices of infrastructure maintenance are explored. The question why maintenance is done is answered by the presence of deterioration. The question what maintenance is performed is answered by comparing maintenance schemes from public infrastructure owners with commercial engineering firms and contractors. Each party in the maintenance sectors seems to use different schemes and annotations to execute maintenance. An official generalisation of maintenance to be performed on bridges has not been found. A list of (general) maintenance activities for which an impact quantification has been developed is the result of this question. The probabilistic intervals for these activities are generated in the COTA method.

Third, the measurement instrument for infrastructure quality has been investigated. Infrastructure quality can be measured technically as well as by appearance. The NEN2767-4 functions is a standard to measure the technical condition and the Dutch knowledge platform CROW developed a guideline to assess the appearance of assets. Both guidelines make use of a ranking by which the state of an asset is marked. The NEN2767-4 is an official Dutch standard and therefore used in the COTA method by asking the time by which an asset reaches a condition score regarding the NEN2767-4.

A questionnaire has been developed with the gained insight from subquestions and data found at the Dutch contractor VolkerInfra and the municipality of Amsterdam. An amount of 28 Dutch experts from VolkerInfra, Antea Group, IV-Infra, Royal Haskoning DHV and the municipalities of Rotterdam and Amsterdam with management and maintenance related functions participated in the questionnaire.

The questionnaire simulates an infrastructure inspection. Instead of planning maintenance in the future, the age of inspected damages has to be estimated by expressing uncertainty through the method of expert judgement. Experts show whether they have the ability to assess condition over time by quantifying the impact of deterioration. Expert judgement objectifies subjective probabilities by obtaining uncertainty assessments in form of three values, representing the favourable, unfavourable and most feasible outcome for each question. The uncertainty assessment skill, representing the 'COTA' skill, depends on the accuracy and informativeness of their assessments. After the assessment of damages for which the timespan is known, assessments are asked for the period it takes an element to deteriorate to a condition score regarding the NEN2767-4. The quantifications of experts are combined, depending on their performance during the simulation. Probabilistic intervals are generated by the optimal combination of expert opinions, with the highest statistical accuracy and informativeness.

Analysing the uncertainty assessments of every expert leads to the conclusion that the participating experts in general have trouble with estimating condition over time. Given the opportunity to express uncertainty with minima and maxima, experts use wide intervals to express uncertainty but still miss the right value in the simulation half the time. Estimating the interval for certain maintenance activities to preserve a set quality level regarding the NEN2767-4 resulted in very discrepant answers among experts. Leaving out the most discrepant questions did not generate any improvements in the results. Though, a combined opinion has been generated which is 25 times more accurate, but it does not express a lot of confidence in his answers as wide ranges are generated. The answers consist of distributions for a set of maintenance activities on bridges in an urban environment and represent a probabilistic interval.

This research took place in the context of improving the reliability of long term asset planning. The results of the questionnaire have not been fed back to the existing long term asset planning of the municipality of Amsterdam. The use of expert judgement did not solve the problem of lacking data. The topical interest of quantifying deterioration over time is proven however. Huge differences exist in the opinion of experts who advice on maintenance planning.

A recommendation is given to deal with the complexity of infrastructure deterioration in the future. Instead of an expert driven approach the industry should set up a more data driven approach. Every bridge in function is a physical experiment itself and information about these real-life laboratoria should be administrated to initiate a database in which the relation between bridge type, use and matter of deterioration can be monitored. An analogy with medical science is made to illustrate the concept of statistics and infrastructure. As soon as enough data have been gathered, analyses in the deterioration process may show why and how bridges deteriorate. By doing so, more reliable probabilistic intervals can be generated at different scales in the future.

Figure 2 Amsterdam, bridge 491 - Bascule bridge

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1. Introduction

Amsterdam

Amsterdam, the capital city of the Netherlands is renowned for its canals and bridges which connect the outer city with the city centre. Bridges are types of infrastructure serving the transportation of people and goods. Economical development and other functions as the delivery of essential services, the support of social needs and even quality of life have strong dependencies with road infrastructure (Too, Betts, & Kumar, 2006). The city of Amsterdam has been developing ever since the end of the Neolithic age till now where thousands of bridges are in function. The oldest bridge in active state is the Torensluis Bridge which dates from 1684. A lot of things happened in the period till the 21st century. The population nowadays is almost four times as big and the development of the car started in 1885. You can imagine that the initial design would totally be unaligned with the present demand and not all information in the meantime has been stored. It addresses a problem which will be furtherly explained in the upcoming paragraphs.

Infrastructure deterioration

Bridges can be found in all kinds of forms or types and differ from each other in material, dimensions, loads and lots of other characteristics. All these characteristics are parameters for a continuous deterioration process. Deterioration is an ongoing process where the value and performance of assets reduces over time due to stressful conditions. Deterioration is fortified by factors like increasing use, climate change, higher loads, heavier rainfall and stronger winds (Klatter & Roebers, 2017). Infrastructure assets like bridges are ageing, and an increasing number of bridges will reach their end of lifetime in the coming decades. It is hard to exactly specify this moment due to several aspect. At first, the quantification of deterioration is hard and deterioration is not always visible. Second, data to predict the moment of replacement or to model the deterioration process are rare and mostly absent. As the construction timeline of the bridges in Amsterdam is not linear, the expenditures on maintenance activities are not linear as well, resulting in high expenses in a short period of time. This effect can best be seen when the asset planning accounts for the longer term instead of a short term where it could occur that no replacement or major overhauls have to be performed.

Bridge maintenance

Maintenance on bridges can roughly be categorized in daily maintenance, major overhauls and replacements. Independent of the condition of assets, maintenance activities are currently planned by a deterministic time interval for types of bridges in Amsterdam and elsewhere. Due to uncertainties by lots of deterioration factors and usage, this interval is very unfeasible and more likely to shift over time. If overhauls and replacements on bridges could be postponed, costs will be saved, resulting in a lower output for maintenance expenditures. If overhauls and replacements on bridges should be put forward, firing risks will be prevented, resulting in a possible lower output for (corrective) maintenance expenditures (Alaswad & Xiang, 2017). The first situation appears to be more probable and the actual intervention moment for maintenance activities probably differs from the deterministic values that are currently used by public infrastructure owners.

Long Term Asset Planning

To have insight in the future maintenance expenditures for bridges and other infrastructure, the concept of long term asset planning (LTAP) has been developed. LTAP has the goal to show the proposed expenditures, capital and operational expenditures (CAPEX and OPEX), for the long term. This creates the ability to build up a monetary buffer to absorb the CAPEX which is necessary when a period of large expenditures due to multiple major overhauls or replacements comes up. LTAP also gives the opportunity to program major overhauls and replacements which create the advantage of spreading expenses over a longer term. Other public infrastructure owners like Rijkswaterstaat, the executive agency within the Dutch ministry of Infrastructure and Environment, are facing the budget challenge of replacing multiple infrastructures within a short period of time as well.

The concept of long term asset planning can be seen in Table 1. A sample of the current LTAP in Amsterdam is shown. It consists of a list of maintenance activities that can be done on small movable bridges and their deterministic frequencies. The frequency values are deterministic and do not take uncertainties into account.

Table 1 LTAP concept in Amsterdam for small movable bridges

	Maintenance activity	Interval	Unit costs
Daily Maintenance	Wear layer repair	5	€56,92
	Inspections	2	€580,-
	Cleaning drainage system	1	€243,00
	Lubricate machinery	1	€10,78
Major Overhauls	Railing conservation	10	€23,18
	Girder conservation	10	€50,00
	Wear layer replacement	10	€51,57
	Concrete repairs	10	€166,00
Replacements	Refurbishment/replacement	100	€4000,-
	Revision machinery	20	€432,34

Condition over time assessment

The interval of the maintenance activity is based on a certain quality level that is being endeavoured. Connecting a frequency to this quality level implies that insight has been retrieved in the deterioration process over time. Doubts exist however whether this deterministic value corresponds with the expenses in reality to maintain this quality level. By giving insight in the CAPEX and OPEX for multiple assets on the long term, infrastructure owners have a decision-making tool to plan expenses on infrastructure maintenance. It is thus important to have reliable input to come to a proper cost perspective and budget allocation for the long term. This thesis will focus on the development of a method by which one's uncertainty assessment skill regarding the deteriorating condition over time on infrastructure assets is quantified with the purpose to develop probabilistic intervals for maintenance activities on bridges. A probabilistic interval consists of a mean for a maintenance activity with a spread to cover uncertainties within the deterioration process. This concept of a certain mean and variance does exist but needs a lot of data to be generated which is not always available. The added value of this concept against the current practices, together with the reason why it is not there yet will be covered in the next chapter.

2. Problem statement

2.1 Introduction

This chapter will cover the urge for the research on the determination of probabilistic maintenance intervals and the reasons why it is hard to assess condition over time of infrastructure assets. Literature and interviews explain the causes for the need of probabilistic maintenance intervals.

2.2 Uncertainties in infrastructure asset management

Uncertainties in asset management are a major challenge and very dependent on the condition of an asset. Uncertainties may either be aleatory or epistemic. Aleatory uncertainties cannot be reduced and will not be discussed. The focus will be on epistemic uncertainties that influence asset condition. Asset condition, which specifies the likelihood of asset failure, is uncertain due to a condition dependent hazard rate or deterioration. The uncertainty about asset condition leads to early maintenance interventions to prevent risks from firing which creates additional costs (Feinstein & Morris, 2010). Directly adding to this is the fact that LTAP's have their uncertainties as well while they should give a reliable output for a given period. The difficulty in the reliability level of strategies like LTAP are attributed to the uncertainties about performance prediction and deterioration rates (Frangopol & Soliman, 2016). These uncertainties can be related to different causes and data might help in developing approaches to quantify these uncertainties. Relevant data to predict the deterioration process are absent however. The current type of data (sometimes) only reveals passport information of assets, not showing the dynamics since they were built. The lack of data fortifies the uncertainty about infrastructure assets.

Uncertainties and LTAP

Dekker (Dekker, 1996) defines uncertainties relevant for the reliability and optimization of LTAP's. At first there is a need for a decision support system to optimize maintenance planning. The problem with input parameters for these decision support systems is that they are often not measurable or defined (yet), creating a problem to take decisions based on such a model. RAMS[1] aspects are not taken into account yet in the LTAP of Amsterdam for instance. Secondly, and relevant for this research, the gathering of data to define a more reliable probabilistic maintenance interval or identify asset condition is not only a costly activity but should also have strict rules to ensure the reliability of the data. From interviews with municipalities of Amsterdam, Rotterdam and the province of North Holland, it turned out that absence of data about assets, containing dynamic information such as the last maintenance moment is a common thing. Passport information such as materials and building year are administrated but a comparison with maintenance administration as with cars for instance is yet far away. At last theory and practice are not aligned. In the optimal situation, asset managers possess all the necessary data to propose an optimized maintenance plan. The data consist of the exact states and information of assets, perfect interventions and inspections. However, actual situations show the near opposite or at maximum an approach of the optimal situation. Uncertainties due to imperfect data, actions and inspections exist. The asset manager has to create a maintenance plan with assumptions to fulfil the strategic demands. The impact of uncertainties is often not considered.

The uncertainty about data and asset condition is not very unlikely as uncertainty with assets starts from the beginning. The consideration of the effects of random variability in the strength and loads for assets is covered within the field of probabilistic design. Design parameters for instance are not only to be assumed deterministic but do have some kind of distribution with a mean and bandwidth. The load on a structure may vary, but so does the strength characteristic of an asset from the beginning. For example, the permittable deviation of cement used in a structure has a significant impact on its actual strength (Jonkman, Vrouwenvelder, Steenbergen, Morales-nápoles, & Vrijling, 2015).

The municipality of Amsterdam is not the only organization who is facing the problem of lacking data and uncertainties. Asset managers in a dynamic politic environment face a major challenge due to increasing performance requirements, less public acceptance, higher legal requirements and limited budget. The challenge to find an optimal balance between performance, costs and risks lies within risk based asset

[1] RAMS = reliability, availability, maintainability, safety.

management but the success of this approach is very dependent on the available data (Klatter & Roebers, 2017).

2.3 Deterioration of instrastructure assets

Due to the unknown impact of all these uncertainties it is very hard to define the 'optimal' moment to perform maintenance. The optimal moment this thesis is looking for can be seen as the moment just before an object reaches an undesired condition. This differentiation is hard to develop and the complexity with uncertainties is visualized in Figure 3 (Biondini & Frangopol, 2016). Figure 3 shows the expected deterioration rate and performance for a certain (sub)asset. The conceptual distributions show the uncertainty which is present in every phase and the uncertainty about the moment of intervention. The focus of this research is on the latter. To be able to assess the optimal moment of maintenance interventions, the uncertainty within maintenance intervals has to be modelled or quantified as other (observed) data is lacking, data which create certainty (R. M. Cooke & Goossens, 2000).

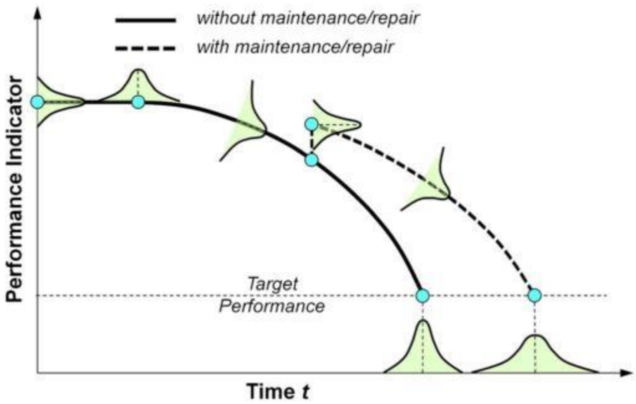

Figure 3 Uncertainties, deterioration rate and performance for a (sub)asset (Biondini & Frangopol, 2016)

Deterioration models describe the effect of internal and external loads. During the operation phase, assets are vulnerable to deterioration caused by mechanical, physical and chemical stressors, harsh environment, and extreme events (Frangopol & Soliman, 2016). Due to continuous deterioration, caused by the mentioned factors, the structural capacity and service life of systems is reduced and an asset's failure rate increases over time, leading to economic and societal loss (Zhang & Gao, 2012). Deterioration is a highly uncertain process and often invisible but the concept can be visualized as in Figure 4 (Kumar & Gardoni, 2013). An n-th load initiates a demand D to be resisted by a system capacity C. The demand D creates a deterioration process which leads to a reduction of the system capacity C. The vertical difference between the two dots for the system capacity induces a difference between the system capacity just before and after a load has appeared. To tackle the impact of deterioration, assets have to be maintained and upgraded in order to perform to their desirable performance levels.

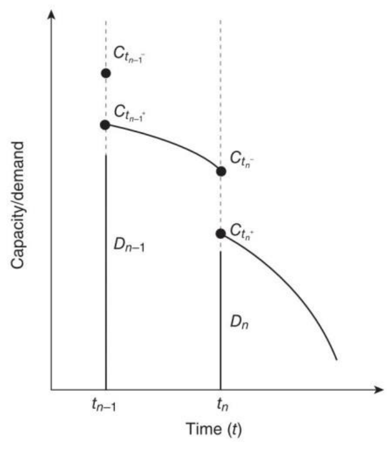

Figure 4 Visualization of the deterioration process (Kumar & Gardoni, 2013)

The input for deterioration models has direct effect on the LTAP as the planning of maintenance interventions is based on these models. Subsequently, the reliability of an LTAP is logically dependent on reliable input. Current deterioration models are of a stochastic nature with a mathematical approach which does not only create difficulties for understanding and interpretation by technicians and managers. The models are based on statistics that predict the properties of a group of structures instead of an individual asset. The parameters which predict the physical behaviour are mostly an assumption and not known with certainty (Klatter & Roebers, 2017). Concluding, a lot of factors cause the concept of deterioration to be patchy. The long life of infrastructure assets, the way asset condition reduces over this time, the lack of data, and how this process affects the maintenance interval are the main reasons for this (Parlikad & Jafari, 2016). The majority of maintenance plans uses only one deterministic value for a maintenance interval. However, as described above with the deterioration process, it is highly uncertain whether this value will give a representative image of the actual need for the maintenance activity to be performed at that interval.

2.4 Probabilistic interval

Probabilistic intervals show the possible periods by which an asset can reach a certain condition. Nicolai (Nicolai, 2015) shows the added value of probabilistic intervention estimates to be able to allocate sufficient funds for the financing of infrastructure overhauls and replacements in the future. The service life and variance of infrastructure assets is therefore estimated. The estimated functional lifetime of assets appears to be higher than the old deterministic lifetime values used by Rijkswaterstaat, owner of public works and water management in the Netherlands, an organization who is facing the same problem and challenge as the municipality of Amsterdam. The variance in lifetime gives the lead to develop a more reliable prospect for planned expenditures on maintenance activities for the long term.

The current LTAP of the Municipality of Amsterdam and many other cities is based on (deterministic) assumptions. The different parameters, maintenance interval, unit cost, engineering factor and so on are defined by means of practice, overestimated to have no risk, and do not have a variance. Due to the lack of relevant data it is very hard to determine a variance which is based on findings about the past. The decisions to be made in such a scenario are based on (large) uncertainties. The urban and dynamic environment of historical cities like Amsterdam also contributes to this. The lack of data and use of deterministic values regarding bridge maintenance as in Amsterdam appears to be a general problem. Other maintenance schemes of both municipalities and engineering firms show the same shortcomings that result in the same issues.

2.5 Different approach

Assuming that data are indeed absent everywhere, a different approach to deal with uncertainties should be sought for in order to develop probabilistic intervals and thus improve the reliability of long term asset planning. The decisions in asset management have to be taken in rational manner instead of biased by uncertainties. A method has to be developed to retrieve the necessary data alternatively to improve the reliability concerning maintenance intervals for the long term asset planning of urban infrastructures.

It is assumed that valuable knowledge about the discussed parameters is present at experts in their specific field of interest. The mean age at public authorities is rising and data that are not available on paper will be inside the heads of personnel (Lombaers, 2015). Experience and knowledge may probably generate a better assumption to assess condition over time, accompanied with an implicit level of subjective confidence, degree or belief, then mathematical approaches in case of lacking data (L. H. J. Goossens, Cooke, Hale, & Rodić-Wiersma, 2008).

Expert judgement combines subjective probabilities from experts in a specific field of interest to develop probabilistic distributions. This approach fits the written circumstances in which uncertainties exist due to the absence of data. Experts might be able to quantify the impact of the mentioned uncertainties by their expertise and experience. This quantification should be seen as the ability to assess the condition or performance of assets over time. Expert expertise is first calibrated againast situations for which answers are known to the researcher. After, their expertise is used for situations the researcher needs answers. By doing so, probabilistic maintenance intervals might be developed. Subjective probabilities become objectified and experts show in this method their ability to provide reliable prospects for future issues. The method of performance-based expert judgement will be elaborated upon in chapter 5.

3. Research question

3.1 Introduction

The previous chapters described the problem and motivation for this report. An approach to deal with this problem has been discussed. The goal of this report is to see whether this approach will indeed solve the illustrated problem. This chapter introduces the research question. This question will result in a methodology to tackle the problem statement.

3.2 Research question

The scope of the research is broken down to the dynamic environment of urban infrastructures. It is further broken down in the definition of the probabilistic interval with mean and variance for maintenance activites on bridges. The objective within this context is to develop a long term asset planning in which uncertainties are incorporated, instead of roughly overestimated. Expert judgement has been depicted to develop these intervals. This leads to the following research question.

*How can **Expert Judgement** be deployed to develop a **probabilistic maintenance interval** for **maintenance activities on bridges** in a **dynamic urban environment** in order to improve the **reliability** of **long term asset planning** in the absence of hard data?*

3.3 Definitions

The highlighted words are defined as follows:

Expert judgement

Expert judgement is a method which creates rational consensus by combining expert opinions. Subjective probabilities are elicitated to quantify uncertainties and develop distributions for situations where data does not exist. Expert opinions are elicitated through a questionnaire which first tests one's uncertainty assessment skill in the concerning field of work. After, new answers are developed for the actual problem. This method will furtherly be explained in chapter 5.

Probabilistic maintenance interval

A probabilistic maintenance interval addresses the possible frequencies (bandwith) by which a maintenance activity should be performed to maintain a certain quality level. The bandwidth consists of a mean and variance which will be developed by expert's estimates on given percentiles in a questionnaire. The percentiles represent the possible times by which an asset reaches a certain condition.

Maintenance activities

Maintenance activities are the activities that upgrade the quality or condition of a bridge. A set of maintenance activities will be selected for which probabilistic maintenance intervals will be developed.

Dynamic urban environment

The properties of a dynamic urban environment indicate a set of typical factors that cause a certain pace in the deterioration process. A dynamic urban environment in this context is characterized by a lot of changes in the use and policies for road infrastructure. The urban environment addresses the typical way bridges are used. Not all aspects of the urban environment can directly be quantified as they are aleatory instead of epistemic. The expertise and experience of experts in the field is used to give an approach.

Reliability

Reliability is a measure to which the long term asset planning performs consistent. The predicted maintenance expenditures are in line with the expenditures in reality.

Long Term Asset Planning

Long term asset planning is a budget planning which shows a list of budget debits that consist of all the maintenance activities to be performed for a specific period in the future. LTAP has the goal to give insight in maintenance expenditures for the specified period.

3.4 Sub-questions

To give an answer to the research question, insight should be gain about several issues. The sub-questions which serve the research question deal with three subjects relevant for the in- and output of long term asset planning. The input of long term asset planning consists of maintenance activities that are performed at a certain interval to tackle deterioration to a degree that assures a certain quality level. The fields of deterioration, maintenance activities and quality will be explored in sub-questions. The sub-questions create the framework of the questionnaire that will be used in the application of expert judgement by covering the why, what and when of maintenance in respectively sub-question 1, 2 and 3.

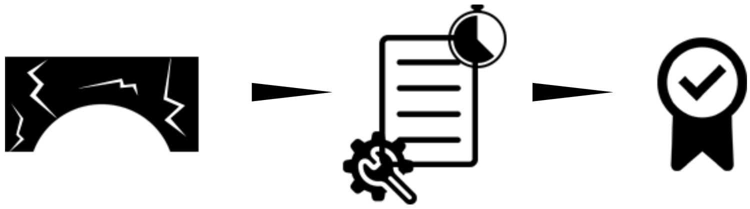

Figure 5 Deterioration leads to maintenance. Maintenance leads to higher quality.

1. ***What are main deteriorating factors on bridges in an urban environment?***

This question proves the relevance of a probabilistic interval and deals with the key characteristics of bridges and the impact of loads they have to bear in an urban environment. Interviews are used for the decomposition of a bridge and to illustrate why bridges deteriorate. The deterioration factors are the factors for which an impact quantification is being sought in the application of expert judgement. This question illustrates the need for maintenance.

2. ***How are bridges maintained in an urban environment?***

This question covers an exploration in the world of maintenance by interviews with both public infrastructure owners and engineering firms on maintenance activities to be performed on bridges in an urban environment. A selection of activities will be developed for which probabilistic intervals will be developed in the application of expert judgement.

3. ***How is the quality of infrastructure being assessed?***

It is important to know how the quality of infrastructure is being measured. Different standards or guidelines exist to which maintenance is planned to assure a quality level. This question will not elaborate which type of maintenance strategy should be used to endeavour a quality level in a network. The question is scoped to the quality level of a single asset.

4. Methodology

4.1 Introduction

This chapter will introduce the necessary steps to conclude the research question in the previous chapter.

4.2 Methodology

The aim of this research is to improve the reliability of long term asset planning in general. From literature it is concluded that the reliability of the long term asset planning will be improved by developing a probabilistic interval for maintenance interventions on bridges which incorporates epistemic uncertainties. The method to cope with the mentioned uncertainties by the development of such a distribution is shown in Figure 6.

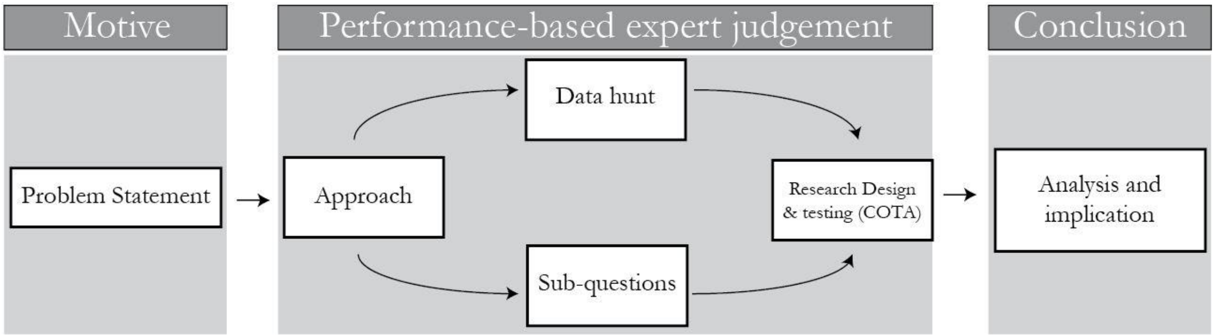

Figure 6 Determining probabilistic intervals for maintenance activities for bridges in a dynamic urban environment (own figure, 2017)

The research will consist of three phases. At first the necessity for this research will be shown under 'motive'. The problem statement introduced an intended improvement and the reasons why this improvement is absent yet. The second phase covers the necessary steps to design the application of expert judgement. Performance-based expert judgement is the chosen methodology in the development of probabilistic intervals. Probabilistic intervals will be developed by providing a test where the condition of assets have to be assessed over time (COTA). The application of the method leads to results. Analyses and implications will be performed during the last phase to conclude the research question. The outcome will be fed back to the problem statement. Each phase will be furtherly explained.

4.3 Motive

The motive has already been explained in chapter 2 - Problem statement. Literature will support the need and added value for a probabilistic interval in the context of long term asset planning. Several reasons create difficulties in the development of this interval. A problem faced by nearly all municipalities in the Netherlands is the absence of reliable registered quantitative data. Secondly, even the presence of past data would not guarantee its' future reliability due to the dynamic characteristic of an urban environment. The use and requirements of bridges can differ over time, while in fact the original state of the bridge was ought to be sufficient. Performance-based expert judgement has been chosen as the approach to assess the condition of assets and to solve the problem of lacking data by eliciting data through expert opinions.

4.4 Performance based expert judgement

The theory of performance-based expert judgement will be explained in the next chapter by consulting literature. The method itself provides a step by step application which will be followed to develop a questionnaire through which the ought probabilistic intervals will be determined. The questionnaire will be given to selected experts. The criteria for this selection and the framework of the questionnaire will be covered in the answering of sub-questions. The development of the questionnaire involves the hunt for data to develop cases by which one's uncertainty assessment skill can be quantified. The sub-questions and data form the building blocks of the research design.

Sub-questions
First, maintenance activities and deterioration factors will be addressed and dependencies between will be analysed. Maintenance activities and key factors that determine the intervention interval will be derived from both literature and interviews with experts from municipalities and engineering firms. By doing so, insight will be retrieved in the difference between estimating maintenance costs and performing maintenance activities which is of significant importance in the development of long term asset planning. The way the condition of assets is being assessed will also be investigated.

Data hunt
Next to the insight that will be gathered about maintenance on bridges in an urban dynamic environment, useful data have to be sought in the form of damage reports for which the impact of deterioration has to be assessed. One's uncertainty assessment skill will be leading to the conclusion whether experts in this sector are able to assess the condition of infrastructure assets over time, and if so, a probabilistic interval for certain maintenance activities. The outcome of the questionnaire will be analysed regarding the features that have been covered in chapter 3: Performance-based expert judgement.

Research design
The answers of the sub-questions together with the gathered data form the fundament and line of reasoning of the COTA method which is visualized in Figure 7. A simulation of an inspection is provided by showing damage reports to an expert. The expert's expertise in this field of work is first calibrated by assessing the time it took to get to this damage by predefined percentiles. After calibrating the expertise, assessments are asked for the term to perform a maintenance activity to fulfil a certain quality or performance level by the same percentiles. The line of reasoning and development of the COTA method will be furtherly explained in chapter 9 - The COTA method.

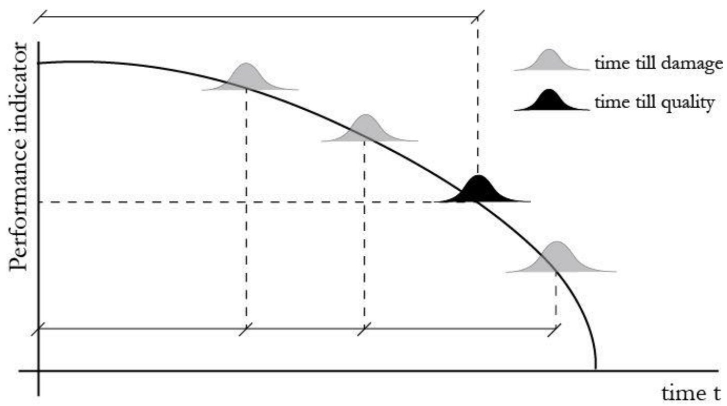

Figure 7 Concept of the COTA method

4.5 Conclusion
The outcome of the analyses of data will show whether the reliability of long term asset planning can be improved with the use of performance-based expert judgement. This outcome may consist of a product which consists of several distributions for maintenance activities that belong in an LTAP or it may conclude that expert judgement is not the right method for reliability improvement. The method will be evaluated, discussed and opportunities for further research on the method will be appointed in recommendations.

4.6 Qualitative versus quantitative
The outcome of this research will be based on quantitative data. This quantitative data will be derived by qualitative research in which several maintenance activities and deterioration factors have been explored, aspects that create the concept of a probabilistic maintenance interval. A direct link between the qualitative research and quantitative data is not made. Expert opinions are elicited that consist of three values representing percentiles and together forming a probability mass function. The distributions represent uncertainties causing the deterioration process but have not been qualified inside this distribution. No verification is made whether experts incorporate the same qualification of uncertainties in their assessments.

4.7 Limitations

As the research questions deals with a specific method that will be deployed to improve a certain issue, most of the limitations will be designated to this method. The outcome of the research will be dependent on the expertise and experience of certain people who will be given the expert judgement questionnaire. Experts in the field of bridge maintenance will be approached. At first a limitation can be set that the 'best' experts might not have been approached. Secondly, as people from different organisations in different regions may participate there is a big probability of biased experts who think in line with their organisation that might be different than others. Individual limitations of participating experts may be due to personal characteristics; being overconfident, hurrying and missing information and lacking motivation to participate for example.

The next chapter will explain the concept of performance-based expert judgement and the mathematical basis.

5. Performance-based expert judgement

5.1 Introduction

This chapter will introduce the literature and general application of performance-based expert judgement, also called Cooke's classical model, named after professor Roger Cooke. Chapter 9 elaborates upon the application of the method in this research. First the method will be explained in general where the procedure and mathematical basis is covered.

5.2 Expert judgement

Expert judgement objectifies subjective probabilities and has been derived from the theory of rational decision making by Louis Savage in *The Foundation of Statistics* (Savage, 1954). Subjective probabilities differ from person to person and they contain a high degree of personal bias. Probabilities are derived from an individual's personal judgement which contains no formal calculations but only reflect the subject's opinions and past experience. The fundamental assumption of the classical model of expert judgement from Roger Cooke is that the reliability or statistical accuracy of expert's opinions for the future can be measured by the reliability or statistical accuracy of their opinions for situations in the past (Roger M. Cooke & Goossens, 2008). Due to this assumption seed variables should resemble as much as possible the variables of target questions (L. Goossens & Cooke, 2005). Combining expert opinions may even result in an opinion that is even more statistically accurate. Past-performance is measured in 'seed' or 'calibration' questions and taken as indicative for their future performance which is measured in 'target' questions or variables of interest. Consensus in a rational manner can thus be reached by validating expert performance by situations in the past in the same field of work.

Seed variables test an expert's uncertainty assessment skill by asking values about situations for which the researcher possesses the true value. Variables of interest, or target questions, relate to questions for which the researcher develops new answers. Experts fill in pre-defined quantiles in a questionnaire to express their uncertainty. The experts' assessments are processed and combined by calculating their accuracy in regard to statistical likelihood and informativeness. An example from Tinae Nane, lecturer in expert judgement at the faculty of Electrical Engineering and Mathematical Sciences in Delft (Nane, 2015), illustrates the difference between seed and target questions.

Seed question or seed variable	-	*What was the average year temperature in 2013?*
Target question or variable of interest	-	*What will be the yearly average temperature in 2016?*

Data should exist to have a direct link between these questions. Research found out that data relevant for infrastructure maintenance are hard to find. However, the method has also been developed for situations where absolutely no data exist according to Nane. It is thus possible to apply expert judgement while the link between calibration and information questions is loose but still a result is being made. Questions should or can be set at the validity of the final result if there is no direct link. The method functions as a 'first' rational approach for particular situations though.

Performance-based expert judgement is based on calibrating expert knowledge and combining expert opinions. Four principles ensure the reproducibility and validity of this interviewing procedure:

1. *Scrutability/accountability*
   Data are open to peer review and results must be reproducible by reviewers.
2. *Empirical control*
   Expert assessments are subjected to empirical quality controls by the use of seed variables.
3. *Neutrality*
   The method for combining and evaluating expert opinion should encourage experts to state their true opinions, and must not bias results.
4. *Fairness*
   Experts are not pre-judged, prior to processing the results of their assessments.

The mathematical basis for applying this method will be elaborated upon in the next paragraphs.

5.3 Calibration

The essence of calibration questions is to define an index for the validity of the hypothesis that one's uncertainty assessment will represent reality in the future. Reality in this case can be visualized by an amount of conditions in time. The conditions or states are indicated by asterisks in Figure 8 and indicate a moment in time for which an assessment has to be made about the time it took to get to that state.

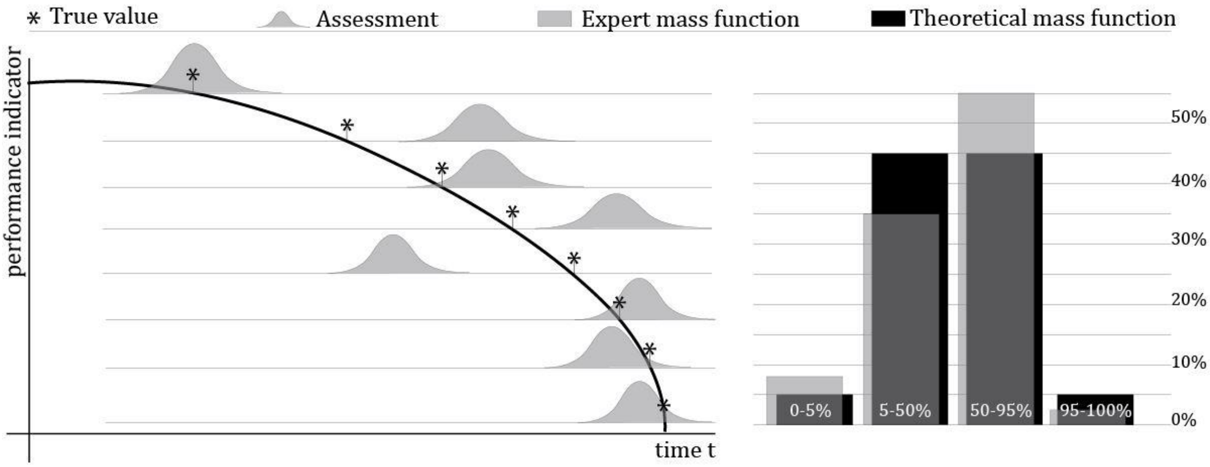

Figure 8 Expert assessment versus theoretical assessment

Experts are asked to express their subjective probabilities by giving probability mass functions. The probability mass functions indicate a subjective division of data within a function. The functions are defined by asking fixed percentiles, to be the 5% - 50% and 95%-tiles that define a border between possible outcomes with a certain probability. Due to the theory of statistical likelihood an amount of 100 uncertainties would then be divided in four intervals where 5 out of 100 uncertainties would fall both in the 0%-5% and 95%-100% interval, and 45 uncertainties would fall both in the 5%-50% and 50%-95% interval if and only if this expert is statistically accurate. Experts show their uncertainty assessment skill by the agreement of their subjective massfunction with the theoretical mass function. Just assessing the right true value with an expert's interval is not enough. To be a good uncertainty assessor, one's assessment should capture the right value in different bins of his interval. In other words, an expert's assessments should be similar to the theoretical assessments. The index for the relative information between the two mass functions is calculated by summing for an n number of seed questions the product between the generated sample mass function $s = (s_1, \dots, s_n)$ and the natural logarithm of s with respect to the theoretical mass function p. Assume $p_i > 0$ for $i = 1, \dots, n$.

$$I(s,p) = \sum_{i=1}^{n} s_i \ln\left(\frac{s_i}{p_i}\right) \quad (1)$$

As mentioned, a good assessment consists of a generated sample mass function which is equal to the theoretical one. This implies that a natural logarithm will produce a value of 0, suggesting no relative information by the theoretical mass function to the expert's mass function. This can best be understood as the measure of surprise or disagreement someone would experience if he believed p and learns s.

Hoel, (Hoel, 1971), proved that the distribution of twice as much samples (M) multiplied with the relative information value follows a chi-squared distribution with $n-1$ degrees of freedom as in equation (**2**).

$$2M \cdot I(s,p) \sim X_{n-1}^2, as\ M \to \infty \quad (2)$$

The calibration of an expert $e, e = 1, \dots, E$, with E the number of experts, is then defined as the index $C(e)$ for getting an information score worse than a score that would be obtained if an experts assessment is equal to the theoretical mass function $(p_0, \dots, p_n)$:

$$C(e) = 1 - X_{n-1}^2(2M \cdot I(s,p)) \quad (3)$$

Where $X^2_{n-1}(2M \cdot I(s,p))$ indicates the cumulative value of a chi-square distribution so a calibration score differs between 0 and 1. If an expert provides no relative information ($I(s,p) = 0$), he receives the maximum calibration score of 1 meaning his assessments (will) represent reality. On the other hand, the worst uncertainty assessor receives a calibration score approaching 0.

Example: consider 20 seed questions, so $M = 20$, for which an expert achieves to capture the true values 20 times by giving his 5%, 50% and 95% percentiles so $n = 3$. The expert's assessment contains 2, 6, 10 and 2 true values in respectively the 0%-5%, 5%-50%, 50%-95% and 95%-100% interval which generates a sample mass function of $s = [0.1; 0.3; 0.5; 0.1]$. Due to the chosen percentiles, the theoretical mass function is $p = [0.05; 0.45; 0.45; 0.0.5]$. Following equation(**1**, the relative information becomes:

$$I(s,p) = 0.1 \cdot \ln\left(\frac{0.1}{0.05}\right) + 0.3 \cdot \ln\left(\frac{0.3}{0.45}\right) + 0.5 \cdot \ln\left(\frac{0.5}{0.45}\right) + 0.1 \cdot \ln\left(\frac{0.1}{0.05}\right) = 0.0697$$

Combining with formula**(2**: $2M \cdot I(s,p) = 2 \cdot 20 \cdot 0.0679 = 2.716,$ and equation(**3** the calibration score becomes:

$$C = 1 - X^2_3(2{,}716) = 0.43752$$

The amount of seed questions is determining for the robustness of the calibration score as the difference between a generated sample mass function and a theoretical one changes faster with a smaller amount of questions (R. Cooke, 1991). The more seed variables the better, but ten is certainly sufficient (L. Goossens & Cooke, 2005).

5.4 Information

Being statistically accurate, i.e. equalling the theoretical mass function p formed by the predefined quantiles, is not the only criterion. The reliability of an expert's uncertainty assessment skill is also evaluated by their informativeness. Informativeness is a measure for the matter of confidence experts put in their assessment which is measured by developing an intrinsic range that captures the range of possible outcomes which was necessary to be accurate. The intrinsic range (x_0, x_{n+1}) is usually developed by using a 10% overshoot for all possible intervals (Bakker, 2004). The minimum (l) and maximum (h) values are defined as follows:

$$l = \min\{x_1(e), r|e\} \quad (4) \qquad x_0 = l - 10\% \cdot [h - l] \quad (5)$$

$$h = \max\{x_n(e), r|e\} \quad (6) \qquad x_{n+1} = h + 10\% \cdot [h - l] \quad (7)$$

The relative information of an expert e on an individual question or variable is then given by:

$$I(e) = \ln(x_{n+1} - x_0) + \sum_{i=1}^{n} p_i \ln\left(\frac{p_i}{x_{i+1} - x_i}\right) \quad (8)$$

The actual informativeness per expert is defined by calculating the average of all information scores per variable. Informativeness is represented by a positive score that increases when an experts uses narrow bounds, i.e. he is confident in his assessments as shown in Figure 9. Informativeness is less dependent on the amount of questions compared to seed variables.

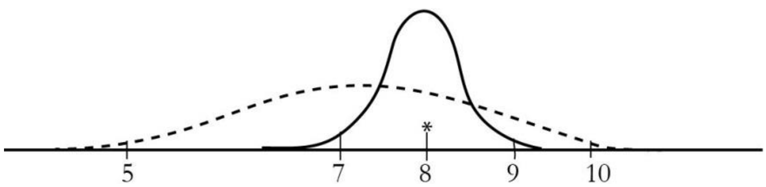

Figure 9 Different confidence level between dashed and continuous line

Example: Two experts have been gathered to estimate the age of a bridge in years based on a damage report and other details. Their assessments are shown in Table 2.

Table 2 Example assessments

	5%	50%	95%
Expert 1	6y	8y	10y
Expert 2	5y	6y	7.5y

The age of the bridge appears to be eight years, a value which is known to the researcher. The intrinsic range, capturing the 0%-100% interval is calculated:

$$x_0=5\text{-}10\%\cdot[10\text{-}5]=4.5$$

$$x_{n+1} = 10 + 10\% \cdot [10 - 5] = 10.5$$

Knowing the intrinsic range, $[4.5, 10.5]$, the information score of both traders can be calculated having in mind that $p = [0.05; 0.45; 0.45; 0.0.5]$. The informativeness for both experts is calculated:

$$I(e_1) = \ln(10.5 - 4.5) + 0.05 \cdot \ln\left(\frac{0.05}{6 - 4.5}\right) + 0.45 \cdot \ln\left(\frac{0.45}{8 - 6}\right) + 0.45 \cdot \ln\left(\frac{0.45}{10 - 8}\right) + 0.05 \cdot \ln\left(\frac{0.05}{10.5 - 10}\right) = 0.1641$$

Analogous we can calculate the information score of the second expert and find:

$$I(e_2) = 0.5708$$

Expert 2 puts more reliability in his assessment which can be seen in the scores. His score is higher than expert 1 but misses the true value which is more important for the weighting and approximation of expert distributions. This will furtherly be explained in the next paragraph.

5.5 Weighting schemes and decision makers

The goal of this method is to derive a distribution from expert opinions. Each individual opinion can contribute to the final distribution in either an equal of permance-based weighting scheme. Giving weights to experts is necessary in the search for a decision maker (DM) – an optimized distribution formed by combining expert opinions that will represent reality as much as possible. The DM can best be seen as a 'virtual' expert who possesses all the knowledge of each participating expert and is asked to answer the questionnaire again. A selective weighting approach represents a shift towards a more homogeneous combination of the views of the most influential experts. The DM can then out-score most, if not all, of the individual experts. On this basis, it could be argued that results obtained under this constrained optimization scheme represent a more robust, and more rational union of opinions than would be provided by making sure the views of the whole group were utilized with equal weight. Experts can be given weights in different ways: equal, item and global weights.

In case an equal weighting scheme is used weights are not based on experts performance but every expert receives the same weight calculated by taking the quotient of 1 over all experts. The resulting distribution is derived by dividing the sum of the experts distributions by the amount of experts E as shown in formula(**8**.

$$F_{EqualDM}(x) = \frac{1}{E}\sum_{e=1}^{E} F_e(x) \tag{9}$$

In case performance-based weights are used it will consist of the product of both calibration and information score and an indicator value.

$$w_e' = C(e) \cdot I(e) \cdot 1_a \cdot \big(C(e)\big) \tag{10}$$

$$w_e = \frac{w'_e}{\sum_{e=1}^{E} w'_e} \tag{11}$$

The indicator function defines a threshold between experts who will and who will not contribute in the final distribution, dependent on a predefined significance level a. The variable $1_a \cdot (C(e))$ turns 1 if $C \geq a$ and turns 0 if $C < a$, dependent on an expert's calibration score in the seed variables. This indicator function prevents experts who are very informative but have poor calibration scores from contributing to the final distribution. The indicator function is used to optimize the final distributions, the so-called decision-maker.

Global weights are calculated by using the global measures of performance on seed variables. These measures are the individual calibration and average relative information score over seed variables. When the significance level is set equal to zero, an expert's global weight is proportional to the product of calibration and average relative information over seed variables. For each expert, global weights are the same for all items. This is not the case in an item-based weighting scheme.

In case of item weights, for every item being dealt with a final distribution F_{dm} can be calculated by summing the product of an expert's weight by his distribution on that item. The item's distributions are made by linear interpolating their given quantiles for each item. This weighting scheme considers the matter of confidence experts put in their assessments per variable of interest. It might appear that an expert is really sure about a particular question and counterwise.

$$F_{DM}(x) = \sum_{e=1}^{E} w_e \, F_e(x) \tag{12}$$

Formula (**12**) shows how the DM is calculated. E stands for the amount of experts. The decision maker is calculated by the sum of the product of the weight per expert (per item) and the expert's distribution on that item. For the mentioned weighting schemes, an optimal decision maker can be developed by applying an optimization procedure over formula (**10**). This procedure entails the use of different values for a that changes the use and weights per expert with the goal to maximize the (virtual) weight for the decision-maker $F_{dm,a}(x)$. Note that the different values for a may change the pool of experts as some experts are not calibrated enough. The optimized final distribution is calculated as shown in formula (**12**).

$$F_{DM,a}(x) = \sum_{e=1}^{E} w_{dm,a} \, F_e(x) \tag{13}$$

5.6 Processing results

After the expert elicitation sessions have been done, the software program EXCALIBUR allows to use variations on the theme in application such as alternative weighting schemes and performing robustness and discrepancy analysis. EXCALIBUR originated in the Safety Science Group at the TU Delft and reached a mature state in the Mathematics Department of TU Delft (L. H. J. Goossens et al., 2008). These analyses create understanding of the data and opportunities to produce a better performing outcome. The analyses give an opportunity to give selected weights to certain questions which are ought to be more relevant for the outcome of the research (Aspinall, 2008). The results of the questionnaire will be analysed by performing a discrepancy and robustness analysis.

Discrepancy

A discrepancy analysis shows whether the given answers show a lot of overlap or significant differences in questions that can be caused by different factors like overestimating, anchoring, misinterpreting questions, or entirely missing the scope of questions. The actual discrepancy can be seen as the matter of agreement among participators, which is measured by comparing the relevant information per participator per item with the assessment of the equal decision maker for that item.

Robustness
A robustness analysis shows whether seed variables have been used that significantly influence the performance of the decision-maker, either in a positive or negative way. The influence on the final decision-maker is seen by leaving out seed variables one by one, or by leaving experts out one by one. By doing so, a more reliable outcome will be produced; a distribution that will better represent reality than the former one. The robustness of the questionnaire is tested in this step.

Expert judgement is deployed through a questionnaire. The way of answering and the processing of results has been explained. The content and framework of the questionnaire itself will be made by answering the sub-questions in chapter 3 regarding deteriorating factors, bridge maintenance, and infrastructure quality assessment.

6. Deterioration on urban infrastructures

6.1 Introduction

This chapter will further define the epistemic uncertainties as explained in the problem statement. Exploratory research in which managers and engineers from different municipalities have been interviewed lead to a rough generalisation of deteriorating factors on bridges in an urban dynamic environment to answer the first sub-question:

What are main deteriorating factors on bridges in an urban environment?

Qualifying these factors is important for quantifying the uncertainty. The quantification of these factors is the essence in the development of probabilistic intervals. Characteristics and deteriorating factors in an urban environment will first be qualified, resulting in a possible classification of bridges indicating different maintenance intervals for different types of bridges.

6.2 Characteristics of bridges in an urban environment

Bridges consist of principal components. A distinction is made between the substructure and superstructure. The following list of components can be made for fixed and movable bridges (Romeijn, 2006).

Substructure

1. Piers
2. Abutment
3. Wing walls
4. Footings and foundation

Superstructure

5. Drainage systems
6. Parapets/railings
7. Bridge deck joints
8. Bearings
9. Deck system
10. Wearing surface

Antea group furtherly distinguishes the super structure into pedestrian lane, cycling lane, traffic lane, wear layers, sub layer and construction beams. The bridge elements are shown in Figure 10.

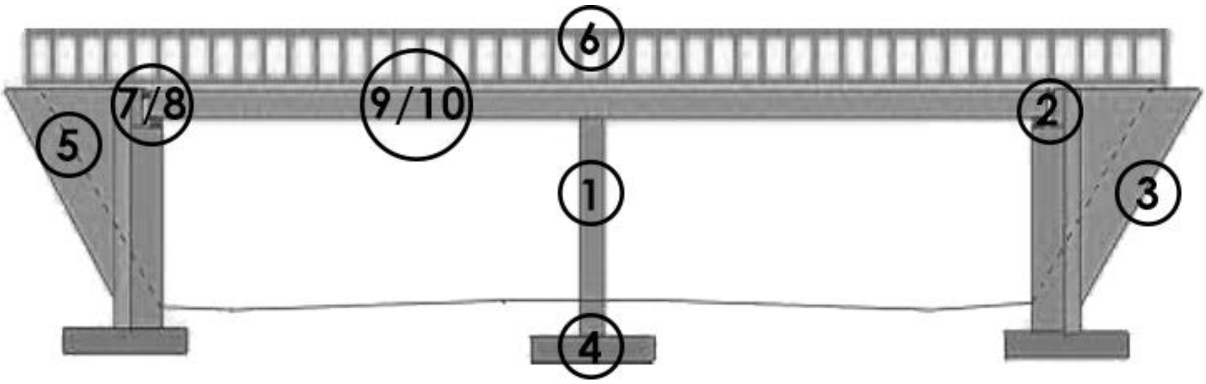

Figure 10 Bridge components (Romeijn, 2006)

This distinction counts for fixed bridges. Movable bridges consist of the same elements but are blessed with a transmission and movable deck. These elements have different characteristics that are dependent on the type of movable bridge. Amsterdam's movable bridges are usually bascule bridges for which a basement is accompanied where the counter weight turns. The transmissions in general are either electromechanical or hydraulic driven (Nederlands Normalisatie Instituut, 2003). The largest bridge basement in Amsterdam is pictured in Figure 11.

Figure 11 Bridge 485 – Oosterdoksbrug basement, revealing the counterweight and safety works

The main substructures of bridges are composed in such a way to fulfill a certain design standard describing the load it should be able to bear. The majority of bridges in urban cities like Amsterdam have been built or replaced in the 20th century. The standards that do apply on these bridges are developed by the Dutch Normalisation Committee The first standard is the 'Design guideline for steel bridges', VOSB 1938. This standard distinguishes bridges classes in four categories; A, B, C and D (Koninklijk Instituut van Ingenieurs, 1938) and can be seen in Table 3.

Table 3 Bridge classes regarding the VOSB1938

Class	Applies to	Permittable load	Axis load
A	Bridges in main routes	400kg/m²	20t
B	Bridges in main routes, derouted heavy traffic	400kg/m²	10-20t
C	Bridges not designated for heavy traffic	350kg/m²	10t
D	Bridges exceptional for light traffic	300kg/m²	5t

These classes can roughly be compared with more recent standards from the standards for designing bridges. The VOSB 1963 distinguishes three design classes in Table 4: VK30, VK45, VK60 (Nederlands Normalisatie Instituut, 1963).

Table 4 Bridge classes regarding the VOSB1963

Class	Applies to	Permittable load	Axis load
VK30	Bridges in main routes	400kg/m²	20t
VK45	Bridges in main routes, derouted heavy traffic	300kg/m²	15t
VK60	Bridges not designated for heavy traffic	200kg/m²	10t
-	Bridges exceptional for light traffic	300kg/m²	5t

Design standards determine the dimensions of the elements in the sub- and superstructure. A problem nowadays is that a lot of bridges have been designed regarding a certain standard which is known, but several parts of bridges have been reinforced without any administration. In 2017, Amsterdam started the program 'Constructive safety' in which the structural integrity of bridges in Amsterdam is recalculated. The reason why is that a new European standard will apply in the future to all existing bridges. New calculations have to be made with lacking information due to the problem described above according to managers of 'Constructive Safety'. Since the year 2012, the Eurocode, an international standard, applies which says that every bridge should fulfill a bearing capacity which is comparable with the former VK60 class. That would imply that even the most ancient bridges in historical city centers, ever built for horse-drawn carriage, should be heavily reinforced.

The dynamic urban environment creates most of the characteristics for the design of a bridge. Difficulties arise as the design of bridges depends on their purpose and use. The problem for Amsterdam is the age and design of bridges that comply with way lower use and other standards in the period they were built. As Leo Klatter and Han Roebers state, the use of bridges will increase over time. It is easier to increase the traffic capacity then increasing the bearing load of a foundation or abutment in such a busy environment where road blocks are not demanded. The designs of bridges are more of a static kind of nature. This creates significant (unforeseen) deterioration paces (Klatter & Roebers, 2017) as design and use become unaligned with each other. The impact of this problem will be addressed in the next paragraph.

6.3 Deterioration factors in an urban environment

Deterioration is being caused by aggressive chemical attacks and other physical damage mechanisms (Ellingwood, 2005). Processes such as carbonation, steel corrosion or fatigueness will not be explicitly mentioned but are certainly relevant in the deterioration process. This paragraph will adress differences in the use of a bridge in a dynamic urban environment. As already stated, the design of bridges depends on use and use depends on policy. Different factors exist by which bridges are used in a different intensity, especially in an urban environment. A significant difference leads to the confirmation for the need of different intervals for different types of bridges, which is the essence of this thesis.

An urban environment is characterized by bridges that perform multiple functions. Bridges overpass waterways and are either fixed or movable if not enough height can be gained for a fixed bridge, which is mostly the case in an urban environment. The transmission within a movable bridge can either be hydraulic or electromechanical, each causing a different intervention interval according to local bridge managers in Amsterdam. Electromechanical transmissions need more maintenance but have lower risk of failure. Electrohydraulical transmissions need less maintenance but are harder to maintain. Sometimes movable bridges lie in an important waterway which is being used for industrial shipping. The presence of important waterways creates significant difference in the opening frequency of movable bridges compared to movable bridges that are not as can be seen in Table 5. These data have been derived from researchers at the municipality of Amsterdam. The Westerkeersluis, Beltbrug and Kattensloot are bridges in a main waterway, while the others are not.

Table 5 Opening frequencies for bridges in Amsterdam between 2013 and 2016

Bridge	Openings
Westerkeersluis bridge	19.152
Beltbrug bridge	15.482
Kattensloot bridge	11.761
Omval bridge	5.683
Meeuwenplein bridge	1.066
Mariniers bridge	562
Le Maire bridge	41

Besides overpassing waterways bridges also serve the traffic going over it. To reach a city's center or other important areas, specific routes (city routes) are addressed to steer the traffic flow in certain direction. This has its influence for the amount of traffic going over a bridge if this bridge is part of the a so-called S-route. Besides more traffic, S-routes are also the main victim of brine as salt is used to prevent slippery roads during the winter. Together with frost, brine forms a significant deterioration factor for asphalt and if unlucky the construction underneath due to the thermal expansion of water that can be captured inside. A comparison of some of the bridges in Amsterdam has been made to show the significant differences in the amount of traffic, related to strength class and the amount of bridge openings.

Table 6 Bridge load comparison in main waterways of Amsterdam - Kostverlorenvaart & Amstelroute

Bridge	Name	Type	Year	Strength	Opening	Light traffic	Middle traffic	Heavy traffic	Trams/ dayhour
199	Overtoom	Bascule	1949	VK33	16.181	21.814	500	331	16.11
423	Berlage	Bascule	1931	B	5.665	16.770	1.616	364	13.20
101	Nw. Amstel	Bascule	1986	VK60	4.678	6.807	55	79	10.57
246	Hogesluis	Bascule	2011	VK45	5.982	6.320	86	73	21.29
350	Toronto	Bascule	1968	VK45	2.101	25.189	630	432	-
151	Willems	Bascule	1928	VK45	13.892	12.969	369	222	-
266	Kinker	Bascule	1936	-	15.452	8.513	125	131	26.77
173	Wieg	Bascule	1931	VK45	15.298	12.318	172	191	37.97
348	Zeil	Draw	2007	VK45	15.356	10.171	1458	206	14.97

Table 6 shows the bridge number, name, type, construction year, strength class, opening frequency, traffic load and average tram load during a day hour. Information has been gathered through Waternet data (responsible company for the waters in Amsterdam), the asset database of the municipality of Amsterdam and verkeersprognoses.amsterdam.nl where a prognosis is made for the traffic load on each road in Amsterdam. The strength class B for the Berlagebrug is derived from a former standard VOSB 1938 and is comparable with strength class VK45 according to Marc Bruchner, constructor at the municipality of Amsterdam. The opening frequency shows the amount of openings between 2013 and 2016. It can also be seen that the strength of the Kinker bridge has not been administrated, illustrating a type of problem which is faced by 'Constructive Safety'. Light, middle and heavy traffic are defined in the law for traffic rules and signs in the Netherlands (Hirsch Ballin, 1990).

1. *Light traffic* is defined as passenger cars with or without trailer and motorcycles.
2. *Middle traffic* is defined as small busses, delivery cars with or without trailer and trucks.
3. *Heavy traffic* is defined as trucks and big busses like touring cars and line busses.

Bridge 199 perfectly illustrates the presence of bridges wearing a high amount of traffic while they have been designed for lower standards. Recent inspections show that the state of the Overtoom bridge is deteriorating faster than other bridges.

Another characteristic of the urban environment is the excessive use of bicycles in the Netherlands. This excessive use also creates the demand of parking these bicycles. The parapets of bridges in Amsterdam are vulnerable to all these bicycles that are causing mechanical damage to the railings which have to be repainted earlier compared to bridges outside the city center. A policy change might reduce this problem. However, mechanical damage by bicycles is a significant deterioration factor for Amsterdam according to local bridge managers in Amsterdam. This phenomenon can be seen in Figure 12.

Figure 12 Bicycle placement against bridge railings is a common thing (Butler, 2011)

The problem of deteriorating conservation as with railings is a problem for girders and concrete as well. Different circumstances and characteristics influence the pace of conservation that is peeling off. First there is a strong dependency in the quality of the conservation and circumstances under which it has been applied. Secondly, factors differing from weather (rain & frost) to geometry of the bridge influence the deterioration pace. Figure 13 shows the Erasmusbrug and Hefbrug in Rotterdam. The conservation of modern bridges like the Erasmusbrug lasts longer than more ancient bridges like the Hefbrug according to local asset managers in Rotterdam. This has to do with the

Figure 13 The Erasmusbrug (1996) in red and Hefbrug (1927) at the right in Rotterdam (Voorthuijsen, 2017)

The steel surface will be painted in the same way but a prediction is made by the local asset manager Kambiz Elmi Anaraki that the conservation of the Hefbrug will need a new paint job way sooner as the construction consist of a lot of clinches which create a lot of angles by which it appears to be that the conservation will last less.

In the end, every bridge is unique, but at the same time they show general characteristics that can be brought back into a classification of bridges. Significant differences can be seen in the way what's demanded, be it the opening frequency or traffic capacity, and the relation between the demand and its design. From interviews it is conducted that this also affects the attention to be paid on maintenance on certain bridges. Other deterioration factors, as the dependencies within bridge characteristics, or less occurring geometries in bridges are chosen for to not take into account in the classification, but should be taken into account in the uncertainty assessments by the experts to cover all kinds of bridges. One of these dependencies can be seen in Figure 14 that shows that wear layers on a wooden bridge deck deteriorates significantly earlier then other decks regarding Ruud Draaijer.

Figure 14 A wooden bridge deck fastens the deterioration process for wear layers

6.4 Bridge classification

When considering all uncertainties consisting of all deterioration factors and the relative influence they have on a maintenance interval, a classification of bridges can be made which distinguishes groups of bridges. The classification in Figure 15 has been made with the collaboration of several employees within the municipality of Amsterdam. The construction date should also be taken into account regarding the fact that the deterioration process fastens over time. This can directly be seen in Figure 3 and Figure 4 and is especially relevant for the influence for activities on the longer term. The influence of weather conditions is assumed to be present in every situation and not taken into account in this classification.

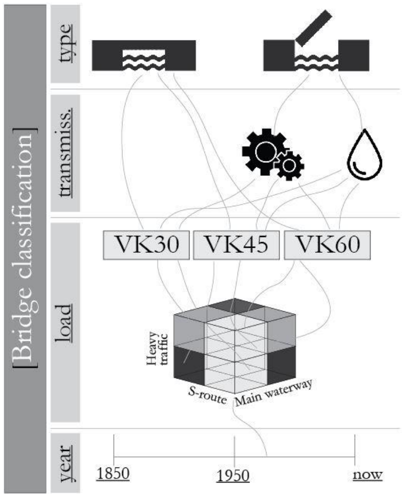

Figure 15 Classification of bridges in their relation between strength and use

Dependent on type, transmission, design strength and construction date, eight types of bridges can theoretically be distinguished. By doing so, a worst case and best case scenario for a bridge can be developed which address a heavily loaded bridge with weak design strength and contrary. Bridges which are loaded regarding their design strength are seen as the 'average' bridge. Note that the main waterway class only affects movable bridges. The highlighted rows in Table 7 represent the extreme demand circumstances under which bridges can theoretically occur and which circumstances have to be taken into account. Revealing the extreme situations or conditions can be useful when the intervals that will be developed have to be traced back to particular bridges that fit in the classification.

Table 7 Possible bridge classes in use

Heavy traffic	City route	Main waterway
X	**X**	**X**
X	X	0
X	0	X
X	0	X
0	X	X
0	X	0
0	0	X
0	**0**	**0**

6.5 Conclusion

This chapter gave all the information necessary to conclude the following subquestion:

What are main deteriorating factors on bridges in an urban environment?

Infrastructure deteriorates at different pace and on different levels. Bridge characteristics in an urban environment have been addressed and significant deterioration factors have been covered, varying from the amount of traffic to mechanical damage by human behaviour. Maintenance is performed to tackle the impact of these deterioration factors. Besides the qualification of deterioration factors, the influence they have on the deterioration pace can be modelled through a rough classification in the differences between design and use of bridges in an urban environment. The significant difference in intensity has been shown by comparing several bridges in the way they have been designed and the way they are used. The quantification of the difference of this intensity has to be developed in a probabilistic interval. The next chapter will show the relation between deterioration and maintenance.

7. Maintenance

7.1 Introduction

This chapter will explore the world of maintenance performed on bridges in an urban environment. The relation between maintenance activities and long term asset planning will be shown. In the end a list of selected maintenance activities will be made for which a probabilistic interval will be developed by applying expert judgement. This chapter will answer the second sub-question.

How are bridges maintained in an urban environment?

Why maintenance is performed has been answered in the previous chapter. This chapter covers what maintenance if performed from a technical point of view, strategic maintenance is not considered. The moment when maintenance is performed will be answered in the next chapter.

7.2 The reason for maintenance

The challenge in the infrastructure industry has shifted from funding new infrastructure to repair, rehabilitate and replace existing infrastructure (Neves & Frangopol, 2005). As already discussed in the last chapter, deterioration is an ongoing process in which the performance of bridges is being reduced over time. To tackle this process, maintenance has to be performed to enhance the quality and reliability of an asset (Yea & Xie, 2015). Maintenance is important to reduce failure frequency and downtime (Wang, 2002). A big challenge faced by the municipality of Amsterdam and other cities is to keep the networks in which these bridges are present safe and serviceable with limited funds (Yang, Frangopol, & Neves, 2004). Strategic differences in maintenance schemes depend on the available budget in a public agency and different interests as risk and image by which an asset may have more attention than others. This can be seen in Figure 16. Landmarks like the Magere Brug in Amsterdam for example receive more attention than other bridges fulfilling the same function. What does it take to preserve safety and please the eyes?

Figure 16 Magere Brug, an Amsterdam landmark

7.3 Analyzing maintenance plans

To find out what maintenance activities are performed and for which an interval can be developed, maintenance schemes of public infrastructure owners, engineering firms and contractors have been compared. By combining these plans it is assumed that from a technical point of view all maintenance activities are included in a general maintenance scheme. After thorough research through different parties a generalisation of bridge maintenance has not been found yet. The result is that companies use different designations for the types of maintenance and maintenance activities while appointing the same. The parties involved are the municipality of Amsterdam, Rotterdam, Haarlem, the contractor VolkerInfra and at last the engineering firm Antea Group. The maintenance schemes used by these parties can be found in Appendix A: Maintenance packages and will be used for the development of a general maintenance scheme. This general level is that level that combines the found differences and similarities in one single plan. The schemes will be analyzed by budget debits, maintenance classes and maintenance activities.

Comparing by budget debits

Not every maintenance activity is mentioned in long term asset planning. An LTAP consists of budget debits and as such these budget debits do only represent the costs of a group of maintenance activities instead of every maintenance activity itself. A sample of a municipal comparison of budget debits in an LTAP for maintenance activities between different public infrastructure owners is shown in Table 8. The difference and similarities between the plans can easily be seen. The frequency which is used in the plans depends on the strategic plan of these parties and the quality level they endeavour. The full comparison is shown in Appendix A: Maintenance packages.

Table 8 Comparing budget debits between municipalities of Rotterdam and Amsterdam

Municipality of Rotterdam	Municipality of Amsterdam
Gutters rainwater drainage	Cleaning of construction
Clean piping rainwater drainage	Clean piping water drainage
Clean tile wands	
Material repairs	Repairing conservation
	Repairing wood
	Repairing masonry
Repairing wear layer on steel	Repairing wear layers
	Repairing wear layer on deck

Comparing by maintenance classes

Public infrastructure owners also classify their maintenance in different ways. A quick municipal comparison in maintenance classification can be seen in Table 9. Either the type of maintenance is classified or the type of bridge. In the end, the maintenance to be done is nearly the same.

Table 9 Comparing maintenance classes

Municipality of Rotterdam	Municipal of Amsterdam	Municipal of Haarlem
Malfunctional maintenance	Daily maintenance	Concrete bridge plan
Periodical maintenance	Major overhauls	Wooden bridge plan
Project-based maintenance	Replacements	Steel bridge plan

According to the definitions used in Amsterdam, daily maintenance is classified as routine-based maintenance with a frequency less than a year. A major overhaul is classified as project-based maintenance with the goal to lengthen the lifetime of an asset. Replacements are defined as the full replacement of an asset. Literature does not point out such a thing as distinguished maintenance for infrastructure assets. Strategies and the types of maintenance itself including optimization models are well found but mostly develop the idea of focussing at the critical objects regarding risk and budget (Wang, 2002). It is hard to simply classify maintenance as a lot of dependencies arise between activities.

Comparing by maintenance activities

Maintenance can be done at different 'levels' and dependencies between these levels exist. Table 10 shows a sample of the combination of maintenance plans of each party on activity level. An approach for a generalised maintenance package can be found in Appendix A: Maintenance packages. To address the dependencies, the classification of the municipality of Amsterdam has been used. The maintenance on asphalt for instance contains smaller interferences like local repairs of the top layer, a replacement of the top layer, or an entire replacement of both the top and bottom layer. If smaller interferences are postponed, the bigger interferences will be put forward. This principle is shown for maintenance classes in Figure 17.

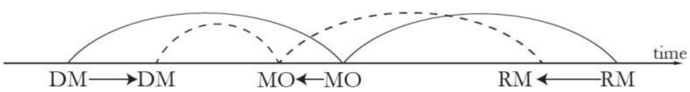

Figure 17 Dependencies in maintenance classes

The classification of Amsterdam though turned out to be controversial as the boundaries between maintenance classes exist of monetary terms instead of qualified maintenance activities. This results in a distinction of maintenance which is not very strict. A general classification should be developed indicating the functional dependencies between maintenance activities to have strict boundaries.

Table 10 Combined maintenance activities from several parties

Daily maintenance/major overhaul	Major overhaul/replacement	Replacement
Conservation concrete	MO concrete	
Conservation concrete railings	Railings concrete	
Conservation wooden railings	Railings wood	
Conservation steel railings	MO railings steel	
Asphalt small repairs	Asphalt top layer	Asphalt sub layer
Bitumen wear layer repair	Replacing deck parts wood	
Epoxy wear layer repair	Replacing deck parts plastic	
Driving iron	Replacing driving iron	
Repave	Replace pavement	
Conservation masonry	Masonry small repairs	Masonry big repairs

Some of the activities mentioned in Table 10 still address a range of activities to be performed. The set of maintenance activities for daily maintenance and major overhauls for materials is furtherly described into detail in Table 11.

Table 11 Maintenance decomposition for materials

Daily maintenance	Major overhauls
Concrete: local repairs	Concrete: structural repairs
Concrete: surface repair	Concrete: partial replacement
Concrete: crack injections	Concrete: paint
Concrete: paint	Hardwood/coniferous: structural repairs
Hardwood/coniferous: local repairs	Hardwood/coniferous: partial replacement
Hardwood/coniferous: paint (tipping)	Hardwood/coniferous: replace railing style
Hardwood/coniferous: paint railing	Hardwood/coniferous: paintjob
Masonry: local repairs	Hardwood/coniferous: paintjob railing
Masonry: replace mortar substance	Hardwood/coniferous: pole replacement
Masonry: crack injections	Masonry: structural repairs
Steel: apply screening provision	Masonry: partial replacement
Steel: paint	Masonry: replace bricks
Steel: local repairs	Steel: structural repairs
Steel: paint (tipping)	Steel: paintjob
Steel: paint railing	Steel: paintjob railing
	Steel: partial replacement

Table 11 shows activities that aren't that relevant for an LTAP. Their costs should be represented by other activities. Besides the attempt to generalise maintenance activities, overlap still exists. The activities to which the questionnaire of expert judgement will apply should be specific and applicable in an LTAP to satisfy the goal of improving LTAP reliability. This means that every participant should directly be aligned in the understanding of what maintenance is addressed. This seems logical, but the exploration through maintenance schedules lead to the recognition that the execution of maintenance is understood differently at several places.

7.4 Maintenance activity selection for expert judgement

It is hard to estimate an interval for certain activities of an LTAP as some activities are just used to have a proper budget in the end to do partial replacements or sub-activities within the same rule. A replacement of a transmission is budgeted but exists of subparts which are expected to last different periods with different budgets. Activities for which an interval is asked have to be specific and not 'just' a budget debit. The distinction between activity and budget debit is made in this stage.

The activities in Table 10 have to be furtherly filtered due to limitations in the methodology. Expert judgement limits the amount of questions to make sure every question gets the same attention. Tiredness, concentration, and other 'deterioration' factors influencing the decision-making model of a human body should not play a significant role according to Tina Nane.

The exploratory research for possible maintenance activities and budget debits, fulfilling the criteria to be present in an LTAP, and fulfilling the criteria to be used in the application of structured expert judgement lead to a final selection of maintenance activities. Table 12 shows the selection of maintenance activities derived from table x for which a probabilistic interval to fulfill a certain quality level will be demanded.

Table 12 Activity selection for Expert Judgement

Category	Activity selection	Specification
Sub and superstructure	Conserving railings	Total conservation replacement
	Conserving girders	Total conservation replacement
	Replace asphalt top layer	Total replacement
	Replace asphalt sub layer	Total replacement
	Replace wear layer	Total replacement
	Driving iron replacement	Total replacement
	Joint replacement	Total replacement
	Major overhaul concrete	Structural repairs and paint
	Major overhaul wood	Structural repairs and paint
	Major overhaul masonry	Structural repairs and replacing
	Pavement replacement	
Transmission	Revision safety mechanism	
	Revision transmission - elec	
	Revision transmission - hydr	
	Revision closing installation	

The enhancement of quality by performing maintenance is the concept for the development of target variables and is shown in Figure 18. The probabilistic interval that is being sought for will comply with a measurable performance indicator. The list of maintenance activities forms one of the aspects of these target variables. The measurement instrument will be explained in the next chapter.

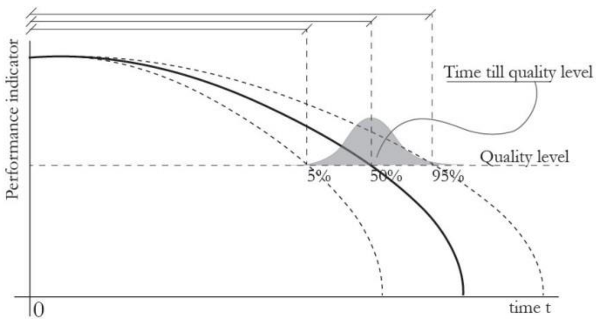

Figure 18 Target variable concept

7.5 Conclusion

This chapter gave all the information necessary to conclude the following subquestion:

How are bridges maintained in an urban environment?

Maintenance is planned differently but performed the same by various parties. Comparing the maintenance plans of the municipalities of Haarlem, Rotterdam and Amsterdam together with engineering firm Antea Group and contractor Volkerinfra, leads to differences and similarities in budget debits, classifications, and maintenance activities. Combining the plans leads to an approach of a generalised maintenance schedule in Appendix A: Maintenance packages. In maintenance a lot of dependencies exist. Dependencies create difficulties for quantifying uncertainties as several assumptions should be made about preceding maintenance activities that should have been done in time. The investigation in this chapter resulted in the list of maintenance activities for which a probabilistic interval will be developed by the use of expert judgement that can be seen in Table 12.

8. Assessing infrastructure quality

8.1 Introduction

The previous chapter described the maintenance activities that can be performed on bridges in an urban environment. This chapter will discover at what term maintenance should be performed. This chapter will answer the third sub-question:

How is the quality of infrastructure being assessed?

Instruments for assessing infrastructure quality will be described. The use of these instruments in expert judgement to test one's skill in assessing condition over time will also be explained.

8.2 The moment of intervention

As discussed, maintenance serves two purposes. The appearance of an asset can be important, as is the technical condition. A Dutch (official) standard has been developed for the visual assessment of the technical state of an asset. A guideline exists for the aesthetical assessment as well which will be explained. The assessment of infrastructure condition creates a measurable instrument to plan maintenance endeavour a certain quality level. The most renowned and first official objective way to assess infrastructure assets is by inspecting with the system of the NEN 2767-4 (Nederlands Normalisatie Instituut, 2011). Another system, developed by the Dutch knowledge platform CROW, qualifies and quantifies the appearance of infrastructure. Both insturments will be elaborated upon in the next paragraphs.

NEN 2767-4: condition assessment for infrastructure

The quantification of infrastructure appeared to be difficult for a long time since there was no objective system to assess infrastructure quality. Different parties had their own perception about the definition of infrastructure quality. The Dutch Normalization Institute has developed the NEN 2767-4 in 2008 to visually assess the technical condition of assets in the built environment. The method consists of a ranking by which different elements, categorized by another system, have to be assessed. All the possible elements and failure modes with degrees are named in this system. The ranking is shown in Table 13.

Table 13 NEN2767 methodology

Condition score	Explanation
1	Excellent condition
2	Good condition
3	Normal condition
4	Poor condition
5	Bad condition
6	Worst condition

The NEN2767-4 infrastructure assessment is based on a theoretical deterioration curve and commonly used in the Netherlands to get to know the technical condition about infrastructure assets and develop a maintenance planning to secure a strategic (minimal) condition. The standard prescribes a uniform decomposition for types of assets and failure modes. The NEN2767-4 does not tell anything about the appearance of an asset if there is no interface with the technical state of the elements. The visual inspection might give an outcome which prescribes further research to detect a deeper cause for certain damages or to monitor an object for the longer term. It depends on the maintaining party to hear these advices. The method to define a condition score is based on qualifying and quantifying shortcomings. Three parameters are determining, to be the seriousness, size and intensity of a shortcoming. The three categories and their distinction are shown in Table 14, Table 15 and Table 16.

Table 14 Seriousness division

Seriousness	Example	Description
Very serious	Wood rot	Causes loss of function
Serious	Erosion	Causes deterioration without direct loss of function
Low	Colour change	No impact on function

Table 15 Size divison

Size	Percentage	Description
1	<2%	Incidental shortcoming
2	2% - 10%	Local shortcoming
3	10% - 30%	Regular shortcoming
4	30% - 70%	Significant shortcoming
5	≥ 70%	Dominating shortcoming

Table 16 Intensity division

Intensity	Stadium	Description
1	Beginning	Shortcoming is barely visible
2	Progressive	Shortcoming is obviously visible
3	Final	Shortcoming can't be denied, can't be fixed and won't deteriorate furtherly.

Shortcomings are first distinguished in their seriousness and are plotted with the size and intensity in their seriousness category, which in the end results in a condition score regarding Table 13. A distinction is also being made by what level the condition score is given. An aggregation is done when one looks at the building part level, containing all different condition scores at elemental level where building parts are composed of building elements. The exact method for defining one condition score for composed components won't be furtherly explained.

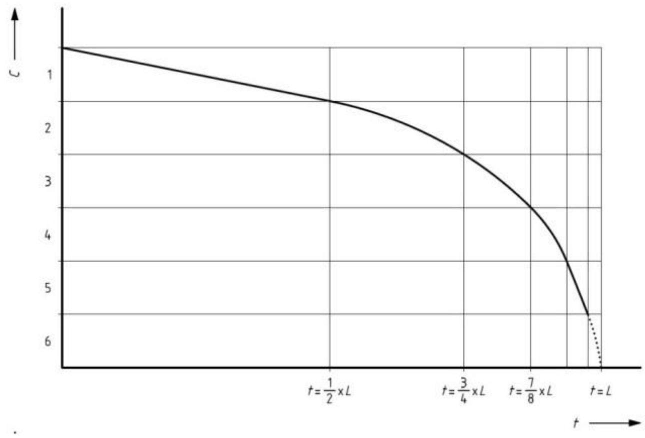

Figure 19 Theoretical condition progress as a function of lifetime regarding the NEN2767-4.

Another method exists for components whose condition can't be visually assessed. The main construction or transmission consists of a lot of these components. A condition score for bearings in a transmission of a movable bridge for instance is given by its theoretical life time as shown in Figure 19. Amsterdam constructor Hans van Kleef addresses a common problem that engineers have difficulties with life-time based design. As such, condition scores for hidden elements that are based on their theoretical lifetime do not necessarily represent their actual state.

CROW: appearance assessment for infrastructure

An asset might be performing technically 100% while the exterior looks abandoned. The NEN2767-4 is a visual inspection which only says something about the technical condition of infrastructure elements. Next to a technical condition municipalities demand more. The visual appearance of infrastructure is also of importance but hard to qualify and to quantify. Another system, developed by a Dutch knowledge platform CROW, qualifies and quantifies the appearance of infrastructure (CROW, 2013). The CROW also works with a ranking system by which the visual quality of assets is assessed as can be seen in Table 17.

Table 17 CROW methodology

Maintenance level	Description	Quality indication
A+	Very good	Nearly unworn
A	Good	Nice and comfortable
B	Sufficient	Functional
C	Poor	Busy image, discomfort,
D	Bad	Destructive, loss of function, juridical liable

The difference between the NEN and CROW can be seen in Figure 20. It is difficult to develop an aggregated score which expresses the entire 'state' of an infrastructure area as condition and appearance will never be of equal weight. Condition tells something about safety. Appearance tells something about image. There is not a 'correct' guideline yet for comparing or aggregating these scores. The NEN2767-4 addresses the RAMSSHEEP[2] method to take these aspects into account with the aggregation of the technical condition and strategical demands. The appearance of an asset might fall under the political aspect of RAMSSHEEP but an official way to make this measurable does not exist yet. Asset managers in Amsterdam tried to aggregate both NEN and CROW score in one value to express the condition.

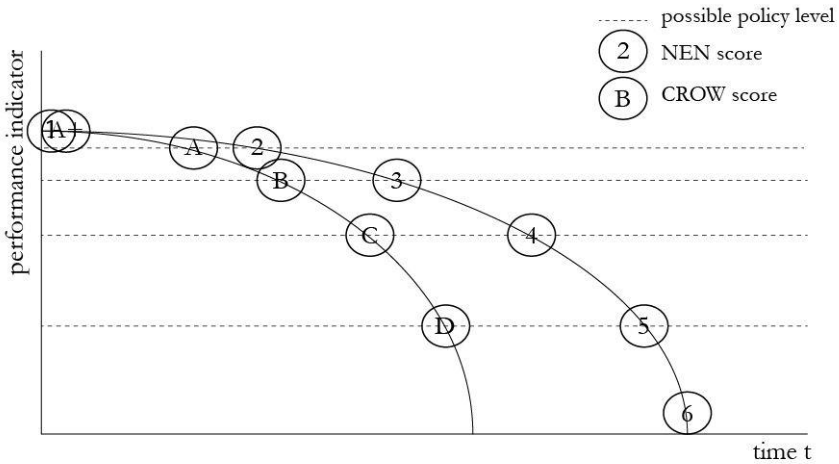

Figure 20 NEN & CROW have different degradation curves

Table 18 Aggregating NEN & CROW in Amsterdam

CROW	NEN 2767	Description
A+	1	No shortcoming, lacks or ageing symptoms.
A	2	Incidental shortcomings and lacks or beginning of ageing process.
B	3	Shortcomings and lacks appear. Ageing process is visual.
C	4	Ageing process starts dominating the asset. Failures appear.
D	5	Shortcomings and lacks are usual, ageing process can't be turned.

The municipality of Amsterdam strives for the ambition level 'well-cared for' which consists of a measurement combined of CROW and NEN assessments, shown in Table 18. Aggregating the scores creates the effect that an asset manager, influenced by the policy maker's ambition level, expresses his assets as being well-cared for, while everything might be in perfect condition, but might look abandoned. The aggregation is shown in Table 19 and Figure 20.

[2] RAMSSHEEP = reliability, availability, maintainability, safety, security, health, environment, economics, political.

Table 19 Amsterdam's ambition level in relation to aggregated NEN & CROW score

Ambition		Quantification: A+/1, A/2, B/3, C/4, D/5
Top+	As new, 100% clean	>90% in A+/1
Top	In control, beautiful appearance, no pollution	>90% in A+/1 or A/2
Well-cared for	Functions, cared appearance, little pollution	>90% in A+/1, A/2 or B/3
Sober	Less comfort, trash, pollution is present	>90% in A+/1, A/2, B/3 or C/4
Behind	Loss of function, dirt	>10% in D/5 or worse

The CROW guideline won't be furtherly explained. The focus for assessing the technical condition of infrastructure will be on the NEN 2767-4 standard. The implications of the NEN on maintenance planning will be explained in the next paragraph.

8.3 NEN 2767-4 and maintenance planning

Decisions regarding maintenance are confounded by uncertainties associated with the deterioration of structural uncertainties (Pandey & Yuan, 2006). Inspections by a standard like the NEN-2767-4 are necessary to give insight in an asset's (technical) condition. As soon as asset elements are given a condition score by the NEN, an advice to plan maintenance is often accompanied, dependent on contractual terms. The condition scores in a NEN report predict the 'expiry' date, the date at which a building part reaches a mature state that is not aligned with the strategic policy level of the infrastructure owner. As covered in the problem statement, a lot of uncertainties can occur in this period of time. To quantify these uncertainties, the NEN 2767-4 will be applied in the expert judgement series to function as a measurement instrument by which the condition of an asset has to be estimated over time. This concept is shown in Figure 21 and is present in the concept for the development of target variables as well.

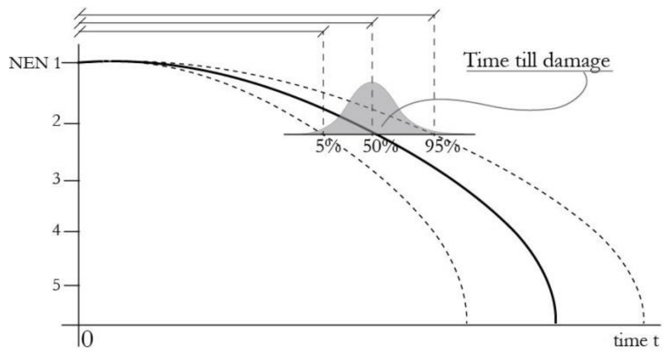

Figure 21 Condition over time assessment (COTA)

To assess whether someone can predict the period of time in which an asset will reach a certain state, a test will be given in which the period of time has to be assessed to come to a certain damage which is caused by 'regular' deterioration. As explained, seed variables test an expert's uncertainty assessment skill by asking values about situations for which the researcher possesses the true value. These seed variables have to resemble the variables of interest in Table 12 as much as possible. Concluding, damage reports have to be sought that refer to the deterioration of asphalt, railings, transmission and specific materials. Data are needed that fulfills the following criteria:

- The process of deterioration can be clearly seen.
- The deteriorating object is known.
- The deterioration cause is known.
- The performed maintenance between registered moment has to be administrated. This period can last from the date of operation from an asset to a first inspection where in between no maintenance has been done or where maintenance is registered. Another possibility is the registration of 2 moments, be it a photo or report, where a difference in time and damage can be estimated while knowing the fact that in between these moments no maintenance has been performed. At last, data can also be retrieved from measurements or reports at a bridge for which the entire development is known.

8.4 Acquiring data

The hunt for data lead to the recognition that data barely exist and when it exists it did not always fulfill the mentioned criteria. Data have been searched for in Amsterdam, the Province of Noord-Holland, Rotterdam, and Haarlem. A common problem found for a lot of municipalities is the storage of historical maintenance data. Municipalities are becoming more aware of the fact that this will help them improving their maintenance programming. A small amount of data fulfilling the conditions as stated was only found to be present at the municipality of Haarlem, where maintenance is contracted out to the contractor VolkerInfra. Another useful case has also been developed in Amsterdam.

Municipality of Haarlem

The municipality of Haarlem has a performance-based contract for ten years to maintain a set of fixed bridges with contractor VolkerInfra to comply with a certain (NEN) quality level. VolkerInfra inspects the infrastructure every three years. Some of the infrastructure has been built since 2000, creating opportunities for the participation in this research due to maintenance which hasn't been performed yet. An amount of 259 bridges has been investigated for their usefulness resulting in 15 bridges where mentionable and/or significant deterioration had been detected in their NEN inspection reports. For 7 of these bridges it has been made sure that the maintenance history is known.

Municipality of Amsterdam

The database of Amsterdam consists of passports of all the infrastructure and every now and then documents with the inspections that have been done on bridges. These inspections can be compared to the reports that are made with the NEN2767-4 regulation. However some data exist, it does not guarantee usefulness. The format of the report does not allow any analyses to be done. The administration in Amsterdam does register inspections but no maintenance interventions between these moments. A tour with service provider Peter Joosten along movable bridges in Amsterdam lead to another case which will be used in this expert judgement series. Combining data from Google Streetview and Figure 14 showed a period where in between no maintenance had been performed while serious deterioration at a wear layer was going on. Table 20 shows the bridges that will be used for seed variables in this expert judgement series.

Table 20 Bridges to be used for this expert judgement series

Name	City	Building year	Deterioration	Type of bridge
Noorderhoutbrug	Haarlem	2003	Railing corrosion	Pedestrians/cyclists
Belle van Zuylenbrug	Haarlem	2010	Deformation	Normal traffic
Zuiderfietsbrug	Haarlem	2012	Wear layer	Pedestrians/cyclists
Hagedisbrug	Haarlem	2000	Wear layer	Pedestrians/cyclists
Duinvlietvoetbrug	Haarlem	2009	Conservation	Pedestrians/cyclists
Bosbeekjufferbrug	Haarlem	2006	Antiquity	Pedestrians/cyclists
Lantaarntjebrug	Haarlem	2006	Antiquity	Pedestrians/cyclists
Mariniersbrug	Amsterdam	1935	Wear layer	Normal traffic

Resemblance of target variables

As can be conducted from Table 12 and Table 20, not every target variable is being resembled by seed variables. This has been inevitable due to the lack of data and the demand to develop intervals for multiple maintenance activities. The seed variables mainly describe damages on wear layers and railing deterioration, applying to bridges that are mainly used by pedestrians and cyclists. There is no direct proof for the relation of assessing condition on wear layers and railing deterioration and deterioration of other elements on a bridge. This will be furtherly reviewed in the discussion.

8.5 Problems with NEN

The NEN has been introduced as the first objective way to assess infrastructure condition. However, inspections by the NEN are done by inspectors that somehow assess the condition in a subjective way by an objective standard. People might see things differently and assess them in a different way along the three categories. It happens that damages remain unseen or are forgotten. The theoretical deterioration curve can be misused in these situations which is something that actually happens. These issues have the consequence of people giving different condition while given the same information. The NEN is perceived as 'at least it's something' by multiple companies.

8.6 Conclusion

This chapter gave all the necessary information to conclude the following sub-question:

How is the quality of infrastructure being assessed?

Quality or condition can be measured with different instruments in the Netherlands. A distinction is made however between the technical state and appearance of an object. The NEN2767-4 is the first objective way for the technical condition assessment of infrastructure in the Netherlands. In order to perform maintenance, it should be known what the minimal permitted quality level or policy level is. To assess whether people can estimate the deterioration of condition over time to reach this policy level, the NEN2767-4 will be used as a measurement instrument on cases for which it is known that no maintenance has been performed since the delivery or a given moment in time. For the usefulness of the outcome, the policy level will be set at a NEN condition score of 3 which complies with the ambition level of Amsterdam. This score can best be compared with a lot of small damages, or a small serious damage. The condition over time assessment skill of experts will be tested by estimating the 5%-50%-95% quantiles for the period it took to get to a certain damage. The probabilistic interval for the maintenance activities in Table 12 will be developed by the 5%-50%-95% estimates of experts for the period it takes to get to a condition score of 3.

9. The COTA method

9.1 Introduction

This chapter will cover the stepwise application of expert judgement to quantify the impact of uncertainties in bridge maintenance to develop probabilistic intervals for maintenance activities on bridges in a dynamic urban environment. Three building blocks of the expert judgement questionnaire have been investigated in the answering of sub-questions regarding the uncertainty to be quantified, a list of maintenance activities for which probabilistic intervals will be developed and the method to measure infrastructure quality. The questionnaire can be found in Appendix B: Elicitation format document.

9.2 Concept

The fundamental concept of this expert judgement series is visualized in Figure 22. If an expert is able to quantify the impact of uncertainties for situations the true value is known by estimating the time it took to get to certain damages, he is able to give a reliable estimate of the period it will take an element to reach a certain policy level or condition. The fundamental issue of this case is whether experts are able to assess the (possible) conditions over time of an asset (COTA). If so, a product can be made which exists of multiple distributions for the maintenance activities in Table 12.

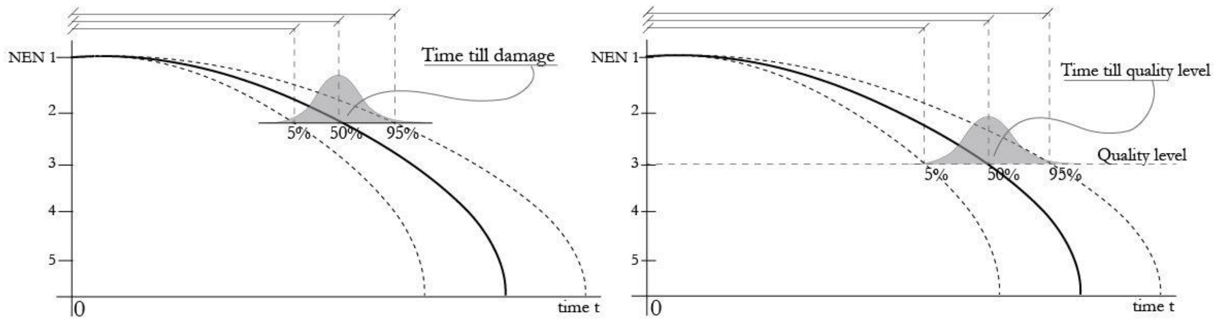

Figure 22 Concept of seed variable (red) and variables of interest (blue)

9.3 Expert judgement procedure

The protocol used for expert judgement stems from Cooke and Goossens (R. M. Cooke & Goossens, 2000). The outcome of each step will be covered briefly. The considerations for each step can be found in the answering of each sub-question which describes the scope of the research.

Preparatory phase

1. *Definition of case structure*

The purpose of this case structure is to develop probabilistic intervals for major overhauls on bridges. The case structure provides a test that shows whether people are able to assess the impact of uncertainties on the condition over time on bridges as explained in chapter 8 Assessing infrastructure quality.

2. *Identification of target variables*

The target variables consist of the maintenance activities for which a probabilistic interval or distribution will be developed. These activities have been derived from chapter 7.4 Maintenance activity selection for expert judgement. To align the experts in this research a selection has been made of maintenance activities that are clear and general. The activities are mentioned in Table 12.

3. *Identification of query variables*

Query variables consist of the variables that will be questioned out in both seed and target variables. These are the variables that are directly resembled. In this expert judgement series 23 query variables are questioned out consisting of 8 seed variables and 15 variables of interest. The seed variables and variables of interest can be found in respectively Table 12 and Table 20.

4. *Identification of seed variables*

Seed variables have been developed with the underlying concept to simulate an infrastructure inspection regarding the NEN2767-4 by looking for bridges for which no maintenance has been performed or for which it is known at what time maintenance has been done. This addressed a problem as historical maintenance reports were spare or not useful in this research. Seven relatively young bridges in the municipality of Haarlem in the Netherlands have been selected for use in this research. Another bridge in Amsterdam has been selected as well. For these cases it is known that when, if applicable, maintenance has been performed, and damage reports are present. The bridges used in this expert judgement series can be seen in Table 20 in chapter 8.4 Acquiring data.

5. *Identification and selection of experts*

The questionnaire will be handed out to experts fulfilling the following criteria. At first, experience with knowledge of the Dutch norm NEN-2767-4: Infrastructure condition assessment is essential as this standard is used as a measurement instrument. Secondly, experience should be present with the inspection of bridges and/or planning maintenance activities. Theoretically, an expert should also be able to quantify the impact of uncertainties on the maintenance interval already. This skill will be evaluated in this expert judgement application. A selection of 28 experts has been made. Regarding the TU Delft expert judgement data base, this is a lot. An amount of 45 expert panels had an average amount of experts of 10 (Roger M. Cooke & Goossens, 2008). As the infrastructure sector is not present yet in this database, a higher amount of participants will be involved to take away the risk of unreliable answers or other unforeseen aspects. The companies that are represented in this research by their contribution are shown in Table 21. The participating experts are shown by their function in Appendix C: Expert Judgement participants.

Table 21 Participating companies

Company name	Expertise	Participants
Municipality of Amsterdam	Bridge management & inspections	5
Municipality of Rotterdam	Bridge management & inspections	2
IV-infra	Inspecting & advisory	5
VolkerInfra	Inspecting & advisory	9
Antea Group	Inspecting & advisory	6
Royal Haskoning DHV	Advisory	1

6. *Definition of elicitation format document*

The questionnaire that shows both seed variables and variables of interest is shown in Appendix B: Elicitation format document. Attention has been paid to make the questionnaire look attractive. Awareness of the research and added value of each participant has been made clear by introductions during the elicitation sessions.

7. *Dry-run exercise*

Two dry-run exercises have been done with maintenance engineers from VolkerInfra and bridge managers from the municipality of Amsterdam. The sessions found out that the first questionnaire was too hard without any explanation on the methodology and topic. Improvements have been made in the way of questioning out target variables and an explanation on the methodology has been added.

8. *Expert training session*

During each workshop or elicitation session a thorough explanation on the methodology has been given to make sure everybody was able to answer all questions.

Elicitation

9. *Expert elicitation session*

Different types of workshops have been organized. In some cases it wasn't possible to get multiple participants from one company together which resulted in 1-on-1 sessions. Experts had the opportunity to look at each other's answers afterwards to get aligned in case information had been missed. It turned out that nobody was willing to change their answers while answers appeared to be very discrepant. The 1-on-1 sessions did not have the opportunity to look at other's answers.

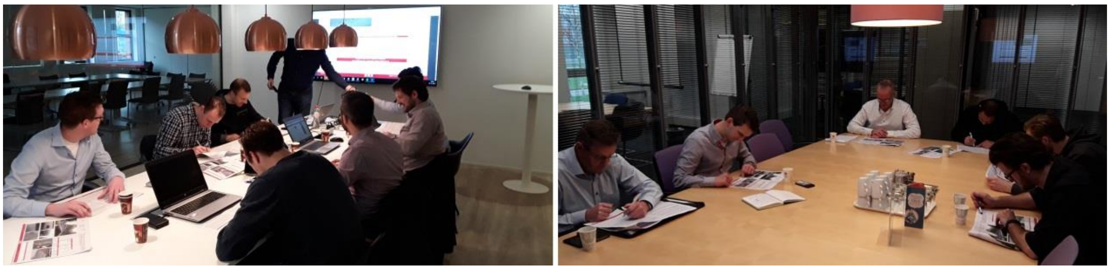

Figure 23 Elicitation sessions at VolkerInfra (left) and Antea Group (right)

After elicitation phase

10. *Combination of expert assessments*

The combination of expert assessments will be elaborated upon in the next chapter.

11. *Discrepancy and robustness analysis*

The analyses on the combination of expert assessments will be elaborated upon in the next chapter.

12. *Feed back*

The results of all answers will be fed back to the participating companies. This report, the final thesis, will also be presented to these companies. The evaluation of the results will happen internally and will not be processed in this thesis.

13. *Post-processing analyzes*

Not applicable in this study.

14. *Documentation*

All the results are documented in this thesis. The final results will be presented in a presentation at the Technical University of Delft and the Municipality of Amsterdam.

The next chapter will elaborate upon the last phase of the application expert judgement.

10. After elicitation

10.1 Introduction

This chapter will elaborate upon the after elicitation phase of the expert judgement application of the COTA method. Expert assessments will be combined and a discrepancy and robustness analysis will be done with the goal to see whether experts are able to evaluate the condition of assets over time. If so, an applicable distribution for maintenance activities that represents reality to a certain degree might be developed as well. Analyses will be illustrated with tables covering samples from the actual data in Excalibur. The full tables can be found in the appendices. The following appendices have been used:

1. Appendix B: Elicitation format document
2. Appendix C: Expert Judgement participants
3. Appendix D: Expert assessments
4. Appendix E: Excalibur output

10.2 Strategy

The questionnaire consists of three types of questions. The first type relates to seed variables S_x . The second type of questions relate to target variables for fixed bridges; T_1, T_2, T_3, T_4, T_5, T_9, T_{10}, T_{11}, T_{12}, T_{13}, T_{14}. The third type relates to target variables for movable bridges; T_6, T_7, T_8, T_{15}. The variables are shown in Appendix B: Elicitation format document. This separation has been done due to 3 experts who weren't familiar with movable bridges. Their assessments would cause huge discrepancy or disagreement with other experts and result in outcomes with large uncertainty. The performance measurement through seed variables remains the same for each expert as no seed variables regarding movable bridges have been found. Different weighting schemes and analyses as explained in chapter 3 - Performance-based expert judgement will be applied with the goal to maximize the statistical accuracy and informativeness of the decision maker's distribution.

Figure 24 explains the strategy for the analysis. As explained, the questionnaire consists of questions related to fixed and movable bridges. The two types of questions will be analysed separately by applying the different weighting schemes and features as discussed in chapter 4.4 Performance based expert judgement. A more applicable result might be obtained by tweaking the calibration and information scores. After the robustness and discrepancy analysis the final conclusion will be drawn.

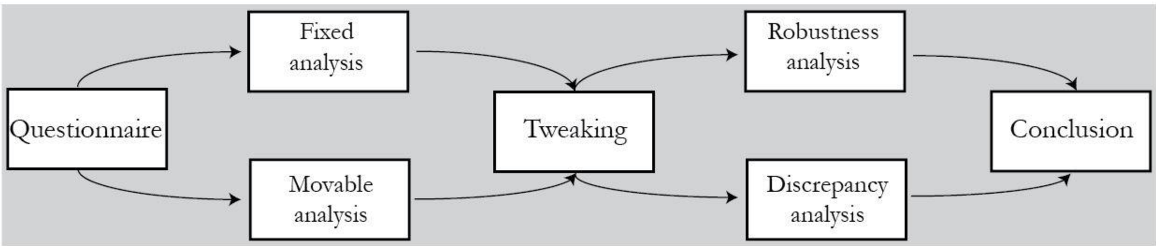

Figure 24 Analysis strategy

Dummy table

The expert's assessments from the questionnaire result in tables that illustrate their individual calibration and information score. Table 22 functions as a dummy table and will be explained. Expert names are covered by ID's in column 1 in order to prevent blackening. The second column shows the calibration score for each expert; the index for their statistical accuracy with a domain between 0 and 1. A higher score indicates a better uncertainty assessor. The third and fourth column reveal the information score for each expert; the index for the range one needs to express his uncertainty for respectively all and just seed questions with a domain between 0 and ∞. A higher score means higher confidence and a smaller bandwidth. The amount of seed variables is shown in column 5. The sixth column shows the un-normalized weight which is derived from formula (**10**). The normalized weight without the decision-maker in column 7 is calculated by taking the quotient of 1 over the amount of participating experts as an equal weighting scheme has been applied. The last column normalizes the un-normalized weight in the sixth column in combination with the decision maker.

Table 22 Excalibur sample for fixed bridges with equal weights

1	2	3	4	5	6	7	8
ID #	Calibr.	Mean rel. total	Mean rel. seed	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 4	5,86E-07	1,095	1,093	8	6,40E-07	0,03704	5,43E-06
Exp. 19	0,000144	2,051	1,743	8	0,000251	0,03704	0,002129
Exp. 23	0,01644	0,8191	0,8412	8	0,01383	0,03704	0,1173
EqualDM	0,08041	0,2786	0,2188	8	0,0176		0,1492

Table 23 illustrates the meaning of the values in column 2 and 4 in Table 22 for several experts. A bad, average, and well calibrated expert are personalized by respectively expert 4, 19 and 23. Seed questions and expert opinions are revealed in the remaining columns by the expert's 5%-50%-95% quantiles. The second row shows the true value or realisation for each seed variable. Note the difference in calibration and information score and how this is represented by their assessments.

Table 23 Illustrating the representation of calibration and information values on seed variables

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Realisation	4	7	6	10	15	13	10	38
Exp. 4	4-6-8	2-6-10	15-25-35	20-30-40	15-25-35	15-20-25	15-20-25	4-6-8
Exp. 19	4-10-15	7-10-12	10-15-20	20-30-40	10-14-18	15-20-30	8-12-16	36-60-72
Exp. 23	3-5.5-8	5-7-10	6-10-15	10-15-20	10-13-25	10-13-25	15-20-30	24-60-84

10.3 Combining expert assessments for fixed bridges

The mean calibration score of the experts is very low regarding Table 40. Summing the scores and dividing them by the amount of experts gives a mean calibration score of 3,59E-03. The mean information score on all questions and just seed questions is respectively 1,49 and 1,35. According to Nane, the calibration and information score are relatively low and high. Several reasons may exist for the slightly wider range in the variables of interest. Uncertainties might have a different impact on the variables of interest for which a higher range is necessary to capture these uncertainties. Not all variables of interest are resembled by the seed questions. The matter of confidence in their assessments per expert might be the cause as well. Ambiguity in the variables of interest may play a large role here. Analyses will cope with this issue.

Different weighting schemes might result in a virtual expert with a better performance. First an equal weighting scheme will be applied whereafter the performance-based weighting schemes will be analysed.

Equal decision maker on fixed bridges

An equal weighting scheme is applied in Table 24. This scheme results in a very low calibration and information score for the equal decision maker (EqualDM). The calibration score of the decision maker (0,08041) is almost three times higher than the highest calibrated expert (0,02651). Low calibration may occur due to overconfidence, ie. using narrow bounds. This is not the case for the EqualDM as the information score is very low as well. The information score fluctuates with a factor 3 among experts. The EqualDM has an information score (0,2786) almost four times as low as expert 21 who used the largest bounds in the questionnaire (0,7568). Narrow bounds indicate a high information score. This can be seen at expert 6, 11, 13, 14 and 22. It also happens that experts use a wide range but still miss the realisation and have a low calibration score. Expert 21 illustrates this and appears to be a worse uncertainty assessor than other participants. Some experts perform significantly better as can be seen when their weight is normalized with the decision maker in column 8. Experts 3, 8, 17, 23 and 24 have a weight comparable to the equal decision maker. Expert 3 performs best in this weighting scheme with a weight of 0,2277. The EqualDM has a weight of 15%.

Table 24 Excalibur output samples using equal weights

ID #	Calibr.	Mean rel. total	Mean rel. real.	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 3	0,02651	1,24	1,013	8	0,02685	0,03704	0,2277
Exp. 6	5,86E-07	2,122	1,975	8	1,16E-06	0,03704	9,81E-06
Exp. 8	0,01644	1,502	1,11	8	0,01825	0,03704	0,1548
Exp. 11	1,79E-08	1,928	1,852	8	3,32E-08	0,03704	2,82E-07
Exp. 13	3,72E-06	1,974	1,862	8	6,93E-06	0,03704	5,88E-05
Exp. 14	3,72E-06	1,912	1,729	8	6,44E-06	0,03704	5,46E-05
Exp. 17	0,01566	1,26	1,107	8	0,01734	0,03704	0,1471
Exp. 21	1,75E-05	0,7568	0,7584	8	1,33E-05	0,03704	0,000113
Exp. 22	1,29E-06	1,74	1,807	8	2,32E-06	0,03704	1,97E-05
Exp. 23	0,01644	0,8191	0,8412	8	0,01383	0,03704	0,1173
Exp. 24	0,01566	1,208	1,021	8	0,01598	0,03704	0,1355
EqualDM	0,08041	0,2786	0,2188	8	0,0176		0,1492

Using a performance-based weighting scheme will probably increase the calibration and information score and weight of the decision maker by excluding bad calibrated participants. A relatively more reliable output may be developed by doing so.

Performance-based decision makers on fixed bridges

Table 25 shows the application of both global and item weights decision makers (GlobalDM and ItemDM). Using a performance based weighting scheme indeed results in a higher calibration and information score for both the global and item decision maker.

Table 25 Fixed bridge sample with global and Item weights under significance level of 0,01644

ID #	Calibr.	Mean rel. total	Mean rel. real.	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 3	0,02651	1,24	1,013	8	0,02685	0,4556	0,07736
Exp. 8	0,01644	1,502	1,11	8	0,01825	0,3097	0,05259
Exp. 23	0,01644	0,8191	0,8412	8	0,01383	0,2347	0,03984
Exp. 24	0,01566	1,208	1,021	8	0	0	0
GlobalDM	0,6876	0,5039	0,419	8	0,2881		0,8302
ItemDM	0,6876	0,5461	0,441	8	0,3033		0,8373

Both schemes exclude the same experts by using a significance level of 0,01644 and thus receive the same calibration score. Expert 24 for instance has a calibration score of 0,01566 < 0,01644 and is therefore excluded. This value for α maximizes the weight of the decision makers. By the use of this value just the best calibrated experts join the pool and other experts are excluded. Both weighting schemes result in a calibration score for the decision maker of 0,6876. This score is almost 9 times higher than the calibration score of the EqualDM and 26 times higher than the highest calibration score (Expert 3 with 0,02651). The information scores are more than 2 times higher than the information score of the EqualDM. The information score of the ItemDM is slightly higher than the GlobalDM on both seed variables (0,441 vs 0,419) and variables of interest (0,5461 vs 0,5039). By using performance-based weights, only 3 out of 27 experts managed to achieve a calibration score high enough to contribute to the virtual expert. Expert 3, 8 and 23 would respectively receive a weight of 7%, 5% and 3%. Both decision makers receive a weight of 83%.

The assessments for fixed bridges have been explored. The analysis will continue with the assessments for movable bridges.

10.4 Combining expert assessments for movable bridges

The outcome of combining assessments for variables of interest related to movable bridges in Table 42 differs slightly from the variables of interest for fixed bridges in Table 40. The reason for this is that expert 3, 22 and 24 have been excluded from the research.

The mean calibration score shifted from 3,59E-03 to 2,29E-03. The overall information score shifted from 1,49 to 1,40. This means that relative to the variables of interest for fixed bridges larger bounds are used. The mean values of the calibration and overall information score are lower for movable bridges. This means that a well calibrated expert (Expert 3) left the panel and experts have less confidence in their estimates on the variables of interest for movable bridges.

The assessments for movable bridges will first be analysed through the application of an equal weighting scheme whereafter the performance-based weighting schemes will be explored.

Equal decision maker on movable bridges

The EqualDM for movable bridges has the same calibration score as the EqualDM for fixed bridges, as can be seen in Table 42. The total information value lowers from 0,2786 to 0,2003. The information value on seed variables lowers from 0,2188 to 0,2109. The reason for this has already been given. The calibration score and information score on seed questions of each individual expert logically remains the same. The information score still fluctuates with a factor 3 among experts. The weight of the EqualDM is now 22%. A performance-based weighting scheme might improve the values of the decision maker for movable bridges.

Performance-based decision makers on movable bridges

A performance-based weighting scheme generates a calibration score of 0,5405 as seen in Table 26. The information score of the ItemDM compared to the EqualDM rose from 0,2003 to 0,6239 and 0,2109 to 0,4786 for respectively all and just seed variables. The ItemDM again has a slightly better information score than the GlobalDM. The weight of the decision makers is 89%.

Table 26 Movable bridge sample with global and Item weights under significance level of 0,01644

ID #	Calibr.	Mean rel. total	Mean rel. real.	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 8	0,01644	1,27	1,11	8	0,01825	0,5689	0,06466
Exp. 23	0,01644	0,9098	0,8412	8	0,01383	0,4311	0,04899
GlobalDM	0,5405	0,6051	0,4629	8	0,2502		0,8864
ItemDM	0,5405	0,6239	0,4786	8	0,2587		0,8897

10.5 First conclusions

After calculating the different decision makers for both fixed as movable bridges several conclusions can be drawn. The individual calibration scores in general are low with a mean score of 3,59E-03. The mean information score is 1,49 on all variables but with a score of 1,35 lower on seed variables. From these values it can be concluded that experts in general have difficulties estimating the condition of assets over time. The individual calibration scores are relatively low and information scores relatively high compared to the performance-based decision makers. The representation of these values can be illustrated by looking back at Table 23.

Due to the low individual calibration scores the calibration score of the EqualDM is low as well (0,0841). The majority of the expert panel consists of low calibrated experts which outperform high calibrated experts in both fixed and movable bridges. Weighting the significant different opinions of experts equally results in very large bounds for each variable that makes them unusable in practice.

The calibration and information scores of the performance-based decision makers differ significantly from the EqualDM in a positive way. The calibration score of the ItemDM for fixed and movable bridges is 0,6876 and 0,5405 and preferred above the GlobalDM in both cases. The ItemDM for movable bridges however needs larger bounds. The information scores are 0,5461 and 0,6239 for fixed and movable bridges. The combined opinion of experts gives an approach to reality but expresses a lot of uncertainty by using a larger range to reach this performance in variables of interest for both types of bridges.

Experts 3, 8 and 23 appear to have the best representing opinion. Revealing their characteristics might explain why. Expert 3 is aged 26 years and has 3 years of experience as an inspector. Expert 8 is aged 36 years and has 11 years of experience as maintenance engineer. Expert 23 is aged 30 with 2 years of experience as advisor on civil infrastructures. It strikes that relatively young experts outperform elder participants with more experience in the field of work. The mean age of experts is 42 and the mean years of experience on fixed and movable bridges is respectively 11 and 9 years.

Other things struck as well in the outcome of the questionnaire. Several experts gave very wide answers for target variables whilst others did not. Some experts gave a maximal timespan to reach a NEN condition score of 3 of 10 to 30 years for the conservation of railings. An uncertainty interval of 20 years in a maximal timespan of 30 years seems odd but is not necessarily wrong. Comparing with other answers creates restraint however. Multiple examples with discrepant assessments of experts can be seen in Appendix D: Expert assessments. Several reasons could apply for the differences in opinions. Filtering ambiguous questions may improve the information score and result in more reliable intervals. A discrepancy and robustness analysis will be performed to see whether better results can be produced. After these analyses, the final results will be displayed and concluded.

10.6 Discrepancy analysis

Chapter 4: Methodology described possible limitations regarding the use of performance-based expert judgement. A lot of effort has been put in the explanation how to answer all the variables by giving the different percentiles. It is assumed that this did not cause discrepancies after all. Though, the results show differently as experts use totally different bounds as can be seen in the different information scores. Ambiguous questions are questions for which it can be addressed that significant different opinions have been estimated. It makes sense that opinions differ, but to a certain degree. Several causes can be appointed for disagreement among experts. Each reason will be briefly covered.

1. Different organisational strategy and working field
2. Different individual function or experience
3. Different interpretation of the impact of uncertainties
4. Different interpretation of the NEN-2767-4
5. Different interpretation of variables of interest

1. Different organisational strategy and working field

Different companies with different backgrounds participated in the questionnaire. IV-infra for example is a company which is mainly contracted on highway bridges that have different characteristics than bridges in an urban environment. This may create the bias that experts unconsciously reflect to situations that do not directly resemble the situation that is being asked for. The scope of the urban environment however has been addressed multiple times in the questionnaire.

2. Different individual function

Regarding the expert panel which is shown in Appendix C: Expert Judgement participants it can be seen that the participants have different individual functions. Only five participants, experts 2, 3, 5, 12 and 23, wear the title of inspector while others have been promoted to a more supervising or advising function. Although the inspectors generally score slightly better than people with other functions, only 1 inspector is involved in the decision maker. No direct conclusion can be drawn from the generated data but different individual functions might have an impact on the way people look at infrastructure assets.

The different individual function can tell something about the experience experts have with inspecting bridges. An important question is what reference they use in the questionnaire. Some experts might have seen similar bridges whilst others have not. Experience is only known in years and not in the amount of bridges experts have seen.

3. Different interpretation of the impact of uncertainties

This research aims to quantify uncertainties which are not fully qualified. Two difficulties arise here. Experts might estimate the impact of uncertainties differently and might not know which actual uncertainties apply in the deterioration process of physical infrastructure. This can create huge discrepancies as 'known unknowns' have to be quantified. It has not been validated whether experts took the same uncertainties and circumstances into account.

4. Different interpretation of the NEN 2767-4

Although the NEN 2767-4 has been introduced as an objective way to assess infrastructure condition, the assessment is still made by humans who have to assess the infrastructure visually. The NEN2767-4 is a good standard but does not necessarily present a 100% similar result by different inspectors according to several interviews. The standard has a little bit of slack in the interpretation and realisation of the condition scores.

5. Different interpretation of variables of interest

The different interpretation of target variables can be taken away by performing a discrepancy analysis on these questions. A discrepancy analysis shows till what degree experts agree with the 'mean' opinion. This mean opinion in this case is an equal decision maker where every expert is represented. Though, if discrepancy among the variables of interest can be taken away, the discrepancy among seed variables will still exist.

The overall relative information experts express regarding the equal decision maker on fixed bridges can be seen in Table 45. The most (dis)agreeing experts have been pointed out in Table 27. Expert 2 agrees the most with the EqualDM. Expert 19 disagrees the most with the EqualDM. It can be seen that the mean relative information in the entire questionnaire and just the seed questions is quite high. This implies that experts in general do not agree with the EqualDM. This can be read as a significant disagreement among experts in general. Performing a discrepancy analysis per target variable might show which questions cause the biggest discrepancies.

Table 27 Extreme discrepancy values

ExpID#	Rel.Inf to total	Rel.Inf to realis.
2	0,7785	0,7172
6	1,766	1,791
19	1,825	1,429
Mean	1,2154	1,1321
EqualDM	0	0

Discrepancy per target variable

Table 28 shows a sample of experts with the discrepancy per target variable per expert. The entire table can be seen in Table 44. T_x denotes the target variables in Appendix B: Elicitation format document. The mean discrepancy per variable and maximal difference among experts is given by **Mean/t** and **Max dif**. Extraordinary values have been highlighted and indicate the (dis)agreement with the EqualDM.

Table 28 Discrepancy per target variable

ExpID#	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}
1	0,50	0,72	1,01	0,70	1,32	1,43	**2,32**	1,80	0,52	0,95	1,01	1,90	0,98	0,53	1,26
2	0,59	0,68	0,69	0,64	0,71	**0,65**	0,27	0,73	0,87	0,55	1,19	0,91	1,29	0,93	1,06
3	**0,28**	1,60	1,01	1,27	0,96	-	-	-	1,07	1,09	1,64	**0,29**	1,49	0,52	-
4	0,59	0,40	**0,22**	**0,38**	1,08	0,83	0,40	0,91	0,98	0,55	1,25	0,75	0,93	1,31	0,50
6	1,77	1,02	1,33	1,65	**2,05**	**2,29**	1,37	1,86	**2,58**	1,83	1,51	1,27	2,15	2,06	2,24
12	1,46	1,21	1,99	1,65	1,15	1,22	1,57	1,82	1,19	1,09	1,09	2,07	1,66	**2,91**	1,82
13	1,42	1,85	1,78	1,60	1,56	1,98	1,72	2,11	1,48	1,01	1,84	1,45	2,11	1,95	**2,29**

ExpID#	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}
14	1,55	1,22	1,56	**1,84**	1,45	2,29	1,69	1,33	1,52	1,36	1,98	1,81	2,30	1,63	1,56
15	1,56	1,21	1,33	1,01	1,24	2,05	2,18	**2,16**	0,85	1,14	1,51	1,22	1,43	1,34	1,81
17	1,18	1,73	1,45	0,97	1,08	1,67	0,62	**0,56**	1,22	1,11	1,46	1,37	1,48	1,17	1,20
18	1,01	**2,20**	1,45	1,82	1,06	1,43	1,69	1,52	2,04	**2,09**	2,08	**2,11**	2,43	2,06	1,22
19	1,93	1,22	2,01	1,65	1,24	2,02	1,72	1,64	2,29	2,09	**4,54**	2,07	2,43	1,79	1,19
20	1,24	0,36	1,81	1,06	1,44	1,09	**0,23**	0,61	**0,40**	**0,25**	**0,25**	0,47	**0,41**	0,49	**0,49**
21	**2,08**	1,21	0,95	1,28	**0,48**	1,26	0,84	1,14	2,53	1,14	1,78	0,49	2,57	1,26	0,88
25	1,32	**0,20**	0,60	0,85	1,52	1,29	1,32	1,13	1,06	0,95	1,36	1,37	1,27	0,12	0,75
27	0,94	1,59	**2,36**	1,17	1,32	1,10	0,84	1,35	1,40	0,85	1,51	1,07	**3,10**	**0,08**	0,88
Mean/t	0,72	0,68	0,80	0,72	0,73	**0,84**	0,70	0,77	**0,81**	0,67	**0,96**	0,76	**1,04**	0,75	0,71
Max dif	1,79	**2,00**	**2,14**	1,46	1,57	1,64	**2,09**	1,60	**2,18**	1,84	**4,29**	1,82	**2,70**	**2,83**	1,79

The last row shows the maximum discrepancy between 2 experts. The extreme values have been highlighted. From the last two rows it can be concluded that discrepancy exists in significant matter for every target variable. Considering the amount of experts this is not weird. Performance-based decision makers filter the majority of experts. Questions T_9, T_{11} and T_{13} show both a high value for the mean discrepancy per target variable and a high difference in agreement among experts. The high matter of discrepancy of certain target variables might affect the overall performance of both experts and decision makers. The maximal differences are seen in T_9, T_{11} and T_{13} and are represented in Table 29.

Table 29 Biggest discrepancies among experts

	T_9	T_{11}	T_{13}
Lowest assessment	7-10-15	2-7-12	2-5-10
Highest assessment	70-80-90	96-98-100	40-60-80

A new analysis will be done after excluding questions T_9, T_{11} and T_{13}. The influence on the decision maker will be analysed. Removing target variables influences the overall relative information per expert and the discrepancy with each experts compared with the decision maker. This will have impact on the relative information on the decision maker as well. The results on the target variables relevant for movable bridges remain the same as the excluded questions apply to fixed bridges only.

The new values for the relative information on all variables per expert can be seen in Table 47. Table 30 shows a sample of the outcome of Excalibur without and with eliciting answers for questions T_9, T_{11} and T_{13}. The calibration score and thus weights for each decision maker remain the same as no adjustments have been made here. The fourth column shows the relative information on all variables including questions T_9, T_{11} and T_{13}. The third column shows the relative information on all variables without the discrepant variables.

Table 30 Decision makers sample without questions T_9, T_{11} and T_{13}

ExpertID#	Calibration	Relative info new	Relative info old
3	0,02651	1,093	1,24
8	0,01644	1,348	1,502
23	0,01644	0,7749	0,8191
ItemDM	0,6876	0,5174	0,5461
GlobalDM	0,6876	0,4835	0,5039
EqualDM	0,08041	0,2801	0,2786

It can be concluded that the relative information gets worse with the exclusion of questions T_9, T_{11} and T_{13} for the performance-based weighting schemes. The information score of the EqualDM gets better. This can be explained as the most discrepant answers have been removed. The resulting information score for the performance-based weighting schemes gets worse as the experts in the pool have information scores higher than the mean on the removed questions. The information score did not improve by excluding discrepant questions with discrepant assessments. The next paragraph will describe the effect of a robustness analysis.

10.7 Robustness analysis

A robustness analysis will show whether the calibration score improves by excluding either experts or seed questions. The goal of excluding experts is to see whether the expert judgement series is robust on experts or seed variables. Conclusions are made against the dependency and intensity each time the decision maker changes when experts or variables are excluded. Table 48 and Table 49 represent the full analysis.

Robustness on experts

Excluding experts might have an impact on both the calibration score as the relative information on all variables and just seed variables of the decision maker. A change in these aspects is noticed when expert 3, 8 and 22 will be excluded from the expert panel as can be seen in Table 31. Excluding expert 3 leads to a change in the calibration of the ItemDM from 0,6876 to 0,5405 as can be seen in the second column. The relative information in column 1 rises from 0,5461 to 0,6358. This can be argumented by the fact that the calibration score of expert 3 is relatively high compared to other experts. Expert 3's overall information value is relatively low and below the mean information score as can be derived from Table 24. The same consequences apply for expert 8 and 23 but to a different extent. Note that these are the experts that would only contribute as soon as performance based weights apply.

The fourth column shows the relative information which is given to the original ItemDM by the new decision maker when an expert is excluded. A score close to zero means that there is a big resemblance with the original decision maker. Expert 9 and 20 represent the maxima of the relative information to the original decision maker. The effect of removing experts is small when comparing the discrepancy analysis as well. The maximal relative information to the original decision maker is 0,5829 in case expert 22 is being removed. This value is lower than the mean discrepancy in Table 27 which means that the obtained results in this questionnaire are robust against the choice of experts.

Table 31 Robustness analysis sample on experts using item weights

Excluding expert#	Rel.info total	Calibration	Rel. Info/or DM total
3	0,6358	0,5405	0,2664
8	0,3753	0,5338	0,3683
9	0,5461	0,6876	0
20	0,5116	0,6876	0,003406
22	0,4852	0,5338	0,5829
None	0,5461	0,6876	0

Robustness on seed variables

Excluding seed variables impacts the calibration score as can be denoted in Table 32. Due to the (small) amount of seed questions and the fact that a calibration score is very dependent it can be seen that the results are not very robust against the choice of seed variables. The last column shows a lot of relative information between the original and resulting decision maker.

Table 32 Robustness analysis on seed items using item weights

Excluding seed#	Rel.info total	Calibr.	Rel.info/or DM total
S_1	0,9882	0,5539	0,3678
S_2	0,8606	0,6552	0,8763

Excluding seed#	Rel.info total	Calibr.	Rel.info/or DM total
S_3	0,5309	0,5332	0,4723
S_4	0,8635	0,6789	0,4723
S_5	0,5828	0,6789	0,6736
S_6	0,8818	0,423	0,7598
S_7	1,017	0,5539	0,4271
S_8	0,5709	0,6789	0,6424
None	0,5461	0,6876	

Concluding
The discrepancy analysis showed a lot of disagreement among experts for certain target variables. Removing these target variables did not improve the informativeness of the decision makers. The results of the elicitation are robust against the choice of experts but not to the choice of seed variables due to the small amount of available data on which these seed variables are based.

The optimized decision maker in this questionnaire is results in a performance-based expert panel on item weights and is shown in Table 33. This decision maker should be seen as the virtual expert that gathers the information of the highest calibrated experts and fills in the questionnaire with their knowledge.

Table 33 Resulting decision makers for variables of interest regarding fixed and movable bridges

	Calibration	Information
ItemDM /fixed	0,6876	0,5461
ItemDM / movable	0,5405	0,6239

10.8 The probabilistic interval

The decision makers in Table 33 show a calibration and information score. A sample of the resulting probabilistic interval by the ItemDM on fixed bridges can be seen in Table 34. The decision maker may capture a true realisation but there is no guarantee for it. The size of the bounds it gives can be seen as well. The final results for all seed variables and variables of interest can be seen in Table 50 and Table 51.

Table 34 Sample results of the ItemDM solution for fixed bridges

Variable	5%-tile	50%-tile	95%-tile	True value	Full Name
S_5	3,297	9,215	23,7	15	Brug 158
S_8	3,163	14,52	23,01	38	Brug 272
T_1	3,211	7,271	18,7		Railing maintenance
T_2	1,73	6,351	11,82		Asphalt wear layer

The results consist of the three percentiles given by the experts, together forming a probabilistic interval for all variables of interest. The values in the table induce years. When the decision maker for fixed bridges would answer the seed variables, the true value is captured by his interval in 6 out of 8 cases using a quite big range.

The answers of the decision maker for movable bridges are quite similar to the decision maker for fixed bridges although experts have been removed from the panel. This complies with the information in Table 33. The range of the ItemDM for movable bridges is slightly more narrow which is seen in the information value of both decision makers. No conclusions are made because of the difference in variables of interest between the decision makers.

10.9 Conclusions on the COTA method

This chapter described the use and outcome of the COTA method where experts have been asked to assess the condition over time on seed variables and variables of interest. Several conclusions have already been drawn in 10.5 First conclusions but didn't elaborate upon the final result. The final outcome of the COTA method and the applicability of this outcome will first be concluded. After, the method itself will be evaluated.

COTA outcome

An amount of 27 experts have been requested to give their percentiles on 8 seed variables and 15 variables of interest. The experts have trouble in general with assessing uncertainty for situations in the past in this field of work. The individual calibration scores are generally low and accompanied with discrepant and large ranges. Experts thus have trouble to express confidence in the seed variables used in the method. Their combined opinion in a performance-based weighting scheme however results in a more statistical accurate opinion, though with a large range.

A robustness analysis has been done to purify the overall calibration score of the performance-based decision makers. The robustness analysis shows whether the results of the questionnaire are very dependent on particular experts or questions. The questionnaire appears to be quite dependent on seed variables. However a minimum of ten seed variables is recommended, only 8 variables have been developed due to the lack of data which is probably the reason for this dependency. The questionnaire was not dependent on the choice of experts. The statement that experts have trouble with finding the right value in this method remains standing.

The confidence issue remained the same for the variables of interest, situations in the future for which the answers are unknown yet. The same amount of information is presented to each expert with seed variables, which in theory should result in similar or at least comparable answers. For variables of interest this is different and the estimates among experts still appeared to be very discrepant. Several reasons can be thought of and have been written down in 10.6 Discrepancy analysis. Filtering and omitting ambiguous questions did not generate an increment of the information score for the variables of interest.

For each variable of interest a distribution has been made with the 5%-50%-95%-tiles. The reliability of these estimates is at least questionable due to several reasons. As written in 8.4 Acquiring data the target variables are not fully resembled by the seed variables. A direct relation has not been found due to the lack of available and usable data. Due to the calibration score of the item-based decision maker it cannot be guaranteed that the decision maker will represent reality. Though the outcome verifies the presence of uncertainties in infrastructure deterioration by the large range in the assessments of the experts.

A theoretical perfect calibration score for the combination of experts in this research would still not assure the applicability of the outcome for the variables of interest in this case. The information score would still imply a large range for the variables of interest to that degree where it becomes unapplicable. One reason for this has already been explained and is due to the characteristics of experts and their lack of confidence in the answers. Another reason could be that uncertainties do have a large impact on the deterioration process which causes a large range. Due to the discrepancy present in both seed variables and variables of interest and the outcome of the robustness analysis this last reason is not very feasible. It can be concluded that experts have trouble quantifying uncertainties in the COTA method.

Applicability of the results

The outcome of the COTA method showed probabilistic intervals for maintenance activities. Each distribution consists of three values representing the 5%, 50% and 95%-tile. By linear interpolating these values a cumulative density function can be developed. In case of feasible results, an asset manager then has a mean to maintain his assets to a certain percentage of risk that corresponds with the organisational risk acceptance level.

The uncertainty which is expressed in the range per maintenance activity is not qualified however. The applicability of these ranges can be done on a strategic level but are difficult to apply on short term planning for which the qualification of bridges is more important. Further research should be done to validate the COTA outcome and to link the outcome of the method to the qualification of uncertainties.

Method evaluation

The COTA method has been developed as an approach to quantify the impact of uncertainties on bridge maintenance in the absence of hard data. The quantification of uncertainties has been translated in the development of a probabilistic interval for maintenance activities on bridges in an urban environment. The method tries to confirm whether inspections in the construction industry indeed predict valid terms for maintenance to be performed on infrastructure assets by the use of performance-based expert judgement. It does so by simulating a 'reversed' procedure of an infrastructure inspection regarding the NEN2767-4. Images of damages on infrastructure assets are provided with passport information by which the age of the damage has to be estimated. A verdict is asked for a period in the past instead of a period in the future which would be the case in the regular procedure of an infrastructure inspection regarding the NEN2767-4. It is assumed that the reliability of expert performance in the future is reflected in their performance in the past. Next to the validation of the maintenance predictions which are currently given, the method also strived to produce probabilistic intervals for certain maintenance activities which are reflected in variables of interest.

The reliability of the method really depends on the quality of the simulation of the inspection. Though it is assumed that by providing the same quality of information to experts, similar or comparable results would be achieved. This was not the case as can be seen in the outcome. Reviewing the method with participating experts revealed difficulties with estimating the age of damages by just some photos and passport information. The results have been discussed with some of the participants by confronting them with the discrepant answers. As concluded from the outcome that experts have trouble quantifying deterioration, this statement has been concluded from the feedback sessions as well. One of the fears and experiences of participating firms was to bring out an advice regarding maintenance to be performed within a period of time which is not heard. It may occur, and it actually occurred, that the condition of a bridge 10 years later was still the same while no maintenance had been performed. The maintenance predictions are a bit controversial and the industry is well aware of it. The COTA method has limitations but confirmed this conclusion.

11. Conclusion

This chapter concludes on the main research question which evolved from the introduction and problem statement. Sub-questions have been answered and a research has been executed in order to produce results that could solve the issue from this thesis. Deterioration can be modelled with the use of data but the parameters involved that predict the physical behavior are mostly an assumption and not known with certainty. Expert judgement has been depicted to respond to the given situation and to answer the research question:

*How can **Expert Judgement** be deployed to develop a **probabilistic maintenance interval** for **maintenance activities on bridges** in a **dynamic urban environment** in order to improve the **reliability** of **long term asset planning** in the absence of hard data?*

Frangopol indicates the presence of uncertainties in the deterioration process of infrastructure assets due to several reasons. Other literature proves that the development of probabilistic intervals can improve the reliability of long term asset planning. The COTA method has been developed to quantify one's ability to assess condition over time. Quantifying the impact of uncertainties on infrastructure assets through the use of performance-based expert judgement results in distributions that induce a probabilistic interval. Besides deterioration factors in literature, the presence of this probabilistic interval has also been shown by addressing significant differences between use and demand on bridges in a dynamic urban environment. The development of the method was associated with the generalisation of maintenance activities and implementing the way infrastructure quality is being assessed. The dynamic urban environment is represented by using cases that correspond with this environment.

The deployment of expert judgement in the COTA method is based on the assumption that one's uncertainty assessment skill for situations in the future can be measured by measuring the performance of their uncertainty assessment skill for situations in the past. One's uncertainty assessment skill for situations in the future is measured by the use of variables of interest. One's uncertainty assessment skill for situations in the past is measured by the use of seed variables. The COTA method simulates an infrastructure inspection and makes use of damage reports on infrastructure assets for which it is known what time it took to get to this damage. These damages are measurable with the NEN2767-4 standard and vary from a condition score of 1 to 6. New probabilistic maintenance intervals are generated by asking experts what time it will take for certain infrastructure elements to reach a predefined NEN-score, dependent on an organisational strategy. Combining the expert opinions and applying different weighting schemes that change the pool of participating experts, results in an optimized opinion representing a probabilistic interval for specific maintenance activities. Analyses show the reliability of these interval by assessing the statistical accuracy and informativeness, aspects that are dependent on expert opinions.

The COTA method has been deployed in the context of the municipality of Amsterdam whose quality level complies with a NEN condition score of three. Analysing the assessments of the COTA method in this thesis lead to the conclusion that the participating experts have trouble in general with estimating condition over time. Given the opportunity to express uncertainty with their 5%-50%-95%-tiles, experts use a large range to express uncertainty and still miss the true value in the simulation. Estimating the interval for certain maintenance activities to preserve a set quality level regarding the NEN2767-4 resulted in very discrepant answers among experts. Though, a combined opinion has been generated which is 25 times more accurate but does not express a lot of confidence in the resulting probabilistic intervals as wide ranges are generated.

The aim of this thesis has been to improve the reliability of long term asset planning. The results of the questionnaire have not been fed back to the existing long term asset planning of the municipality of Amsterdam due to the low statistical accuracy and informativeness. The method however confirms the presence of uncertainties in infrastructure deterioration and the added value for probabilistic maintenance intervals. The next chapter provides a discussion on the outcome of this thesis and use of the COTA method in the given conditions. Recommendations will show opportunities for further research in order to generate more reliable and applicable probabilistic intervals.

12. Discussion

This chapter discusses the outcome of this thesis and the journey leading to it. The final outcome is considered by first discussing the development of the COTA method, the framework of the questionnaire and the participating experts. This chapter gives the points of reference for further research and summons the link to the recommendations in the next chapter.

Development of the method

Expert judgement has been depicted to develop probabilistic intervals in order to improve the reliability of long term asset planning in the absence of hard data. With the development of the COTA method, suitable data had to be found to be able to rank experts by their uncertainty assessment skill. The choice for expert judgement as the method for the mentioned issue creates a dependency on the verdicts of experts, instead of a dependency on the verdicts of hard data. Analysing the data without the use of expert judgement would have provided unbiased answers without the (individual) limitations regarding the expert judgement method. Theoretically, probabilistic intervals could have been developed by just analysing the type of data that has been used in this thesis. After a thorough exploration, it has been assumed that not sufficient data would have been present to develop data-driven intervals with this alternative method.

The COTA method is based on the fundamental assumption that past performance can predict future performance. The questionnaire simulates an inspection by giving notified damages of one single moment. Based on the uncertainty assessment of this single moment, conclusion are drawn about the uncertainty assessment skill of the experts. In practice however, multiple moments are used to predict the deterioration process of infrastructure assets according to maintenance engineers from VolkerInfra. It is unknown whether other companies make use of the same procedure. The conclusions on the uncertainty assessment skill are therefore not waterproof but confirm a gut feeling. Though, every expert receives the same information which would hypothetically results in similar results as the experts are based in the same field of work as well.

In addition to the way the infrastructure inspection has been simulated it should also be mentioned that experts might interpret pictures in a different way. The purpose of the damage reports is to assess the time it took to get to that picture. However, bridge characteristics, bridge design and environment are also shown and (unconsciously) taken into account in the assessments. In case a bridge has a synthetic bridge deck it is assumed that this bridge has an age of maximal 10 years as this technique is relatively young. Some of the questions also showed damage which was due to accidents or mistakes in the construction of the bridge. These factors may bias an expert's verdict. Although every expert receives the same information, the processing of this information might happen in different ways.

Given the fact that the method makes use of the expertise and experience of experts it is hard to say whether the use of expert judgement also satisfies in the development of probabilistic intervals for maintenance activities that have a very low frequency as the total replacement of bridges for example. It is assumed that very little experts have experienced the total lifespan of a bridge, which can be over 100 years. Probabilistic intervals for activities like these may increase the reliability of an LTAP the most as they cover the biggest investments.

Framework of the questionnaire

The application of expert judgement has done by the use of a questionnaire. The framework of this questionnaire consists of seed variables and variables of interest related to bridge maintenance. Seed variables are not discussed here as these variables are assumed to be clear and without doubt in their line of reasoning. The answers for these variables are known and validated with the local asset manager. The line of reasoning for the variables of interest however is different and creates discussion and discrepancy which has been covered in 10.6 Discrepancy analysis. The interpretation of the NEN and maintenance activities are discussed.

The variables of interest are made measurable by using the NEN2767-4: condition assessment for infrastructure. Characteristics of this standard however make that the final condition score in certain cases might vary among experts due to its visual assessment. A condition score of 3 has been presented by a small damage with a large size or either way around. This is widely interpretable and thus it is not assured that every expert used the same threshold or quality level for their estimates. The condition score of 3 can arise in different ways, dependent on different scores for the categories that have been described in chapter 8 - Assessing infrastructure quality.

Secondly the interpretation of the maintenance activities is relevant in this discussion. Although research has been done to create a proper and shared understanding in maintenance to be performed on bridges in an urban environment, an official generalisation of maintenance does not exist yet. Together with the individual expert experience, this might have been the most important reason for discrepancies in the answering of seed variables and variables of interest. An additive on the existing NEN standard could be developed for assessing infrastructure quality in the future which says how, and eventually when, infrastructure managers should maintain these prescribed quality levels. By doing so, a shared understanding of maintenance arises. Organisations themselves can decide how to implement this generalisation in their maintenance strategy.

Participating experts

The experts in this research have been selected from contractors, engineering firms and municipalities. Experts with different functions participated in the questionnaire. It is assured that every expert fulfils the set criteria in chapter 9 - The COTA method. It is not assured however that the best performing experts have been involved in the research. Several reasons for discrepant answers have been given and may be appointable to expert's individual characteristics such as different organisational background or strategy, different individual functions, interpretation of uncertainty impact, possible interpretation of the NEN 2767-4 and different interpretation of the variables of interest. It is assumed though that the pool of experts sufficiently represents the level of knowledge at this topic in the industry.

The data which have been used in the questionnaire has mainly been derived from the municipality of Haarlem. Experts from VolkerInfra, maintenance partner of the municipality of Haarlem, participated in the research and might have been pre-judged as they work in the same field as the questions. Although these experts were officially biased, differences in their performance have not been discovered.

Thesis outcome

The previous paragraphs described flaws that were not totally insuperable in this research. They do not exert too much influence on the conclusion that experts have trouble assessing the condition of infrastructure assets over time. Besides this finding, the product in form of the probabilistic intervals is discussed.

The outcome of the method consists of distributions for maintenance activities that are not fully resembled in seed variables. An estimate on the replacement of driving-irons has little to do with estimates on seed variables for the deterioration process of railings. However, the method creates an approach for these situations due to the lack of data. The outcome is still questionable by the given facts. For a proper execution of the method in the future, more useful data in the form of damage reports should be gathered to serve two purposes. At first a full resemblance between seed and target variables might be achieved. Next to that, the scope of the research may be adjusted to bridges in and outside the urban environment.

The uncertainty which is expressed in the range per maintenance activity has not been qualified. The reason for the wide ranges that are used in the answering of target questions may be due to the fact that experts have trouble assessing condition over time. The questions themselves do not deal with specific scenarios, leaving a lot of freedom to an expert's imagination. The applicability of these ranges can be done on a strategic level by accepting a certain risk percentage but are difficult to apply on short term planning for which the qualification of bridges is more important. A rough qualification of bridges has been developed in 6.4 Bridge classification but there is no link between this qualification and the results in this thesis. Further research should be done to link the outcome of the COTA method to the qualification of uncertainties, or to develop more specific questions.

The next chapter will give recommendations for the future development of the COTA method to solve the aspects that have been discussed.

13. Recommendations

The previous chapter described the flaws that played a role in the execution of expert judgement during this research. Instead of the development of probabilistic intervals, a finding has been produced that doubts one's ability to assess condition over time in the maintenance sector of the construction industry. Doubting the current practices leads to two recommendations. At first a recommendation for public infrastructure owners is given to coope with the existing situation. Another recommendation is given in order to be able to produce more reliable probabilistic intervals in the future.

Coping with the existing situation

The existing situation can be described as the situation where asset managers have to make decisions that are accompanied with uncertainties about asset condition due to lack of data and the unquantified impact of the deterioration process. It is very important for an asset manager that knowledge about his assets is present in his organisation. Assets are currently being assessed regarding the NEN2767-4, showing the current state of that object, accompanied with an advice to undertake action at a particular term. The NEN provides a good mean to show the current state of an object but more important might be why an asset reaches a certain state. The thorough search after useful data in this research lead to the recognition that historical (maintenance) data are barely available. As assumed with the use of expert judgement that data might be present inside the minds of people, a lot of information about Amsterdam's assets is present in the minds of local bridge managers. Given the lack of asset information and the findings in this thesis it is thus important for public infrastructure owners to have experienced people in their organisation who have knowledge about the timeline of particular assets. It is recommended to develop a system with the purpose to administrate their knowledge as soon as possible.

Probabilistic intervals in the future

The use of expert judgement brought in a variety of limitations that are devoted to experts' individual characteristics and the framework of the questionnaire. Experts have been selected in this research for their experience regarding bridge maintenance. Data that is not present on paper may be generated by objectifying subjective probabilities, derived from their individual frame of reference. Expert judgement quantified their uncertainty assessment skill by the use of seed variables, illustrating bridges with damage for which their timeline is known.

Chapter 12 - Discussion discusses the choice for expert judgement. Expert judgement has been chosen due to the lack of useful data. In the future, more reliable intervals can be developed by a more data driven instead of expert driven approach. A lot of data can be developed by administrating the physical experiments that are already happening at bridges that have been built. By doing so, the frame of reference which is now dependent and limited to the participating experts can be extended beyond this barrier. This thesis developed a 'virtual expert', consisting of the combined opinion of experts. A 'virtual maintenance assistant' should be developed in the future in form of a database in which the type of data that has been used in this research is gathered. Damage reports and bridge characteristics should be gathered to see the impact of different deterioration factors such as traffic load on asphalt and opening frequency on bridge machinery. In this way objective probabilities will be developed that are limited to a bigger frame of reference.

The underlying thought of this database has been derived from the practices in the medical industry. The medical industry has the ability to predict the development of diseases and to treat complaints. Research and monitoring in 'human experiments' provided a lot of knowledge about healthcare. For instance, people are distinguished in groups that have a bigger chance or risk of developing certain diseases by their physique and way of life. Research created the ability to provide a more accurate advice and effective treatment when someone encounters complaints. On the other hand, malicious growth in a human body has been examined lots of time, even creating the opportunity to predict someone's lifespan when diagnosed with a terminal disease. The same line of reasoning may be implemented in the infrastructure industry.

Instead of the 10 bridges some experts might have inspected in their life, the 'virtual maintenance assistant' has access to a frame of reference in which an infinite set of bridges can be present. Assets with similar characteristics can be searched for to see what time it will take in general to reach a certain state at the moment maintenance has to be planned. This maintenance planning can be done from the delivery phase but also from the moment when typical damage is discovered. The limiting individual experience factor in this thesis is taken away by doing so. The COTA skill becomes a more automated process instead of a personal assessment.

The data necessary for such a system can be the same as the reports that have been used in this thesis. The NEN2767-4 provides a good standard for the production of data in form of damage reports. The data still has to fulfil the criteria for usefulness. Useful data consists of reports by which two moments of the same damages can be established. This could be from delivery to a single damage report for which it is known no maintenance has been done or a period between two damage reports for which it is known no maintenance has been done in that particular period.

At the moment the system has gathered sufficient data, the NEN or another party should develop an additive on the existing infrastructure assessment standard that tells what maintenance should be done at what time in order to maximize the lifespan of bridges in the future. This includes an official generalisation of maintenance activities to be performed, but 'general' probabilistic intervals for these activities as well. Sufficient data is gathered when a broad spectrum of types of bridges is present in the database. Probabilistic intervals for types of bridges are made by analysing an amount of bridges that are similar to this type. The database creates the ability to develop probabilistic intervals on different levels varying from rough to detailed. A classification as has been developed in 6.4 Bridge classification will make sense at that moment.

Having said that, this thesis can be closed. Nature provides all the elements causing entities to be unique. Although this causes a lot of uncertainties, for science nothing should be seen as a bridge too far.

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Appendices

Appendix A: Maintenance packages

Antea

Activiteit	Type onderhoud
Vervangen opzetwerk	Technisch onderhoud
5-Jaarlijks onderhoud elektromech aandrijving complex incl. 3140	Verzorgend onderhoud
5-Jaarlijks onderhoud elektromech aandrijving incl. 3140	Verzorgend onderhoud
5-Jaarlijks onderhoud hydraulische aandrijving eenvoudig incl. 3140	Verzorgend onderhoud
5-Jaarlijks onderhoud hydraulische aandrijving incl. 3140	Verzorgend onderhoud
Asfalt vervangen onderlaag	Technisch onderhoud
Asfalt vervangen toplaag	Technisch onderhoud
Conservering beton overlagen	Verzorgend onderhoud
Conservering metselwerk overlagen	Verzorgend onderhoud
Conservering overlagen bovenbouw (hout)	Verzorgend onderhoud
Conservering overlagen bovenbouw (staal)	Verzorgend onderhoud
Conservering overlagen langsligger (staal)	Verzorgend onderhoud
Conservering overlagen leuning (beton)	Verzorgend onderhoud
Conservering overlagen leuning (hout)	Verzorgend onderhoud
Conservering overlagen leuning (staal)	Verzorgend onderhoud
Conservering overlagen onderbouw (hout)	Verzorgend onderhoud
Conservering overlagen onderbouw (staal)	Verzorgend onderhoud
Conservering staal overlagen	Verzorgend onderhoud
Groot onderhoud beton	Technisch onderhoud
Groot onderhoud bovenbouw (hout)	Technisch onderhoud
Groot onderhoud bovenbouw (staal)	Technisch onderhoud
Groot onderhoud langsligger (hout)	Technisch onderhoud
Groot onderhoud Langsligger (staal)	Technisch onderhoud
Groot onderhoud leuning (beton)	Technisch onderhoud
Groot onderhoud leuning (hout)	Technisch onderhoud
Groot onderhoud leuning (kunststof)	Technisch onderhoud
Groot onderhoud leuning (RVS)	Technisch onderhoud
Groot onderhoud leuning (staal)	Technisch onderhoud
Groot onderhoud metselwerk	Technisch onderhoud
Groot onderhoud onderbouw (hout)	Technisch onderhoud
Groot onderhoud onderbouw (staal)	Technisch onderhoud
Groot onderhoud opzetwerk	Technisch onderhoud
Groot onderhoud staal	Technisch onderhoud
Herstraten elementenverharding	Technisch onderhoud
Klein onderhoud metselwerk	Technisch onderhoud
Onderhoud aandrijving handbediend	Technisch onderhoud
Onderhoud rij-ijzer	Technisch onderhoud
Reviseren opzetwerk	Technisch onderhoud
Reviseren slagboom	Technisch onderhoud
Reviseren slagboom elektro	Technisch onderhoud
Vervangen bediening- en besturingsinstallatie	Technisch onderhoud
Vervangen beweegbare brug (beton)	Vervangen
Vervangen beweegbare brug (hout)	Vervangen
Vervangen beweegbare brug (kunststof)	Vervangen
Vervangen beweegbare brug (staal)	Vervangen
Vervangen dekdelen (hout)	Technisch onderhoud
Vervangen dekdelen (kunststof)	Technisch onderhoud
Vervangen elektromechanische aandrijving complex	Technisch onderhoud
Vervangen elektromechanische aandrijving eenvoudig	Technisch onderhoud
Vervangen Elektromechanische aandrijving normaal	Technisch onderhoud
Vervangen fiets-voetbrug (beton)	Vervangen

Vervangen fiets-voetbrug (hout)	Vervangen
Vervangen fiets-voetbrug (kunststof)	Vervangen
Vervangen fiets-voetbrug (metselwerk)	Vervangen
Vervangen fiets-voetbrug (staal)	Vervangen
Vervangen hydraulische aandrijving complex	Technisch onderhoud
Vervangen hydraulische aandrijving eenvoudig	Technisch onderhoud
Vervangen hydraulische aandrijving normaal	Technisch onderhoud
Vervangen rij-ijzer	Technisch onderhoud
Vervangen slagboom elektro	Technisch onderhoud
Vervangen slagboom handbediend	Technisch onderhoud
Vervangen slijtlaag (bitumen)	Technisch onderhoud
Vervangen slijtlaag (epoxy)	Technisch onderhoud
Vervangen verkeersbrug (beton)	Vervangen
Vervangen verkeersbrug (hout)	Vervangen
Vervangen verkeersbrug (kunststof)	Vervangen
Vervangen verkeersbrug (metselwerk)	Vervangen
Vervangen verkeersbrug (staal)	Vervangen

Amsterdam (LTAP)

Activiteit	Type onderhoud
Herstellen van betonschade (kolommen en landhoofden)	Groot onderhoud
Herstellen van houtschade + houtconservering	Groot onderhoud
Herstellen van metselwerkschade	Groot onderhoud
Herstellen van (beton)schade onderzijde dek	Groot onderhoud
Herstel beton conserveringen	Groot onderhoud
Herstel staal conserveringen	Groot onderhoud
Herstel conservering leuningen	Groot onderhoud
Vervangen slijtlaag dek	Groot onderhoud
Plaatselijk vervangen dekdelen incl. Slijtlaag	Groot onderhoud
Vervangen toplaag asfalt en herstel stootplaten	Groot onderhoud
Vervangen asfalt	Groot onderhoud
Variabel onderhoud E-installatie (vervangen besturingsinstallatie)	Vervangingen
Variabel onderhoud W-installatie (vervangen bewegingswerken)	Vervangingen
Grootschalige vervanging/renovatie	Vervangingen

Haarlem

Activiteit
Vervangen conservering stalen leuningwerk
Vervangen conservering betonoppervlak
Vervangen conservering staaloppervlak
Beton reparatie 1-10m²
Conserveren stalen leuningwerk
Conserveren houten leuningwerk
Conserveren staaloppervlak
Vervangen slijtlaag op betonnen dek
Vervangen slijtlaag op houten dek
Vervangen bitumineuze deklaag
Vervangen bitumineuze verharding
Vervangen houten dekbeplanking
Vervangen hout fiets- en voetgangersbrug
Vervangen stalen fietsbrug
Vervangen betonnen (aan)brug/viaduct
Vervangen houten leuningwerk
Vervangen stalen leuningwerk
Vervangen houten dekbeplanking

Rotterdam

Storingsonderhoud	Niet gedefinieerd
Periodiek onderhoud	Goten/putten hemelwaterafvoer
	Doorspuiten afvoerbuizen hemelwaterafvoer
	Onderhoud aan gemalen
	Baggeren gemaalkelder
	Reinigen van tegelwanden
	Klein onderhoud aan wegdek
	Onderhoud mechanisch
	Onderhoud elektrisch
Projectmatig onderhoud	Vervangen van slijtlaag op staal
	Vervangen voegconstructies en stootplaten
	Schadeherstel aan beton, hout of staal
	Vervanging meerpalen & remmingswerk
	Vervanging afsluitboominstallatie
	Vervanging besturingsinstallatie
	Vervanging elektro hydraulisch/mechanisch
	Vervangen van asfaltlaag/-constructie op beton
	Vervangen van elementenverharding
	Vervanging van conservering op staal en beton
	Vervanging van leuningen, hekwerk en geleiderrail
	Renovaties of vervanging elektrisch gemalen
	Renovaties of vervanging mechanisch gemalen
	Vervangen van tegelwerk tegelwanden

Table 35 LTAP budget debit comparison between Rotterdam and Amsterdam

Municipality of Rotterdam	Municipality of Amsterdam
Gutters rainwater drainage	Cleaning of construction
Clean piping rainwater drainage	Repairing wear layers
Clean tile wands	Repairing conservation
Small maintenance pavement	Clean piping water drainage
Mechanical maintenance	Electrical maintenance
Electrical maintenance	Mechanical maintenance
Replacement wear layer on steel	Repairing concrete
Replacement junction construction	Repairing wood
Material repairs	Repairing masonry
Replacing closing installation	Repairing concrete deck bottom
Replacing operating system	Repairing concrete conservation
Replacing transmission	Repairing steel conservation
Replacing asphalt on steel and concrete	Repairing handlebar conservation
Replacing of pavement	Repairing wear layer on deck
Replacing conservation steel and concrete	Local replacement of deck parts incl. wear layer
Replacing handlebars	Replacing top layer asphalt
Replacing tile wands	Replacing asphalt
	Replacements on electrical installation
	Replacements on mechanical installation
	Big replacements

Table 36 Generalised maintenance package

	Dagelijks onderhoud	Groot onderhoud	Vervangingen
Conservering	Conservering beton overlagen	Groot onderhoud beton	Vervangen beweegbare brug (beton)
	Conservering overlagen leuning (beton)	Groot onderhoud leuning (beton)	Vervangen beweegbare brug (hout)
	Conservering overlagen leuning (hout)	Groot onderhoud leuning (hout)	Vervangen beweegbare brug (kunststof)
	Conservering overlagen leuning (staal)	Groot onderhoud leuning (staal)	Vervangen beweegbare brug (staal)
		Groot onderhoud leuning (kunststof)	Vervangen fiets-voetbrug (beton)
		Groot onderhoud leuning (RVS)	Vervangen fiets-voetbrug (hout)
			Vervangen fiets-voetbrug (kunststof)
	Conservering overlagen langsligger (staal)	Groot onderhoud langsligger (hout)	Vervangen fiets-voetbrug (metselwerk)
		Groot onderhoud Langsligger (staal)	Vervangen fiets-voetbrug (staal)
			Vervangen verkeersbrug (metselwerk)
	Conservering staal overlagen	Groot onderhoud staal	Vervangen verkeersbrug (staal)
			Vervangen verkeersbrug (beton)
			Vervangen verkeersbrug (hout)
			Vervangen verkeersbrug (kunststof)
	Conservering metselwerk overlagen	Klein onderhoud metselwerk	Groot onderhoud metselwerk
	Conservering overlagen onderbouw (hout)	Groot onderhoud onderbouw (hout)	
	Conservering overlagen onderbouw (staal)	Groot onderhoud onderbouw (staal)	
	Conservering overlagen bovenbouw (hout)	Groot onderhoud bovenbouw (hout)	
	Conservering overlagen bovenbouw (staal)	Groot onderhoud bovenbouw (staal)	
	Conservering overlagen remmingwerk (staal)		Vervangen remmingwerk (hout)
			Vervangen remmingwerk (kunststof)
			Vervangen remmingwerk (staal)
Rijdek	Afalt: plaatselijk herstel	Asfalt vervangen toplaag	Asfalt vervangen onderlaag
	Asfalt: afdichten scheuren		
	Vervangen/bijwerken slijtlaag (bitumen)	Vervangen dekdelen (hout)	
	Vervangen/bijwerken slijtlaag (epoxy)	Vervangen dekdelen (kunststof)	
	Asfalt: aanbrengen zaagsnede/voeg		
	Onderhoud rij-ijzer	Vervangen rij-ijzer	
	Herstraten elementenverharding	Vervangen elementenverharding	
	Voegovergang: herstellen	Voegovergang: rubber vervangen	Voegovergang: vervangen
Aandrijving	Groot onderhoud opzetwerk	Reviseren opzetwerk	Vervangen opzetwerk
	5-Jaarlijks onderhoud elektromechanische aandrijving complex incl. 3140	Reviseren electromechanische aandrijving	Vervangen elektromechanische aandrijving complex
	5-Jaarlijks onderhoud elektromechanische aandrijving incl. 3140		Vervangen elektromechanische aandrijving eenvoudig
of	Aandrijving en bewegingswerk: smeren w-installaties - Electromechanisch		Vervangen Elektromechanische aandrijving normaal
	Aandrijving en bewegingswerk: klein onderhoud w-installaties - Electromechanisch		
	Aandrijving en bewegingswerk: conserveren w-installatie - Electromechanisch		
	5-Jaarlijks onderhoud hydraulische aandrijving eenvoudig incl. 3140	Reviseren hydraulische aandrijving	Vervangen hydraulische aandrijving complex
	5-Jaarlijks onderhoud hydraulische aandrijving incl. 3140		Vervangen hydraulische aandrijving eenvoudig
	Aandrijving en bewegingswerk: smeren w-installaties - Hydraulisch		Vervangen hydraulische aandrijving normaal
	Aandrijving en bewegingswerk: klein onderhoud w-installaties - Hydraulisch		
	Aandrijving en bewegingswerk: conserveren w-installaties - Hydraulisch		
	Onderhoud aandrijving handbediend	Reviseren mechanische aandrijving	Vervangen mechanische aandrijving
of	Aandrijving en bewegingswerk: smeren w-installaties		
	Aandrijving en bewegingswerk: klein onderhoud w-installaties		
	Aandrijving en bewegingswerk: conserveren w-installaties		
		Reviseren slagboom elektro	Vervangen slagboom elektro
		Reviseren slagboom handbediend	Vervangen slagboom handbediend
Diversen	Bedienings- en besturingssysteem: klein onderhoud E-installatie		Vervangen besturingsinstallatie
	Diversen: (HD)-reinigen oppervlakken		Laagspanningsinstallatie: vervanging
	Diversen: begroeiing verwijderen		Landverkeerssein: vervanging
	Diversen: herstellen		Scheepvaartsein: vervanging
	Diversen: repareren		
	Diversen: vervangen onderdeel		
	Goten/putten hemelwaterafvoer		
	Doorspuiten afvoerbuizen hemelwaterafvoer		

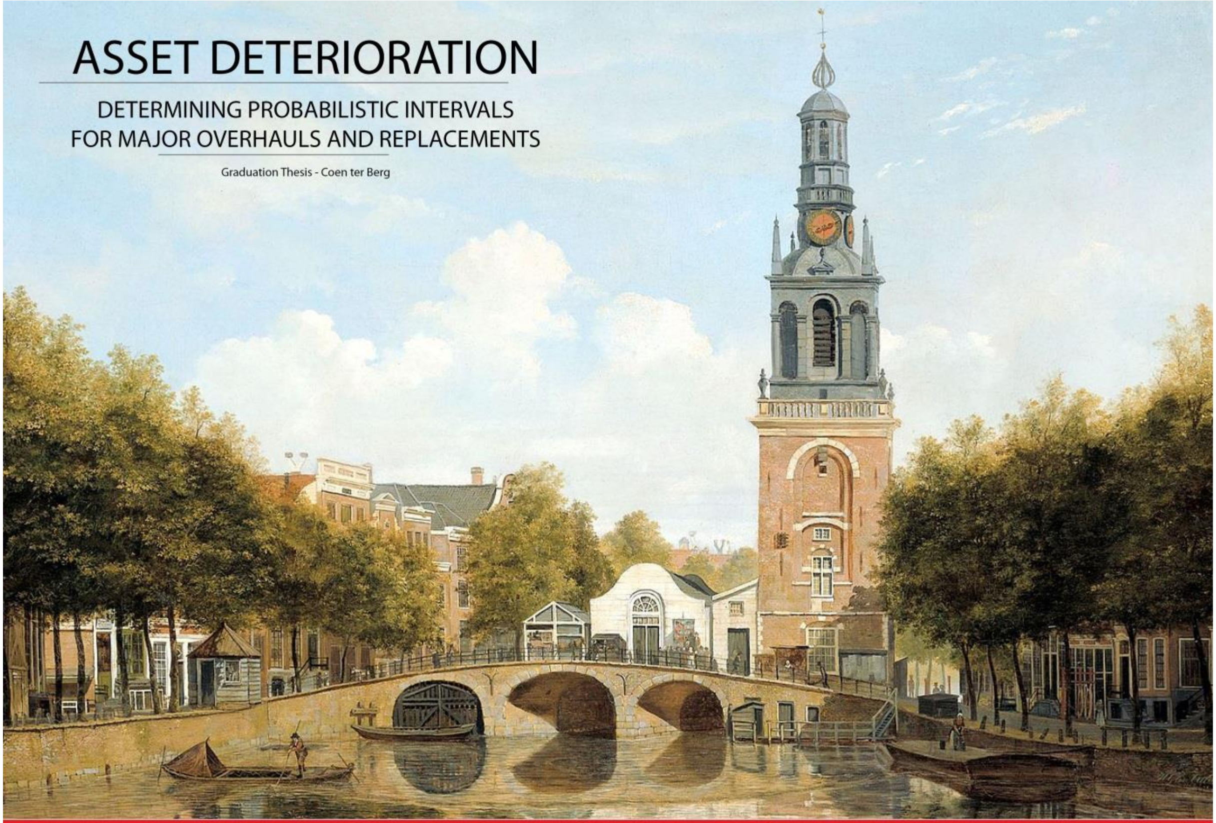
Appendix B: Elicitation format document

Seed variables

S_1	Given the passport and damage of this bridge, what would be the age of wear layer and railing?
S_2	Given the passport and damage of this bridge, what would be the age in years?
S_3	Given the passport and damage of this bridge, what would be the age of wear layer and railing?
S_4	Given the passport and damage of this bridge, what would be the age in years?
S_5	Given the passport and damage of this bridge, what would be the age in years?
S_6	Given the passport and damage of this bridge, what would be the age in years?
S_7	Given the passport and damage of this bridge, what would be the age in years?
S_8	Given the passport and damage of this bridge, how many months or years are between A & B?

Variables of interest

T_1	What time does it take for railings to degrade to a NEN-condition of 3?
T_2	What time does it take for wear layers to degrade to a NEN-condition of 3?
T_3	What time does it take for asphalt top-layers to degrade to a NEN-condition of 3?
T_4	What time does it take for asphalt sub-layers to degrade to a NEN-condition of 3?
T_5	What time does it take for pavements excluding asphalt to degrade to a NEN-condition of 3?
T_6	What time does it take for safety works to degrade to a NEN-condition of 3?
T_7	What time does it take for electromechanical transmission to degrade to a NEN-condition of 3?
T_8	What time does it take for electrohydraulic transmissions to degrade to a NEN-condition of 3?
T_9	What time does it take for concrete to degrade to a NEN-condition of 3?
T_{10}	What time does it take for wood to degrade to a NEN-condition of 3?
T_{11}	What time does it take for masonry to degrade to a NEN-condition of 3?
T_{12}	What time does it take for girders to degrade to a NEN-condition of 3?
T_{13}	What time does it take for driving irons to degrade to a NEN-condition of 3?
T_{14}	What time does it take for joints to degrade to a NEN-condition of 3?
T_{15}	What time does it take for closing installations to degrade to a NEN-condition of 3?



ASSET DETERIORATION

DETERMINING PROBABILISTIC INTERVALS FOR MAJOR OVERHAULS AND REPLACEMENTS

Graduation Thesis - Coen ter Berg

Afstudeer thesis - Coen ter Berg - TU Delft

Bepalen van probabilistische onderhoudsintervallen op bruggen

Expert judgement evaluatie van onderhoudsintervallen op bruggen in een stedelijke omgeving

Introductie

Vraagstukken voor bepaalde situaties bestaan waarbij mensen op basis van het verleden geen precieze inschatting kunnen maken. Een voorbeeld daarvan is het schatten van de leeftijd van een brug. Diverse parameters dragen er aan bij dat deze leeftijd door verschillende mensen totaal anders wordt geschat. Asfalt verweert bijvoorbeeld enerzijds door weersinvloeden, maar ook in verschillende snelheid door de hoeveelheid verkeer die aanwezig is. Dit onderzoek vraagt om dergelijke onzekerheden mee te nemen in een inschatting voor de leeftijd van diverse bruggen waarvoor bekend is dat er nog geen of weinig onderhoud gepleegd is. De leeftijd is bij ons bekend. Vervolgens zal gevraagd worden op welke termijn een bepaalde onderhoudsactiviteit gedaan moet worden om niet onder een NEN-score van 3 te komen.

Uw inschatting bestaat in dit onderzoek uit 3 waardes, zogenaamde 5%, 50% en 95% waardes. Deze waardes vertegenwoordigen respectievelijk de minst gunstige, meest waarschijnlijke, en meest gunstige omstandigheden. Uw inschatting wordt vervolgens beoordeeld op 'nauwkeurigheid' en 'informatief', dwz; is de inschatting ongeveer correct en hoe onzeker (breed) wordt de inschatting gemaakt.

Stel dat u als volgt antwoord:

Wat was de leeftijd van deze brug?		
5%	50%	95%
5 jaar	7 jaar	10 jaar

Deze antwoorden zeggen dat er een 90% kans is dat de leeftijd van de brug tussen 5 en 10 jaar ligt. Een deelnemer heeft oordeelkundig inzicht als zijn schatting het juiste antwoord treft en als deze inschatting smal is. Stelt u voor dat de leeftijd van de brug 8 jaar is. Een interval met 5% en 95% percentiel van respectievelijk 6 en 9 jaar zal dan beter scoren dan de nummers ingevuld in het voorbeeld. Het juiste antwoord wordt nog wel getroffen maar met een grotere kans/ bandbreedte. Zodra experts zekerder van hun zaak zijn, en het juiste antwoord raken, dan hebben zij meer invloed op de vragen waarvoor we nieuwe antwoorden willen genereren. Dit zijn vragen die op dit moment niet beantwoord kunnen worden aan de hand van statistische data. Voorgaand verhaal is hieronder geïllustreerd:

Beide kleuren bevatten het 'juiste' antwoord. De informatiedichtheid van de blauwe verdeling is hoger. De verdeling is conceptueel.

Scope

Door deel te nemen in dit onderzoek, draagt u bij aan mijn onderzoek naar de ontwikkeling van probabilistische onderhoudsintervallen voor groot onderhoud en deelvervangingen op bruggen in een dynamische stedelijke omgeving wat als doel heeft om de betrouwbaarheid van lange termijn asset planning te verbeteren. Om onderhoud te kunnen programmeren, is het van belang welk onderhoud op welke termijn gepleegd moet worden om een bepaalde kwaliteitsniveau te handhaven. Aanleiding hiervoor is om de verschillende factoren die meespelen in het verweer van bruggen te verwerken in de planning. Hiervoor dient de impact van deze factoren wel bekend te zijn.

Inhoud

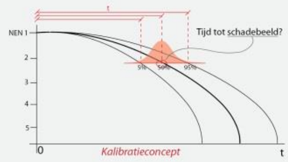
Dit document bestaat uit 8 kalibratievragen en 1 pagina met informatie vragen.

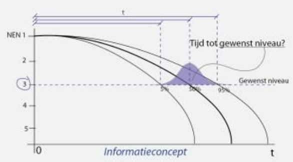
Kalibratie

De kalibratie vragen gaan over bruggen waarvoor bekend is dat er geen onderhoud op gepleegd is, tenzij anders vermeld. Aan de hand van een opname met schadebeelden en paspoortgegevens wordt gevraagd om een inschatting van de leeftijd van de brug. Probeer hierbij onzekerheden mee te nemen. Deze onzekerheden moeten een zo gunstig tot een zo ongunstig mogelijke situatie representeren.

Informatie

De informatievragen bestaan uit activiteiten die terugkomen in lange termijn asset planning waarvoor we een inschatting van het interval willen maken om een conditiescore van 3 te kunnen handhaven volgens de NEN 2767-4.





Persoonlijke gegevens

Naam .... m/v
Leeftijd ....
Bedrijf ....
Functie ....
Jaren in 'inspectiewereld' ....
Ervaring vaste bruggen ....
Ervaring beweegbare bruggen ....

Afstudeer thesis - Coen ter Berg - TU Delft

Bepalen van probabilistische onderhoudsintervallen op bruggen

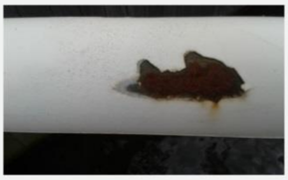
Casus 1
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	29 - houten brug
Totale breedte:	7,80m
Totale lengte:	7,90m
Lengte/oppervlakte:	95,91 m^2

Toelichting
Gegeven een fiets- en voetgangersbrug met 1 algemene foto en 6 schadebeelden. Het eerste schadebeeld betreft de slijtlaag op een kunststof dekbeplanking. De leuning en het kunststof rijdek van de brug zijn op hetzelfde moment vervangen. Gevraagd wordt hoe lang dit geleden is. De brug bevindt zich tussen meerdere wijken met een gemiddelde populatie van **4000** inwoners. Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!

Element	Bouwdeel	Materiaal soort
Hoofddraagconstructie	Langsligger	Hout
Hoofddraagconstructie	Rijdek	Kunststof
Hoofddraagconstructie	Beschermlaag	Conservering
Leuning	Leuning, algemeen	Staal
Leuning	Beschermlaag	Conservering
Steunpunt	Landhoofd	Beton
Steunpunt	Oplegbalk	Hout
Steunpunt	Paal	Hout
Talud	Talud, algemeen	Grond

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Slijtlaag	Functie, verminderd	Basiskwaliteit en veroudering	Serieus	Beginstadium	Incidenteel <2%
Leuning	Corrosie, uniform	Materiaaloppervlak	Serieus	Eindstadium	Plaatselijk 2% - 10%
Leuning	Krassen	Materiaaloppervlak	Serieus	Beginstadium	Plaatselijk 2% - 10%






Vraag

Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd van het rijdek met slijtlaag en de leuning?		
5%	50%	95%

Afstudeer thesis - Coen ter Berg - TU Delft   Bepalen van probabilistische onderhoudsintervallen op bruggen

Casus 2
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	4 - stalen brug
Totale breedte:	3,00m
Totale lengte:	5,60m
Lengte/oppervlakte:	16,95 m^2

Toelichting
Gegeven een fiets- en voetgangersbrug met 1 algemene foto en 6 schadebeelden. De schadebeelden hebben betrekking op de onthechting van de leuning. Gegeven is dat er sinds het opleveren van de brug geen onderhoud is gepleegd. De brug bevindt zich op de rand van een stad tegen een wijk aan van ongeveer **4000** inwoners. Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!

Element	Bouwdeel	Materiaal soort
Hoofddraagconstructie	Langsligger	Staal
Hoofddraagconstructie	Rijdek	Kunststof
Hoofddraagconstructie	Beschermlaag	Conservering
Leuning	Leuning, algemeen	Hout
Leuning	Beschermlaag	Conservering
Steunpunt	Landhoofd	Beton
Steunpunt	Kesp	Hout
Steunpunt	Paal	Hout
Voegovergang	Voegovergang, alg	Staal
Talud	Talud, algemeen	Grond

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Rijdek	Aangroei	Afwerking	Gering	Eindstadium	Regelmatig 10%-30%
Leuning	Onthechting	Materiaalintrinsiek	Ernstig	Eindstadium	Plaatselijk 2% - 10%






Vraag

Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd in jaren van deze brug?		
5%	50%	95%

Afstudeer thesis - Coen ter Berg - TU Delft   Bepalen van probabilistische onderhoudsintervallen op bruggen

Casus 3
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	26 - beton brug
Totale breedte:	8,10m
Totale lengte:	18,20m
Lengte/oppervlakte:	150,12 m^2

Toelichting
Gegeven een verkeersbrug met 1 algemene foto en 6 schadebeelden. De schadebeelden hebben betrekking op de verwering, deformatie en onthechting van de houten leuning. Gegeven is dat het rijdek met zijn slijtlaag en de leuning op dezelfde termijn aangepakt zijn. De leuning is hierbij opnieuw geconserveerd inclusief houtrotherstel en het rijdek is in zijn geheel vervangen. De brug bevindt zich tussen meerdere wijken met een gemiddelde populatie van 8500 inwoners. Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!

Element	Bouwdeel	Materiaal soort
Geleideconstructie	Gording	Hout
Hoofddraagconstructie	Rijdek (loopdeel)	Kunststof
Hoofddraagconstructie	Rijdek (wegdek)	Hout
Hoofddraagconstructie	Beschermlaag	Conservering
Kerende constructie	Vleugelwand	Beton
Kerende constructie	Wand	Beton
Leuning	Leuning, algemeen	Hout
Leuning	Leuning, algemeen	Staal
Leuning	Beschermlaag	Conservering
Oplegging	Kesp	Hout
Schampkant	Randelement	Staal
Steunpunt	Fundatie	Beton
Steunpunt	Landhoofd	Beton
Steunpunt	Steunpunt, algemeen	Beton
Steunpunt	Paal	Hout
Voegovergang	Rij-ijzer	Staal

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Leuning	Oppervlakteschade	Materiaaloppervlak	Serieus	Beginstadium	Incidenteel <2%
Leuning	Verwering	Materiaaloppervlak	Serieus	Beginstadium	Incidenteel <2%
Leuning	Deformatie, niet kritiek	Constructief secundair	Serieus	Beginstadium	Plaatselijk 2% - 10%
Leuning, beschermlaag	Onthechting	Materiaalintrinsiek	Ernstig	Gevorderd st.	Regelmatig 10-30%

Vraag

Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd van het rijdek met slijtlaag en de leuning?		
5%	50%	95%

Casus 4
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	4- stalen brug
Totale breedte:	3,00m
Totale lengte:	5,60m
Lengte/oppervlakte:	52,77 m^2

Toelichting
Gegeven een fiets- en voetgangersbrug met 1 algemene foto en 6 schadebeelden. De schadebeelden hebben betrekking op de vervuiling, afbrokkeling, corrosie, houtrot, scheurvorming en overige schades. Gegeven is dat er geen onderhoud is gepleegd tussen het opleveren van de brug en het maken van de foto's. De brug bevindt zich aan de rand van een wijk met ongeveer 6600 inwoners. Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!

Element	Bouwdeel	Materiaal soort
Hoofddraagconstructie	Langsligger	Staal
Hoofddraagconstructie	Rijdek	Hout
Hoofddraagconstructie	Beschermlaag	Conservering
Kerende constructie	Vleugelwand	Beton
Kerende constructie	Paal	Hout
Kerende constructie	Gording	Hout
Leuning	Leuning, algemeen	Staal
Leuning	Beschermlaag	Conservering
Steunpunt	Landhoofd	Beton
Steunpunt	Oplegbalk	Beton
Steunpunt	Oplegbalk	Hout
Steunpunt	Kesp	Beton
Steunpunt	Paal	Beton
Verharding wegtype 4	Betonverharding	Steen
Voegovergang	Voegovergang, alg.	Beton
Talud	Talud, algemeen	Grond

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Rijdek	Oppervlakteschade	Materiaaloppervlak	Serieus	Eindstadium	Regelmatig 10-30%
Rijdek	Scheur, niet construct.	Basiskwaliteit en veroudering	Serieus	Eindstadium	Aanzienlijk 30-70%
Beschermlaag	Vervuiling	Afwerking	Gering	Beginstadium	Regelmatig 10-30%
Vleugelwand	Afbrokkelen	Constructief primair	Ernstig	Eindstadium	Plaatselijk 2-10%
Paal	Houtrot	Materiaalintrinsiek	Ernstig	Eindstadium	Algemeen >=70%
Leuning, algemeen	Corrosie, uniform	Materiaaloppervlak	Serieus	Gevorderd	Plaatselijk 2-10%
Leuning, beschermlaag	Vervuiling	Afwerking	Gering	Gevorderd	Regelmatig 10-30%
Leuning, beschermlaag	Krassen	Materiaaloppervlak	Serieus	Eindstadium	Regelmatig 10-30%
Leuning, beschermlaag	Oppervlakteschade	Materiaaloppervlak	Serieus	Gevorderd	Regelmatig 10-30%
Verharding	Verzakking	Constructief primair	Ernstig	Eindstadium	Regelmatig 10-30%
Voegovergang, algemeen	Onderdeel ontbreekt	Basiskwaliteit en veroudering	Serieus	Eindstadium	Algemeen >=70%

Vraag

Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd in jaren van deze brug?		
5%	50%	95%

Casus 5
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	28- stalen brug
Totale breedte:	2,80m
Totale lengte:	56,75
Lengte/oppervlakte:	143,58 m^2

Toelichting
Gegeven een fiets- en voetgangersbrug met 1 algemene foto en 7 schadebeelden. De schadebeelden hebben betrekking op de aanslag op de stalen ligger, gaten in het rijdek en overige schades. Gegeven is dat er geen onderhoud is gepleegd tussen het opleveren van de brug en het maken van de foto's. De brug bevindt zich tussen 2 wijken met een gemiddelde van 5500 inwoners Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!


Element	Bouwdeel	Materiaal soort
Geleideconstructie	Geleiderail	Staal
Hoofddraagconstructie	Beschermlaag	Conservering
Hoofddraagconstructie	Rijdek	Hout
Hoofddraagconstructie	Langsligger	Staal
Hoofddraagconstructie	Beschermlaag	Conservering
Leuning	Leuning, algemeen	Staal
Schampkant	Randelement	Hout
Steunpunt	Beschermlaag	Conservering
Steunpunt	Landhoofd	Beton
Steunpunt	Paal	Beton
Talud	Talud, algemeen	Grond

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Beschermlaag	Aangroei	Afwerking	Gering	Eindstadium	Aanzienlijk 30-70%
Rijdek	Gaten	Materiaalintrinsiek	Ernstig	Eindstadium	Aanzienlijk 30-70%
Beschermlaag	Functie, verminderd	Basiskwaliteit en veroudering	Serieus	Eindstadium	Aanzienlijk 30-70%






Vraag

Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd in jaren van deze brug?		
5%	50%	95%

Casus 6
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	28- stalen brug
Totale breedte:	2,50m
Totale lengte:	26,30m
Lengte/oppervlakte:	65,06 m^2

Toelichting
Gegeven een fiets- en voetgangersbrug met 1 algemene foto en 8 schadebeelden. De schadebeelden hebben betrekking op de aangroei, verwering, corrosie, functievermindering en overige schades. Gegeven is dat er geen onderhoud is gepleegd tussen het opleveren van de brug en het maken van de foto's. De brug bevindt zich tussen wijken met een gemiddelde populatie van 3500 inwoners. Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!



Element	Bouwdeel	Materiaal soort
Hoofddraagconstructie	Langsligger	Staal
Hoofddraagconstructie	Rijdek	Hout
Hoofddraagconstructie	Beschermlaag	Conservering
Kerende constructie	Beschoeiing	Hout
Leuning	Leuning, algemeen	Staal
Leuning	Leuning, algemeen	Staal
Leuning	Beschermlaag	Conservering
Steunpunt	Landhoofd	Beton
Steunpunt	Paal	Beton
Steunpunt	Kesp	Beton
Talud	Talud, algemeen	Grond

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Beschermlaag	Functie, verminderd	Basiskwaliteit en veroudering	Serieus	Eindstadium	Aanzienlijk 30-70%
Rijdek	Verwering	Materiaaloppervlak	Serieus	Beginstadium	Aanzienlijk 30-70%
Leuning, algemeen	Corrosie, uniform	Materiaaloppervlak	Serieus	Eindstadium	Plaatselijk 2-10%
Kesp	Aangroei	Afwerking	Gering	Gevorderd	Aanzienlijk 30-70%
Talud	Uitspoeling	Werking primair	Ernstig	Eindstadium	Plaatselijk 2-10%
Talud	Verzakking	Constructief primair	Ernstig	Beginstadium	Incidenteel <2%






Vraag

Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd in jaren van deze brug?		
5%	50%	95%

Casus 7
Kalibratie

NEN 2767:	7 - bruggen (vast)
Kunstwerken objecttype:	04 - stalen brug
Totale breedte:	2,50m
Totale lengte:	onbekend
Lengte/oppervlakte:	52,70 m^2

Toelichting
Gegeven een fiets- en voetgangersbrug met 1 algemene foto en 10 schadebeelden. De schadebeelden hebben betrekking op de diverse schades. Gegeven is dat er geen onderhoud is gepleegd tussen het opleveren van de brug en het maken van de foto's. De brug bevindt zich aan de rand van een wijk met ongeveer 6600 inwoners. Hieronder volgt een decompositie van de brug en een tabel met door een inspecteur geconstateerde gebreken. Trek niet de conclusie dat elk gebrek geconstateerd is!








Element	Bouwdeel	Materiaal soort
Hoofddraagconstructie	Langsligger	Staal
Hoofddraagconstructie	Beschermlaag	Asfalt
Hoofddraagconstructie	Rijdek	Hout
Kerende constructie	Gording	Hout
Kerende constructie	Paal	Hout
Kerende constructie	Vleugelwand	Beton
Leuning	Leuning, algemeen	Staal
Leuning	Beschermlaag	Conservering
Steunpunt	Landhoofd	Beton
Steunpunt	Paal	Beton
Steunpunt	Kesp	Beton
Steunpunt	Oplegbalk	Beton
Verharding wegtype 4	Betonverharding	Steen
Talud	Talud, algemeen	Grond

Bouwdeel	Gebrek	Soort gebrek	Ernst gebrek	Intensiteit	Omvang
Langsligger	Aangroei	Afwerking	Gering	Gevorderd	Regelmatig 10-30%
Rijdek	Scheur, niet construct.	Basiskwaliteit en veroudering	Serieus	Eindstadium	Incidenteel <2%
Paal	Houtrot	Materiaalintrinsiek	Ernstig	Eindstadium	Algemeen >=70%
Vleugelwand	Deformatie, niet kritiek	Constructief primair	Serieus	Eindstadium	Regelmatig 10-30%
Leuning, algemeen	Corrosie, uniform	Materiaaloppervlak	Serieus	Beginstadium	Plaatselijk 2-10%
Leuning, algemeen	Oppervlakteschade	Materiaaloppervlak	Serieus	Beginstadium	Incidenteel <2%
Beschermlaag	Oppervlakteschade	Materiaaloppervlak	Serieus	Beginstadium	Plaatselijk 2-10%
Beschermlaag	Onthechting	Materiaalintrinsiek	Ernstig	Eindstadium	Plaatselijk 2-10%
Kesp	Aangroei	Afwerking	Gering	Eindstadium	Aanzienlijk 30-70%
Oplegbalk	Aangroei	Afwerking	Gering	Eindstadium	Aanzienlijk 30-70%
Paal	Aangroei	Afwerking	Gering	Eindstadium	Aanzienlijk 30-70%

Zie volgende pagina





Casus 8
Kalibratie

Toelichting
Gegeven een beweegbare brug waar normaal verkeer over heen gaat. De verkeersbelasting is gegeving in de rood-witte tabel. Bekend van deze brug is dat hij beschikt over een houten dekbeplanking waarvan de planken door de belasting speling hebben. Te zien is dat er tussen foto A en foto B significante slijtage te zien is op de slijtlaag van deze brug.

Verklaring afkortingen:

ETM	Etmaal
MVT	Motorvoertuigen
MR	Motorfietsen
LV	Licht verkeer: personenauto's, motoren, aanhangers
MV	Middelzwaar verkeer: bakwagens, kleine autobussen, grote bestelauto's (+ aanhangers)
ZV	Zwaar verkeer: vrachtwagens, grote autobussen, touringcars & lijnbussen
GDU	Gemiddeld daguur
GAU	Gemiddeld avonduur
GNA	Gemiddeld nachtuur

Gegevens

NEN 2767:	Beweegbare brug
Constructie:	Staal-hout, aanbrug gew-beton
Functie:	Normaal verkeer
Bouwjaar:	1935
Belastingklasse:	Klasse 60
Fundering:	Houten palen
Landhoofden, muren	Metselwerk - graniet
Brugdek:	Stalen liggers - houten rijdek
Oppervlakte:	855 m^2
Openingsfreq.	572 keer (2013-2016)

ETM MVT	ETM LV	ETM MV	ETM ZV	ETM Bus
10169	9916	38	38	177
GDU MVT	GDU LV	GDU MV	GDU ZV	GDU Bus
594.71	579.71	2.62	2.5	9.88
GAU MVT	GAU LV	GAU MV	GAU ZV	GAU Bus
393.48	384.83	0.76	0.66	7.23
GNU MVT	GNU LV	GNU MV	GNU ZV	GNU Bus
176.24	171.45	0.44	0.61	3.74

Vraag
Gegeven het paspoort en de schadebeelden van de brug, wat is de leeftijd in jaren van deze brug?

5%	50%	95%

Vraag
Gegeven het paspoort en de schadebeelden van de brug, hoeveel maanden/jaren zitten er tussen foto A en B?

5%	50%	95%

Casus 9

Informatie

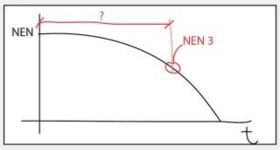
Toelichting

De informatievragen zijn vragen waarop geen 'juist' antwoord bestaat. Dit juiste antwoord wordt gevormd, mede door uw deelname aan dit onderzoek. De vragen hebben betrekking op bepaalde onderhoudsactiviteiten die deel uit kunnen maken in lange termijn asset planning, waarvoor bepaalde intervallen geschat moeten worden waarop bouwdelen een conditiescore van 3 krijgen volgens de NEN 2767.

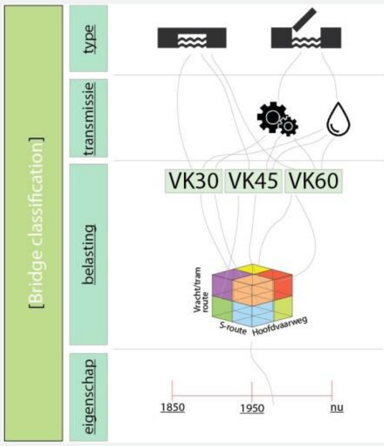
De volgende activiteiten zijn geselecteerd:

Categorie	Aciviteit	Specificatie
Onderbouw & bovenbouw	Conservering leuning	Totale vervanging conservering
	Conservering langsligger	Totale vervanging conservering
	Vervangen asfalt toplaag	Totale vervanging
	Vervangen asfalt onderlaag	Totale vervanging
	Vervangen slijtlaag	Totale vervanging
	Rij-ijzer vervanging	Totale vervanging
	Voeg vervanging	Totale vervanging
	Groot onderhoud beton	Structuurlijke reparaties, deelvervangingen en verf
	Groot onderhoud hout	Structuurlijke reparaties, deelvervangingen en verf
	Groot onderhoud metselwerk	Structuurlijke reparaties, deelvervangingen (baksteen)
	Vervangen verharding	
Transmissie	Revisie opzetwerk	
	Revisie transmissie - elektromechanisch	
	Revisie transmissie - hydraulisch	
	Revisie afsluitbomen	

Voor het inschatten van de activiteiten is het uiteraard belangrijk om de omstandigheden te weten. Ook hier geldt weer dat 3 waardes, het 5% 50% en 95% percentiel, gevraagd worden. Ga daarbij uit van de minst gunstige, meest waarschijnlijke, en meest gunstige omstandigheden. De eerste activiteit betreft het opschuren en schilderen van een leuning. Verschillende niveaus van verweerfactoren bepalen het interval waarop iets onderhoduen moet worden. De eerste onzekerheid ligt bijvoorbeeld in het materiaal van de leuning. Vervolgens wordt gekeken naar nog diepere onzekerheden zoals de invloed van het weer. Mocht de minst gunstige situatie een houten leuning zijn waar veel fietsen tegen aangezet worden, dan kunnen weersomstandigheden/oneffenheden zorgen dat deze situatie nog minder gunstig wordt. Op deze manier wordt bruikbare data gegenereerd die toegepast kan worden op specifieke bruggen. Probeer dergelijke factoren mee te nemen in het interval. Op de rechterhelft van deze pagina zijn een aantal factoren op een bepaald abstractieniveau gegeven.



Gevraagd wordt telkens om een inschatting te maken hoe lang de periode duurt om tot een NEN-score 3 te komen volgens de NEN2767-4.



Bovenstaande classificatie heeft als doel om geclassificeerde bruggen een eigen onderhoudscyclus te geven. Een onderscheid wordt gemaakt in vaste/beweegbare bruggen, waarvan de aandrijving van beweegbare bruggen te verdelen is in elektromechanisch en hydraulisch. Vervolgens wordt de relatie tussen ontwerpklasse en gebruik aangekaart. Het gebruik wordt gedefinieerd aan de hand van 3 ja/nee factoren: Vracht/tramverkeer, S-route en hoofdvaarweg. Deze factoren kaarten de last van het verkeer over de brug, en de openingsfrequentie van beweegbare bruggen aan.

Nu volgen 15 vragen met betrekking tot de gegeven onderhoudsactiviteiten. Ga er van uit dat DO frequent gebeurt en laat menselijke fouten (verkeerd aanbrengen conservering) achterwege. Alvast dank voor de medewerking!

Op welke termijn zou je de leuning van een brug conserveren om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Afstudeer thesis - Coen ter Berg - TU Delft

Bepalen van probabilistische onderhoudsintervallen op bruggen

Onderhoudsactiviteiten voor bruggen in een stedelijke omgeving

Op welke termijn zou je de slijtlaag vervangen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de asfalt toplaag vervangen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de asfalt onderlaag vervangen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je verhardingen - buiten asfalt - herstraten om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je het opzetwerk reviseren om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de electromechanische transmissie reviseren om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de hydraulische transmissie reviseren om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je groot onderhoud op beton (landhoofden/kolommen ed.) plegen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je groot onderhoud op het constructieve houtwerk plegen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je groot onderhoud op metselwerk plegen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de balken van een brug conserveren om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de rij-ijzers vervangen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de voegovergangen van een brug vervangen om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Op welke termijn zou je de afsluitboominstallatie reviseren om een conditiescore van 3 te behouden volgens de NEN 2767-4?

5% 50% 95%

Afstudeer thesis - Coen ter Berg - TU Delft

Bepalen van probabilistische onderhoudsintervallen op bruggen

Appendix C: Expert Judgement participants

ID#	Function
1	Project leader
2	Inspector
3	Inspector
4	Project leader / advisor
5	Senior inspector
6	Junior maintenance engineer
7	Maintenance engineer
8	Maintenance engineer
9	Maintenance engineer
10	Maintenance engineer
11	Maintenance engineer
12	Assistant inspector
13	Asset Management advisor
14	Asset management advisor
15	Asset management advisor
16	Bridge manager
17	Bridge manager
18	Civil advisor
19	Asset management advisor
20	Manager & Execution
21	Manager
22	Civil advisor
23	Inspector
24	Advisor
25	Sr. Advisor
26	Sr. Advisor
27	Civil Advisor
28	Asset management advisor

Appendix D: Expert assessments

Table 37 Experts assessments for $S_1 - S_8$

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Real.	4	7	6	10	15	13	10	38
Exp. 1	7-10-12	5-7-10	7-13-20	10-15-20	7-10-15	15-20-25	25-30-35	8-12-16
Exp. 2	8-18-28	5-10-20	5-10-15	15-25-35	15-30-40	15-25-35	15-25-35	1-4-6
Exp. 3	5-7-10	5-7-10	5-10-15	10-15-20	7-10-15	7-10-15	10-15-20	3-6-9
Exp. 4	4-6-8	2-6-10	15-25-35	20-30-40	15-25-35	15-20-25	15-20-25	4-6-8
Exp. 5	2-3-5	2-3-4	10-15-18	18-20-25	15-20-25	20-25-30	20-25-30	180-240-300
Exp. 6	3-4-5	4-5-6	6-7-8	15-17-20	10-12-14	17-19-21	20-21-23	15-24-30
Exp. 7	5-6-7	4-6-8	8-10-12	6-7-8	15-18-20	8-10-12	10-12-14	20-24-28
Exp. 8	4-6-8	5-7-9	8-10-12	5-7-9	12-15-20	15-20-25	10-15-18	48-60-72
Exp. 9	3-5-7	7-9-11	5-9-13	6-10-14	10-13-16	8-11-14	7-10-13	36-60-72
Exp. 10	3-5-7	5-10-12	4-6-8	5-10-15	8-10-12	3-5-7	5-7-10	12-24-36
Exp. 11	7-9-12	8-11-15	8-10-12	7-8-11	13-15-20	20-25-30	10-13-15	6-12-24
Exp. 12	5-6-7	3-4-5	20-25-30	20-22-25	15-17-20	15-17-20	15-17-20	60-72-84
Exp. 13	4-5-6	5-7-9	12-14-16	12-14-16	13-15-17	18-20-23	14-16-20	24-36-48
Exp. 14	7-8-10	7-9-11	10-12-14	8-10-12	8-10-12	15-17-19	10-12-14	24-36-48
Exp. 15	8-10-12	16-18-20	20-22-25	20-35-40	38-40-45	12-15-20	15-16-17	8-10-12
Exp. 16	3-6-8	5-10-15	8-10-12	12-15-18	20-25-30	18-20-22	13-15-18	36-60-72
Exp. 17	5-8-10	3-6-10	5-10-20	8-15-25	8-18-25	16-19-35	17-19-30	15-18-20
Exp. 18	4-8-15	3-5-8	12-15-20	12-18-25	15-18-25	12-15-18	8-12-18	12-24-36
Exp. 19	4-10-15	7-10-12	10-15-20	20-30-40	10-14-18	15-20-30	8-12-16	36-60-72
Exp. 20	5-15-25	5-16-26	10-20-30	10-20-30	15-30-45	10-30-40	10-40-45	2-4-6
Exp. 21	3-5-7	12-14-16	5-7-9	22-26-30	16-20-22	27-30-33	32-36-40	60-72-84
Exp. 22	2-4-6	3-5-10	1-2-3	3-5-10	3-5-7	5-10-15	10-15-20	6-12-24
Exp. 23	3-5.5-8	5-7-10	6-10-15	10-15-20	10-13-25	10-13-25	15-20-30	24-60-84
Exp. 24	3-7-10	2-4-6	15-20-30	20-27-30	4-7-10	3-6-10	7-10-15	24-48-72
Exp. 25	7-10-13	12-15-20	10-17-20	6-7-15	17-22-27	12-15-20	20-25-30	18-24-30
Exp. 26	10-15-20	7-11-15	15-20-25	12-15-18	13-18-23	15-20-25	18-20-22	36-60-84
Exp. 27	2-3-5	10-20-30	10-15-20	5-15-25	10-15-20	15-20-25	20-30-40	12-24-36
Exp. 28	8-10-12	5-7-9	8-10-12	10-15-20	10-13-16	12-14-16	8-10-12	60-72-84

Target variables $T_1 - T_8$

Table 38 Experts assessments for $T_1 - T_8$

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
Exp. 1	5-10-15	8-13-16	7-10-12	10-15-20	15-20-25	25-30-35	35-40-45	35-45-60
Exp. 2	10-20-30	8-10-20	8-12-18	15-22-30	10-15-25	20-40-60	10-25-40	15-25-35
Exp. 3	5-10-20	5-6-7	7-10-12	15-17-20	10-15-20	-	-	-
Exp. 4	10-20-30	5-15-25	5-15-25	10-20-30	20-30-40	20-30-40	10-20-30	20-30-40
Exp. 5	5-10-15	10-12-15	9-12-15	20-25-30	15-25-35	18-25-27	18-20-25	25-30-35
Exp. 6	5-6-7	7-8-9	9-10-11	18-20-22	6-7-8	6-7-8	13-15-17	11-12-13
Exp. 7	10-12-14	6-8-10	7-8-9	22-25-27	10-12-14	9-10-11	12-14-16	12-15-18
Exp. 8	12-15-17	8-10-12	10-12-15	20-30-35	8-10-12	4-5-6	4-5-6	4-5-6
Exp. 9	7-10-13	8-10-12	12-15-18	20-25-30	12-15-18	-	15-18-21	18-21-24
Exp. 10	5-6-7	8-10-12	10-15-20	20-25-30	5-10-15	12-15-20	5-10-15	5-7-15
Exp. 11	7-9-11	6-7-8	6-7-8	13-15-20	8-10-13	8-10-12	5-8-15	5-8-15
Exp. 12	15-18-20	8-10-12	10-12-15	20-22-25	15-17-20	15-18-20	7-9-10	8-10-15
Exp. 13	4-5-7	17-18-19	6-7-8	20-22-24	6-8-10	25-30-35	12-14-16	25-30-35
Exp. 14	16-18-20	6-8-10	18-20-22	35-40-45	8-10-12	13-15-17	5-6-7	5-6-7
Exp. 15	8-9-10	10-12-15	10-12-15	20-22-25	20-22-25	35-38-40	18-20-25	16-18-20
Exp. 16	5-7-9	8-10-12	12-15-18	12-15-18	12-15-18	20-25-30	20-25-30	12-15-18
Exp. 17	6-9-12	8-10-12	8-9-12	12-15-18	10-12-15	15-20-25	16-20-25	10-12-15
Exp. 18	3-6-10	12-15-18	15-20-25	30-40-50	25-30-40	30-40-60	25-30-35	25-30-35
Exp. 19	5-7-10	8-10-14	8-12-15	15-20-25	12-15-18	10-15-20	10-12-15	8-12-15
Exp. 20	15-30-45	6-12-18	20-40-60	25-50-100	25-50-100	25-50-80	10-20-40	15-30-60
Exp. 21	25-30-35	8-10-12	6-8-10	12-14-16	10-13-16	-	35-40-45	25-30-35
Exp. 22	3-5-7	1-3-5	2-5-10	8-12-20	3-5-7	2-5-10	10-15-20	7-10-12
Exp. 23	6-10-15	5-10-15	7-9-14	15-18-25	5-7-15	-	-	-
Exp. 24	3-4-6	3-5-8	5-7-10	10-15-30	6-8-10	10-15-20	20-25-30	12-16-25
Exp. 25	8-10-12	5-12-20	7-15-20	21-45-60	20-25-30	20-25-30	25-30-35	12-15-20
Exp. 26	6-8-12	7-10-12	6-8-10	16-20-24	8-10-12	7-10-15	10-15-20	7-10-15
Exp. 27	10-15-20	15-20-25	14-15-16	20-25-30	15-20-25	30-40-50	10-15-20	20-25-30
Exp. 28	13-16-19	8-10-12	10-11-12	35-40-45	7-9-11	35-45-55	30-35-40	35-40-45

Target variables $T_9 - T_{15}$

Table 39 Experts assessments for $T_9 - T_{15}$

	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}
Exp. 1	30-50-80	25-35-45	40-60-80	30-45-60	8-12-20	5-10-25	25-30-50
Exp. 2	40-60-80	20-30-40	40-50-70	15-20-30	40-60-80	10-15-25	20-25-30
Exp. 3	10-15-20	25-30-35	25-30-35	5-20-30	20-25-30	5-15-25	-
Exp. 4	30-40-50	20-30-40	30-40-50	15-25-35	5-10-15	10-15-20	10-20-30
Exp. 5	20-25-30	25-30-35	30-40-50	18-20-25	20-25-30	20-25-30	12-15-20
Exp. 6	30-35-40	20-25-30	15-17-20	6-8-10	5-6-7	19-21-23	13-14-15
Exp. 7	13-15-18	16-20-24	22-25-28	13-15-17	18-20-22	35-40-45	10-12-14
Exp. 8	20-25-40	15-20-25	20-25-30	10-15-18	25-30-35	25-30-35	4-5-6
Exp. 9	35-40-45	16-20-24	16-20-24	12-15-18	16-20-24	30-35-40	12-15-18
Exp. 10	20-25-30	20-25-30	10-20-30	5-10-15	10-20-30	20-30-40	7-10-15
Exp. 11	50-60-75	10-15-20	40-50-60	20-25-30	15-20-25	20-25-30	7-10-12
Exp. 12	20-25-30	15-18-20	20-22-25	20-25-30	40-45-50	20-25-30	5-8-10
Exp. 13	21-23-25	16-18-20	27-30-33	21-23-25	22-24-26	18-20-22	6-8-10
Exp. 14	33-35-37	16-18-20	96-98-100	7-8-9	21-23-25	8-10-12	4-6-8
Exp. 15	46-48-50	26-28-30	20-25-30	12-15-20	26-28-30	18-20-22	26-28-30
Exp. 16	30-40-50	30-40-50	17-20-23	5-7-9	30-40-50	15-20-25	30-40-50
Exp. 17	25-28-30	25-28-32	20-25-30	10-12-15	15-18-30	10-12-15	12-15-17
Exp. 18	40-50-60	25-30-35	30-40-50	5-7-10	40-50-60	15-20-30	25-30-35
Exp. 19	15-20-30	10-12-15	20-25-30	7-10-12	15-20-25	10-12-15	10-15-20
Exp. 20	20-40-60	5-15-30	10-30-60	10-25-50	15-40-60	15-30-45	10-30-45
Exp. 21	70-80-90	15-20-25	60-70-80	12-14-16	60-65-70	15-20-25	17-20-23
Exp. 22	7-10-15	2-5-10	2-7-12	1-3-5	2-5-10	1-3-5	10-15-20
Exp. 23	25-30-35	15-20-25	15-25-30	10-12-15	15-20-30	7-10-15	-
Exp. 24	20-30-36	10-12-14	30-35-40	3-6-8	20-25-30	5-15-40	3-6-12
Exp. 25	20-30-35	16-20-30	25-30-40	20-25-30	40-50-60	5-7-15	10-20-25
Exp. 26	20-25-30	10-15-20	15-20-30	8-10-15	30-35-40	10-15-25	10-15-18
Exp. 27	25-30-35	5-10-15	20-25-30	7-10-15	39-40-41	3-8-10	10-15-20
Exp. 28	40-50-60	25-30-35	35-50-65	20-22-24	50-60-70	45-50-55	16-18-20

Appendix E: Excalibur output

Table 40 EqualDM fixed bridge

ID#	Calibr.	Mean rel. total	Mean rel. seed	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 1	6,63E-05	1,279	1,377	8	9,13E-05	0,03704	0,000774
Exp. 2	1,75E-05	1,053	0,8418	8	1,47E-05	0,03704	0,000125
Exp. 3	0,02651	1,24	1,013	8	0,02685	0,03704	0,2277
Exp. 4	5,86E-07	1,095	1,093	8	6,40E-07	0,03704	5,43E-06
Exp. 5	5,86E-07	1,54	1,47	8	8,61E-07	0,03704	7,30E-06
Exp. 6	5,86E-07	2,122	1,975	8	1,16E-06	0,03704	9,81E-06
Exp. 7	2,31E-05	1,59	1,514	8	3,50E-05	0,03704	0,000297
Exp. 8	0,01644	1,502	1,11	8	0,01825	0,03704	0,1548
Exp. 9	0,000144	1,398	1,192	8	0,000172	0,03704	0,001456
Exp. 10	0,001547	1,365	1,129	8	0,001746	0,03704	0,01481
Exp. 11	1,79E-08	1,928	1,852	8	3,32E-08	0,03704	2,82E-07
Exp. 12	0,002029	1,815	1,591	8	0,003228	0,03704	0,02738
Exp. 13	3,72E-06	1,974	1,862	8	6,93E-06	0,03704	5,88E-05
Exp. 14	3,72E-06	1,912	1,729	8	6,44E-06	0,03704	5,46E-05
Exp. 15	1,75E-05	1,583	1,426	8	2,50E-05	0,03704	0,000212
Exp. 16	0,01566	1,26	1,107	8	0,01734	0,03704	0,1471
Exp. 17	6,63E-05	1,601	1,432	8	9,49E-05	0,03704	0,000805
Exp. 18	0,000144	2,051	1,743	8	0,000251	0,03704	0,002129
Exp. 19	6,63E-05	2,056	1,693	8	0,000112	0,03704	0,000952
Exp. 20	1,75E-05	0,7568	0,7584	8	1,33E-05	0,03704	0,000113
Exp. 21	1,29E-06	1,74	1,807	8	2,32E-06	0,03704	1,97E-05
Exp. 22	0,01644	0,8191	0,8412	8	0,01383	0,03704	0,1173
Exp. 23	0,01566	1,208	1,021	8	0,01598	0,03704	0,1355
Exp. 24	0,000576	1,2	1,026	8	0,000591	0,03704	0,005008
Exp. 25	6,63E-05	1,37	1,416	8	9,39E-05	0,03704	0,000796
Exp. 26	1,29E-06	1,481	1,436	8	1,85E-06	0,03704	1,57E-05
Exp. 27	0,001547	1,403	1,02	8	0,001578	0,03704	0,01338
EqualDM	0,08041	0,2786	0,2188	8	0,0176		0,1492

Table 41 GlobalDM & ItemDM fixed bridges

ID # 27	Calibr.	Mean rel. total	Mean rel. real.	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 1	6,63E-05	1,279	1,377	8	0	0	0
Exp. 2	1,75E-05	1,053	0,8418	8	0	0	0
Exp. 3	0,02651	1,24	1,013	8	0,02685	0,4556	0,07736
Exp. 4	5,86E-07	1,095	1,093	8	0	0	0
Exp. 5	5,86E-07	1,54	1,47	8	0	0	0
Exp. 6	5,86E-07	2,122	1,975	8	0	0	0
Exp. 7	2,31E-05	1,59	1,514	8	0	0	0
Exp. 8	0,01644	1,502	1,11	8	0,01825	0,3097	0,05259
Exp. 9	0,000144	1,398	1,192	8	0	0	0
Exp. 10	0,001547	1,365	1,129	8	0	0	0
Exp. 11	1,79E-08	1,928	1,852	8	0	0	0
Exp. 12	0,002029	1,815	1,591	8	0	0	0
Exp. 13	3,72E-06	1,974	1,862	8	0	0	0
Exp. 14	3,72E-06	1,912	1,729	8	0	0	0
Exp. 15	1,75E-05	1,583	1,426	8	0	0	0
Exp. 17	0,01566	1,26	1,107	8	0	0	0
Exp. 18	6,63E-05	1,601	1,432	8	0	0	0
Exp. 19	0,000144	2,051	1,743	8	0	0	0
Exp. 20	6,63E-05	2,056	1,693	8	0	0	0
Exp. 21	1,75E-05	0,7568	0,7584	8	0	0	0
Exp. 22	1,29E-06	1,74	1,807	8	0	0	0
Exp. 23	0,01644	0,8191	0,8412	8	0,01383	0,2347	0,03984
Exp. 24	0,01566	1,208	1,021	8	0	0	0
Exp. 25	0,000576	1,2	1,026	8	0	0	0
Exp. 26	6,63E-05	1,37	1,416	8	0	0	0
Exp. 27	1,29E-06	1,481	1,436	8	0	0	0
Exp. 28	0,001547	1,403	1,02	8	0	0	0
GlobalDM	0,6876	0,5039	0,419	8	0,2881		0,8302
ItemDM	0,6876	0,5461	0,441	8	0,3033		0,8373

Table 42 Excalibur graph for movable bridges with equal weights

ID # 24	Calibr.	Mean rel. total	Mean rel. real.	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 1	6,63E-05	1,468	1,377	8	9,13E-05	0,04167	0,001226
Exp. 2	1,75E-05	0,8754	0,8418	8	1,47E-05	0,04167	0,000198
Exp. 4	5,86E-07	1,053	1,093	8	6,40E-07	0,04167	8,60E-06
Exp. 5	5,86E-07	1,556	1,47	8	8,61E-07	0,04167	1,16E-05
Exp. 6	5,86E-07	2,085	1,975	8	1,16E-06	0,04167	1,55E-05
Exp. 7	2,31E-05	1,56	1,514	8	3,50E-05	0,04167	0,00047
Exp. 8	0,01644	1,27	1,11	8	0,01825	0,04167	0,2452
Exp. 9	0,000144	1,227	1,192	8	0,000172	0,04167	0,002306
Exp. 10	0,001547	1,301	1,129	8	0,001746	0,04167	0,02346
Exp. 11	1,79E-08	1,756	1,852	8	3,32E-08	0,04167	4,46E-07
Exp. 12	0,002029	1,704	1,591	8	0,003228	0,04167	0,04336
Exp. 13	3,72E-06	1,98	1,862	8	6,93E-06	0,04167	9,31E-05
Exp. 14	3,72E-06	1,783	1,729	8	6,44E-06	0,04167	8,65E-05
Exp. 15	1,75E-05	1,502	1,426	8	2,50E-05	0,04167	0,000335
Exp. 17	0,01566	1,081	1,107	8	0,01734	0,04167	0,233
Exp. 18	6,63E-05	1,336	1,432	8	9,49E-05	0,04167	0,001275
Exp. 19	0,000144	1,739	1,743	8	0,000251	0,04167	0,003373
Exp. 20	6,63E-05	1,693	1,693	8	0,000112	0,04167	0,001507
Exp. 21	1,75E-05	0,7152	0,7584	8	1,33E-05	0,04167	0,000178
Exp. 23	0,01644	0,9098	0,8412	8	0,01383	0,04167	0,1858
Exp. 25	0,000576	1,057	1,026	8	0,000591	0,04167	0,007932
Exp. 26	6,63E-05	1,434	1,416	8	9,39E-05	0,04167	0,001261
Exp. 27	1,29E-06	1,344	1,436	8	1,85E-06	0,04167	2,48E-05
Exp. 28	0,001547	1,128	1,02	8	0,001578	0,04167	0,0212
EqualDM	0,08041	0,2003	0,2109	8	0,01696		0,2278

Table 43 Excalibur graph for movable bridge with global and item weights

ID # 24	Calibr.	Mean rel. total	Mean rel. real.	#seed	UnNorm. weight	Norm.weight w/o DM	Norm.weight w/ DM
Exp. 1	6,63E-05	1,468	1,377	8	0	0	0
Exp. 2	1,75E-05	0,8754	0,8418	8	0	0	0
Exp. 4	5,86E-07	1,053	1,093	8	0	0	0
Exp. 5	5,86E-07	1,556	1,47	8	0	0	0
Exp. 6	5,86E-07	2,085	1,975	8	0	0	0
Exp. 7	2,31E-05	1,56	1,514	8	0	0	0
Exp. 8	0,01644	1,27	1,11	8	0,01825	0,5689	0,06466
Exp. 9	0,000144	1,227	1,192	8	0	0	0
Exp. 10	0,001547	1,301	1,129	8	0	0	0
Exp. 11	1,79E-08	1,756	1,852	8	0	0	0
Exp. 12	0,002029	1,704	1,591	8	0	0	0
Exp. 13	3,72E-06	1,98	1,862	8	0	0	0
Exp. 14	3,72E-06	1,783	1,729	8	0	0	0
Exp. 15	1,75E-05	1,502	1,426	8	0	0	0
Exp. 17	0,01566	1,081	1,107	8	0	0	0
Exp. 18	6,63E-05	1,336	1,432	8	0	0	0
Exp. 19	0,000144	1,739	1,743	8	0	0	0
Exp. 20	6,63E-05	1,693	1,693	8	0	0	0
Exp. 21	1,75E-05	0,7152	0,7584	8	0	0	0
Exp. 23	0,01644	0,9098	0,8412	8	0,01383	0,4311	0,04899
Exp. 25	0,000576	1,057	1,026	8	0	0	0
Exp. 26	6,63E-05	1,434	1,416	8	0	0	0
Exp. 27	1,29E-06	1,344	1,436	8	0	0	0
Exp. 28	0,001547	1,128	1,02	8	0	0	0
GlobalDM	0,5405	0,6051	0,4629	8	0,2502		0,8864
ItemDM	0,5405	0,6239	0,4786	8	0,2587		0,8897

Table 44 Discrepancy target variables

ID#	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}
1	0,50	0,72	1,01	0,70	1,32	1,43	2,32	1,80	0,52	0,95	1,01	1,90	0,98	0,53	1,26
2	0,59	0,68	0,69	0,64	0,71	0,65	0,27	0,73	0,87	0,55	1,19	0,91	1,29	0,93	1,06
3	0,28	1,60	1,01	1,27	0,96	-	-	-	1,07	1,09	1,64	0,29	1,49	0,52	-
4	0,59	0,40	0,22	0,38	1,08	0,83	0,40	0,91	0,98	0,55	1,25	0,75	0,93	1,31	0,50
5	0,47	1,02	1,10	1,17	0,90	1,56	1,37	1,52	1,00	1,09	1,25	1,61	1,49	1,17	1,14
6	1,77	1,02	1,33	1,65	2,05	2,29	1,37	1,86	2,58	1,83	1,51	1,27	2,15	2,06	2,24
7	0,93	1,21	1,38	0,98	1,45	1,29	1,14	1,33	0,98	1,54	1,79	1,33	1,05	1,26	1,95
8	0,83	1,21	1,27	0,98	1,31	1,28	1,06	1,33	2,02	1,35	1,51	1,61	1,25	1,79	1,50
9	0,78	0,95	0,94	0,85	1,45	1,20	1,39	0,99	0,84	1,57	1,51	1,44	1,48	1,79	0,88
10	0,58	1,04	1,19	1,04	1,43	1,02	1,32	1,52	1,19	1,09	1,25	1,18	1,27	1,01	1,49
11	1,73	1,21	1,33	1,65	1,82	1,99	1,60	0,99	1,29	1,90	2,06	1,37	1,78	1,17	1,02
12	1,46	1,21	1,99	1,65	1,15	1,22	1,57	1,82	1,19	1,09	1,09	2,07	1,66	2,91	1,82
13	1,42	1,85	1,78	1,60	1,56	1,98	1,72	2,11	1,48	1,01	1,84	1,45	2,11	1,95	2,29
14	1,55	1,22	1,56	1,84	1,45	2,29	1,69	1,33	1,52	1,36	1,98	1,81	2,30	1,63	1,56
15	1,56	1,21	1,33	1,01	1,24	2,05	2,18	2,16	0,85	1,14	1,51	1,22	1,43	1,34	1,81
16	1,42	1,21	0,90	1,17	0,51	1,46	0,63	0,63	1,29	1,01	0,69	0,79	0,76	0,73	0,85
17	1,18	1,73	1,45	0,97	1,08	1,67	0,62	0,56	1,22	1,11	1,46	1,37	1,48	1,17	1,20
18	1,01	2,20	1,45	1,82	1,06	1,43	1,69	1,52	2,04	2,09	2,08	2,11	2,43	2,06	1,22
19	1,93	1,22	2,01	1,65	1,24	2,02	1,72	1,64	2,29	2,09	4,54	2,07	2,43	1,79	1,19
20	1,24	0,36	1,81	1,06	1,44	1,09	0,23	0,61	0,40	0,25	0,25	0,47	0,41	0,49	0,49
21	2,08	1,21	0,95	1,28	0,48	1,26	0,84	1,14	2,53	1,14	1,78	0,49	2,57	1,26	0,88
22	0,96	1,47	1,06	0,96	1,69	-	-	-	1,83	1,50	1,62	1,67	1,52	1,82	-
23	0,62	0,40	0,78	0,85	0,56	1,20	1,14	0,84	1,40	1,14	1,16	1,61	1,13	1,23	0,83
24	1,35	0,71	0,69	0,40	1,06	-	-	-	0,98	1,74	1,75	1,05	1,49	0,20	-
25	1,32	0,20	0,60	0,85	1,52	1,29	1,32	1,13	1,06	0,95	1,36	1,37	1,27	0,12	0,75
26	0,82	1,01	0,95	1,04	1,24	1,11	0,84	0,79	1,29	1,11	1,06	1,27	1,54	0,93	1,08
27	0,94	1,59	2,36	1,17	1,32	1,10	0,84	1,35	1,40	0,85	1,51	1,07	3,10	0,08	0,88
EqualDM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
mean/q	1,11	1,10	1,23	1,13	1,23	1,28	1,08	1,13	**1,34**	1,23	**1,54**	**1,32**	**1,58**	1,23	1,11
Max dif	1,79	**2,00**	**2,14**	1,46	1,57	1,64	2,09	1,60	**2,18**	1,84	**4,29**	1,82	**2,70**	**2,83**	1,79

Table 45 Discrepancy analysis for fixed bridges

ID #27	Rel.Inf to total	Rel.Inf to realis.
Exp. 1	0,9829	1,066
Exp. 2	0,7785	0,7172
Exp. 3	0,9255	0,7964
Exp. 4	0,796	0,8357
Exp. 5	1,21	1,341
Exp. 6	1,766	1,791
Exp. 7	1,23	1,185
Exp. 8	1,145	0,8276
Exp. 9	1,084	0,8735
Exp. 10	0,9931	0,8257
Exp. 11	1,554	1,528
Exp. 12	1,498	1,376
Exp. 13	1,61	1,567
Exp. 14	1,594	1,509
Exp. 15	1,22	1,168
Exp. 16	1,029	1,132
Exp. 17	1,228	1,139
Exp. 18	1,648	1,371
Exp. 19	1,825	1,429
Exp. 20	0,7605	0,7844
Exp. 21	1,465	1,51
Exp. 22	1,299	1,072
Exp. 23	0,894	0,7634
Exp. 24	0,9845	0,9123
Exp. 25	1,03	1,119
Exp. 26	1,102	1,085
Exp. 27	1,165	0,8426
EqualDM	0	0

Table 46 Discrepancy analysis for movable bridges

ID#24	Rel.Inf to total	Rel.Inf to Realis.
Exp. 1	1,273	1,059
Exp. 2	0,7035	0,7177
Exp. 4	0,7703	0,8251
Exp. 5	1,345	1,32
Exp. 6	1,827	1,772
Exp. 7	1,274	1,198
Exp. 8	0,9893	0,8379
Exp. 9	0,9611	0,8852
Exp. 10	1,007	0,8407
Exp. 11	1,486	1,53
Exp. 12	1,464	1,392
Exp. 13	1,732	1,585
Exp. 14	1,59	1,527
Exp. 15	1,469	1,179
Exp. 17	1,052	1,132
Exp. 18	1,102	1,148
Exp. 19	1,415	1,39
Exp. 20	1,519	1,458
Exp. 21	0,7181	0,7735
Exp. 23	1,048	1,056
Exp. 25	0,9281	0,8931
Exp. 26	1,124	1,125
Exp. 27	1,036	1,077
Exp. 28	0,9167	0,8537
EqualDM	0	0

Table 47 Column with new relative information and discrepancy

ExpertID#	Calibration	Relative information total	Relative information seed	Relative information w/ DM	Relative information w/o DM
1	6,63E-05	1,31	1,377	1,01	1,066
2	1,75E-05	0,9909	0,8418	0,715	0,7172
3	0,02651	1,161	1,013	0,8368	0,7964
4	5,86E-07	1,049	1,093	0,7477	0,8357
5	5,86E-07	1,529	1,47	1,204	1,341
6	5,86E-07	2,045	1,975	1,706	1,791
7	2,31E-05	1,567	1,514	1,222	1,185
8	0,01644	1,432	1,11	1,061	0,8276
9	0,000144	1,373	1,192	1,048	0,8735
10	0,001547	1,302	1,129	0,9477	0,8257
11	1,79E-08	1,894	1,852	1,525	1,528
12	0,002029	1,835	1,591	1,533	1,376
13	3,72E-06	1,967	1,862	1,572	1,567
14	3,72E-06	1,861	1,729	1,531	1,509
15	1,75E-05	1,566	1,426	1,212	1,168
17	0,01566	1,274	1,107	1,05	1,132
18	6,63E-05	1,582	1,432	1,198	1,139
19	0,000144	1,972	1,743	1,547	1,371
20	6,63E-05	1,863	1,693	1,589	1,429
21	1,75E-05	0,7634	0,7584	0,8375	0,7844
22	1,29E-06	1,63	1,807	1,31	1,51
23	0,01644	0,8234	0,8412	1,232	1,072
24	0,01566	1,148	1,021	0,8309	0,7634
25	0,000576	1,093	1,026	0,9056	0,9123
26	6,63E-05	1,316	1,416	0,9926	1,119
27	1,29E-06	1,439	1,436	1,065	1,085
28	0,001547	1,21	1,02	1,007	0,8426
EqualDM	0,08041	0,2801	0,2188	0	0

Table 48 Robustness on seed items

Excluding item	Rel. Info/bg total	Rel. Info/bg realisation	Calibration	Rel. Info/or total	Rel. Info/or realisation
S_1	0,9882	0,7037	0,5539	0,3678	0,2174
S_2	0,8606	0,5955	0,6552	0,8763	0,7364
S_3	0,5309	0,4746	0,5332	0,4723	0,3209
S_4	0,8635	0,6717	0,6789	0,4723	0,3219
S_5	0,5828	0,5516	0,6789	0,6736	0,7079
S_6	0,8818	0,632	0,423	0,7598	0,5301
S_7	1,017	0,7231	0,5539	0,4271	0,2602
S_8	0,5709	0,5172	0,6789	0,6424	0,6334
None	0,5461	0,441	0,6876		

Table 49 Robustness on experts

Excluding expert	Rel.info/bg	Rel.info/bg	Calibr.	Rel.info/or	Rel.info/or
1	0,5445	0,441	0,6876	0,000163	0
2	0,5394	0,4284	0,6876	0,001169	0,002461
3	0,6358	0,4786	0,5405	0,2664	0,1562
4	0,5445	0,4372	0,6876	0,000146	0,000346
5	0,5377	0,4209	0,6876	0,002212	0,005255
6	0,5461	0,441	0,6876	1,01E-07	1,07E-07
7	0,5452	0,441	0,6876	0,000185	0
8	0,3753	0,3517	0,5338	0,3683	0,2883
9	0,5461	0,441	0,6876	0	0
10	0,5461	0,441	0,6876	0	0
11	0,5461	0,441	0,6876	4,51E-08	1,07E-07
12	0,5443	0,441	0,6876	0,000184	9,59E-09
13	0,5461	0,441	0,6876	0	0
14	0,5461	0,441	0,6876	4,04E-09	9,59E-09
15	0,5461	0,441	0,6876	0	0
17	0,539	0,4241	0,6876	0,000134	0,000318
18	0,5461	0,441	0,6876	1,62E-08	3,84E-08
19	0,5461	0,441	0,6876	5,90E-08	6,55E-09
20	0,544	0,441	0,6876	0,000258	0
21	0,5116	0,4322	0,6876	0,003406	0,000697
22	0,5442	0,441	0,6876	8,70E-05	6,55E-09
23	0,4852	0,3816	0,5338	0,5829	0,3741
24	0,5461	0,441	0,6876	0	0
25	0,5461	0,441	0,6876	0	0
26	0,5461	0,441	0,6876	0	0
27	0,5461	0,441	0,6876	0	0
28	0,5437	0,4353	0,6876	4,11E-05	9,77E-05
None	0,5461	0,441	0,6876	0	0

Table 50 ItemDM solution for fixed bridges

Id	5%	50%	95%	Real	Full Name
S_1	2,328	7,27	14,59	4	Brug 106
S_2	3,111	6,544	10	7	Brug 162
S_3	1,141	7,294	18,21	6	Brug 98
S_4	3,488	13,28	23,63	10	Brug 199
S_5	3,297	9,215	23,7	15	Brug 158
S_6	5,561	12,32	32,23	13	Brug 76
S_7	10,09	17,21	29	10	Brug 200
S_8	3,163	14,52	23,01	38	Brug 272
T_1	3,211	7,271	18,7		Railing maintenance
T_2	1,73	6,351	11,82		Asphalt wear layer
T_3	2,989	9,144	12		Asphalt top layer
T_4	9,066	16,2	19,99		Asphalt sub layer
T_5	3,41	11,96	19,81		re-Pavement
T_9	7,713	18,59	29,93		Concrete major overhaul
T_{10}	3,769	28,48	34,88		Wood major overhaul
T_{11}	3,836	27,37	34,91		Masonry major overhaul
T_{12}	1,374	11,48	28,21		Girders
T_{13}	3,15	22,58	29,95		Driving-iron
T_{14}	1,392	11,42	23,91		Joints

Table 51 ItemDM solution for movable bridges

Id	5%	50%	95%	Real	Full Name
S_1	2,172	5,926	9,954	4	Brug 106
S_2	3	5,477	10	7	Brug 162
S_3	1,046	2,717	18,67	6	Brug 98
S_4	3,133	8,921	24,26	10	Brug 199
S_5	3,101	6,503	24,31	15	Brug 158
S_6	5,374	17,11	34,07	13	Brug 76
S_7	10,23	18,06	29,59	10	Brug 200
S_8	6,284	17,25	23,78	38	Brug 272
T_6	2,415	17,7	24,9		Safety works
T_7	10,17	18,03	24,91		Electromechanical transmission
T_8	7,093	11,02	14,96		Hydraulic transmission
T_{15}	10,07	15	19,89		Closing installation