

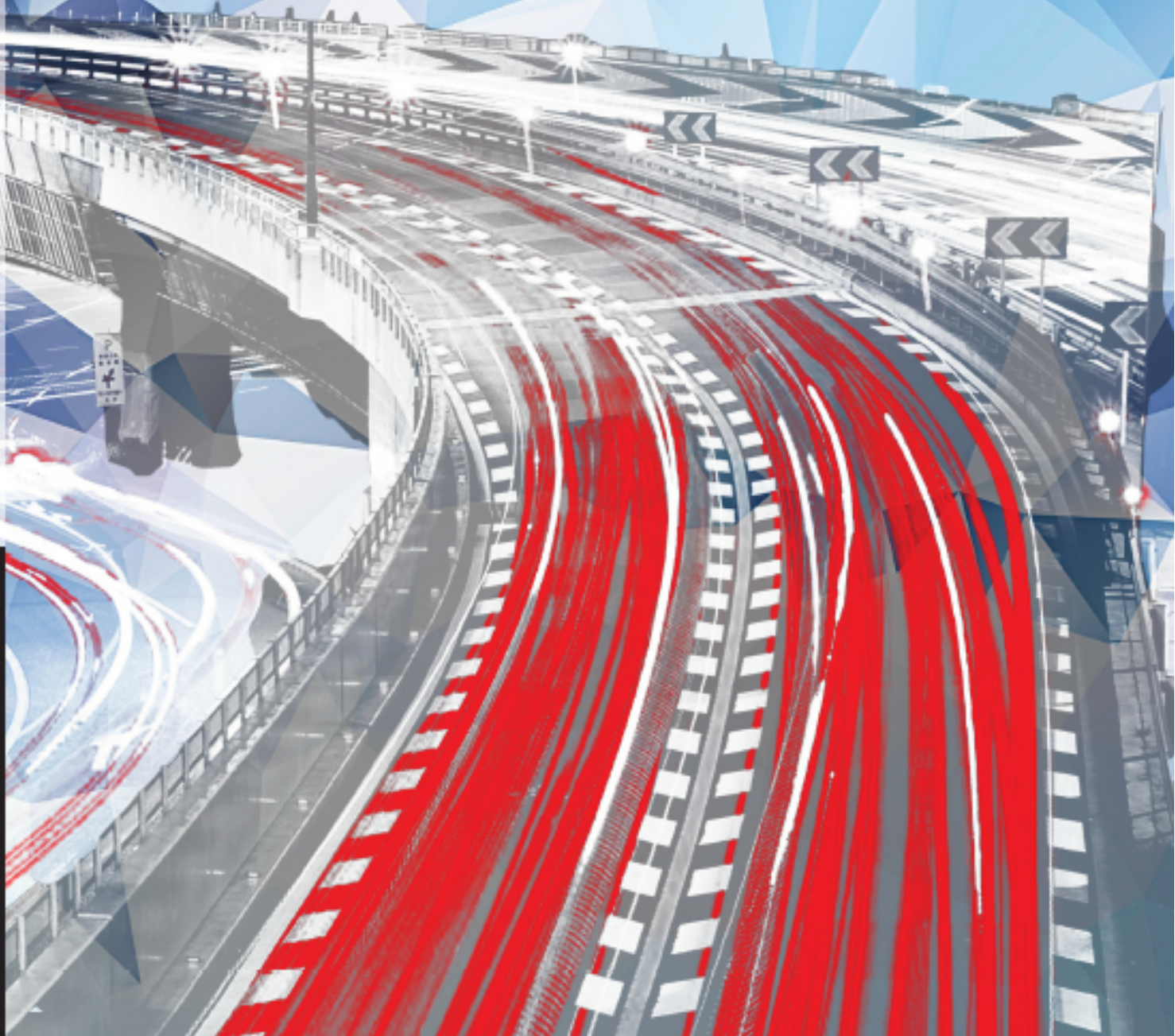
# THE USE OF NEW DATA SOURCES IN BRIDGE MAINTENANCE DECISION-MAKING

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MSc Construction, Management & Engineering

THE USE OF NEW DATA SOURCES IN BRIDGE MAINTENANCE DECISION-MAKING

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# THE USE OF NEW DATA SOURCES IN BRIDGE MAINTENANCE DECISION-MAKING

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ON THE EFFECT OF USING NEW DATA SOURCES DURING DECISION MAKING MOMENTS OF BRIDGE  
MAINTENANCE EXPERTS THROUGH A SERIOUS GAME BASED EXPERIMENT.

In partial fulfilment of the requirements for the degree of

Master of Science

Construction Management and Engineering

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By **Jasper Spiegel**

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Instead of drones flying with infrared and laser technologies to assess our infrastructure, ground personnel walks around in orange jackets with paper writing pads and rulers trying to figure out a crack's dimensions, or discussing upon the brownish-ness of a certain colour of corrosion.

How come there are opportunities within the next years for brain implant sensors that could take away a permanent spinal cord injury within the extremely complex and sensitive brain environment (Regalado, 2017), but we are not able to determine the condition of a thorough concrete static structure once every five years?



## ABSTRACT

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The current practice of bridge maintenance decision-making is informed by subjective visual inspection data with a long time interval between measurements, which creates inefficiencies and possible loss of value in the maintenance entity's capabilities. New opportunities from technology-related innovations for measurement devices are available for better-informed decision-making and for improved knowledge on the condition of a bridge. Even though, the adoption and use of these opportunities seems to be disregarded by the market and the main focus of innovation pushing organisations is mostly on the technical capabilities of these systems. This research presents a study on the effects of using technology-related opportunities on maintenance decision-making from a user-centric perspective. It performed a serious gaming experiment where bridge maintenance decision-making professionals were questioned to set up maintenance advices based on different types of data. No previous similar research was found through extensive literature search. Bridge deterioration scenarios were presented to experts throughout a within-subject fractional factorial experiment design. The experiment treatment groups consisted of data presentation from new innovative or potential bridge condition assessment mechanisms and the experiment control group consisted of the current data source, which is visual inspection. To observe the effects, the experiment used a quantitative and qualitative approach that considered expert judgement, maintenance decisions, and explanations of the experts for observing whether differences occurred between the different settings. It was indicated that significant differences were present if new data sources were added to the current visual inspection data, but no significant differences were observed between different types of data sources. It is expected that the differences are caused by the ability to observe quantified values of important performance indicators better, and that they provided indicative values that can be used during decision-making. It is expected that the latter described indifferences were caused by a lack of guidance by the market on how to use new data sources properly and consistently. These outcomes mean that for efficient and effective adoption of new data sources, more standards and guidelines about threshold values and causal links between deterioration parameters and possible deterioration causes are needed for practical guidance during maintenance decision-making. It suggests that in order to provide a broad facilitation for adoption of new data sources, long-term strategy behaviour must be considered by the market in order to provide a safe space for pilots and trials to learn about these innovations.

**Keywords:** Bridge Maintenance; Maintenance Decision-Making; Serious Game; Bridge Inspection; Condition Assessment Mechanisms; Impact of Innovation; Structural Health Monitoring (SHM); Wireless Sensors; Non-Destructive Evaluation Techniques (NDT)

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## SUMMARY

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The purpose of this thesis is to analyse the effects of using data obtained from technological advanced bridge condition assessment mechanisms during decision-making moments from bridge maintenance engineers, compared to only using visual inspection data. This research addresses a relatively unexplored research topic and could enhance the insights for the market about the usability and opportunities of new bridge condition assessment mechanism innovations. The thesis is composed of six chapters.

**Chapter One** is introductory and explains the lead to the research, the questions that will be answered by the research, the objectives, scope and method. The motivation for this research comes from ageing and deteriorating highway overpasses in the Netherlands that are in need of efficient and effective maintenance. Therefore, good maintenance decision-making is crucial. Current maintenance decisions are based on subjective and inefficient data from visual inspections, while new types of data from new innovative bridge condition assessment devices are becoming more and more feasible for usage in practice. Nevertheless, in practice, the adoption of these new data sources remains low and their usefulness for decision-making is often not known. In the scientific body of knowledge, current literature tends to focus primarily on the technical aspects of these systems and seems to be leaving research that could facilitate these systems into practice effectively aside. Existing literature suggests that more research should be conducted about the effects of using new data sources within current bridge maintenance decision-making in practice. The main research question that is used as red thread through the report and that will provide the answer on the above mentioned problem is as follows: *“What is the effect of introducing new data sources during decision-making moments on the maintenance advice from concrete highway overpass experts?”*. In order to come to the answer on the main research question, the research is divided and structured by five sub-questions of which the first three provide a theoretical foundation for the research model and form the literature body of knowledge, and the fourth and fifth research questions address the measured results from this research quantitatively and qualitatively.

**Chapter two** examines the theoretical framework of bridge maintenance decision-making. The maintenance of bridges can be described as a process that leads to the fulfilment of the safety and functioning of a bridge regarding its users during the full extent of its service life (Radomski, 2002). It includes, but is not limited to, works of inspection, repairs, rehabilitation, or replacements of the components that make up a full bridge’s asset system. In order to perform the right maintenance actions, good decisions must be made by maintenance decision makers (Cole, 2008). These decision makers are generally called asset managers, maintenance advisors, or maintenance engineers (Homeland Security, 2010; SBRCURNET, 2015). The mutual benefits for the stakeholders are found in minimising the risks at the bridge assets, while using as little resources as possible (Cole, 2008). The system operates by regulations from the law, contracts, scientific standards, or agreed processes and it uses data about the condition of the bridges as indicators to decide upon the most necessary maintenance interventions and at which moment in time to perform these interventions (Weykamp et al., 2010). The ability to translate these condition assessment data into the “correct” decision correlates significantly with the effectiveness and efficiency of the output of the system (Nicholas, 2015). Current opportunities for improvement of the bridge maintenance systems are to be found by learning from experiences and innovations in current processes, materials, or technologies (Bouwcoalitie,

2017). The Chapter continues with an explanation about the most occurring deterioration mechanisms within concrete, of which chloride-induced corrosion within bridge decks was chosen as main deterioration mechanism to focus further on, since this is considered to be a relevant deterioration mechanism in the Netherlands. Chapter two continues with a listing of possible condition assessment mechanisms that could observe the important deterioration parameters of chloride-induced corrosion damage. Visual inspection is identified as the current main data source. Furthermore, a categorisation is made between dynamic sensing systems that can measure the full extent of the concrete structure and need to be operated by personnel, referred to as *On-Site Sensing Systems*, and wireless or remote sensor systems that are embedded or placed at the structure and can monitor the bridge from a singular location, referred to as *In-Situ Sensor Systems*. Chapter Two continues with the expected uses of these new data sources, which are derived from literature review. By means of this review, a testable research model was designed. The research model tests the propositions between three constructs: it expected that new data sources have an effect on expert judgement and maintenance decisions, where expert judgement mediates effects on the maintenance decision as well.

**Chapter Three** starts with an operationalization of the construct research model into testable hypotheses. It breaks the constructs down into variables that can be identified or measured. An experiment method was chosen for testing the proposition and hypotheses in this research model. Through a within-subject experiment design with fractional factorial treatment, four experiment groups were compared that included four types condition assessment mechanisms. The experiment groups are as follows: visual inspection data are used in the control group, In-Situ Sensing Systems with chloride content & corrosion sensor data and frequency-based damage detection data are used as treatment group one, On-Site Sensing System with ground penetrating radar contour plots measured once are used as treatment group two, and On-Site Sensing System with ground penetrating radar contour plots measured every two years are used as treatment group three. The experiment was operationalized by theories of serious gaming in order to simulate the maintenance decision-making moments realistically, meaningfully, and playfully. The serious game was tested extensively and thereby improved iteratively until a feasible and viable experiment was obtained for measuring the effects.

**Chapter Four** includes the results. 17 participants participated in the experiment and were debriefed to explain the quantitative results in their context. The introduction of the more objective new data sources during maintenance decision making moments of concrete highway overpass experts, based on different deterioration phases and speeds from chloride-induced corrosion in concrete bridge decks, leads to a significant difference in maintenance advice when comparing this to the use of only less objective visual inspection data. The measured differences shown that larger and more direct actionable maintenance interventions were chosen, the maintenance was planned more urgent, risks levels were estimated higher, and the rest life was estimated shorter. Maintenance engineers were able to observe the deterioration progression by indicative parameters in earlier phases more quantitatively, and were thereby guided in their expert judgement and maintenance decisions. It seems to have caused them to behave more conscious and conservative in certain situations. These findings are also expected to be accountable for similar relatively slow progressing deterioration mechanisms as carbonisation or alkali-silica reactions, as explained by the participated experts, but this has not been examined further in this research. These significant differences are not observed when comparing the new data sources to each other. No significant differences were observed between the outcomes of

locally measured In-Situ Sensing System data and globally measured On-Site sensing system data, nor were there differences observed between non-frequent measured on-site data and more frequently measured On-Site data. The results are tested through post-hoc tests for more robustness, but no significant different conclusions were observed, except for one: during faster deterioration progression speed, the urgency of the maintenance grew higher for more frequently measured On-Site data. Furthermore, it is noticeable that the conclusions of the research are more evident during deterioration phases that are invisible to the bare eye, compared to visible deterioration to the bare eye. However, this needs to be investigated some more, since not enough power was obtained for significant results.

**Chapter Five** discusses the results by means of reflecting these to the found and used other literature. Since no previous similar research was found, the results are discussed with theories and expectations derived from the literature review. It seems that the results indicate that more preventive maintenance actions are advised when introducing new data sources during decision moments. There is a lack of knowledge on maintenance effectiveness, which makes the results hard to interpret in terms of good or bad. It causes an unclear answer on the effect of using new data sources in terms of an increase or decrease in loss of opportunity, since it only suggests that maintenance is performed earlier on in deterioration phases and thereby decreases the risks in the structure, but not the overall effectiveness.

**Chapter Six** concludes on the research by answering the main research question. It can be stated that the introduction of new data sources will affect maintenance decision making in such way that experts' advice upon more risk adverse maintenance. The maintenance decision-making experts were able to observe the deterioration parameters more objectively and quantitatively and used these as indicators for their decision. However, no differences were observed between the types of new data sources. The inconsistencies and indifferences between the effects of the new data sources are most likely caused by a lack of experience and a lack of guidelines on how to use these data sources. Experts explained that they generalised local measured data to the full structure of the bridge, because they did not have previous experience with new data sources beforehand. Also, more frequent measurements gave an indication of the progression speed of the deterioration, but the participants sometimes also used the more frequent measurements as consistency check to observe whether the measurement system was reliable (despite being informed that these were accurate, reliable, and consistent during the experiment). Having a lack of a reference point for the progression speed of deterioration by standards and guidelines caused the maintenance engineers to have to use their expertise to decide whether the deterioration was progressing slowly or fast. This likely resulted in more urgent maintenance planning due to seeing faster deterioration, but no other maintenance types or increased risks. For further research, it is recommended to broaden the boundary of the research model by including more deterioration mechanisms, multiple bridge components, and also other types of new data sources. Improved knowledge on deterioration and maintenance action effectiveness would benefit the bridge maintenance market tremendously in general. Serious gaming has proven to be applicable for measuring valid results and conclusions. It is important that more research is conducted to the adoption and integration of technical concepts or products into practice, since it also requires organisations to cooperate and create a safe space for innovation to happen.

# 1. INTRODUCTION

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The current bridge maintenance practice needs well informed decision-making for efficient and effective maintenance decisions. Innovations seem to be available for enhancing current practices with improved information. Nevertheless, adoption of these innovations seems to be disregarded. This chapter explains why and how this research is formed and performed and what is included.

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“IN THE ERA OF INFORMATION TECHNOLOGIES, THE POTENTIAL OF INFORMED DECISION-MAKING IS DISREGARDED” (ZONTA, GLISIC, & ADRIAENSSENS, 2014, P. 1044).

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## 1.1 BRIDGE MAINTENANCE AND ITS OPPORTUNITIES

Bridges deteriorate and need to be maintained for keeping them structurally safe and functioning (SBRCURNET, 2015). In the USA, the 40 years old I-35W bridge in Minnesota collapsed in 2007 with 13 casualties due to a faulty design that was incapable of holding the increasing weight that was applied by repair jobs over the years (Wald, 2008). In Europe, Italy, two viaducts collapsed within one year due to insufficient and wrongly applied maintenance methods, both collapses involved casualties and serious injuries (BBC, 2016; Squires, 2017). In the Netherlands, the Merwede Bridge had to be closed off for heavy traffic due to fatigue cracks in the steel main structure (Rijkswaterstaat, 2016b), leading to almost 15 million euro's economic loss for surrounding industries (Rijkswaterstaat, 2016b).

Therefore, bridge maintenance engineers must decide upon timely and effective interventions before such serious problems occur (Weykamp et al., 2010). According to Okoh, Schjøberg, and Wilson (2016) and Bogaard and Akkeren (2011), maintenance is performed during to the largest phase of a construction's life cycle and is regarded as one of the largest contributors for retaining value of the assets within Asset Management. Asset Management is broadly stated *"the coordinated activity of an organization to realise value from assets"* (IAM, 2014, p. 8). Hence, well-established maintenance decisions play an important role to the retaining of value of bridges, or even restoring of this value (Nicholas, 2014). After all, if bridges are maintained insufficiently or wrongly, the chance that a failure occurs increases (Radomski, 2002).

The Netherlands counts 2760 concrete highway overpasses and around 750 other bridges in its main-infrastructure system (Rijkswaterstaat, 2007). Most of these bridges and highway overpasses have been built during the 1970-1980's with a general life expectancy of around 70-100 years which means that a large sum of these highway overpasses will reach their end-of-service life in almost 15-30 years from 2007 (Rijkswaterstaat, 2007). On top of this, throughout the last decades, the frequency and weight of traffic that drives on these bridges has also increased, which makes qualitative maintenance even more crucial (Algemene Rekenkamer, 2014). The Dutch government has noted that maintenance and preservation is already the highest cost factor for the infrastructure sector and that it is likely that the national budget will not tolerate a great scale replacement of the ageing bridges (Algemene Rekenkamer, 2014). Instead, initiatives have been organised for creating uniformity and transparency about the current infrastructure assets (including bridges), in order to preserve them more diffusive (Bouwcoalitie, 2017).

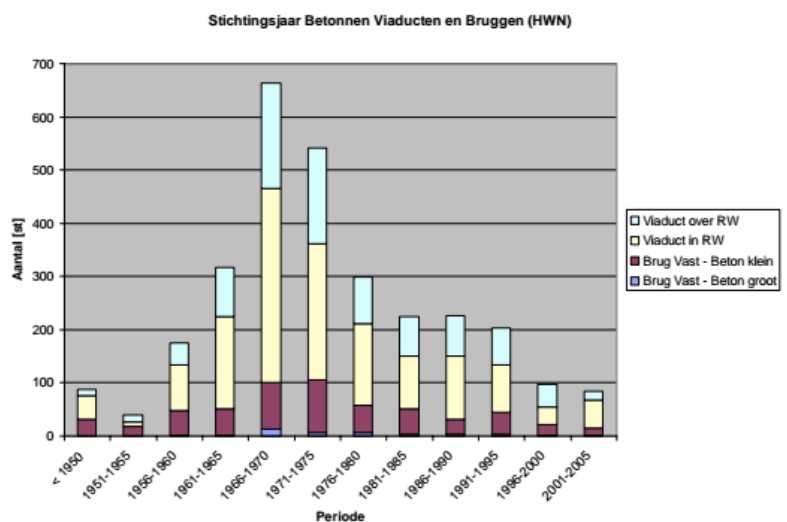


FIGURE 1. HISTORICAL DATA OF CONCRETE BRIDGE CONSTRUCTIONS (RIJKSWATERSTAAT, 2007, P. 31).



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### 1.1.1 THE IMPORTANCE OF KNOWLEDGE, INFORMATION, AND DATA

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Maintenance engineers that perform decision making use performance indicators of the bridge to come up with the right intervention (Miyamoto, Kawamura, & Nakamura, 2000). These performance indicators come as pieces of data or information from systems that can measure, observe, document, or calculate the condition of the bridge (Weykamp et al., 2010). These systems are referred to as 'condition assessment mechanisms' (Omar & Nehdi, 2016). It is up to the maintenance engineer to translate these indicators to maintenance actions as is required (Weykamp et al., 2010). However, it seems that the current decision making process is experiencing limitations in its potential due to inefficient knowledge, information and data management.

Firstly, when observing the distribution of knowledge about maintenance decision making, it is noticeable that in lots of cases the knowledge on how to preserve ageing infrastructure is centred around a small group of (older) employees and is not documented properly within an organisation (SBRCURNET, 2015). With a greying population, this might add up as increasing problem in this sector since this can create a loss of crucial knowledge (Interview Iv-Infra, 1-12-2016; SBRCURNET, 2015).

Secondly, the currently most used condition assessment mechanism, which is visual inspection, is limited in its capabilities (SBRCURNET, 2015). It is performed at an interval of averagely five years by a trained inspector that observes the bridge at 'within-hands-reach distance' and documents any found flaws or risk related items by documentation standards (Kallen, 2007; SBRCURNET, 2015). Current documentation standards and guidelines that are not as rigid and consistent as wished upon (SBRCURNET, 2015). This leaves the condition assessment of the bridge open for interpretation of the inspector and requires significant experience and expertise to provide qualitative information about the performance indicators of the bridge (Phares, Washer, Rolander, Graybeal, & Moore, 2004). Next to this, some deterioration mechanisms initiate from inside the structure, which makes them invisible to the naked eye until they have advanced into a more serious state. In general, there seems to be a lack of objectiveness and uniformity in the data that is generated from visual inspections (Gastineau, Johnson, & Schultz, 2009; Phares et al., 2004; Sanford, Herabat, & McNeil, 1999; SBRCURNET, 2015).

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### 1.1.2 THE OPPORTUNITIES OF INNOVATIONS AND DEVELOPMENTS

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Improvements in processes, equipment, materials, methods, and maintenance products can increase the overall productivity of the maintenance system by improving the service life of a bridge with less or a similar amount of resources (Weykamp et al., 2010). The need for improved knowledge about the current condition of the bridges and improved technologies that can measure the performance indicators of this bridge condition is increasingly heard throughout the market (Belzen, 2016; Rijkswaterstaat, 2016a; Weykamp et al., 2010).

Unsurprisingly, there is an increasing focus on techniques that measure the condition status of a bridge more easily, effectively, and/or efficiently than current methods (IBM, 2016). In fact, the possibility of using innovative condition assessment techniques for bridges has been proposed by researchers and engineers since the early 1940's (Wang, Lynch, & Sohn, 2014). Over the years, much of these techniques have already shown their potential by case studies in the field (Gastineau et al., 2009; Inaudi, 2010). These

measurement systems come in many forms and can measure a very broad range of bridge condition parameters (Wang et al., 2014). Terms as structural health monitoring, remote sensing, wireless sensing, civionics, or non-destructive evaluation techniques are highly representative in literature (Figueiredo, Moldovan, & Marques, 2013; Wang, 2014). Container terms as “Internet of Things (IoT)” and “Big Data” are increasingly heard within companies, and other markets provide opportunities for rapid technological advancements for these new measurement techniques (IBM, 2016; Iv-Groep, 2016). For example, IoT could enable maintenance decision-makers to monitor data about the condition status of a bridge remotely and real-time by applying wireless sensors to a bridge (IBM, 2016). Other technological innovations such as laser measurements systems, magnetic devices, or satellite photography enable maintenance decision makers for remote or more improved data extraction that can be used to determine the condition status of a bridge (International Atomic Energy Agency, 2002). The output data from these innovative condition assessment mechanisms is referred to as “new data sources” in this research and is discussed more thoroughly further in the report.

## 1.2 LIMITATIONS FOR INNOVATION ADOPTION

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### 1.2.1 PRACTICAL PROBLEMS

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On national level, Rijkswaterstaat (2016a) has initiated an innovation agenda in order to provide a platform from which new opportunities for maintenance practices, information management, and new data sources can be studied and made ready for adoption. Despite the addressed importance of such innovations and better informed decision-making, the use of New Data Sources seems to be disregarded in current Bridge Asset Management (Figueiredo et al., 2013). New technologies are not widely adopted and early adoption pilots seem to be insufficient to convince the market (Figueiredo et al., 2013). According to Zonta et al. (2014), this can be explained by a general sense of scepticism regarding the use of new data sources from decision-makers, which creates the following paradox: *“in the era of information technologies, the potential of informed decision-making is disregarded”* (Zonta et al., 2014, p. 1044). While it is acknowledged by the market that the current source of information, namely visual inspection, is also limited in its capabilities (SBRCURNET, 2015).

Some studies suggest that there is a need for familiarisation with the technologies to be able to convince their usefulness to the market (Figueiredo et al., 2013). However, no asset owner wants to increase the risks in their asset portfolio or have increased costs by trying out new measurement systems (Figueiredo et al., 2013). Increased knowledge on why, when, and how to apply these technological innovations, and what their methods of measuring and limitations are, could benefit the maintenance market by providing more insights in the usefulness and possibilities of new data sources (Kuckartz & Collier, 2016).

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### 1.2.2 THEORETICAL KNOWLEDGE GAP

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It is noticeable that most of the current literature about new data sources only focuses on technical progression of the condition assessment mechanisms without taking the full maintenance process or end-user into account (Zonta et al., 2014). Research regarding new data sources that is performed throughout a user-centric perspective could be beneficial and result in a great leap forward for creating a (literal) bridge between scientific body of knowledge and the existing market (Kuckartz & Collier, 2016).

However, after an extensive scan of literature, not much literature was found that addressed the topic of how new data sources affect current decision making, though, the need for such research is mentioned by other literature (Braaksma, 2016; Figueiredo et al., 2013; Malings & Pozzi, 2016; Zonta et al., 2014).

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### 1.2.3 PROBLEM STATEMENT

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Highway Overpasses in the Netherlands are ageing and deteriorating and are in need of qualitatively good maintenance. Thereby, good maintenance decision-making is crucial. Current maintenance decision-making processes rely on the subjective and inefficient data source visual inspection, while new types of data from new innovative bridge condition assessment devices are becoming more and more feasible for usage in practice. Nevertheless, in practice, the adoption of these new data sources remains low and their usefulness for decision-making is often not known. In the scientific body of knowledge, current literature tends to focus primarily on doing research on the technical aspects of these systems and seems to be leaving research that could facilitate these systems into practice effectively aside. Existing literature suggests that more research should be performed towards the effects of using new data sources within current bridge maintenance decision-making in practice. This would address a relatively unexplored research topic and could enhance the insights for the market about the usability and opportunities from new bridge condition assessment mechanism innovations.

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## 1.3 RESEARCH QUESTIONS

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This research addresses the above-mentioned problem by analysing the following topics: 1) Do new data sources have an effect on maintenance decisions? And; 2). What does this effect mean? The main research question is the red thread through the thesis and will provide the answer on the problem is as follows:

*“What is the effect of introducing new data sources, during decision-making moments, on the maintenance advice from concrete highway overpass experts?”*

In order to come to the answer on the main research question, the research is divided and structured by five sub-questions. The first three questions provide a theoretical foundation about the status of the current bridge maintenance practice and to form the literature body of knowledge. The fourth and fifth research questions address the measured results from this research quantitatively and qualitatively.

1. *What does the current bridge maintenance decision-making process look like?*
2. *What condition assessment mechanisms can measure the deterioration parameters of concrete bridges?*
3. *What are the expected effects of introducing new data sources in current bridge maintenance decision-making?*
4. *What are the measured effects of using new data sources during maintenance decision-making moments?*
5. *How can these measured effects be explained?*

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## 1.4 RESEARCH OBJECTIVES

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As primary objective, this research assesses whether there is an effect of using new data sources on the decision-making behaviour of maintenance engineers.

Secondly, it observes the direction of this effect. Both of the before mentioned objectives will be achieved through quantitative and qualitative analysis.

As a third objective, the research aims to provide a better understanding of the current technological readiness of the new data sources and the available technologies for the bridge maintenance market. The research aims to induce an understanding by experts about possible developments, future processes, and possible future scenario's, because these subjects must not only be spoken of within the walls of already innovating facilities like universities. It must also be presented to the market for a thorough review for their usefulness and for valorisation.

The objectives aim to create an understanding of the usefulness of innovations for maintenance decision-making regarding highway overpasses. Their aim is not to advice to organisations to invest in these innovations.

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## 1.5 SCOPE OF THE RESEARCH

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This research can be considered as study on the translation from technology-related opportunities into a user-centric perspective of their usefulness.

Asset management is considered as balancing risks, costs and time towards an optimal equilibrium and focuses on the full lifecycle of an asset. Maintenance is a part of this process and is mainly performed during the operations phase of the asset. This research only focuses on this maintenance phase. Within this phase, the 5-yearly maintenance decision-making moments are within the scope of this research.

Furthermore, the critical components of concrete highway overpasses in the Netherlands with their most common deterioration type are considered because these are most relevant in practice; it primarily involves the bridge deck with chloride-induced corrosion (see chapter 2 for explanation). Other deterioration types and possible new data sources for measuring these will be also listed but not included in the main body of the research. Secondary elements as lightning systems, guardrails and expansion joints will not be included in this research.

The effect will not be measured through use of real bridges and real bridge condition assessment mechanisms, since there was a limitation in time and resources for conducting such extensive research. Instead, this research will obtain its results by simulating reality into a feasible experiment and performs this with real world maintenance experts. Theoretical frameworks are used to design this experiment for creating validity and reliability.

A measured effect on maintenance advice can be briefly described as a change in the maintenance advice that an expert would give during certain situations where a bridge needs to be maintained, when he bases his decisions on different types of data. In other words, an effect is observed when bridge maintenance experts change their maintenance advice regarding the structural safety and capacity of a bridge due to using new data sources instead of only using current data sources, while the situation to be advised upon has not changed.

The current data source comes from visual inspection reports. The new data sources that will be compared to the use of visual inspection reports are selected by their applicability for the Dutch bridge maintenance market. Despite that some of the innovations are not one hundred percent ready for practice; this research assumes in the simulation that the selected innovations are fully working properly. The ones selected are: In-Situ chloride & corrosion sensing systems, In-Situ frequency based damage detection sensing systems, and On-Site ground penetrating radar systems. The selection and description of these data sources is included in chapter 2. Some of the sensing systems

Lastly, the measured effect will not include monetary, process, or aesthetics oriented aspects, since these influence the maintenance decision-making by other means than the bridge's condition status itself and thus have no direct relation to the effects of using new data sources in this context.

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## 1.6 RESEARCH METHOD

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### 1.6.1 RESEARCH THEORY

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This thesis report is structured by chronologically answering the research questions, which is a method proposed by Elling, Andeweg, de Jong, and Swankhuisen (2005) as is illustrated in Figure 2. The first three questions form the theoretical framework of the research and create a foundation for the research model. It is chosen to elaborate thoroughly on the current situation and existing practices of bridge maintenance since it is of importance to



understand what the exact boundary of the research model is, in order provide clear and consistent conclusions on the main question.

During the research period, literature is used in cooperation with unstructured interviews with experts on the subject. Literature was (mostly) obtained from the university library and Google scholar. The experts were situated at the company from the internship of the researcher and at the university where this research was fulfilled. The information from both sources is used to enhance each other and for validation, since some information that is available in practice was not available in literature and vice versa.

The first research question provides an overview of the current bridge maintenance decision-making practice. A systems engineering framework that is proposed by Wasson (2006) is used to structurally list what aspects comprehend the total bridge maintenance system and how the decision-making process enables its capabilities. The content and aspects of this model are obtained from literature and are reviewed through unstructured interviews for reality check.

The second research question is used to structure and list the new data sources and their capabilities towards measuring deterioration. For listing the types of deterioration in bridges and for finding new data sources, literature and conference papers are used that focus on relevant deterioration mechanisms and state-of-the-art condition assessment techniques.

The third research question is answered through a literature review as it is described by Webster and Watson (2002); by identification of relevant literature, structuring reviews, and evaluation of theories. This will denote current ideas on the usefulness of the new data sources and aims to provide a current view on the expected impact from main research question. Thereby, a foundation is created for setting up a research model that can be tested with the experiment.

The thesis proceeds with the research model that is designed through theories from Bacharach (1989). It uses constructs and propositions to state abstract relations that could give a conclusion on the research question. The constructs used in this research are 'new data sources', 'expert judgement', and 'maintenance decision making'. Each of these can be further divided into identifiable or quantifiable variables, in order to operationalize a measurable relation between these; the hypotheses.

The results for testing these hypotheses will be obtained by performing a field experiment that uses maintenance advice as output, based on different types of presented data as input. Thus, experts will perform their maintenance decision-making based on different types of data during different decision-making moments from the lifecycle of a concrete bridge deck. This method was chosen for the following three reasons: 1) as described in the scope, this research does not have the resources to perform real world tests. 2) Since new data sources are not broadly adopted yet, case study analysis was not applicable for this research. 3) Conducting interviews could result in conclusions that could be biased by subjectivity from both the interviewee and the interviewer.

The experiment is considered as a field experiment rather than a true experiment, since the aim of this research is to provide realistic conclusions (rather than creating a fully controlled environment with less external validity)(Shuttleworth, 2017). Though, in an attempt to minimise any confounding variables, the experiment will use a within-subject

design where the same participant performs all treatments (Seltman, 2012). This design method minimises any differences that normally could be present between participants, such as: expertise, experience, or personal based preferences (Mead, 1988).

The treatments will be created throughout a factorial design of experiments (Mead, 1988). However, some combinations of variable levels are unnecessary for the scope of this research. This is why a fractional factorial design is used, which enables the research to 'filter' the most interesting combinations of variables and thereby create more resource efficiency in the experiment process (Mead, 1988).

The simulation experiment uses 'serious gaming' theory to define a measurement tool and for operationalization of the experiment (Harteveld, 2011). By using a digital environment for setting up this 'serious game', a structured method is introduced that makes sure that every participant experiences the same treatments, briefings and decision-making moments. The serious game was tested with students, professionals, and finally with experts on the research' subjects for improvement by design iterations.

The measured quantitative output from the serious game will be statistically analysed throughout a defined statistical test and by using SPSS software (IBM, 2015).

The qualitative output will be obtained through the debriefing framework of Hoogen, Lo, and Meijer (2016), which evaluates the validity, reliability, and generalizability of the experiment and serious game with the participants and also discusses possible future directions for the research or market from their point of view.

The quantitative and qualitative findings will be combined into a final result on the propositions from the research model. A post-hoc test is performed to assess the robustness of the results and to exclude the possibility of unnoticed observations from the measured data that could provide for new insights to the discussion.

The discussion reflects the results of the analyses and the post-hoc tests on the used literature and theories from the first three research questions. Finally, a conclusion is given together with the research' implications, limitations, and recommendations for further research.

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## 1.6.2 RESEARCH OUTLINE

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In Chapter two, a theoretical foundation is presented that forms the body of knowledge for the research. First, the existing situation of bridge maintenance as a system entity is presented with the decision making process. Then, the types of deterioration in highway overpasses are documented and the main deterioration type in the Netherlands, namely 'chloride induced corrosion', will be analysed more thoroughly in order to examine its main characteristics and parameters. It proceeds with an explanation of the types of condition assessment mechanisms that are used now and that are addressed as being innovative. The chapter finalises with a cause-effect model that forms the proposition and proposed theory of the research in more approximated and general lines.

Chapter three starts with the immediate translation of the constructs and propositions into a testable research model with variables and hypotheses. It then explains the boundary of this research model by a selection of controlled variables. This chapter then continues with the experimental design that can test the results of the hypotheses from the research

model. It starts by describing experiment theories and elaborates on the experimental design and processes. It proceeds with the operationalization of these elements into a 'playable serious game' for the participants that can obtain the quantitative data for analysis.

Chapter four describes the results and observations of the experiment. It starts with the quantitative statistical analysis and will thereby test the hypotheses. After this, the qualitative analysis will be presented as summary of the debriefing interviews.

Chapter five will provide a discussion about the interpretation of the found results from the quantitative and qualitative analyses and aims to bring both together into a final conclusion. A post-hoc analysis is performed for observing the robustness of the found results and the implications and limitations of the research method will be discussed.

Chapter six includes a short recapture of the research and gives the final answer to the main research question. It will also discuss the implications of the research findings and brings these findings back into theoretical perspective. It will do so by referring to the literature study presented in chapter two.

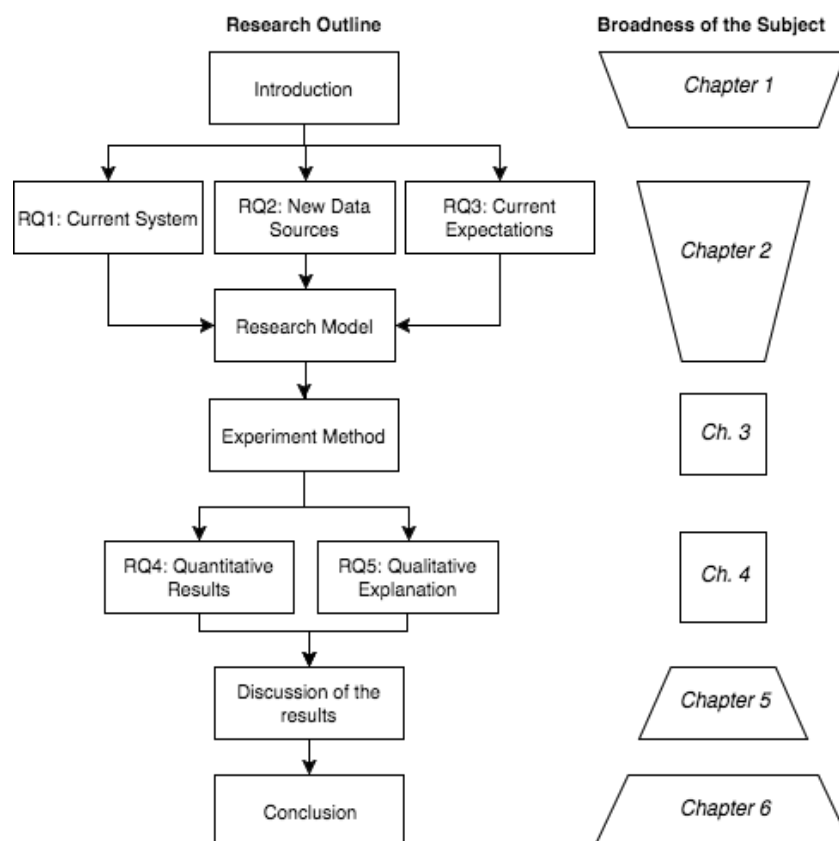


FIGURE 2. RESEARCH OUTLINE, STRUCTURE, AND SUBJECT BROADNESS OF THE CHAPTERS

## 2. THEORETICAL FRAMEWORK OF BRIDGE MAINTENANCE DECISION-MAKING

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A theoretical foundation is presented about the current bridge maintenance practice. Current methods are described and possible new measurement technologies are investigated for their usefulness in these current methods. The chapter finishes with the proposed research model.

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"IN THEORY THERE IS NO DIFFERENCE BETWEEN THEORY  
AND PRACTICE. IN PRACTICE THERE IS." – YOGI BERRA

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## 2.1 THE CURRENT BRIDGE MAINTENANCE SYSTEM

The following section elaborates on the first sub question of the research “What does the current bridge maintenance decision-making process look like?” by defining the bridge maintenance system through a structured framework proposed by Wasson (2006). In the first part of his book, Wasson (2006) systematically describes how every process, organisation, or abstract entity can be decomposed, structurally analysed, and presented in a system entity diagram. The example system entity is illustrated in Figure 3.

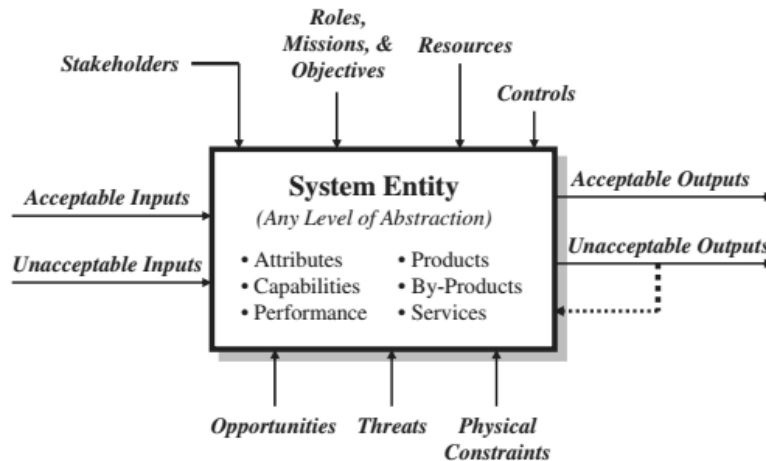


FIGURE 3. CONCEPTUAL SYSTEM ENTITY FRAMEWORK BY WASSON (2006, P. 22)

The middle square (the “black box”) is the system entity’s mechanism of processes that create the capability of this entity (Wasson, 2006). These capabilities are influenced by the attributes surrounding the square. The attributes will be briefly described below and are extensively listed in Appendix I.

### 2.1.1 STAKEHOLDERS, ROLES, MISSIONS & OBJECTIVES

The mission of the bridge maintenance system is to keep the infrastructure constructions safe and functioning within the limitations of the available budget (IAM, 2014). The main role of the bridge maintenance system is to assess the infrastructure in its condition and safety and to decide upon the necessary maintenance interventions at crucial moments (Nicholas, 2015). Objectives to be achieved for this mission are related to the retaining of the required safety for the users, the structural capacity of the constructions, the functioning of the assets, and the aesthetics of the assets (Bogaard & Akkeren, 2011).

The main stakeholders that are involved in the decision making process are the asset owners, the contractors that perform the maintenance, and the engineering consultants that aid in assessments and necessary maintenance actions (Tsang, 2002). Contractors generally perform maintenance on a contractual basis, which includes the cleaning and smaller observations for bridge condition assessments and preservation of (not unimportant) secondary elements such as guard rails, expansion joints, asphalt, drainage systems, or electrical systems (Phares et al., 2004). Engineering consultancies assist in the decision making process if additional expertise is required.



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### 2.1.2 RESOURCES & CONTROLS

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In order to achieve the objectives of the bridge maintenance system, monetary resources are one of the primary drivers for bridge maintenance interventions (Nicholas, 2015). Next to this, time is considered as a resource because it is generally related to resource allocation, it determines the availability of the bridge for its users, and it is used as an indicator of the urgency of the maintenance interventions (Nicholas, 2015).

Historical data is important because it includes design and construction documents that can specify the bridge's construction method into detail, but historic data can also provide information about the previous condition statuses of the bridge component for reference (Bridges Working Group, 2002).

The controls for the maintenance system are determined by contracts between the stakeholders. Most of these contracts determine the scope of the maintenance projects and how risks are allocated to the involved parties (Tsang, 2002). There is a difference between fixed and variable maintenance contracts. Fixed maintenance contracts require a contractor to superficially observe the condition state of the bridge by short site visits every year (SBRCURNET, 2015). The contract generally includes the performance of small maintenance actions, such as cleaning the bearings and expansion joints, sweeping the deck, and unclogging the drainage system (SBRCURNET, 2015). For variable maintenance contracts, there is a significantly larger inspection at the bridge that focuses on the actual structural condition state (SBRCURNET, 2015). This is averagely performed once every five years (Kallen, 2007).

Further controls of the maintenance process come from standards, guidelines, and working methods like ISO55000, NEN-2767, or CUR-SBRNET 117-115 and have the purpose of bringing uniformity in processes and documentation, and thereby providing quality to the maintenance and data collection system (NEN-2767, 2016; Okoh et al., 2016; SBRCURNET, 2015). Finally, there are control documents about general laws of deterioration in bridges that may provide the minimum requirements for keeping the structure safe and sound (Rijkswaterstaat, 2015).

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### 2.1.3 INPUT

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The input of the maintenance system consists of data about all obtainable relevant parameters that could determine or make up the condition status of a bridge and data that contain criteria towards the assessment of the bridge. This data could be obtained by condition assessment mechanisms that measured these parameters or by observing historical data about the bridge (Hesse A, Atadero R, & Ozbek M, 2015; Homeland Security, 2010) and are further explained in paragraph C. Condition Assessment Mechanisms

The criteria for decision-making come from the controls of the system: contracts, guidelines, and deterioration laws (which are general statements, threshold identifications and other standards that can be used to determine the amount of deterioration or its impact on a structure). Other inputs could be from new insights or knowledge from external sources, or from relevant aspects within the scope of the projects.

Sometimes, data about the condition status of the bridge is insufficiently documented or unknown (Campbell, Perry, Connor, & Lloyd, 2016). This is unacceptable for the bridge maintenance system to function up to its full capabilities (Hesse A et al., 2015). Unrealistic

requirements regarding costs, time, or risks from contracts could also hamper the system's capabilities and output quality (Hesse A et al., 2015).

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#### 2.1.4 OUTPUT

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Output from the maintenance system mainly consists of the maintenance intervention itself. The capabilities of the bridge maintenance system can be described in the effectiveness and efficiency of these maintenance interventions, which means that the intervention is in-time, effective, and within limits of available resources (Radomski, 2002).

Furthermore, it is important to gradually update any database regarding the condition data of a bridge for future usage together with an update of planning and budgeting plans (IBM, 2013).

Communication is also listed as output from this system, since it is also important to attain transparency for all involved stakeholders from the system (and beyond)(Algemene Rekenkamer, 2014).

Unacceptable output would be the opposites of the above-mentioned output: no effective maintenance interventions, no database updates, or no communication transparency.

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#### 2.1.5 THREATS & PHYSICAL CONSTRAINTS

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As the Dutch Ministry of Infrastructure already concluded (Algemene Rekenkamer, 2014), there is a limited budget for the maintenance of all infrastructure assets in the Netherlands. This could form a serious constraint and even a threat to the capabilities of the maintenance system. Further constraints could come from inefficiencies in the currently used methods, processes, and existing data infrastructure.

There is a high chance of human error in the maintenance system's processes, since much of the output of the system is based on experience and expert-judgements (Zonta et al., 2014). Next to this, the actual effectiveness of the maintenance types themselves is sometimes not known (Figueiredo et al., 2013). Finally, external threats from the environmental situation at the bridge can also form a threat (unforeseen events such as earthquakes, terrorist attacks, flooding, or e.g. black swans) (Radomski, 2002).

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#### 2.1.6 OPPORTUNITIES

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According to a research from Homeland Security (2010), there are lots of opportunities available for the current bridge maintenance system. Tsang (2002) divides these into process-related and technology-related opportunities. Rijkswaterstaat (2016a) addresses in its innovation agenda that for the maintenance of infrastructure, there must be focus on opportunities that are process-oriented (e.g. agile, lean, or six-sigma), condition assessment mechanism-oriented, data infrastructure-oriented, and knowledge-oriented. In the further development of this chapter, opportunities for condition assessment mechanisms are observed and listed.

### 2.1.7 THE “BLACK BOX”: BRIDGE MAINTENANCE DECISION-MAKING

The “black box” of the systems entity represents the maintenance decision-making process of the bridge maintenance system. This process uses the input information to translate this into actual maintenance actions as output of the system entity. In this research, the decision making process will be explained by means of several used literature documents and through unstructured interviews with maintenance engineers operating in the field. A flowchart of the decision-making process is illustrated in Figure 4 (Cole, 2008, p. 137; Interview Iv-Infra, 1-12-2016, 16-01-2017, 19-12-2016; Interview TNO, 23-12-2016; Interview Vergoossen, 20-01-2017; Malings & Pozzi, 2016, p. 81; Radomski, 2002, p. 87).

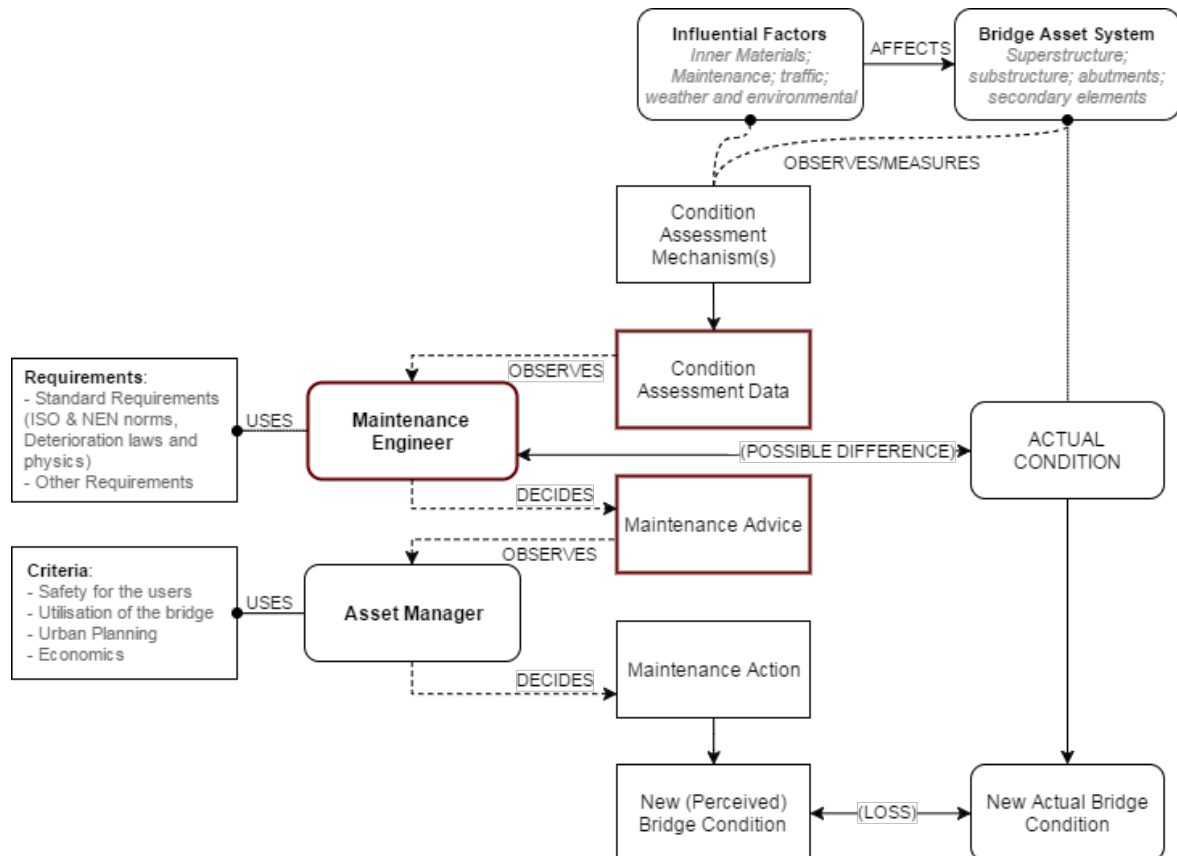


FIGURE 4. BRIDGE MAINTENANCE DECISION MAKING FLOWCHART, THE RESEARCH' FOCUS IS INDICATED WITH RED THICKER LINES

The conceptual model of Malings and Pozzi (2016, p. 81) shows how influential factors may affect the physical and chemical properties of one (or more) of the bridge components, causing them to deteriorate. The properties and characteristics of these bridge components that can describe this on-going deterioration process are referred to as “deterioration parameters” (Morcoux, Lounis, & Mirza, 2003). By using a condition assessment mechanism, the decision maker creates the ability to retrieve a set of data about these deterioration parameters (Al-Ostaz, 2004).

Unfortunately, no feasible or available condition assessment mechanism can (yet) attain or measure all the parameters of all the bridge components. This creates an unfortunate situation where the decision maker can only observe a subset of parameters (Malings & Pozzi, 2016).

Due to this limitation, a possible difference between the observed condition state of that bridge component and its actual real life condition state could be present (Malings & Pozzi, 2016). The difference can result in an ineffective or inefficient maintenance decision by creating a mismatch between what intervention is actually necessary for retaining or restoring the value of the bridge component, and what has been decided by the maintenance engineer as best maintenance intervention to be performed in the end (Malings & Pozzi, 2016). This mismatch can be referred to as “loss” (meaning: a loss in the maximum possible value that could have been captured by intervention)(Malings & Pozzi, 2016). Maintenance engineers and scientists strive to find ways to reduce this loss as much as possible, but this is very hard since it cannot be expressed properly without knowing all relevant deterioration parameters (Malings & Pozzi, 2016).

After the condition assessment data is produced, a maintenance engineer (or specialist) observes the data and forms a maintenance advice for which the system control attributes provide guidelines for decision-making. The maintenance engineer sometimes also uses historical documents such as old inspection reports or design and construction documents (Interview Iv-Infra, 16-01-2017). The control attribute provides the requirements regarding the structural capacity, safety, and durability of the bridge (Interview Iv-Infra, 16-01-2017; Krauss, Lawler, & Steiner, 2009).

Finally, the maintenance advice is communicated to an asset manager, who checks whether the advised maintenance interventions can be ‘fitted’ into the criteria of budget and time schedule within the full portfolio of infrastructure assets to be maintained by the organisation (Interview Rijkswaterstaat, 20-04-2017). The asset manager also uses criteria from the own organisation or other involved stakeholders to assess whether the bridge fulfils the required aesthetics, functionality, or urban planning of the surroundings (Radomski, 2002). In the end, the manager determines which maintenance action will be performed.

This research focuses on the effect of using new data sources during the decision-making moments based on the five-yearly inspections. It includes the first level of interaction with the retrieved data from the condition assessment mechanisms and the translation of this data into a maintenance advice. The final decision by the asset manager with the definitive maintenance action is not included, since this is based on other requirements that do not directly relate to the effect of using new data sources on maintenance decisions regarding interventions for keeping a sufficient structural and durable condition status of the bridge components, but merely provide a framework of criteria in which the technical maintenance advice needs to be “fitted” (Interview Vergoossen, 20-01-2017).

#### MAINTENANCE ADVICE - OUTPUT

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It is the task of the bridge maintenance system to perform interventions that counter deterioration of a bridge and that can retain the condition status of a bridge above the required threshold level. The deterioration of a bridge component can be visualised in a condition curve as in Figure 5 (NEN-2767, 2016). This curve illustrates how a condition status of a bridge component decreases incrementally overtime. When the condition curve reaches a certain threshold value, it is regarded as failure.

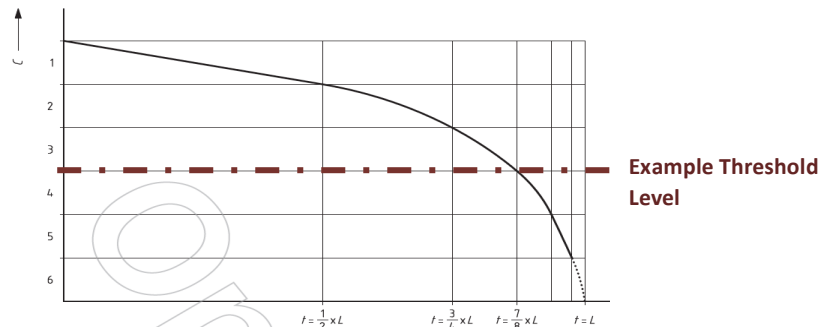


FIGURE 5. THE CONDITION CURVE OF A BRIDGE COMPONENT, ALTERED (NEN, 2016, P. 17)

Several types of actions can be distinguished that have different kinds of influences on the condition curve. At the most basic level, the type of maintenance can be generally divided into 'doing nothing' or 'doing something' (Radomski, 2002). More specifically, 'doing something' can be further divided into types of interventions (Radomski, 2002; Rijkswaterstaat, 2015):

Firstly, a **more detailed or additional inspection** can be requested if there is not enough information about the condition status of the bridge or if it is unsure what has caused the deterioration to happen. Operational actions for detailed inspection could comprehend (but are not limited to) core-tests, spectroscopy, impact-echo, structural capacity calculations, or load-tests (Radomski, 2002). Deciding to perform a more detailed inspection will not directly have an influence on the condition status of a bridge system and is generally not wished upon due to the necessity of having to use more resources (close the bridge off an extra time, additional time needed, additional personnel to be operationalized, equipment costs). However, it can prove to be very useful to determine the correct maintenance action to be performed later on (Interview Iv-Infra, 16-01-2017).

Secondly, **preventive or preservation maintenance** can be advised to preserve and conserve the component to decrease the progression speed of any deterioration (Krauss et al., 2009; Radomski, 2002). Operational actions mostly consist of (but are not limited to) (re)applying protection seals onto the concrete, cleaning parts or components, or renewing paint layers (Hong & Hastak, 2007). When illustrated into a deterioration curve, it decreases the steepness of the slope.

Thirdly, rehabilitation of the component will bring the condition to an improved condition state but does not fully take away the deterioration symptoms (simply put: **repair or corrective maintenance**) (Radomski, 2002). It consists of actions such as the (re)application of concrete onto a section, injections of concrete into cracks, or the strengthening of bridge components towards its load carrying capacity (Hong & Hastak, 2007). When illustrated into a condition curve, the condition curve will retain its current slope but increase with a certain value.

Finally, **replacement** can be seen as the most extensive maintenance action (Bogaard & Akkeren, 2011; Radomski, 2002). It simply consists of replacement of the deteriorated bridge component and is most likely chosen as maintenance when the deterioration is considered irreversible and too risky, or when the component does not function anymore for its intended purpose. This intervention would reset the condition curve towards its starting point (or to an even better level when improved). An example of the service life cycle with the explained maintenance interventions is conceptually illustrated in Figure 6.

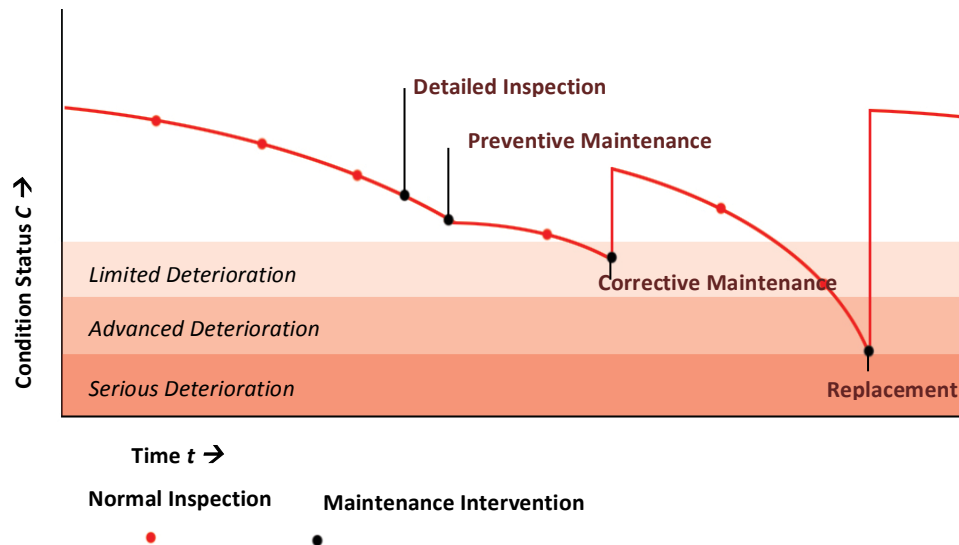


FIGURE 6. EXAMPLE MAINTENANCE INTERVENTIONS CONCEPTUALLY VISUALISED IN A DETERIORATION CURVE (OWN FIGURE)

Next to the required maintenance type, there are some other aspects that are included in the output of a maintenance advice. One of these aspects is the urgency of the maintenance action, which is mostly specified in years (Interview Iv-Infra, 16-01-2017). Based on this urgency, the asset manager can schedule the required maintenance interventions and prioritise the required interventions over the years.

Another aspect that is included in a maintenance advice is the risk level of the bridge component (Bogaard & Akkeren, 2011). Risk is used to give more criticality and bring attention to the critical bridge components for future maintenance and inspection actions regarding that particular component (Bogaard & Akkeren, 2011). This indicates something different than the condition status because a bridge can be deteriorated (thus have a low condition status) but if the deterioration is at points where it forms no risks towards the end-user, its risk can still be described as less significant (Bogaard & Akkeren, 2011; Thompson, Sobanjo, & Kerr, 2013).

Some organisations also estimate the rest life of the bridge during maintenance advice (Interview Iv-Infra, 16-01-2017). A lot of research is performed on improving deterioration curves and making standard curves for all types of bridges and their components. However, in the market these complex models are not used very often since every bridge is considered as unique structure with a deterioration speed that may vary due to many variables (Interview TNO, 23-12-2016). Therefore, the estimation the rest life of a bridge is mostly used in the field between engineers as indicator of a person's mind-set towards that bridge and its future condition (Interview Iv-Infra, 16-01-2017).

### CURRENT DECISION MAKING LIMITATIONS

The current decision making process has some limitations. There are no standard recognised procedures for organisations that form a framework for decision-making. There are standardised decision models available from literature, but these seem to be disregarded in practice (Bouwcoalitie, 2017). This causes maintenance experts to develop their own preferences towards certain interventions overtime and form their own within-company experiences and knowledge, which mostly remains within the organisation and

are not always transparently communicated towards other organisations (SBRCURNET, 2015).

The lack of guidance within decision making also causes a discussion about whether certain types of interventions are “good” or “bad” for the bridge condition state (Figueiredo et al., 2013). This discussion is fuelled by the fact that there are not much reassessments performed after maintenance interventions, which means that feedback towards maintenance effectiveness is left aside and maintenance engineers do not specifically know how “good” their maintenance actions have really worked out (Figueiredo et al., 2013). The decision upon the correct maintenance intervention to be performed is now regarded as craftsmanship and is mostly based on expert judgement (Zonta et al., 2014).

The duration of the decision making process can also be very long. After inspection data is produced, it can take weeks to several months before a maintenance advice is prepared and sent to the asset manager because most advices are part of larger maintenance projects with large batches of constructions in them, which needs to be communicated in once. The asset manager then also has to schedule all the required actions, which could also take up a significant time. Finally, all maintenance interventions need to be outsourced to the market, which is done in operational contracts for which also time has to be reserved. It is due to this long lasting cycle that much knowledge gets lost in the process and that feedback can hardly be provided effectively (Interview Rijkswaterstaat, 20-04-2017; Interview Vergoossen, 20-01-2017).

Finally, alongside all other uncertainties in the decision making, it is generally hard to predict certain events or situations that could occur at the bridge site because some influences occur at random (Radomski, 2002) and causes experts to trust on their expertise when having to forecast the future of a bridge’s lifetime (Miyamoto et al., 2000).

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#### 2.1.8 BRIDGE MAINTENANCE SYSTEM ENTITY SUMMARY

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The maintenance of bridges can be described as a process that leads to the fulfilment of the safety and functioning of a bridge regarding its users during the full extent of its service life (Radomski, 2002). It includes, but is not limited to works of inspection, repairs, rehabilitation, or replacements of the components that make up a full bridge’s asset system. Bridge maintenance is especially necessary, since bridges deteriorate over time with an increased chance of deterioration when growing older (Radomski, 2002; Washer et al., 2014).

In order to perform the right maintenance, good decisions must be made by maintenance decision makers (Cole, 2008). These decision makers are generally called asset managers, maintenance advisors, or maintenance engineers (Homeland Security, 2010; SBRCURNET, 2015) and form the bridge maintenance system’s capabilities. The mutual benefits for the stakeholders are found in minimising the risks at the bridge assets, while using as little resources as possible (Cole, 2008). The system operates by regulations from the law, contracts, scientific standards, or agreed processes and it uses data about the condition of the bridges as indicators to decide upon the most necessary maintenance interventions and at which moment in time to perform these interventions (Weykamp et al., 2010). The ability of translating these condition assessment data into the “correct” decision correlates significantly with the effectiveness and efficiency of the output of the system (Nicholas, 2015). Current opportunities for improvement of the bridge maintenance systems are to



be found by learning from experiences and innovations in current processes, materials, or technologies (Bouwcoalitie, 2017). The filled in bridge maintenance system entity is illustrated in Figure 7.

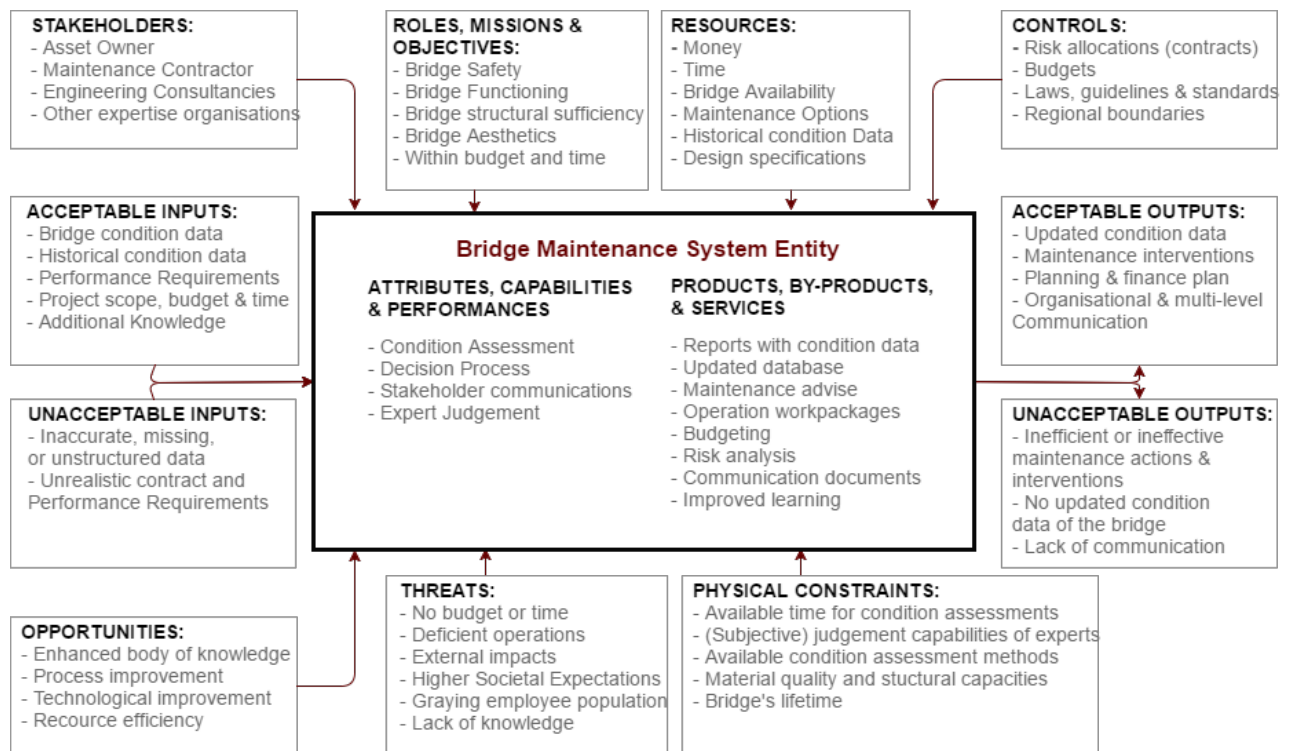


FIGURE 7. BRIDGE MAINTENANCE SYSTEMS ENTITY (OWN FIGURE BASED ON WASSON (2006, P. 22))



## 2.2 DETERIORATION MECHANISMS

As part of sub question two of the research “*What condition assessment mechanisms can measure the deterioration parameters of concrete bridges?*” it is mandatory to know what types of deterioration could occur at concrete highway overpasses and to explain why this research focuses on chloride induced corrosion damage. Through identification on what parameters are of importance for measuring, a more narrowed scope is given for the review of condition assessment mechanisms that are capable of measuring relevant deterioration parameters.

### 2.2.1 INFLUENCES AT A HIGHWAY OVERPASS

Concrete highway overpasses can be described as bridge systems with elements that are categorised into the following subsystems: the primary load-carrying elements (superstructure), the secondary load-carrying elements (substructure), durability & safety elements, ancillary elements, and sometimes other elements (e.g. machinery, embankments, wing walls)(Bridges Working Group, 2002). A general system includes components such as the bridge deck, girders, bearings, abutments, structural columns, expansion joints, drainage systems, guardrails, and lightning systems (Radomski, 2002).

Radomski (2002) explains that deterioration of concrete bridge components can come from several influential factors that are either caused by human activities (subjective factors) or objective factors, and that the primary factors for deterioration are fairly similar for every country though the intensiveness of occurring could be different. These influential deterioration factors consist of internal structural factors, environmental factors, traffic conditions, and the maintenance processes on the system (Radomski, 2002). All these factors can be broken down into a more explicit list of deterioration parameters or causes, including the frequency, speed & loading of vehicles, chemical intrusion, de-icing agents, impacts, earthquakes, penetration of CO<sub>2</sub> into the concrete from the atmosphere, or the quality of the routine maintenance (Radomski, 2002; Sanford et al., 1999). This research focuses primarily the deterioration of the concrete bridge components.

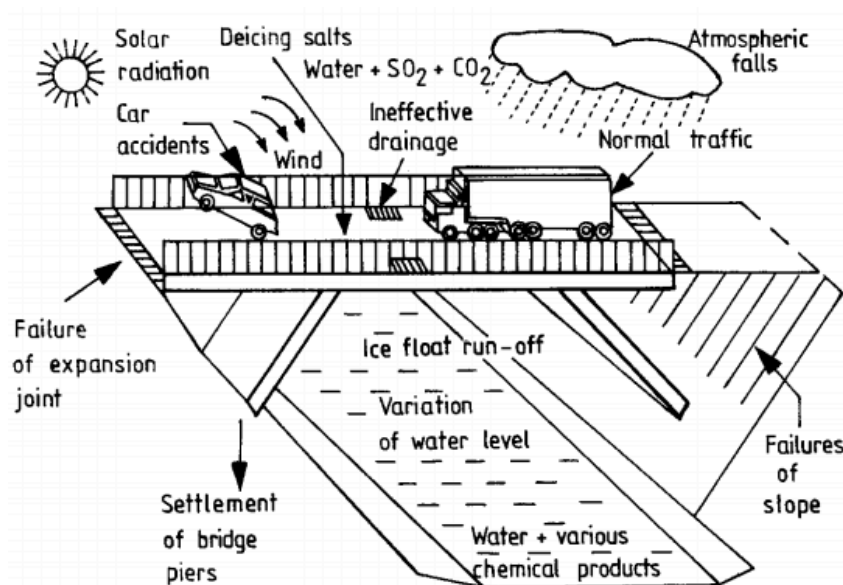


FIGURE 8. A CONCEPTUAL SKETCH OF AN HIGHWAY OVERPASS AND ITS INFLUENTIAL FACTORS, BY RADOMSKI (2002, P. 11).

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## 2.2.2 CONCRETE DETERIORATION MECHANISMS

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Deterioration of concrete is mostly visible throughout cracks that are present at the surface of the structure (Radomski, 2002). These cracks can have some recognisable characteristics, such as its time of occurrence in the service life of the bridge, their speed of formation, their external appearance or pattern, possible extruding materials such as rust or gels, and their width and number (NEN-2767, 2016; Radomski, 2002). However, in some cases, significant expertise and knowledge is necessary to relate the found damage in the concrete to the correct cause that made it happen (Homeland Security, 2010; Radomski, 2002; SBRCURNET, 2015). Most known failures in concrete come from chemical or physical interactions with influential factors, for example: thermal shrinkage, alkali-silica reactions, corrosion, service loading, or restraints in by external forces (Yehia, Abudayyeh, Fazal, & Randolph, 2008). A more detailed list of concrete deficiencies is given in Appendix II. This research will focus on a much occurring and relevant deterioration mechanism at concrete structures in the Netherlands; namely corrosion induced by chlorides (Dooms B. & Pollet V., 2008).

There are cases of service loading cracks in the Netherlands, but most of the highway overpasses have been designed with large safety factors for dynamic and static loads, which makes this damage type less observed within the Dutch National Infrastructure system (Rijkswaterstaat, 2007). Accidents are also a major cause for damages of civil constructions, but these are caused by sudden events and cannot be accounted for throughout improved condition assessments mechanisms other than enhanced risk analyses (McLinn, 2009). Therefore, these subjects are out of the scope of this research.

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### CORROSION INDUCED DAMAGE CAUSES

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In general, corrosion of the reinforcement steel inside the concrete is caused by two initiating events; carbonation of the concrete and chloride ingress into the concrete (Dooms & Pollet, 2007; Dooms B. & Pollet V., 2008; Rijkswaterstaat, 2015). Both mechanisms induce corrosion by creating a beneficial environment for the reinforcement within the concrete to form an electrochemical reaction that lets the metal surface of the steel bars erode (Dooms & Pollet, 2007). Corrosion increases the diameter of the reinforcement steel and thereby generates internal stresses in the surrounding concrete, which ultimately results in damages and cracks since concrete has a low modulus of elasticity (Dooms & Pollet, 2007).

During interviews with experts, it was considered that chloride ingress is a generally a larger perceived problem in the Netherlands than carbonation (Interview Iv-Infra, 1-12-2016, 16-01-2017; Interview Vergoossen, 20-01-2017). This study further focuses on chloride induced corrosion as deterioration mechanism, but will also briefly describe carbonation for the purpose of clarity between both mechanisms.

**Carbonation** is a reaction that happens during the chemical gas phase of carbon dioxides in the air that react with the concrete structure (Dooms & Pollet, 2007). It is a reaction that is dependent on the concrete quality during casting, the type of concrete used, and the grain distribution within the concrete (Dooms & Pollet, 2007). The carbon dioxide reaction with the concrete generally progresses into the structure as a front along the full concrete element and reduces the pH value of the concrete. A pH value of around 12 to 14 is necessary to provide a passive layer where the reinforcement steel does not corrode. A

reduced pH value results in depassivation of this protection layer and becomes a beneficial environment for corrosion to happen (Dooms & Pollet, 2007).

**Chloride ingress** is a reaction stems from the liquid phase when de-icing agents or salts are sprayed onto the road decks, or when moist air seawater containing makes contact with the concrete, and intrudes into the pores of the concrete (Dooms B. & Pollet V., 2008). It is also possible that chlorides are already present in the mixture of the concrete itself by the cement mixture of used type of sand (Torres-Luque, Bastidas-Arteaga, Schoefs, Sánchez-Silva, & Osmá, 2014). It is not directly a threat to the concrete itself, but when the chloride ions intrude towards the depths of reinforcement steel and the percentage of chloride ions at this level in the concrete reaches a certain threshold, it may attack the passive layer of the reinforcement steel causing it to corrode (Dooms B. & Pollet V., 2008). The dry-wetting cycle of the chloride contaminated water that reaches the concrete is of importance for the intrusion speed (the diffusion coefficient) of the chloride into the structure (Dooms B. & Pollet V., 2008). This dry-wetting cycle is present in the Netherlands (Dooms B. & Pollet V., 2008). The chronological process of this mechanism is stepwise illustrated below and is based on theories from Hearn and Shim (1998), Dooms B. and Pollet V. (2008).

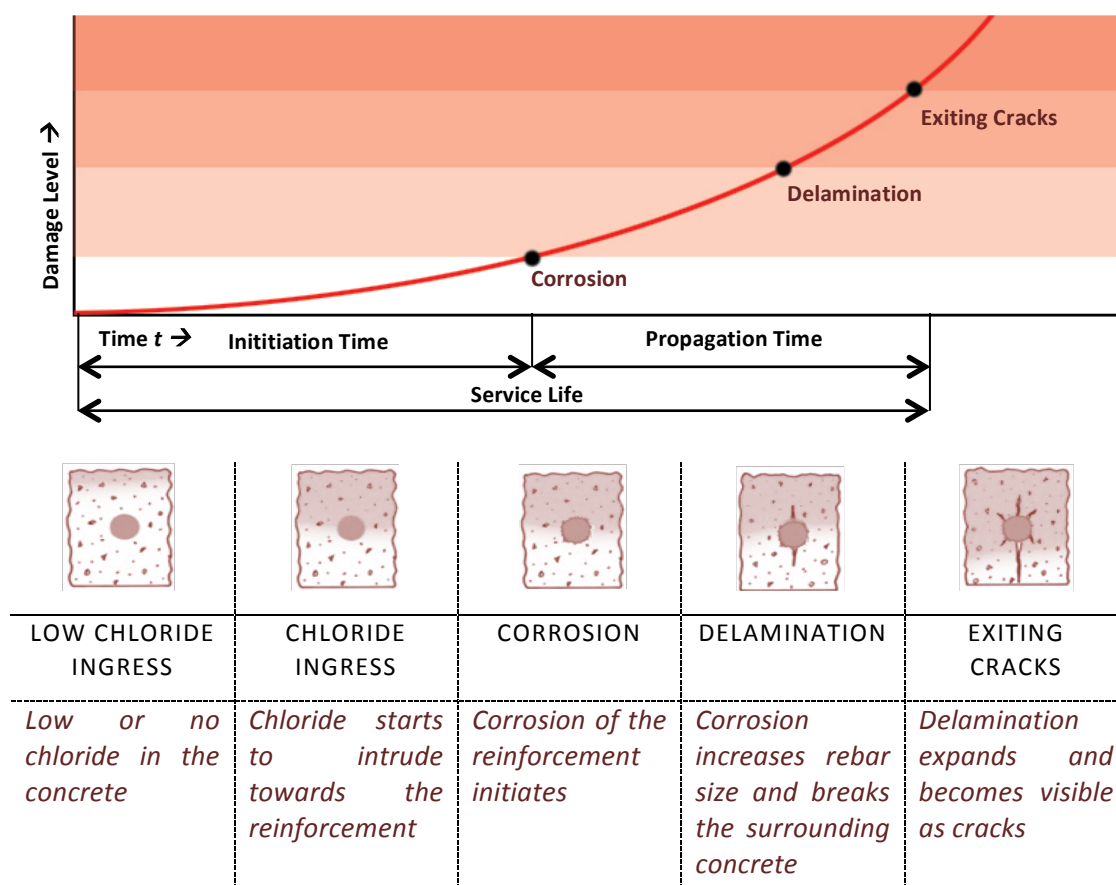


TABLE 1. THE CHRONOLOGICAL PROCESS OF CHLORIDE INDUCED CORROSION. ADJUSTED IMAGES FROM (GALVANIZER ASSOCIATION, 2017).

### 2.2.3 OTHER (NON-CONCRETE) DETERIORATION MECHANISMS

Other deteriorate types during the lifecycle of a bridge mainly consist of malfunctioning secondary members or non-concrete members (Radomski, 2002). Some element's deterioration may be the cause of other element's deterioration, for instance, leaking

expansions joints may result in (chloride containing) water reaching subsurface elements as the bearings, piers (columns), concrete girders or the side of the bridge deck (Radomski, 2002). Next to this, the drainage system along the curbs of the construction needs to be cleaned on a regular interval or it could cause still standing water onto the concrete surfaces, which may also cause deterioration (Radomski, 2002). The drainage is generally included as a key performance indicator for contractors as maintenance object for yearly cleaning (Interview Iv-Infra, 16-01-2017). Also, the asphalt on top of the deck surface may cause deterioration in the bridge deck throughout water standing still in cracks, or by changed dynamic loading of the traffic due to ravelling, increased roughness, or uneven levels of the approach zones from the abutment to the construction (Radomski, 2002). Finally, other secondary deterioration types can also be listed within the bridge asset system, such as malfunctioning lightning systems or mechanical systems, corroded railguards, or graffiti. Most of these latter described deterioration mechanisms have no direct consequences to the primary structural capacity of the construction and are therefore not included in this research' scope, but they can have an effect on the safety for the user or the aesthetics of the bridge system and therefore also need to be maintained (Sanford et al., 1999).

## 2.3 CONDITION ASSESSMENT MECHANISMS

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Condition assessment mechanisms obtain information about the condition state of the bridge, the future condition state of the bridge, or other specialised sets of information that aid the maintenance decision making for bridges (Sanford et al., 1999; SBRCURNET, 2015). Typical output data of these mechanisms are images, condition state inspections, risk analyses, construction ratings, rest-life estimations, laboratory research, financial & costing plans, deterioration parameter measurements, or digital monitoring data (Campbell et al., 2016). Unfortunately, there are multiple constraints, such as limitations in time, resources and budget, that make it unfeasible for maintenance engineers to obtain all deterioration parameters by these mechanisms (Malings & Pozzi, 2016).

This first part of this paragraph elaborates on the currently most used condition assessment mechanism ‘visual inspection’, the second part elaborates on what new techniques and systems can be identified for obtaining new data sources to be used during maintenance decision-making moments.

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### 2.3.1 CURRENT METHOD: VISUAL INSPECTION

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Currently, the most used condition assessment mechanism is visual inspection (Kallen, 2007). The goals of visual inspections range from performing a short superficial oversight to highly detailed field tests or laboratory tests (SBRCURNET, 2015). Averagely, every five years, a larger inspection session is performed for more detailed and specialised observation, it is performed by trained personnel that visits and closely observes the bridge elements at a ‘within-hands-reach’ distance (Kallen, 2007).

The condition inspection has an inspection report as output that includes general information about the bridge, general information about the performed inspection method, and the condition status of each bridge component (Sanford et al., 1999). The broadly used NEN-2767 (2016) method summarises the condition status of a bridge into a ‘condition score’ by a fuzzy scoring method where one is near perfect and six is highly critical. NEN-2767 (2016) does not recognise any guidelines towards the minimum condition of a construction. It merely is the instrument of documenting findings in a structured manner. The condition score is determined by a six step-method:

1. The total bridge is decomposed into components.
2. The type of found deficiency is determined (per component)
3. The intensity of the found deficiency is determined (per component)
4. The extent of the damage is determined (per component)
5. Step two to four can be filled out a conversion table to determine the condition score (per component)
6. A (criticality related) weighing factor is applied to each component’s condition score and a total condition score can be derived for the bridge.

The NEN method is generally supplemented with photographs of the bridge and descriptions of the found situations. The outcomes of the inspections are (in the Netherlands) documented within a database, which is the DISK-System of Rijkswaterstaat (2017). An example of an inspection report is illustrated in Figure 9.

IH-onderdeelnaam	toestand	Risico tav Aspect
Geleideconstructie, staal, (middel)stijf	2 - In goede staat	
Hemelwaterafvoer (HWA), staal, -	2 - In goede staat	
Hoofddraagconstructie, beton, -	2 - In goede staat	
Leuning, staal, -	2 - In goede staat	
Oplegging, rubber, -	2 - In goede staat	
Schamplank, beton, -	2 - In goede staat	
Steunpunt, beton, -	2 - In goede staat	
Verharding wegtype 1, Hoofdwegennet, zoab op dab, -	2 - In goede staat	
Voegovergang, bitumen, -	4 - In matige staat; Voldoet niet aan het BON	Hoog 8.2-Ec

Aspecteis t.a.v IHonderdeel	Risico-omschrijving	Risicoanalyse	Toestand indicator	Risico niveau
8.2-Ec Voegovergang	Groot(schalige(re) gevolgschades (aan andere onderdelen)	Als gevolg van lekkage van de voegovergangen wordt de onderliggende betonconstructie belast met vocht en dooizouten met mogelijk chloride geïnitieerde wapeningscorrosie en vervolgens sterkteverlies tot gevolg.	4 - In matige staat; Voldoet niet aan het BON	Hoog



Steunpunt, beton,



Verharding wegtype 1, Hoofdwegennet, zoab op dab,



Voegovergang, bitumen,

FIGURE 9. EXAMPLE INSPECTION REPORT OF A HIGHWAY OVERPASS

### 2.3.2 NEW DATA SOURCES

This part of the paragraph reviews methods that can obtain the important deterioration parameters of a highway overpass in other (more innovative) manners than visual inspection. In literature, multiple definitions have been used for referring to these innovative condition assessment mechanisms. “Structural Health Monitoring, Non-Destructive Evaluation Techniques, Field-Tests, Remote Sensing Systems, Wireless sensing, embedded sensor nodes, SMART assets, Monitoring systems, and Civionics” are some of them (Ahlborn et al., 2010; Duffó & Farina, 2009; Figueiredo et al., 2013; Iv-Groep, 2016; Vaghefi et al., 2012; Wang, 2014; Wang et al., 2014; Watters et al., 2003). Due to all these definitions, misunderstandings in interpretation could occur since some of the terms could be used interchangeably. Therefore, this research separates the new condition assessment mechanisms into two main categories: **In-Situ Sensor Systems** and **On-Site Sensing Systems**. These terms have been chosen based on literature where the categories were evidently apparent: Du, Hu, Huang, and Lin (2006); Figueiredo et al. (2013); International Atomic Energy Agency (2002); Omar and Nehdi (2016); Terry et al. (2010). The explanation of each of the two categories is as follows:

**In-Situ Sensing Systems** are sensing systems with the following traits: They are installed at the bridge or embedded inside its structural components, *hence In-Situ*. They measure their data throughout metrics of acceleration, strain, temperature, imagery, electrical currents, laser or light fractioning (fibre optic cables), or chemical reactions. *In-Situ systems* are ought not to be moved, and thus obtain their measurement data from a single location (but their measured values may present data about more than that location only). They can measure certain deterioration parameters continuously or at short interval because they are present in or at the structure. In general, *In-Situ Sensing Systems* can be described as sensor nodes, and are related to making objects “smart” and able to “communicate”.

Some related terms that came up throughout the literature study of these systems are: structural health monitoring, wireless sensing, wireless monitoring, Internet of Things enabled sensors, and embedded sensing systems.

**On-Site Sensing Systems** are techniques that have to be directed towards- or placed against the bridge's component and can measure important parameters of the bridge by electrical currents, potential differences, sound pulses, imagery, electromagnetic waves, laser, x-ray, or ultrasonic waves. Personnel or operational steering systems have to operate these systems on, at, or around the location, *hence On-Site*. They are dynamic in movements and thus (are able to) retrieve data about multiple locations from the bridge. In order to obtain the data, the measurements have to be scheduled and performed On-Site. Furthermore, these On-Site Systems can be categorised once more into "remote" and "contact-based" systems. This means that systems that use radar, spectral analysis, photogrammetry, laser, infrared, or sound waves do not have to make contact with the bridge component in order to measure and obtain their output (Gucunski, Pailles, Kim, Azari, & Dinh, 2016). Systems as electrical resistivity, half-cell potentials, or impact-echo's do require contact with the concrete of the bridge components for measuring their parameters (Gucunski et al., 2016). Terms from the literature that were related to these systems were: non-destructive evaluation techniques, Remote sensing mechanisms, dynamic sensing systems, expert generated data sources, and condition assessment scanning devices.

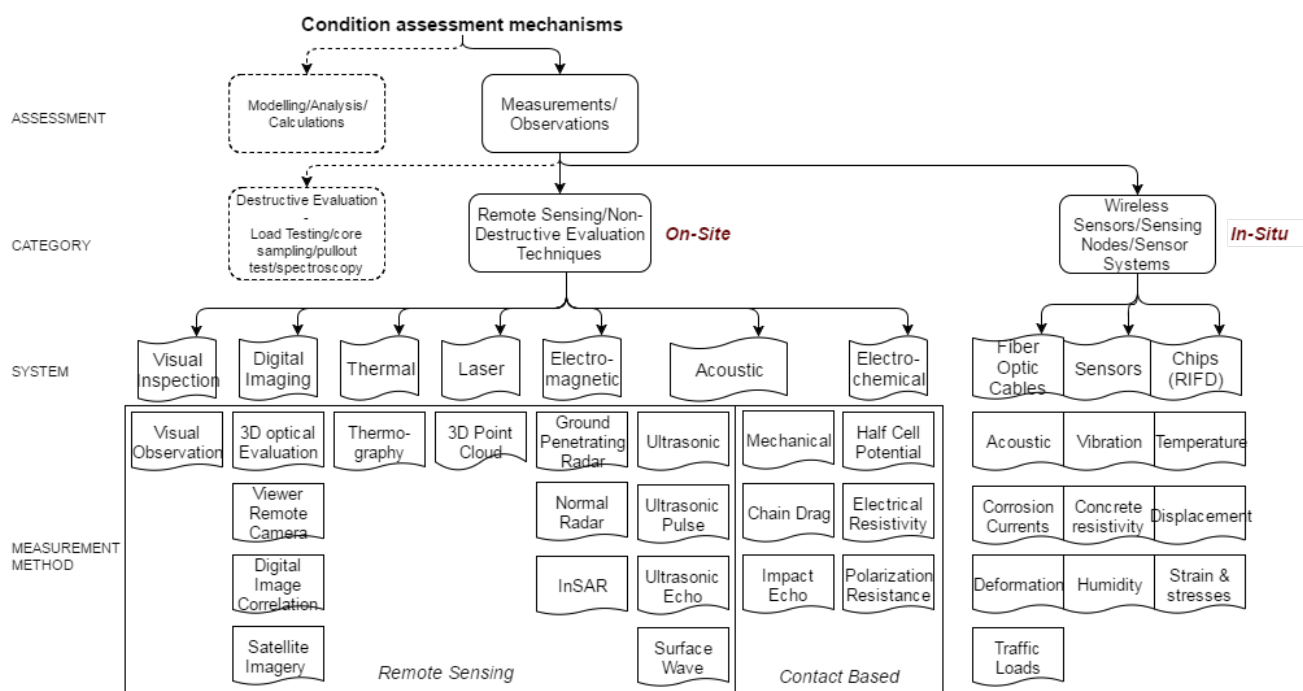


FIGURE 10. CONDITION ASSESSMENT MECHANISMS OVERVIEW (OBTAINED BY LITERATURE REVIEW)

During the literature search for new data sources, many different technologies have been found. As part of the third objective of the research, *“develop certain acknowledgement of possible developments, future processes, and possible future scenario’s by experts for more market involvement in these innovations”*, the found technological innovations are documented in Appendix III in a capabilities table with description and are also illustrated in Figure 10 by category. Not all new data sources will be treated in the following section,



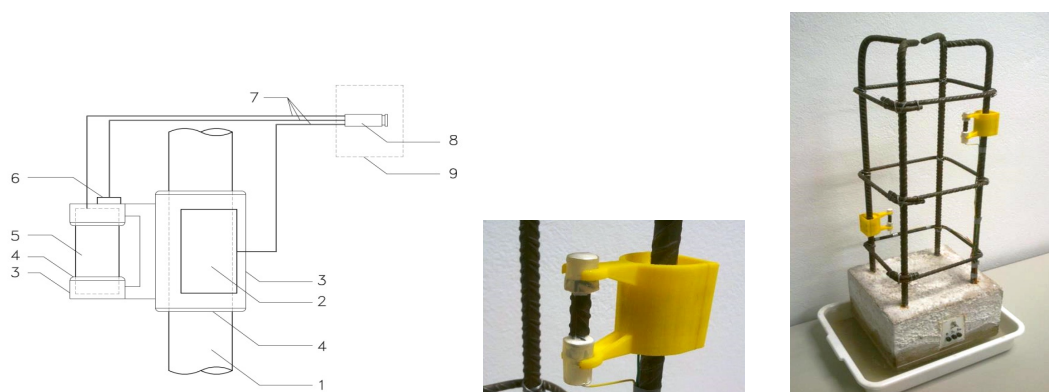
only new data sources that can retrieve import deterioration parameters about the Chloride Induced Corrosion mechanism.

### CHLORIDE INDUCED CORROSION SPECIFIED NEW DATA SOURCES

From the extensive table with all condition assessment mechanisms in Appendix III, a more specified table regarding only chloride-induced corrosion can be obtained with applicable condition assessment mechanisms. These are listed and reviewed in Table 2 on the next page and are explained hereafter. This type of table presentation is proposed by Hearn and Shim (1998) and is also used by Sanford et al. (1999). It connects the condition states of a concrete component to the phases of chloride induced corrosion, and then documents the condition assessment mechanisms that can measure these stages by a fuzzy scoring method respectively. According to Hearn and Shim (1998), the five condition states presented at the second row are mutually exclusive, detectable by sensing mechanisms, and give an indication of the all chloride induced corrosion deterioration phases and their severity. All condition assessment mechanisms presented in Figure 10 and are explained further below, except for visual inspection since this has already been elaborated on previously.

### IN-SITU – CHLORIDE & CORROSION COMBINATION SENSORS

When regarding the literature for In-Situ sensing methods that could measure the chemical parameters from chloride-induced corrosion, much research was available (Abbas, 2015; Duffó & Farina, 2009; Muralidharan et al., 2007; Wang et al., 2014; Watters et al., 2003; Xu, Li, & Jin, 2013; Zamora et al., 2016). The sensing mechanisms operate via current densities, resistance measurements, potential differences, capacitance, temperature, and other chemical properties like the pH- or oxygen value of the concrete (Zamora et al., 2016). The sensors have to be installed at- or attached to the reinforcement steel and therefore have to be casted (embedded) into the concrete component during construction (Abbas, 2015). Some claim that these sensors can be also be drilled into the concrete later on for instalment in existing structures (Watters et al., 2003). They generally measure both the deterioration parameters of the concrete as the reinforcement steel (Du et al., 2006). The output values of these sensors can be translated into different metrics, of which the diffusion coefficient, the chloride content per mass of cement or concrete, the corrosion-rate, and chances to having corrosion are clear indicators for usage in maintenance decision making (Dooms B. & Pollet V., 2008; Du et al., 2006; Zamora et al., 2016).



Front and top schematic views of a corrosion sensor. 1. Rebar 2. Connexion clamp 3. Support 4. Sealing gasket 5. Sensor 6. Temperature sensor 7. Connexion wirings 8. External connector 9. Connexion box

FIGURE 11. EXAMPLE SETUP OF IN-SITU CHLORIDE AND CORROSION SENSORS (ZAMORA, ROMERO, PAYÁ, & PRATS, 2016, P. 73)



VULNERABILITY OF THE BRIDGE COMPONENT

Deterioration Phases	<i>Deterioration Phases →</i>	<b>1 Protected</b>	<b>2 Exposed</b>	<b>3 Vulnerable</b>	<b>4 Attacked</b>	<b>5 Damaged</b>
	<b>Exposure (chloride content)</b>	No Ingress	Concentration below threshold	Concentration at threshold		
	<b>Corrosion Mechanism</b>			Possible corrosion activity	Corrosion activity	
	<b>Rebar Damage</b>				No loss in rebar area	Loss of rebar section
	<b>Concrete Damage</b>				Delamination	Large spalls
CONDITION ASSESSMENT MECHANISM		MEASUREMENT OUTPUT VALUES (FUZZY)				
<b>Current Method</b>	<b>Visual Inspection</b> (Krauss et al., 2009; NEN-2767, 2016)	(Indirect description of failure causes possible) <b>Invisible</b>			<b>Visible</b>	
<b>In-Situ</b>	<b>Chloride Sensor</b> (Watters et al., 2003)	<b>Low</b>	<b>Medium</b>	<b>High</b>		
	<b>Corrosion Sensor</b> (Zamora et al., 2016)	<b>Low</b>		<b>Medium</b>	<b>High</b>	
	<b>Frequency-Based Sensing</b> (Casas Rius & Moughty, 2017)	<b>Low</b>			<b>Medium</b>	<b>High</b>
<b>On-Site (remote)</b>	<b>Ground Penetrating Radar</b> (Vemuri, 2016)	<b>Low</b>		<b>Medium</b>	<b>Advanced</b>	<b>High</b>
	<b>Thermal Scanning</b> (Vemuri & Atadero, 2016)	<b>Low</b>			<b>Medium</b>	<b>High</b>
<b>On-Site (Contact-based)</b>	<b>Electrical Resistance &amp; Half-Cell Potential</b> (Gucunski et al., 2016)	<b>Low</b>	<b>Medium</b>	<b>High</b>		

TABLE 2. RELATION TABLE BETWEEN THE DETERIORATION PHASES AND THE MEASURED VALUES OF THE CONDITION ASSESSMENT MECHANISMS. TABLE LAYOUT BASED ON HEARN AND SHIM (1998, P. 52 & 53).

## IN-SITU - FREQUENCY BASED DAMAGE DETECTION

Next to the chemical properties of the chloride-induced damage, *In-Situ* sensors can also obtain physical properties. These refer to the loss of area at the reinforcement steel and structural cracks within the concrete, or simply: physical damages. In-Situ sensing methods can measure these parameters throughout acoustics, vibrations, and strain (Brincker, Andersen, & Zhang, 2002; Casas Rius & Moughty, 2017; Fan & Qiao, 2011; Kuleli, Nagayama, & Su, 2016). Frequency domain related measurement methods decompose the structural vibrations into mode shapes and natural frequencies of the bridge component (Brincker et al., 2002). By different types of calculation programs (e.g. Fourier analysis or canonical variate analysis), changes in the structural behaviour of the bridge component can be measured (Brincker et al., 2002). The output of these calculations can be translated to damage intensities and the location of the damages (Fan & Qiao, 2011), as is shown in Figure 12.

Despite successes in different experimental settings, these measurements are still less reliable when applied in the field, due to the increased complexity of an asset system and environmental influences such as traffic (Fan & Qiao, 2011). The more complex the asset system or different kinds of damages are, the less likely a clear result can be obtained about the damage state of the bridge component (Fan & Qiao, 2011). Yet, much attention is paid to this type of sensing and much progress is made overtime (Casas Rius & Moughty, 2017). Nevertheless, as is explained in the scope of the research, in this research it is assumed that the frequency-based damage detection is operating properly.

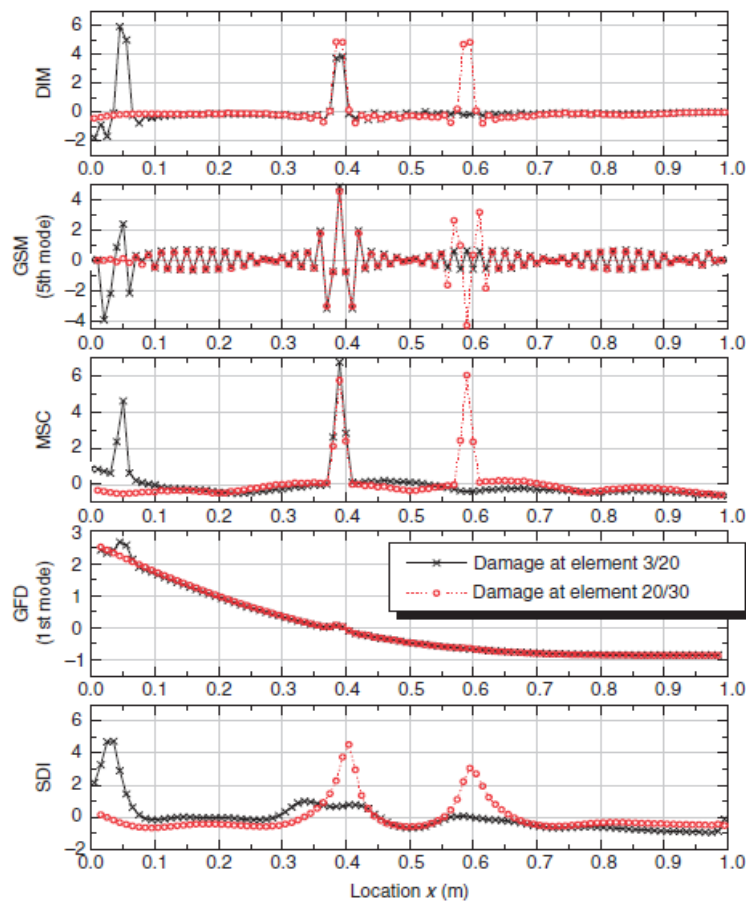


FIGURE 12. DIFFERENT ALGORITHMS CALCULATE THE NATURAL FREQUENCY DOMAINS AND PRESENT FAIRLY SIMILAR RESULTS FOR DAMAGE DETECTION (FAN & QIAO, 2011, P. 101)

## ON-SITE – REMOTE SENSING SYSTEMS - GROUND PENETRATING RADAR

Ground Penetrating Radar (GPR) is a system that remotely evaluates deficiencies in the concrete by electromagnetic waves that are being sent and reflected from different interfaces (as a sonar principle, but then with magnetic waves instead of sound waves)(Vemuri & Atadero, 2016). The reflective signal can be used to review the internal structure of a concrete component. Its signal is attenuated and deformed by multiple factors such as: the cover depth of the concrete, dielectric differences in present materials (between steel, moisture and concrete), ion concentrations, cross-sectional areas of steel, and concrete cracking and delamination (Abouhamad et al., 2017). After the measurements, an algorithm software corrects background noises and filters the different factors within the concrete for reviewing (Vemuri & Atadero, 2016). The output visualisation is mostly presented as a contour plot with a ranged set of colours that are related to the reflected signal strengths in decibels; with red being poor conditions such as delaminated parts, yellow & orange could indicate smaller delaminated areas or corrosive environments (by chlorides for instance) and green and blue is normal attenuation of the concrete (normal condition)(Zou, 2014). The latest trends are to enhance a driving vehicle with such radar mechanisms, and according to Vemuri and Atadero (2016), GPR is useful for measurements below asphalt layers too which makes it applicable for Dutch highway overpass systems that generally have asphalt layers. In short, GPR has to potential to obtain both high ion-concentrated areas as damages in the concrete.

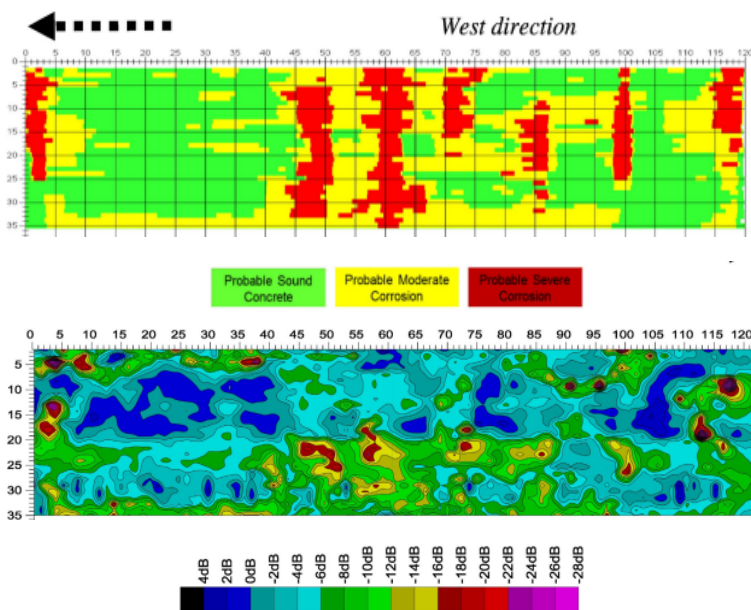


FIGURE 13. LEFT: GPR CORROSIVENESS CONTOUR PLOT & ATTENUATION MAP USING AMPLITUDE ANALYSIS (ABOUHAMAD, DAWOOD, JABRI, ALSHARQAWI, & ZAYED, 2017, P. 6) RIGHT: TWO GPR EQUIPPED UTILITY VEHICLES FROM PENETRADOR (2017).

## ON-SITE – REMOTE SENSING SYSTEMS - INFRARED THERMAL SCAN

Thermal Infrared Scanning systems evaluate the structure by observing 'hotspots' or 'cold spots' in the concrete. These spots can indicate a deficiency within the structure (Zou, 2014). It detects delaminated areas and obtains the clearest values when these have moist in them. It is dependent when the structure is evaluated, because the air or moist in the open spaces in the concrete (delamination) need to have a different temperature than the rest of its surrounding structure in order to be observable. This temperature difference is

mostly present during temperature shifts of the environment (such as late noon or early morning) (Zou, 2014). The visualisation of the data is also presented in contour plots or 3D models where the deficiencies are shown as red parts that indicate a different temperature than its environment (Ahlborn et al., 2010; Vaghefi et al., 2012).

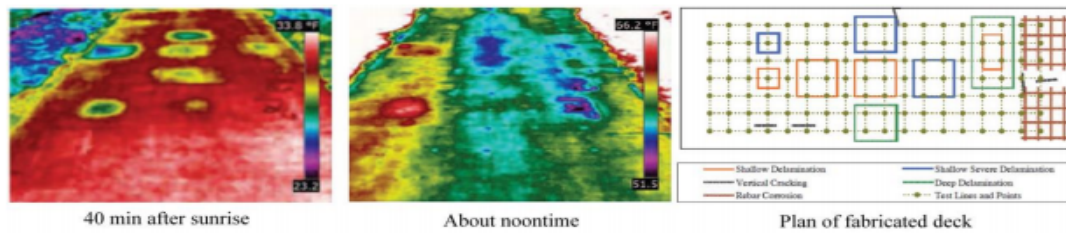


FIGURE 14. INFRARED THERMOGRAPHY SCAN AT DIFFERENT TIMES (HIASA, 2016, P. 15)

### ON-SITE – CONTACT-BASED SENSING SYSTEMS - ELECTRICAL RESISTIVITY & HALF-CELL POTENTIAL

Both electrical resistivity (ER) and Half-Cell Potential (HCP) measure the condition of the concrete throughout electrical resistance (International Atomic Energy Agency, 2002). The main difference between both systems is that HCP requires a wired contact with the reinforcement steel and ER can be applied onto the concrete without contact with the reinforcement steel. This means that a small destruction or space for connection with the reinforcement steel is required for HCP (Gucunski et al., 2016). When ER measures a high resistive concrete, it is less likely for reinforcement steel to pass off its negative ions, which simply means a higher resistivity against corrosion and thus a lower corrosion rate (Gucunski et al., 2016). HCP measures in potential difference between the reinforcement steel and the concrete, which indicates the transitioning speed in which ions can flow from the reinforcement steel into the concrete, this simply means the probability in which corrosion will happen (Gucunski et al., 2016). Both systems are heavily influenced by presence of moist, oxygen, chlorides, and existing current flows in the concrete (Ahlborn et al., 2010). Both systems present their outcomes in a contour plot where red areas indicate a low resistivity in  $k\Omega m$  for ER (and thus a corrosion friendly environment), and a high potential difference in mV for HCP (and thus a high corrosion probability) .

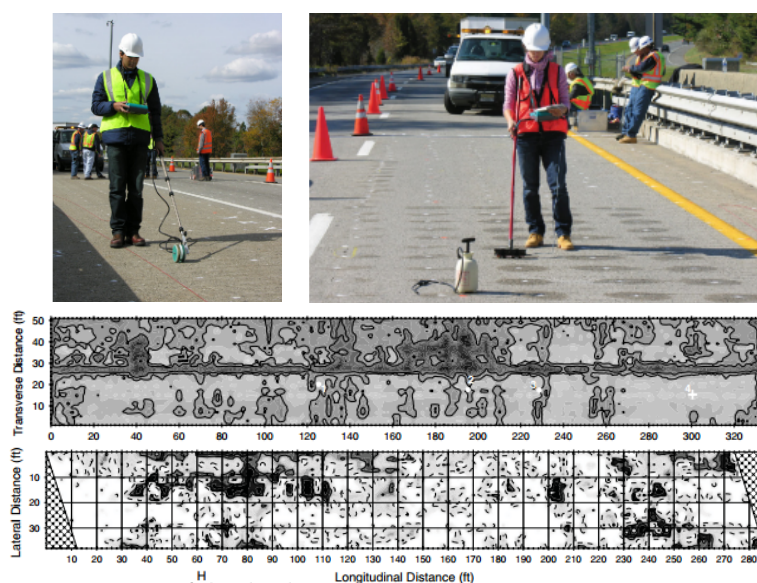


FIGURE 15. LEFT TOP: AN HCP MEASUREMENT IS PERFORMED. RIGHT TOP: AN ER MEASUREMENT IS PERFORMED. MIDDLE: THE OUTPUT VALUES OF THE HCP MEASUREMENT IN A CONTOUR PLOT. BOTTOM: THE OUTPUT VALUES OF THE ER MEASUREMENT IN A CONTOUR PLOT. ALL IMAGES ARE RETRIEVED FROM GUCUNSKI ET AL. (2010, P. 37 & 38).

## 2.4 LITERATURE REVIEW ON THE EXPECTED USES OF NEW DATA SOURCES

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The previous paragraph explained what the different types of condition assessment mechanisms and their technologies comprehend. In this section, a literature study is performed by theories of Webster and Watson (2002) to structure and set out current views and theories on how new data sources could influence bridge maintenance decision-making. It starts with defining the practical pros and cons of each of the described condition assessment mechanisms, and continues with the expected enhancements in the quality of data that comes from these mechanisms. Then, the section describes what the results of using new data sources are expected to be when regarding maintenance decision output and assesses whether other uses for new data sources are also expected.

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### 2.4.1 PROS AND CONS OF VISUAL INSPECTION

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**Pros Visual Inspection:** Visual inspection is currently perceived as flexible and easy method to assess a bridge's condition because it uses personnel as measurement systems that can walk around the bridge (Campbell et al., 2016). It provides a quick overview of the observed system of a bridge and trained personnel can sometimes directly conclude upon a relation between a failure cause and the deterioration it causes (Campbell et al., 2016). This can give maintenance advisors or engineers a very practical guidance in their maintenance decision-making.

**Cons Visual Inspection:** When regarding the output of visual inspections, it seems that these are qualitatively not very consistent due to a high amount of subjective judgement possibilities by the inspectors or simply by human error (Kallen, 2007; McLinn, 2009; Phares et al., 2004). A study of McLinn (2009) has shown that inspections are not sufficient for assessing the reliability and condition status of a bridge because it creates inefficient maintenance decision-making based on wrongly data. Furthermore, one of the issues of the current method of visual inspection is that it cannot observe the progression of all deterioration mechanisms (Krauss et al., 2009). Some types or phases of deterioration cannot be observed with the naked eye but can merely mentioned by probabilities of happening (e.g. by a risk description of the use of de-icing agents)(Figueiredo et al., 2013; Radomski, 2002).

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### 2.4.2 PROS AND CONS OF NEW DATA SOURCES

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Generally, the measured output from new data sources is digital and thereby more objectively quantified and faster in direct communication than visual inspections (International Atomic Energy Agency, 2002). Next to more quantified measurements, some condition assessment mechanisms can measure data about certain deterioration parameters that are not visible by eye and thereby create an opportunity for expanding the 'subset' of obtainable deterioration parameters (Vardanega P, Webb G, Fidler P, & Middleton C, 2016).

**Pros In-Situ:** Fast developments are expected from wireless sensing and Long Range Low Power (LoRa) communication networks (KPN, 2016). New ways to power battery-less sensors through radio waves create opportunities to increase the service life of wireless sensors tremendously (Scholles, 2017). When In-Situ Sensing Systems can wirelessly



communicate their data through a network and do not need batteries, they can produce measurement output very frequently (if not; continuous)(Inaudi, 2010). Next to this, being attached at- or in the bridge component itself, In-Situ sensors can measure very specific and absolute values of the deterioration parameters (Inaudi, 2010; Lee, Phares, Jayselan, & Osman, 2016).

**Cons In-Situ:** Once embedded, these systems always remain at one place which bounds them to local measurements (wrongly placed sensor thus may have no use at all)(Figueiredo et al., 2013). This is a disadvantage since deterioration can also happen locally and hardware and software upgrades could also develop overtime. Their robustness in harsh environments is also still unknown due to the limited amount of long duration tests (Vardanega P et al., 2016). Also, for some sensors, it is much more convenient to install them during the construction phase than implementing them later on into existing structures (Figueiredo et al., 2013).

**Pros On-Site:** On-site Sensing technologies can enhance the effectiveness of inspections by being able to observe the construction much more detailed and can be used at specific locations that require additional attention or are critical (Vemuri & Atadero, 2016). The most promising literature shows how some of the systems can be equipped onto a vehicle and drive along with the normal traffic, which would be highly beneficial for the availability of the bridge (Vemuri, 2016; Vemuri & Atadero, 2016). Other systems can be made small enough to function as portable system for the inspector to bring along usual inspections routines (Figueiredo et al., 2013).

**Cons On-Site:** the mounting on a vehicle is only applicable for remote On-Site Systems and not for contact-based On-Site Systems that require a contact point with the structure. Also, the contact-based On-Site Systems are unable to measure values when there is an overlay on top of the concrete such as asphalt (Vemuri, 2016). Furthermore, much expertise is generally required for operating these measurement system or for analysing and converting the measurement data into usable information (Figueiredo et al., 2013).

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### 2.4.3 ENHANCEMENT OF DATA QUALITY ASPECTS

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According to Brous, Janssen, and Herder (2016), the quality of data for decision making can be expressed in five data quality aspects. Data quality means that the data is fit to its levels of use and is up to the requirements to let a decision maker achieve certain goals. The five aspects are completeness, consistency, accuracy, relevancy, and timeliness.

In general, new data sources are expected to enhance the quality of the condition state data about a bridge (Ahlborn et al., 2010). More quantified measures, and being able to extract more deterioration parameters than only visible ones makes the data of new data sources more **objective** than current visual inspection data. It is expected that they decrease the difference between the observed condition and the actual condition of the bridge component. As Ahlborn, Vaghefi, Harris, and Brooks (2012, p. 149) describe it: *“Remote sensing technologies could transform the current state of bridge condition assessment through the elimination of guesswork in the inspector’s toolbox and the replacement of it with reliable and quantifiable tools to measure several health indicators”*.

Once In-Situ systems have been installed, or On-Site Systems are mounted on a vehicle, they are capable of measuring at shorter intervals (higher **frequency**) than current methods since the needed resources to measure the bridge’s condition become lower

(Vemuri, 2016; Zonta et al., 2014). This refers to the timeliness data quality aspect. Maintenance decisions can thereby be based on much more timely data instead of the long durations in the current decision making process, but they also can observe the progression of the deterioration better.

Finally, between In-Situ and On-Site condition assessment mechanisms, the difference can be described as the first having a quantified output that is measured on a singular (per sensor) and **local point**, while the latter is more of a **global measurement** (Hesse A et al., 2015; Inaudi, 2010; Lee et al., 2016). This could be described as the completeness of the data regarding the quantification of the deterioration in the full structure.

The accuracy, reliability, and consistency of the sensing systems are determined by their technological progression, which vary per type of sensing system being developed. It is expected that this technological progression will advance tremendously during the coming years, since there is an increasing focus on these systems (Figueiredo et al., 2013). When functioning optimally and adopted structurally, new data sources are expected to outperform visual inspection on these data quality aspects (Gucunski et al., 2016; Hesse A et al., 2015; Pailles, 2014). Due to these data quality aspects being dependent on technology innovation and research, these are not within the focal point of this research.

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#### 2.4.4 EXPECTED IMPACT ON THE BRIDGE MAINTENANCE SYSTEM

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New data sources are expected to influence crucial aspects within the bridge maintenance systems. When divided into strategic, tactical, and operational processes, as is proposed by Brous, Janssen, Schraven, Spiegelner, and Duzgun (2017, p. 73), some key improvements are identified:

On a strategic level, the use of new data sources is expected to improve communication between stakeholders, documentation, self-organisation, and decision support services. On a tactical level, new data sources could improve the resource management (budgets and planning), evaluation of process performances and decisions, utilisation improvement of the infrastructure, and better control of event occurrences. Finally, on the operational level, the expected uses of new data are the improved efficiency and effectiveness of structural condition assessments, improved maintenance decision-making and maintenance productivity, and improved effectiveness of the performed maintenance operations themselves.

IBM (2016) explains that using technology advanced monitoring data lets the decision maker observe failure indications of an asset earlier. It will enable the maintenance decision makers to change their decision-making practices from reactive to preventive maintenance (IBM, 2013, 2016). It is expected that the interpretation of the data during decision making will move from descriptive (what has happened?) towards predictive and prescriptive (what could happen? & what should happen? Respectively)(IBM, 2016, p. 3). The current decision making process of maintenance engineers based on visual inspection data is regarded as reactive decision-making based on descriptive data (Interview Vergoossen, 20-01-2017). It simply means that maintenance actions are based on visual and aural inspections and mostly performed after failure has occurred at a bridge component. There are some preventive maintenance types already performed during maintenance cycles, such as cleaning, rinsing jobs, or paint works, but these are mostly

based on standard schedules and predetermined contracts and not specified to the necessity regarding the actual condition status of the bridge.

When translating this to the chloride induced corrosion process, it could lead to advised maintenance interventions for deterioration phases where current data sources would generally not result in an advice for interventions.

Zonta et al. (2014) uses Bayesian logic and decision theory to investigate whether the decision to “act” from a maintenance engineer due to the use of new data sources can be justified regarding the costs and budget of an organisation. The research concludes that the use of more information during decision-making results in more justified- and more sureness of taking actions during decisions. They even state: *“anything which produces [relevant] information is useful to take decisions”* (Zonta et al., 2014, p. 1054).

This could mean that more information would lead to more confidence and sureness of the maintenance engineers during decision-making.

Finally, Mufti, Bakht, Tadros, Horosko, and Sparks (2005) take up another statement. They mention that current decision making from maintenance engineers is already risk averse and highly conservative, which makes it an inefficient and traditional practice. They expect that the use of Structural Health Monitoring data (comparable to In-Situ data in this research) will cause more ‘risky’ behaviour from maintenance engineers because they are better able to determine the safety and risks in the construction being examined, and therefore ‘dare’ to wait for scheduling maintenance more towards crucial failure moments.

This would mean that maintenance engineers could delay maintenance actions closer to actual failure moments when using new data sources, rather than using more urgent or more preventive maintenance interventions.

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#### 2.4.5 OTHER EXPECTED USES OF NEW DATA SOURCES

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New Data Sources can be used as verification of (new) design and construction principles and can be used to assess the effectiveness of maintenance interventions (Figueiredo et al., 2013). It can serve as calibration point for other bridges that are comparable to the measured ones, and on the longer term, they can help to improve deterioration laws and physics (Figueiredo et al., 2013). By using new data sources for comparison with visual inspection performances, inspectors can enhance their assessment accuracy and recognition ability of deterioration (Sanford et al., 1999). Statistical learning, machine learning, and network science will become crucial during the translation of new data sources into actionable knowledge and they could play a major role in the decrease of the duration of maintenance decision making process (Archetti, Giordani, & Candelieri, 2015). Sensing data can efficiently be stored in digital databases and archives for quick insights during later moments or for further research by “Big Data” analysis (Zonta et al., 2014). It is expected that the enhancement of using multiple condition assessment mechanisms combined in an integrated condition assessment report can result in a simplified and strongly enhanced maintenance decision-making process, though it is not described what this enhancement of decision making actually means (Ahlborn et al., 2010).



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#### 2.4.6 CONCLUSIONS ON THE EXPECTED USES OF NEW DATA SOURCES

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Though the benefits and opportunities for maintenance decision-making improvements are broadly recognised, actual observations from the effect of using new data sources during maintenance decision making seem to be not readily available. Most literature provide estimates on how future processes most likely will change or how calculation models show the most likely effects of using new data sources. Some of these expectations will be used for determining the propositions and hypotheses in the research model, which will be explained hereafter.

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### 2.5 THE PROPOSED RESEARCH MODEL

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As shown by the decision model in Figure 4, there is an expected relation between the measured data from a condition assessment mechanism and the maintenance advice that follows from this. By addressing the expected uses of new data sources from new types of condition assessment mechanisms in the section above, the relation between maintenance decision-making and the use of new data sources can be given a direction in a theoretical model. The following section describes this research model by identification of the constructs (approximate units). In the following chapter, the constructs will be made measurable through variable identification and hypotheses definitions.

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#### 2.5.1 CONSTRUCTS AND PROPOSITIONS

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The cause effect model of this experiment is illustrated below and is based on the components of a theory how Bacharach (1989) explains this. Field (2013, p. 29) explains that propositions can have a directional effect or a non-directional effect. If any general direction is expected, it will be mentioned in the proposition (or in the hypothesis in the following chapter).

The three constructs that are used in this model are “new data sources”, “maintenance decision making”, and “expert judgement” and are chosen based on the . The New Data Sources is the cause construct and the maintenance decisions is the effect construct as is explained by the decision making model. The expert judgement construct is considered to be a mediator between the other two constructs because it is expected to influence the decision-making behaviour partly (but not fully). It relates to the experience, “guesswork”, and “gut” feeling of the maintenance engineer and is used to give direction to- and check for consistency between all outcome variables. This has been chosen since there could be external guidelines that, despite the higher risks at a bridge, require the expert to not change actual maintenance decision. By measuring both constructs, changes induced by new data sources could be observed that were else left unnoticed.

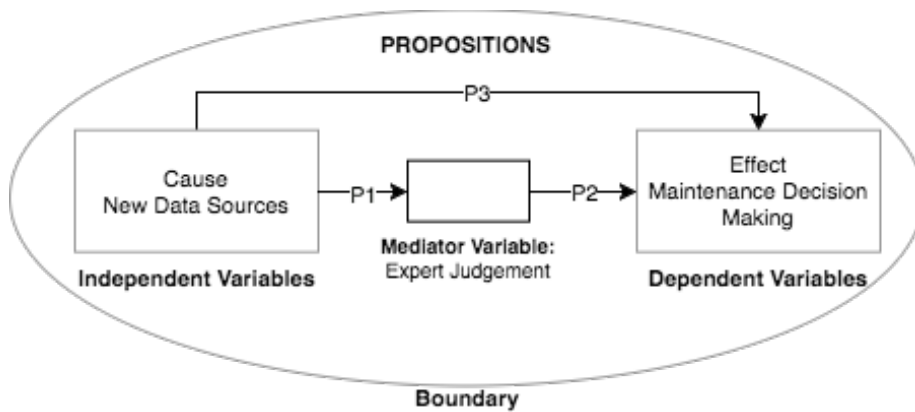


FIGURE 16. RESEARCH MODEL - CONSTRUCTS AND PROPOSITIONS

The propositions of this research model are as follows:

“(P1): The use of New Data Sources during decision making will lead to a change in the expert judgement. (P2) expert judgement has a monotonic relation with Maintenance Decisions. (P3) The use of New Data Sources will affect Maintenance Decision Making.”

*\*Monotonic means that if one increases or decreases, the other also increases or decreases respectively.*

Bacharach (1989) describes that a research model has a boundary that is set by the circle that surrounds the variables, as is shown in Figure 16. This boundary consists of assumptions about time, values, and space that need to be specified and controlled for providing a contextual setting to the found results. In this case, the boundary consist of assumptions about the moment of decision making in the decision making model (Figure 4), the chloride-induced corrosion deterioration mechanism that is considered within concrete bridge decks (Table 1), the data sources that are used as cause for observing effects (Table 2), and the decision output that is generally produced by the maintenance engineer (Figure 6). The boundary is fully described in the following chapter.

## 2.6 SUMMARY OF CHAPTER TWO

This chapter has provided an overview of the current situation of bridge maintenance and it's decision-making process through a systems entity framework proposed by Wasson (2006). It continued with a description of the maintenance decision-making process and the scope of this research within this process: the maintenance advice. It proceeded with a description of the decision-making output that is usually provided by decision makers in practice which is build up by the type of maintenance, its urgency, the risk level at the bridge, and sometimes a statement about the rest life of the bridge. These aspects are used as independent variables in the research model for measuring output.

The chapter followed with an overview of a highway overpass and elaborated more on chloride induced corrosion, since this deterioration mechanism is regarded as critical and

relevant in the Netherlands (Dooms B. & Pollet V., 2008). Based on this mechanism, a literature review is performed on applicable condition assessment mechanisms that are currently focused on by researchers.

New data sources are divided into *In-Situ Sensor Systems* and *On-Site Sensing Systems* for creating a consistent definition to both types of sensing methods. *In-Situ Systems* are referred to as embedded sensor nodes into or at the construction that can monitor parameters of a bridge on a continuous (or short term) interval at a singular and local level. *On-Site Systems* are referred to as remote or contact-based systems that need to be operated and can retrieve their data by moving it along the bridge component. Only the applicable systems for chloride-induced corrosion are explained throughout the report, a larger review of systems that could measure other types of deterioration parameters is included in Appendix III Condition Assessment Mechanisms.

Chapter two then continues with a literature review on the expected uses of new data sources. It observes what the pros and cons of visual inspection as the new data sources are, and elaborates on the possible effects of using new data sources in maintenance decision making.

Finally, based on the findings of research question one to three, a research model is presented that explains the expected cause-effect relations between using new data sources and maintenance decision-making, with expert judgement variables as mediator. How it will be tested is described in the following chapter.

### 3. EXPERIMENT METHOD

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This chapter starts with the identification of how the proposed research model with the more general constructs will be made identifiable by variables and testable by hypotheses. It continues with the design of the experiment to design the hypotheses test method and thereafter explains the design of the product that is used as experiment measurement tool by theories of 'serious game' design. The research model lists the hypotheses that can answer the research question. The experiment design creates validity, reliability, and statistical power for determining how these hypotheses will be tested and for the analysis of the results. The serious game section provides the design of the measurement method of the experiment by balancing its realism, meaning, and play.

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"IT'S NOT AN EXPERIMENT IF YOU KNOW IT IS GOING TO  
WORK" – JEFF BEZOS

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### 3.1 OPERATIONALISED RESEARCH MODEL

According to Bacharach (1989), a construct based research model can be decomposed and operationalized by identifiable variables and measurable hypotheses. In the following section, the construct model that is proposed in section 2.5.1 will be decomposed by this theory into variables and the relations between these variables will form the hypotheses that can be quantifiably tested through analysis. The variables are described below.

#### 3.1.1 VARIABLE IDENTIFICATION

##### CONSTRUCT NEW DATA SOURCES –INDEPENDENT VARIABLES

As explained in section 2.4.3, the new data sources are expected to enhance current data through several quality related aspects. These aspects will be used as input values for the research model to make the effects from using new data sources measurable. As also explained in that section, accuracy, consistency, and reliability of the new sensing systems are mostly related to technological development and innovation progress, which is out of the scope of this research. The chosen quality aspects are as follows:

The difference between the current situation with visual inspection data and scenario where new data sources are used as additional data, is that the presented data will be less subjective and more objective due to the quantified values of the deterioration parameters and the ability to observe more parameters. “**Objectiveness of the measurement data**” is therefore the first variable that is introduced into the new data source construct.

There could be a difference between the types of data: In-Situ Sensing Systems measure on a local scale and On-Site Sensing Systems measure on a global scale. This difference will also be tested and is referred to as the “**Locality of the measured sensor data**”.

The third independent variable addresses the differences that may occur when less frequent measurements of the deterioration parameters or more frequent measurements are presented. This variable will be called: “**frequency of the measured data**”.

##### Independent Variables within New Data Sources construct

Var. Name:	Objectiveness of the Measured Data	Locality of the measured sensor data	Measurement Frequency
Comparison:	<i>Visual Inspection versus the use of new data sources</i>	<i>In-Situ Sensors versus On-Site Sensing</i>	<i>Non-frequent On-Site measurements versus frequent On-Site measurements</i>
Levels:	0. Subjective measured data	0. Locally Measured Data	0. Non-Frequent Measurement
	1. Objective measured data	1. Globally Measured Data	1. Frequent Measurements

TABLE 3. INDEPENDENT VARIABLES OF THE RESEARCH MODEL.

## CONSTRUCTS – MAINTENANCE DECISION & EXPERT JUDGEMENT VARIABLES

The dependent variables of the experiment are determined by the possible choices that experts from the field can use during their maintenance decision-making process as is discussed in the ‘Maintenance Advice - Output’ section.

The **maintenance type** and its **urgency** are considered as *dependent variables* from the maintenance decision-making construct. The **risk level estimate** and **rest life estimate** of the bridge component are considered as *mediator variables* from the expert judgement construct.

### OUTCOME VARIABLES

Dependent Variables: Maintenance Decision		Mediator Variables: Expert Judgement	
Type of maintenance	Urgency	Risk Level Estimate	Rest Life Estimate
a) Do Nothing	a) Direct	a) Negligible	a) One year
b) Detailed inspection	b) Within 1 year	b) Limited	b) 1-5 years
	c) Within 2-5 years	c) Increased	c) 5-15 years
c) Preventive maintenance	d) After 5 years	d) High	d) 15-30 years
	e) After more than 10 years	e) Unacceptable	e) 30-50 years
d) Corrective Maintenance	f) Do Nothing		
e) Replacement			

TABLE 4. DEPENDENT VARIABLES OF THE RESEARCH MODEL

The determination of the independent variable levels is done through the use of an Access Database that is used by professionals in the field. This database has standard maintenance advice options stored and thereby relates to reality when used in the research as independent variable levels (Interview Iv-Infra, 19-12-2016).

### 3.1.2 HYPOTHESES

The hypotheses of the proposed research model are based on the relations between the independent variables and the mediator- and dependent variables as is illustrated in Figure 17. The following part lists all hypotheses between the proposed variables into hypotheses, in order to make them testable for answering the main research question. The hypotheses are grouped per proposition and are described accordingly.

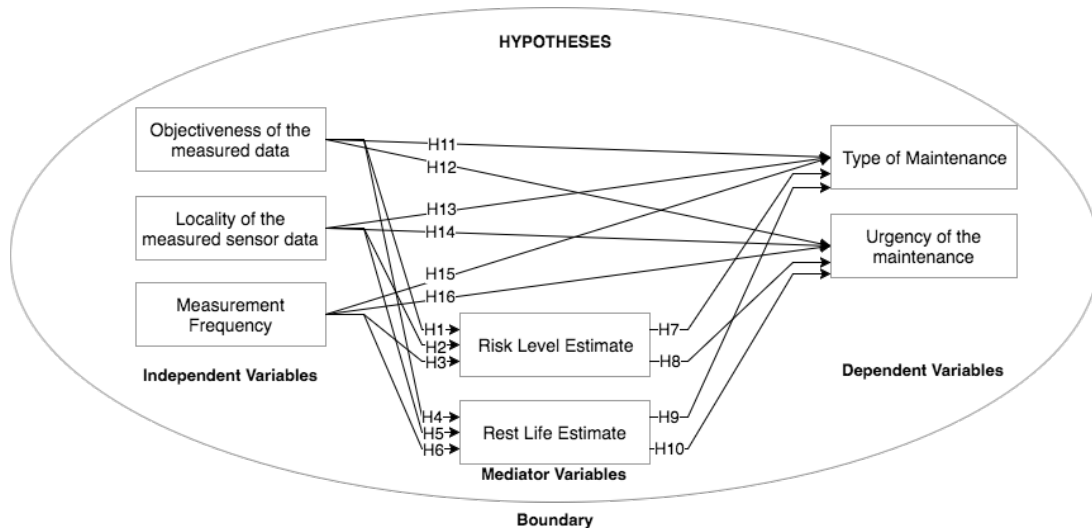


FIGURE 17. RESEARCH MODEL - VARIABLES AND HYPOTHESES

**PROPOSITION 1: NEW DATA SOURCES WILL LEAD TO CHANGED EXPERT JUDGEMENT.**

It is expected that the first variable, objectiveness of the measured data, will increase the perception of risk that an expert has on a situation due to being able to identify potential harmful deterioration parameters more quantitatively. Comparing the situation where the expert estimates the risk level based on current (more subjective) data and when he uses new data sources could test this effect.

**H1.A More objective measurement data lead to higher risk level estimates.**

**H1.Null** *More objective measurement data do not lead to higher risk level estimates.*

When the decision-maker is able to see the full extent of the deterioration instead of a locally measured data point, he will estimate this as higher risk. This can be tested by comparison of outcomes between In-Situ generated data with On-Site generated data.

**H2.A Globally measured data lead to higher risk level estimates.**

**H2.Null** *Globally measurement data do not lead to higher risk level estimates.*

It is expected that more frequent measurements will generate a higher risk perception than low frequency measurements because the expert can observe progression speed of the deterioration better.

**H3.A More frequent measurements lead to higher risk level estimates.**

**H3.Null** *More frequent measurements do not lead to higher risk level estimates.*

It is expected that more objectiveness of the measured data decrease the rest life estimation of the expert towards a deterioration situation due to being able to identify potential harmful deterioration parameters. Comparing the situation where the expert estimates the risk level based on current (more subjective) data and when he uses new data sources could test this effect.

**H4.A More objective measurement data lead to a lower rest life estimates.**

**H4.Null** *More objective measurement data do not lead to a lower rest life*

estimates.

When the decision-maker is able to see the full extent of the deterioration instead of a locally measured data point, he will most likely determine that the structure has a shorter rest life estimate. This can be tested by comparison of outcomes between In-Situ generated data with On-Site generated data.

**H5.A Globally measured data lead to a lower rest life estimates.**

*H5.Null Globally measurement data do not lead to a lower rest life estimates.*

It is expected that more frequent measurements will generate a shorter rest life estimate than less frequent measurements because the expert can observe progression speed of the deterioration better.

**H6.A More frequent measurements lead to a lower rest life estimates.**

*H6.Null More frequent measurements do not lead to a lower rest life estimates.*

## PROPOSITION 2: EXPERT JUDGEMENT HAS A MONOTONIC RELATION WITH MAINTENANCE DECISIONS.

When the decision-maker has perceived a higher risk level, it is likely that he also performs a larger maintenance intervention to improve the condition of the bridge component. The association between the mediator variable and the independent variable can test this.

**H7.A Higher risk level estimates are related to larger maintenance interventions.**

*H7.Null Higher risk level estimates are not related to larger maintenance interventions.*

When the decision-maker has perceived a higher risk level, it is likely that he also wants to perform a maintenance intervention earlier. The association between the mediator variable and the independent variable can test this.

**H8.A Higher risk level estimates are related to a more urgent maintenance interventions.**

*H8.Null Higher risk level estimates are not related to more urgent maintenance interventions.*

When the decision-maker has estimated a lower rest life, it is likely that he also performs a larger maintenance intervention to improve the condition of the bridge component. The association between the mediator variable and the independent variable can test this.

**H9.A Lower rest life estimates are related to larger maintenance interventions.**

*H9.Null Lower rest life estimates are not related to larger maintenance interventions.*

When the decision-maker has estimated a lower rest life, it is likely that he also wants to perform a maintenance intervention earlier. The association between the mediator



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variable and the independent variable can test this.

**H10.A** Lower rest life estimates are related to more urgent maintenance interventions.

*H10.Null* Lower rest life estimates are not related to more urgent maintenance interventions.

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**PROPOSITION 3: THE USE OF NEW DATA SOURCES WILL AFFECT MAINTENANCE DECISION MAKING.**

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If the decision-maker receives more objective measured data, he is able to determine better which type of maintenance action is needed (if any). This results in less detailed inspections and more actual interventions. Next to this, by more objective measurement data, the decision-maker can also see deterioration in earlier phases or by more quantitative values, which is likely to result in an increase in the size of his action.

**H11.A** More objective measurement data lead to larger maintenance interventions.

*H11.Null* More objective measurement data do not lead to larger maintenance interventions.

---

If the decision-maker receives more objective measured data, he is likely to see more quantitative values of deterioration that also results in higher risk and lower rest life estimates. This results in more urgent maintenance actions.

**H12.A** More objective measurement data lead to more urgent maintenance interventions.

*H12.Null* More objective measurement data do not lead to more urgent maintenance interventions.

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When the decision-maker is able to see the full extent of the deterioration instead of a locally measured data point, he will most likely determine that the structures risk is higher and has a shorter rest life estimate. Thus, he will also increase the size of the maintenance intervention and perform this intervention more urgently.

**H13.A** Globally measured data leads to larger maintenance interventions than locally measured data.

*H13.Null* Globally measured data do not lead to larger maintenance interventions than locally measured data.

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**H14.A** Globally measured data lead to more urgent maintenance interventions.

*H14.Null* Globally measured data do not lead to more urgent maintenance interventions.

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It is expected that more frequent measurements of On-Site Systems will generate a higher risk perception than On-Site Systems that only measure once in time because the expert can observe progression speed of the deterioration which induces a higher level of risk and a lower rest life estimate, leading to larger maintenance interventions with more urgency.

**H15.A** More frequent measurements lead to larger maintenance interventions.

<i>H15.Null</i>	<i>More frequent measurements do not lead to larger maintenance interventions.</i>
<b>H16.A</b>	<b>More frequent measurements lead to more larger maintenance interventions.</b>
<i>H16.Null</i>	<i>More frequent measurements do not lead to more larger maintenance interventions.</i>
<i>* H[x].A = Alternative Hypothesis H[x].Null = Null Hypothesis</i>	

### 3.1.3 RESEARCH MODEL BOUNDARY

The research model is tested during the full deterioration cycle of chloride-induced corrosion. This means that it will be tested in multiple cases where bridge decks have deteriorated by this mechanism. These deterioration conditions are determined by the **deterioration phases** of chloride induced corrosion and are retrieved from Table 1 and Table 2. Per phase, the **deterioration progression speed** will be varied as replication of the same deterioration phase and as additional benchmark for determining any effects of using new data sources. The levels of these deterioration aspects are as follows:

SCENARIO VARIABLES

<b>Deterioration Phase</b> (The base condition of the presented bridge component)	<b>Deterioration Speed</b> (Determines the speed of deterioration)
a) Low Chloride Ingress	a) Low Progression Speed
b) High Chloride Ingress	b) High Progression Speed
c) Corrosion	
d) Delamination (and small cracks)	
e) Exiting Damage (large cracks)	

TABLE 5. THE INPUT VARIABLES THAT MAKE UP THE SCENARIOS

### CONTROLLED VARIABLES

To decrease the complexity of the decision making moments and to filter out any interferences from secondary bridge components or other deterioration mechanisms in the decision, only one bridge component with one deterioration mechanism is considered in this research model; the bridge deck with the deterioration phases of chloride induced corrosion. Even with the reduction of complexity, controlled variables are necessary in order to obtain a clear relation between the input variables and the output variables. The following table shows the variables that were controlled during the experiment:

#### CONTROLLED VARIABLES

<b>Physical Properties of the bridge deck</b> <ul style="list-style-type: none"> <li>• Age of the concrete bridge deck (40 years)</li> <li>• Bridge length and width</li> </ul>	<b>Chemical Properties of the bridge deck</b> <ul style="list-style-type: none"> <li>• Oxygen level in the concrete</li> <li>• Humidity level in the air and concrete</li> <li>• pH value in the concrete (around 10 so corrosion is probable by chloride)</li> </ul>	<b>Bridge typology and characteristics</b> <ul style="list-style-type: none"> <li>• Concrete slab bridge deck</li> <li>• Other concurring active deterioration parameters</li> <li>• Theoretical life expectancy of the bridge deck (75 years)</li> </ul>
<b>Other Data Quality Aspects</b> <ul style="list-style-type: none"> <li>• Accuracy of the data (100%)</li> <li>• Reliability of the data (100%)</li> <li>• Completeness of the data (100%)</li> <li>• Timeliness of the data (direct notice)</li> </ul>	<b>Traffic conditions</b> <ul style="list-style-type: none"> <li>• Heavy traffic</li> <li>• Main highway infrastructure: 40 tons</li> </ul>	<b>Environmental situation</b> <ul style="list-style-type: none"> <li>• Av. Daily Temperature (10 to 20 degrees in summer, -10 to -5 in winter)</li> <li>• Winters with use of de-icing agents</li> </ul>
<b>Contract Requirements</b> <ul style="list-style-type: none"> <li>• No closure time fees from client sources</li> <li>• No Budget Limit</li> <li>• Variable maintenance, not fixed maintenance.</li> </ul>		

TABLE 6. THE CONTROLLED VARIABLES DURING THE EXPERIMENT.

#### WHAT CAN THE CONCLUSIONS TO THIS RESEARCH MODEL TELL US?

This experiment is able to specify throughout quantitative analyses whether more objectively measured data will change the outcomes of current decision-making moments within concrete bridge deck maintenance, and aims to observe a direction of this effect. It can specify whether there are differences in the expected usability between locally measured sensor data and globally measured sensor data, and between measuring non-frequently or more frequently by On-Site Sensing Systems. The model does this by measuring a multi-faceted dependent variable selection that forms the foundation of a usual maintenance advice. Two output variables (risk perception and rest life estimate) are considered as more expert judgement based, the other two form the actual maintenance to be performed and are more directly related to existing guidelines and within-organisation protocols (maintenance type and urgency). The hypotheses are tested within all phases and different progression speeds of the deterioration mechanism 'chloride induced corrosion'. If the null hypotheses are rejected, a difference (effect) between the connected variables is measured.

#### WHAT CAN THE CONCLUSIONS TO THIS RESEARCH MODEL NOT TELL US?

The conclusions remain within the boundary of the controlled variables and account only for the observed cases. The research model can give conclusions to observed effects, but

cannot generalise these outcomes to all types of bridges, all types of concrete structures, or all other deterioration mechanisms.

The research model does not include costs, budgeting, or other resource allocations, but specifies only to the necessity of using a maintenance intervention to improve the bridge condition status based on the presented data about a certain deterioration scenario.

The independent variables are categorical and not continuous, which makes them more not capable of specifying how much outcome effects are measured by 'increasing' the category by one independent variable level. The categories are related to the visualisation of the explained data from the condition assessment mechanisms and are thereby not related to quantifiable values. How the data will be visualised is explained in the following chapter.

## 3.2 EXPERIMENT DESIGN

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The following section describes how the above mentioned hypotheses will be validly and reliably tested through experiment design. As described in the research method, an experiment is considered to be the most valuable method for obtaining the results that can test the proposed research model. This paragraph elaborates on the used process for the experiment and how statistical power is created. It explains the scientific measurement method that can obtain the results for analyses and how this analyses are performed. This paragraph thereby enables a measurement tool that can be operationalized through serious gaming theories in the following paragraph.

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### 3.2.1 THEORIES USED

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The experiment has a “within-Subject” or “repeated measures” design as proposed by Field (2013) and Mead (1988). When translated to this research, the maintenance advices from maintenance engineers under different circumstances, where different types of data sources present the same bridge scenario, will be compared to observe whether a change has occurred.

Positive about this method is that it enhances the sphericity of the experiment; this means that there is more equality of variances between the control and treatment situation because the same maintenance engineer performs both (Shuttleworth, 2017). However, care must be taken regarding a possible “learning effect” (which is called fatigue) from the participants between any experiment groups, since this can influence the results (Mead, 1988).

The design of the experiment groups will follow a factorial method where combinations of the levels of independent variables determine the treatments to be conducted in the experiment (Oehlert, 2010). However, in this case a full factorial design requires  $2^3 = 8$  experiment groups (three independent variables with each two levels), which would mean that every same question would be asked 8 times to the same participant which most likely results in large fatigue. Therefore, a fractional factorial design is used to decrease possible fatigue by the reduction of sequences of treatments and thereby also the needed resources for the experiment (Mead, 1988; Sanchez & Wan, 2015). It makes it able to only tests the interesting and relevant combinations of independent variables (Sanchez & Wan, 2015). The selection of these interesting and relevant experiment groups has been made by a trade-off that is explained further in the following section.

Furthermore, to obtain the right statistical power, theories from Field (2013) and Mead (1988) are used for determining the right sample size for an experiment that has no previous data sets available, and with a scarcity of resources. The resource equation and central limit theorem are used as indication of the minimum criteria for the sample size.

Statistical tests are selected from the guidance literature of McCrum-Gardner (2008) and various statistical books that deal with the testing of data are used for more information about the test (Conover & Conover, 1980; Field, 2013; Richardson, 2010). The execution of the tests is performed in SPSS from IBM (2015) with help of structured explanations from Laerd Statistics (2015) and by the SPSS tutorial book of Hinton, McMurray, and Brownlow (2014).

The qualitative data will be obtained by the debriefing theory presented by Hoogen et al. (2016). The theory presents a framework for reviewing a serious gaming experiment by evaluation with the participants. It aims to provide a more robust explanation to the internal and external validity, consistency, generalizability, and future planning of the experiment.

Finally, in order operationalize the experiment into a valid serious game and to make it a valuable tool for measuring output, the Triadic Game Design Framework of Hartevelt (2011) is used because it thoroughly describes a structural method of how to design a serious game properly. This theory will be further explained in the next paragraph.

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### 3.2.2 VARIABLE GROUPING AND DESIGN POINTS

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In order to define the most valuable combinations of independent variable levels, a trade-off has been made between three aspects that influenced this design decision: 1) Throughout perspective of the research model and for testing the hypotheses, it would be most beneficial for measuring all combinations of independent variable levels. 2) However, at the practical side, some combinations of independent variable levels are unrealistic. 3) Too much experiment groups asking the same question likely results in fatigue.

The experiment groups have been defined by iterative interview sessions with experts on the topic and have the following reasoning (Interview Iv-Infra, 16-01-2017; Interview Vergoossen, 20-01-2017):

1. **Visual Inspection** will only be presented as combination of independent variables how they are apparent in the current real world situation. That is; subjective measured data by NEN-2767 standards with a low frequency of measurements of once every five years.
2. It is not likely that **In-Situ** sensors, once embedded and installed, will produce measurement data on a very low frequency (e.g. it is more likely to receive data once per month than once per year or longer). These systems can also not observe the full extent of the structure due to their fixation on, in, or at the structure. Therefore, the **In-Situ** treatment group will have only one (continuous) frequency level of measurements and are considered as objective at one location.
3. **On-Site** Sensing Systems would most likely be used on occasional instances and not on continuous bases. Therefore, a reasonable frequency would be a measurement on a two yearly bases or only one measurement at all. It is also not likely that On-Site mechanisms only measure at one local point since this would be a highly ineffective use of the capabilities; these systems therefore always measure on a global scale.

Throughout the above-mentioned reasoning, the following experiment groups and their related independent variable levels are chosen:

EXPERIMENT GROUPS	Independent variables →		
	Objectiveness	Locality	Frequency
<b>Control Group 0: Visual Inspection</b>  Current Method (visual inspection data)	0	-	0
<b>Treatment Group 1: In-Situ Sensor Systems</b>  Current Method + In-Situ Sensing Mechanisms (chloride & corrosion sensing and frequency based sensing data)	1	0	1
<b>Treatment Group 2: On-site Sensing System (Once)</b>  Current Method + On-Site Sensing Mechanism (GPR contour plot data performed as a single measurement in time)	1	1	0
<b>Treatment Group 3: On-Site Sensing Systems (two yearly)</b>  Current Method + On-Site Sensing Mechanism (GPR contour plot data performed as a two-yearly measurement).	1	1	1

TABLE 7. INDEPENDENT VARIABLE COMBINATIONS INTO EXPERIMENT GROUPS

Now that the four experiment groups are defined, the experiment design points can be formed. Design points make up the “rounds” of the experiment that the participant performs. In this experiment, they consist of combinations of the deterioration phases and speeds, and the method of visualisation by the experiment groups presented in Table 7. The bridge deterioration scenarios exists of the five deterioration phases and the two deterioration speeds, resulting in ten possible scenarios for deterioration, and there are four experiment groups which makes a total of 40 design points per participant. Every design point is coded for easy randomisation later on and represents a measurement on all four dependent variables (risk level estimate, rest life estimate, maintenance type and urgency).

As example: design point 221 represents an experiment round where the bridge has a high amount of chloride ingress that is proceeding slowly and it is visualised through data from visual inspection plus In-Situ Sensing Systems as additional new data source.

EXPERIMENT DESIGN POINTS						
Experiment Groups →			Visual Inspection	Vis. Ins. + In-Situ	Vis. Ins. + On-Site (once)	Vis. Ins. + On-Site Freq.
Scenario Variables ↓			Control group	Treatment 1	Treatment 2	Treatment 3
Det. Phase	Det. Speed		100	200	300	400
Chloride Ingress low	Low	11	111	211	311	411
	High	12	112	212	312	412
Chloride Ingress High	Low	21	121	221	321	421
	High	22	122	222	322	422
Corrosion	Low	31	131	231	331	431
	High	32	132	232	332	432
Delamination	Low	41	141	241	341	441
	High	42	142	242	342	442
Exiting Damage	Low	51	151	251	351	451
	High	52	152	252	352	452

TABLE 8. DESIGN POINTS OF THE EXPERIMENT - EXPERIMENT GROUPS AND DETERIORATION SCENARIO COMBINATIONS

### 3.2.3 EXPERIMENT PROCESS

The experiment will start with a pre-questionnaire to obtain an indication of the participant's knowledge level, understanding of the content to be presented, and expectations towards the experiment. It then proceeds with the pre-briefing with the instructions of the experiment. After the pre-briefing, the main body of the experiment is conducted by randomly letting the participant perform all design points. Per design point, the participant is asked to create a maintenance advice by selecting the appropriate levels of each of the four dependent variables. This process repeats itself for every design point until the final one has been performed. The experiment ends with a post-questionnaire that asks the participant about his or her general opinion of the experiment and the

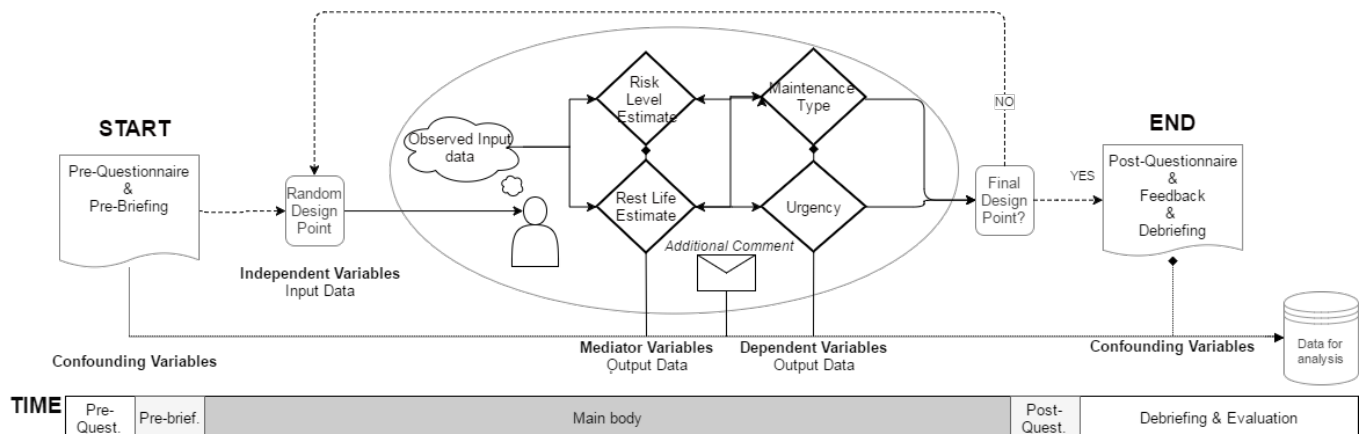


FIGURE 18. THE EXPERIMENT PROCESS, FROM DATA INPUT TO MEASURED OUTPUT (OWN FIGURE).



research subject, after-experiment expectations, and future vision on the subject. Afterwards, the experiment session continues with the debriefing discussion according to the framework of Hoogen et al. (2016).

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### 3.2.4 SAMPLE CHARACTERISTICS

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According to Field (2013), determining a sample size is dependent on the type of experiment, its unit of analysis, and the resources that are available. Generally, a power analysis would have to be performed that is based on a certain expected effect size (Field, 2013). However, when no existing data on research or similar experiments can be attained, there is a scarcity of resources in the population, and no reasonable effect size can be determined by a lack of previous research, other methods can be used as guiding principles for sample size determination. The resource equation method describes the calculation of a sample size throughout a simple formula for within-subject designs. It originated from animal studies where too scarce or too much samples would be highly resource inefficient (e.g. due to possible loss of animal lives)(Mead, 1988). The formula is as follows:  $E = N - B - T$  (Mead, 1988, p. 587).

Where the E is the error degrees of freedom which needs to be between  $10 < E < 20$  for the most resource effectiveness (but with most chance on significant results),  $N = n-1$  is the sample size,  $B = b-1$  is the degrees of freedom for blocking (which is none in this research), and  $T = t-1$  the degrees of freedom for treatments (Mead, 1988). This results in a range of minimum of 13 participants and a maximum of 23 participants for most resource effectiveness.

Furthermore, as a rule of thumb within statistics, the central limit theorem can be used. Field (2013) describes that no matter what distribution the original data has, a sample size of around 30 is sufficient for approximating a normal distribution of the mean of that sample (Field, 2013). Thus for every hypothesis test, a number of at least 30 units of analysis is required at minimum.

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### POPULATION AND REQUIRED SAMPLE PROFILES

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The sample is selected from a population of knowledgeable experts that are acquainted with determining the right maintenance actions for concrete overpasses. Most fitting participants are considered to be maintenance engineers, structural engineers that are involved during maintenance advising, (senior) inspectors, and asset managers (preferably with a technical background). These types of professionals are also used by Terry et al. (2010, p. 1 & 2) in their search for participants for observing best bridge maintenance decision-making practices. The professional perspectives towards maintenance from these professional can be distinguished between highly technical oriented (engineers) to more process, contracting, and costs oriented (e.g. asset managers). Maintenance engineers are regarded as being in the middle of both profiles, they have the capacity to observe the bridge from a technical perspective but also have to translated their advises to a cost and process effective decision (Interview TNO, 23-12-2016).

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### 3.2.5 QUANTITATIVE ANALYSIS – STATISTICAL TEST

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Both questionnaires' results will be given by a descriptive analysis of the measured results by their means, median and standard deviation of the outcomes per question. Also, the used sample and participants are described and elaborated on.

All the dependent variables are of ordinal nature. Urgency and Rest Life Estimate are described in ranges of years which could be arguable as being interval scale rather than ordinal scale, but the ranges of years per variable's levels are not identical in their timespan thus the variables remain considered as ordinal (Field, 2013).

The correct statistical test that is used for this experiment is the Friedman Test and has been chosen based on selection methods from McCrum-Gardner (2008) and Laerd Statistics (2015). The explanation and functioning of the test is provided by statistical books (Conover & Conover, 1980; Field, 2013; Richardson, 2010):

The Friedman Test assumes that the dependent variable data to be tested is ordinal scaled; it assumes that the measured outcomes of the groups are paired (within-subject design); and it assumes that there are multiple groups being compared at once (more than two experiment groups)(McCrum-Gardner, 2008). All assumptions have been met by this experiment design.

The Friedman Test is considered to be the non-parametric alternative to the One-Way Repeated Measures ANOVA (Laerd Statistics, 2015; McCrum-Gardner, 2008). It tests whether there are statistically significant differences between the outcome distributions of the experiment groups and does this firstly by observing if there are any significant differences at all between the groups (Field, 2013). When there is a significant difference, a post-hoc analysis can be performed using pairwise comparisons (Field, 2013). Pairwise comparison means that all the groups are compared to each other and checked for significant differences between them to see which ones differ and which ones do not (Field, 2013).

The Friedman Test adjusts for a phenomenon that occurs when multiple tests are performed at once: the probability of getting a significant result while having performed multiple tests at once is larger than with singular tests, or *"a given alpha for an individual test/comparison may be appropriate, but not for the set of all comparisons"* (Weisstein, 2004, p. 1). This adjustment is made by a Bonferroni correction to the significance of the outcomes of the tests (Conover & Conover, 1980). It divides the alpha value by the number of comparisons being made in order to account for the number of comparisons being performed in the test (Field, 2013). This correction gives the Friedman test an advantage in dealing with Type I errors over singular pairwise comparisons for ordinal data without correction (such as a Sign Test or Wilcoxon Sign Test)(Field, 2013, p. 577).

Furthermore, for Proposition Two (hypotheses seven to ten), analyses are necessary where the association between two ordinal variables is tested. All scales are ordinal and all outcome variables are paired within one observation. These characteristics are the assumptions of the Kendall's tau-b test (Field, 2013). Kendall's tau-b determines whether there is a monotonic relationship between two variables. Its strength over other statistical association tests (such as Spearman's correlation) is that it can deal with ties and is much more accurate (same values between the two variables)(Field, 2013, p. 182). Chances are that the dataset from this experiment includes ties between the outcomes of the experiment groups.

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### 3.2.6 QUALITATIVE ANALYSIS – DEBRIEFING FRAMEWORK

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According to Hoogen et al. (2016), performing a discussion after the performance of an experiment (serious game) with the participant is crucial to explaining any observations, outcomes, or results and to translate the found results better into their context. The framework of Hoogen et al. (2016) consists of nine chronological topics that addresses relevant aspects to reflect on with the participants after performing a serious game, the full framework with the asked questions during the debriefing is provided in Appendix V. It structurally maps out discussion topics for reviewing the game's generalizability, validity (internal and external), sensitivity, and robustness. It also asks for the participant's opinion about using such game as research tool and to give his future vision about the research subject.

From the discussions on these nine addressed topics with every participant, digital minutes (in Dutch) are made per participant. From these minutes, deductive analysis is used to pinpoint all information into concise conclusions. The results from this qualitative study are used to discuss the findings of quantitative analysis, the outcomes of the hypotheses tests, and for the discussion of this research.

After each experiment is played, the participants will be confronted with an evaluation form that lists whether the participant has differed in his maintenance advice between the control group and the treatment groups. This evaluation form is explained at- and presented in Figure 21. It is expected that the use of such evaluation form directly after performing the experiment can enhance the quality of the conversation of the debriefing tremendously, since it provides a topic during the conversation about the actual measured values and performed actions, instead of discussing broadly the general lines of thought of the participant. This method also creates the opportunity to directly point out any strange observations or values in the measured data and to let the participant explain these from his perspective.

### OTHER QUALITATIVE DATA

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For further qualitative analysis, the participants will be granted the opportunity to provide a comment or notation during the experiment for each design point (in Figure 18, this is presented as additional comment). This is included for the participants to clarify their decision, to give comments on the situation, or to comment on the experiment at that specific design point. The outcomes of these notifications will be used during the description of the qualitative results.

### 3.3 EXPERIMENT OPERATIONALISATION: SERIOUS GAME

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“IDEAS DO NOT ALWAYS COME IN A FLASH BUT BY DILIGENT TRIAL-AND-ERROR EXPERIMENTS THAT TAKE TIME AND THOUGHT.” – CHARLES KAO

---

In order operationalize the experiment into a valid serious game and to make it a valuable tool for measuring output, the Triadic Game Design Framework of Harteveld (2011) is used. This framework states that a serious game must be balanced between three “worlds”: reality, meaning, and play.

**Reality** is the perceived realism of the decision-making moments in the game by maintenance experts. It is developed throughout involvement of experts from the field into the design of the game and by using processes, guidelines, and examples from practice.

**Meaning** adjusts the boundary, goals, and content of the serious game to the research model’s boundary, goals, and content. This is achieved by iterative design sessions and by testing until the in-game goals and objectives fit the scope of the propositions from the research model.

**Play** defines how the serious game will be operating functionally and how the actual in-game processes are constructed. This is also achieved by iterations of designing and testing, but is focused on efficient and effective gameplay from a technology and fun point of view.

In order to create a lead in the design of the serious game, some examples have been examined for using their “lessons learned”. These are briefly described below.

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#### 3.3.1 SERIOUS GAMING EXAMPLES

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##### LEEVE PATROLLER (HARTEVELD, 2011)

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The most lessons learned that are used for this research’ game design are mentioned by Harteveld (2011). His book presents a structured method and framework for designing a serious game. In his concluding words, Harteveld (2011, p. 292) sums up important lessons to take into consideration when designing a serious game: it is a multi-perspective and multi-objective problem in a design space of the three worlds Reality, Meaning, and Play. These three worlds need to be balanced for an optimum designed game. It requires trade-offs in the design of a game for dealing with various tensions between the three worlds. Harteveld (2011) expresses that the designing of a game and the balancing of the three worlds is an art form compares it with “magic” or a juggler. With more practice, improved results can be obtained.

Furthermore, Harteveld (2011) says that a too complex game likely results in invaluable output since the relation between the input and output might be diminished by the complexity, but a too simplified game might be too abstract for the participants to identify their real life with. If the participants do not have a clear goal or gaming rules, their scope on the purpose of the game may be misunderstanding the actual problem-solving scope and cause a decrease of valuable output from them. Finally, it is important for the

participant that they can perform all necessary actions and has a certain amount of immersion into the game.

### TNO BRIDGE MANAGEMENT GAME “SO YOU THINK YOU CAN MANAGE YOUR BRIDGE?” (TNO, 2016)

TNO has developed an online game where asset owners have to maintain their bridges during several maintenance cycles. They can choose which type of inspection can be performed, receive an update about the status of the construction or the road, and use this information for a maintenance decision. Costs of the actions versus the available budget, the availability for the traffic on the bridge, and the safety of the bridge have to be balanced for keeping a good score. After every inspection and maintenance round, feedback is given about all three aspects to steer the player into the right direction.

During an interview with one of the creators of the game, it is explained that the meaning of the game's purpose was to let asset owners experience that early investments in costly condition assessment methods can increase the safety later on in the process and causes less use of

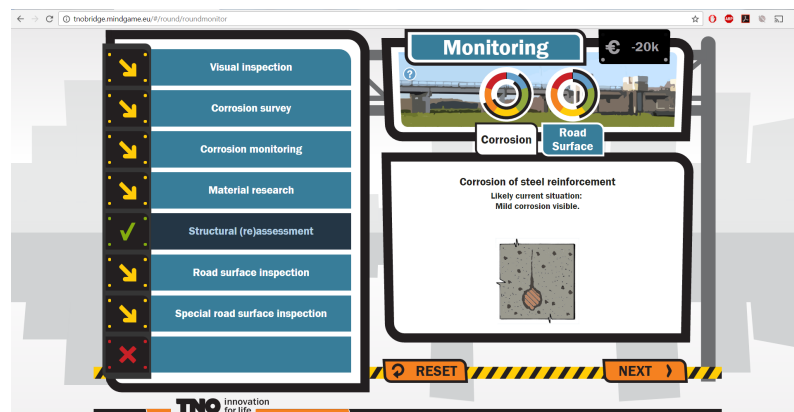


FIGURE 19. SCREENSHOT OF THE GAME OF TNO "SO YOU THINK YOU CAN MANAGE YOUR BRIDGE?" (TNO, 2016)

resources in later stages of the bridge's lifecycle (Interview TNO, 23-12-2016). Unfortunately, the generated output data of this game was not useable for analysis because the game is open for everyone to play (also for people without actual knowledge of bridge deterioration which would influence any valuable output significantly). Next to this, the rules and structure of the game were set up in such way that early investments always won over later investments, this meant that players could improve their score by a tremendous learning effect.

What can be learned from this is that bridge maintenance games are received as fun to play, even without playing in a world where the player can walk around.

### MAINTENANCE IN MOTION - SEWER MANAGEMENT (VAN RIEL, VAN BUEREN, LANGEVELD, HERDER, & CLEMENS, 2016)

van Riel et al. (2016, p. 86 & 87) explains in his lessons learned from a sewer management game that it is important to *"strip the design of the research game to the bone"*. What is meant is that every simplification of the reality towards a basic element (e.g. presented information, gameplay, decision options) should be thought of thoroughly which can be very time consuming. It is mentioned that the simplification of a game design is much harder than increasing complexity (van Riel et al., 2016, p. 86), and with this simplification comes the responsibility to understand the limitations of the decisions. Lesson two is that is important to motivate the decisions that were made during the design of the game; this

creates transparency and is important for explaining validity and reliability to the real world afterwards.

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#### REAL WORLD PROGRAMS AND DECISION MAKING SUPPORT:

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There are two observed instances that are not actually a game but provide valuable and practical guidance to the setup of the serious game. These show working principles from the real world, which can be used as references to setting up the “play” aspect of the game. The first one is the DISK training of Rijkswaterstaat (2017), the second one the assessment and decision making in real life, at the office of an organisation.

#### DISK - TRAINING METHOD & QUESTIONNAIRE

This online questionnaire is used as reference documentation for this research for setting up the types of questions towards maintenance experts. Rijkswaterstaat (2017) uses an online database system, *Data Informatie Systeem Kunstwerken* (DISK), to gather the inspection and maintenance data about their civil infrastructures. A multiple-choice questionnaire has to be filled in order to pass and to be granted access. This test checks the person’s ability to use the system but also general knowledge about civil structures and deterioration. By using consistent definitions with the DISK system (which is NEN-2767), it is expected that maintenance experts of different types of organisations are familiar with the descriptions of the game.

#### DECISION MAKING TECHNOLOGY IN PRACTICE

When observing the current real world assessment process of civil infrastructures, it is noticeable that, on organisational scale, the inspection and condition assessment data is stored and presented in PDF files in separate folders (per civil construction). When assessing a larger areal, multiple folders containing inspection reports are clicked on one-after-one. The important measures and findings from the advisors, inspectors, or engineers are then stored within a database by clicking on predetermined optional answers in an access database. This method seems time consuming and such inefficient method should be avoided or made more efficient in the game for time resource purposes. Further lessons learned from these observations come from real world databases, example inspection reports, and example maintenance advice reports.

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### 3.3.2 SERIOUS GAME DESIGN

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The serious game design has been performed throughout multiple iterations that have been discussed upon, tested with real world experts, and redesigned when necessary. This has led to the game as it is now and this setup is described below per relevant subject. Building a game requires the designing and creation of many aspects; the most important ones are described below.

#### ITERATION 1 – GOALS, RULES, & OBJECTIVES

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The goals, instructions, and objectives of the game have been defined through testing with- and by discussion with two experts in the field of maintenance decision making (Interview Iv-Infra, 16-01-2017; Interview TNO, 23-12-2016; Interview Vergoossen, 24-03-2017). This method of defining the goals and objective was used to increase the level of familiarity from the players towards the content, to include realistic contract requirements, and to give the players an intuitive feel with the game’s descriptions and definitions.

During these sessions, the meaning of the game and the research model was explained to the experts so the overall goal of the research was made clear before making the design. The objectives and instructions to the player are summarised and listed below:

#### SUMMARY INSTRUCTIONS:

- 
- This game consists of question rounds where a maintenance advice is ought to be filled out for an (fictional) asset owner and every round only consist of one decision making moment and the game progresses to another bridge instead of going to a later stage of the same bridge.
  - Every playing round represents one design point from the experiment model, is unique, and is randomly presented.
  - Each round includes one highway overpass bridge deck with a condition status that is based on a deterioration phase and deterioration speed. The condition status is presented throughout one of the types of data source-visualisations (that is: experiment groups).
  - All bridges are 40 years old and preferably need to reach their theoretical end-of-service-life of 75 years before replacement, unless it is not safe to do.
  - A description of the controlled variables is given.
  - The bridge condition may not get below condition score four.
  - The presented data in every round may be considered as true (100% accurate, complete and truthful data).
  - The maintenance advice that is given is about variable maintenance, not fixed maintenance.
  - The maintenance advice can be given throughout a multiple-choice answering panel that includes the maintenance type, the urgency, the risk level estimate, and the rest life estimate. The levels of each variable can be chosen as multiple-choice answer per design point. The player can also give a notation at a blank space below the answering panel (see Figure 20).
  - Every decision type of maintenance will affect the rest life of the bridge according to their impact as it is explained at- and illustrated in Figure 6.
  - Per design point, only one combination of answers in the answering panel is the very best, how much is differed from the predetermined answer model affects the final score.
  - The game does not include costs because it is an advice for the asset owner and he will need to set up a budget according to the maintenance advices.
  - During the game, all instructions from this pre-briefing can be reviewed repeatedly if wished upon.
  - The winner of the game will receive a prize from the asset owner!
-

## ITERATION 2 – FEEDBACK & SCORING

During the design of this scoring method, a problem was stumbled upon. In the maintenance decision-making limitations section in chapter 2, it is explained that there is no consequent definition on when maintenance is good or bad. Secondly, scoring can also over-simplify actual results of the game or the performance of a player (Harteveld, 2011). It therefore ambiguous to include a scoring method, though, giving no feedback at all would be against principles of most learning environments that express the importance of providing feedback to the participant for self-improvement, the game, and for providing a valuable discussion topic (Harteveld, 2011, p. 257).

As solution, a scoring method (based on an American decision model (Krauss et al., 2009, p. 14)) is nevertheless used, but only for introducing a competitive element throughout the participants to enhance their immersion into game, it is not for providing valuable feedback. Instead, afterwards they will be told that their final score is only for fun since it is based on foreign decision-making standards. A possible deception in expectations from the participants is countered with another feedback item, the 'evaluation form':

Ronde 40		Tijd: 2:52:03
Huidig Risico Niveau		Verwachte Restlevensduur vanaf nu (voor onderhoud)
1. Verwaarloosbaar	1. Eén jaar	RESET HIERMEE DE ANTWOORDEN VAN DEZE RONDE!
2. Beperkt	2. 1-5 jaar	
3. Verhoogd	3. 5-15 jaar	
4. Hoog	4. 15-30 jaar	
5. Onacceptabel	5. 30-50 jaar	
Onderhoudstype		Urgentie (jaar van uitvoering)
1. Niets Doen (geen urgentie invullen)	1. Direct	Sla op en ga door naar de Volgende Ronde
2. Nader Onderzoek nodig	2. 0-2 jaar	
3. Preventieve Handeling	3. 3-5 jaar	
4. Correctieve Handeling	4. 6-10 jaar	
5. Gehele dek Vervangen	5. >10 jaar	
Indien gewenst, kunt u hieronder uw instandhoudingskeuze nader toelichten of reageren op deze situatie (houd dit zo kort mogelijk):		

FIGURE 20. DECISION OPTION PANEL PER DESIGN POINT, WITH A BLACK SPACE FOR NOTES FROM THE PARTICIPANT

After conducting the experiment, the participants will receive a form that lists their played outcomes per experiment group per scenario next to each other. This form presents the differences in all four dependent variables by comparing the treatments to the control group. It will be used as introduction to the debriefing after the experiment and it is expected that this method will bring the debriefing discussion directly into depth of the in-game playing experiences.

An example of such evaluation form (for only the maintenance type variable) is given in Figure 21. Every row represents the same scenario of deterioration, the answers that the participant gave through seeing the visualised data from the control group and the treatment groups form the columns. The amount of difference between the groups is denoted by a subtraction in ordinal scale and an intensity of colour is given to the size of this difference, which produces a fast overview for discussion.

Scenarios	Control Group	Treatment 1	Treatment 2	Treatment 3	
1	1. Do Nothing	1. Do Nothing	0 2. Inspection	1 2. Inspection	1
2	1. Do Nothing	1. Do Nothing	0 2. Inspection	1 2. Inspection	1
3	1. Do Nothing	2. Inspection	1 2. Inspection	1 3. Preventive	2
4	1. Do Nothing	2. Inspection	1 2. Inspection	1 3. Preventive	2

FIGURE 21. EXAMPLE EVALUATION FORM FOR MAINTENANCE TYPE OUTPUT FOR FOUR SCENARIOS (THE NUMBERS SHOW THE DIFFERENCES ON THE ORDINAL SCALE AND ARE MADE DARKER ACCORDINGLY FOR FAST OVERVIEW)



### ITERATION 3 - GAMEPLAY & PROCESS

---

It has been chosen that the gameplay will be similar to the online bridge game of TNO (2016). This method of going through “pages” of different decision moments by clicking on decision options is highly effective for storing the output values, is time efficient, and relatable to the current real world on-the-job decision-making. This, unfortunately, reduces the fun part of the game for the players but enhances the realism of the presented cases and lets the participants focus solely on the important aspects of the game and thus reduces confounding variables as ‘possibly going rogue in the game’ (Harteveld, 2011). To still include some fun, cartoons are used about bridge maintenance going wrong to ease up the formality of the game presentation. Due to significant experiences of the researcher with Visual Basic and Microsoft Office Excel, this software package is used for creating the game (Microsoft Office, 2011). The software allows for easy data visualisation and data processing. A description of the working principle of the game is described below, and is illustrated in a flowchart in Figure 22.

#### GAMEPLAY:

---

- The game starts with a welcoming screen and a thank you notification for participating.
  - The game then directly advances to the pre-questionnaire that is used to retrieve the knowledge level of the participants and to see whether they understand the explanations of the data.
  - When the pre-questionnaire has been filled out, the game continues to the pre-briefing and instructions. It consists of the bulletins described in the summarised instructions and makes it a fun story to read. The story is about an incapable asset owner “Harrie” who definitely needs some advice about how to maintain his bridge portfolio and it is up to the participant to do so. This part also elaborates on how the decisions can be performed and what must be and must be not considered during the decision-making.
  - A final moment is given to the participants for last questions to the researcher about the game. The game now starts....
  - The player will be directed to the correct experiment group excel sheet and gets to observe the data, based on the first design point in line of random order. The “engine” of the game that selects the order of the design points consists of a randomiser where the design points are linked to, it is scrambled before each participant starts.
  - The participant can fill out his maintenance advice in a ‘decision panel’ that includes each of the dependent variables of the research model and their ordinal levels. The participant also has the opportunity to fill out a blank section for commenting about his decision or other notifications.
  - After the 40 played design points, the game automatically advances to the post-questionnaire for obtaining immediate feedback on the clarity of the game, objectives, goals, process, and data descriptions, without interruption of the researcher. It also asks for the perceived value of each of the presented data sources during gameplay and asks for feedback from the participant about the realism, expectations, and total game. The participant can leave his e-mail address for receiving an update about the findings from the research.
  - Finally, the game presents the final score of the participant together with the evaluation form. This is the moment that the debriefing commences.
-

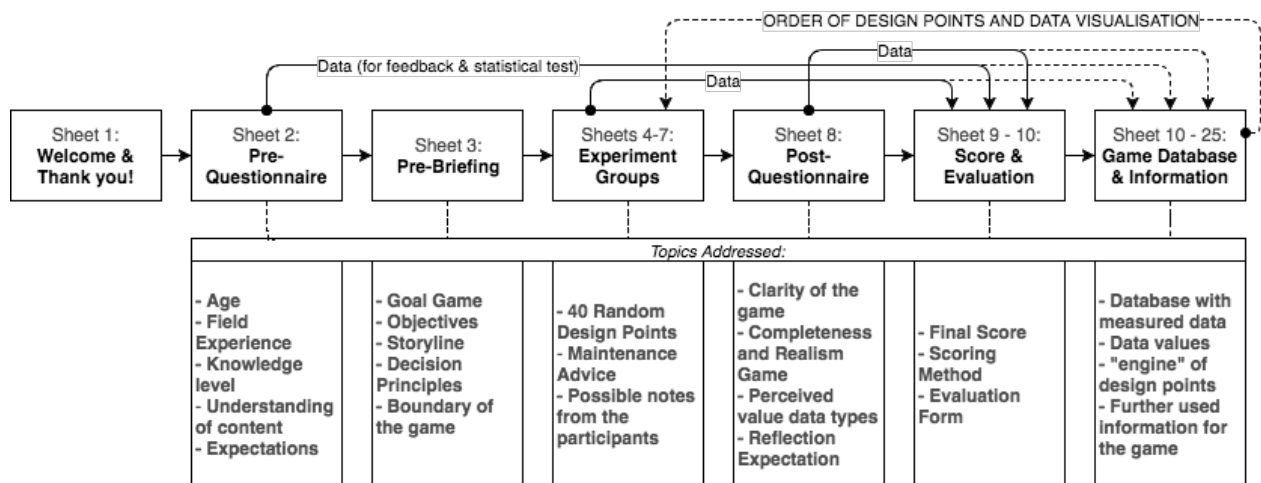


FIGURE 22. EXCEL FILE GAME SETUP FLOWCHART

#### ITERATION 4 – DATA VISUALISATION & MODELLING

The final design iterations defined the data visualisation and how the deterioration scenarios were modelled. The visual inspection data generally is known to maintenance experts and will be visualised throughout NEN-2767 guidelines, which is the broadest used method in the Netherlands (SBRURNET, 2015)

There are no clear examples where NEN-2767 parameters are linked to values from each of the measured parameters from In-Situ or On-Site Sensing Systems. Therefore, general indicators for deterioration are used from formulas and thresholds of deterioration are obtained from standard deterioration laws and guideline documents (Dooms B. & Pollet V., 2008; Siemes, Polder, & Castenmiller, 1999). In order to visualise these in a clear and structured manner, the data presentation approach from Kuckartz and Collier (2016) is used.

In this approach, maintenance decision makers are addressed as being intermediate regarding their knowledge level of important deterioration parameters (since this is part of their job). With this in mind, the data should be visualised explicitly and raw in table- and graphical form, but also with notifications of remarkable values (Kuckartz & Collier, 2016). Threshold levels should be included and the meaning of the data should be described with the data (Kuckartz & Collier, 2016). In general, it is important that descriptions, definitions, text messages, and feedback remains consistent and are clearly expressed between all types of data (Kuckartz & Collier, 2016). The datasets that were used for the game are presented in Appendix VII.

The other In-Situ and On-Site data visualisations are based and extrapolated from the values of the control group dataset.

#### VISUALISATION CONTROL GROUP - VISUAL INSPECTION

The baseline of all presented data visualisation in the serious game comes from the visual inspection data in accordance of principles from NEN-2767 (2016). The visual inspection data has been created with experts from the field (Interview Iv-Infra, 16-01-2017; Interview Vergoossen, 24-03-2017). Together with guidelines from the NEN-2767 (2016), the control group data is composed by the following subjects:

- A general description of the environmental status and risks found in the structure
- The final condition score of the bridge deck by the NEN-2767 conversion table
- The failure type; the deterioration mechanism found by the inspector with a description
- The importance of this failure; the seriousness of the occurring failure
- The intensity of the failure; the shape and stadium of the occurring failure
- The extent of the failure; the size of the occurring failure
- Damage visualisation; a conceptual image of the failure type and intensity
- A location of the damage is given on an image of the bridge deck with red dots

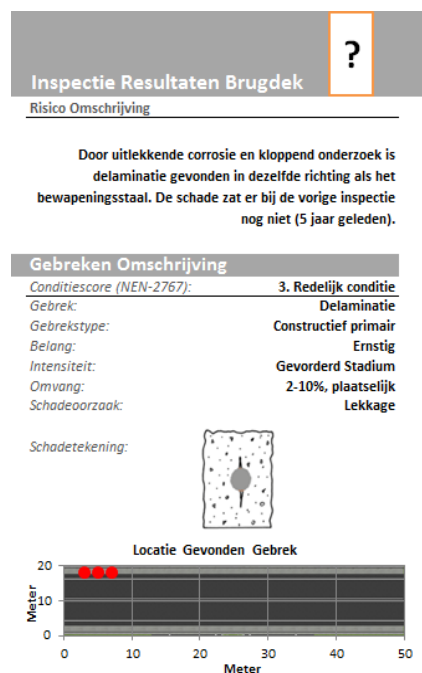


FIGURE 23. CONTROL GROUP DATASET - VISUAL INSPECTION REPORT EXAMPLE. ACCORDING TO NEN-2767 GUIDELINES.

## VISUALISATION TREATMENT GROUP 1 – IN-SITU CHLORIDE & CORROSION & FREQUENCY BASED DAMAGE DETECTION SENSORS

The data visualisation of the **frequency based sensor** is based on theories from Kuleli et al. (2016) that states that the percentage of concrete deck slab-stiffness changes with a percentage of change in damage respectively. Fan and Qiao (2011) expresses how frequency sensors can retrieve the damage location by use of algorithms. Casas Rius and Moughty (2017) show that the data from these sensors can be translated to performance indicator metrics (such as vibrars) and be linked to threshold values.

Based on these assumptions, the frequency based sensing method will express a global location of the damage in percentage of deterioration. The natural frequency of the bridge deck that is used as baseline is 50Hz. Other mode shapes and higher natural frequencies (such as octaves or overtones) are not included for purpose of clarity. The data uses a straightforward approach of indicating the severity and the amount (extent) of the damage in the construction. It compares the latest measured value frequency in hertz with the

original (50 Hz) frequency and calculates the difference and gives this difference percentage amount of damage.

The subjects included in the frequency sensor dataset are:

- Two sensors: A & B, both in the middle of one of the spans of the bridge deck.
- The first measured average baseline frequency (normal natural frequency)
- The last measured average natural frequency
- The amount of deterioration each threshold relates to in line with NEN-2767.
- A graphical presentation of the progression throughout the years of the data (if clicked on the purple box with the sensor name, the graph presents that dataset accordingly).

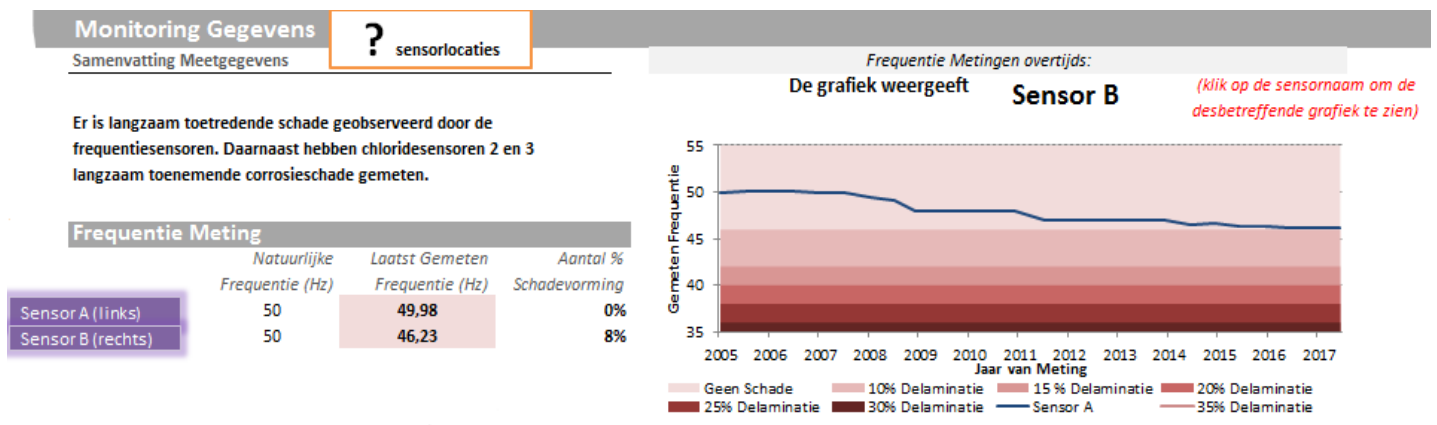
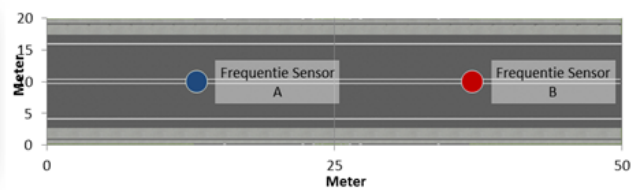


FIGURE 24. TREATMENT GROUP 1 - FREQUENCY BASED SENSING DATASET EXAMPLE

The data of the **chloride & corrosion sensor** is based on the formulas given by Siemes et al. (1999) and Dooms B. and Pollet V. (2008). These data values that are used to indicate chloride ingress or corrosion are the amount of chloride content per mass of cement (%) and the time to corrosion initiation (or if it is already happening). The data is not based on resistivity values from actual output since the latter are less familiar for usage in decision-making and can be converted to the presented ones (Dooms B. & Pollet V., 2008). The threshold value under which no corrosion is expected is 0.4%, and above 1.0% it is sure that corrosion is happening. The progression speed of chloride ingress is presented by the diffusion coefficient in m<sup>2</sup>/s, and is based on different occurring values from practice (Siemes et al., 1999).

The formula that is used to calculate the chloride concentrations and to form the graphs of the data is as follows:  $C(x, t) = C_s - (C_s - C_i) \operatorname{erf} \left( \frac{x}{\sqrt{4De t}} \right)$  (Dooms B. & Pollet V., 2008).  $C(x, t)$  is the chloride concentration on depth  $x$  at time  $t$  after exposure.  $C_s$  is the limit value of the contained chloride content at the outside concrete surface.  $C_i$  is the initial chloride content in the concrete before exposure.  $x$  is the depth below the exposed concrete surface.  $De$  is the diffusion coefficient of the chloride (referred to as ingress speed in

m2/s).  $t$  is the amount of time the concrete surface has been exposed, and  $erf$  is the error function that is used for different types.

The chloride & corrosion sensors system consists of six sensors that are situated at the critical sides of the bridge deck where most of the times chloride induced corrosion is expected (Interview Vergoossen, 24-03-2017). This creates the ability for the participant to observe the location that has the most critical value of chloride ingress of corrosion forming. The following parameters are provided by the chloride and corrosion sensors:

- Six sensors at the sensitive chloride intrusion locations
- The chloride content per mass cement (current value)
- Chance to having corrosion with defined thresholds.
- Calculated time to corrosion (obtained by formula)
- Graphical presentation of each of the sensors overtime (if the participant clicks on the purple box with the sensor's name, the graph goes to that dataset)

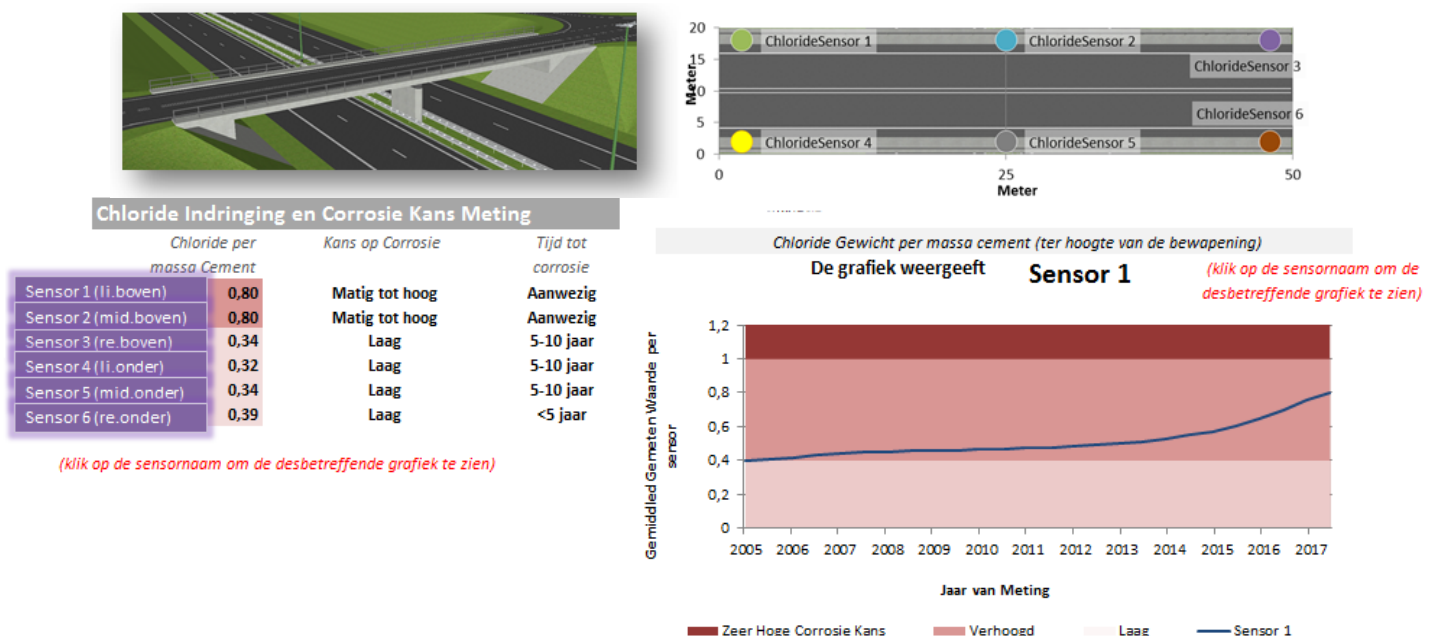


FIGURE 25. TREATMENT GROUP 1 DATASET - CHLORIDE & CORROSION SENSOR EXAMPLE

## VISUALISATION TREATMENT GROUPS 2 & 3– ON-SITE GPR

The visualisation of the GPR data has been based on literature from Gucunski et al. (2016). This article defines a method where a condition score of a bridge deck can be calculated from the measured values of a GPR contour plot. The used formula is as follows: bridge deck condition score =  $\frac{Ag*100+Af*70+Ap*40+As*0}{A_{total}}$ . Where  $A_g$  (area good),  $A_f$  (area fair),  $A_p$  (area poor), and  $A_s$  (area serious) are the areas with GPR signal attenuation with ranges of  $> -15$  dB,  $-15$  dB to  $-17$  dB,  $-17$  dB to  $-20$  dB, and  $< -20$  dB, respectively.

By backwards reasoning, this formula can translate a bridge component condition score from NEN-2767 into a percentage of deteriorated area. The assumption was made that every higher degree of deterioration includes a similar or lesser amount of deterioration area than its lower degrees (Interview Vergoossen, 24-03-2017). The included parameters are as follows:

- Contour plots of the bridge deck (one for Treatment Group 2 and two yearly for Treatment Group 3).
- A legend on how to read the contour plot.
- A table with the amount of deteriorated area percentages.
- A graphical representation of the deteriorated areas.

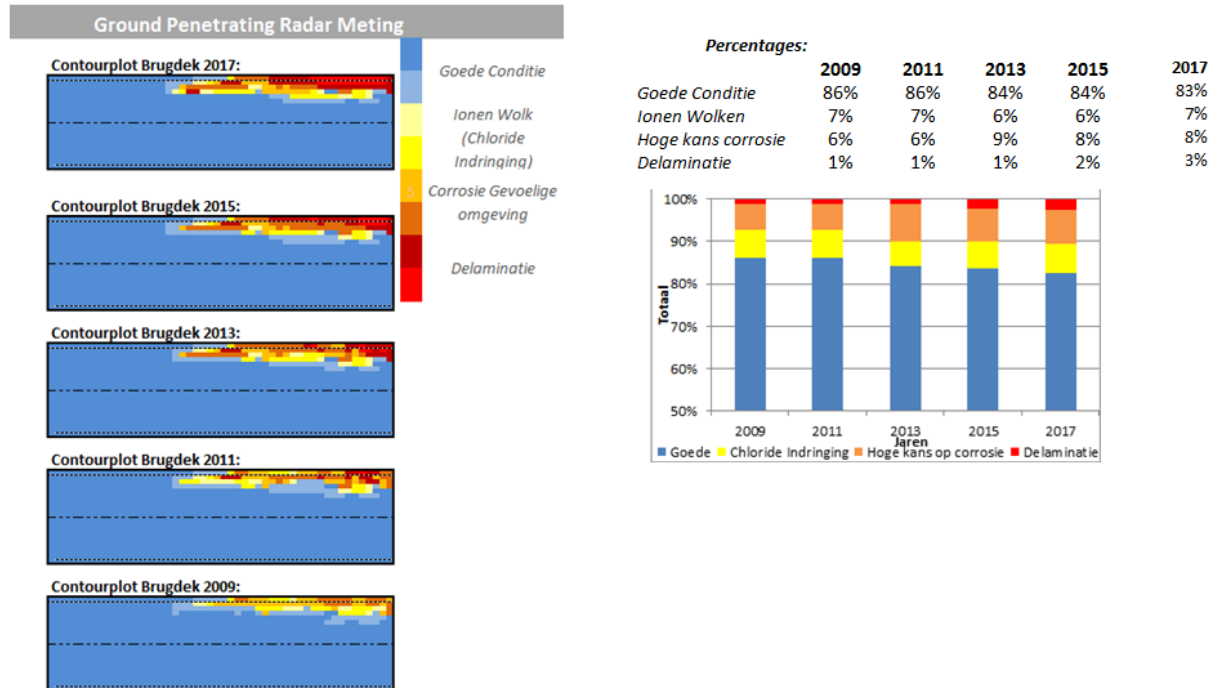


FIGURE 26. TREATMENT GROUP 3 DATASET - GPR EXAMPLE

## 3.4 TESTING & LESSONS LEARNED

Before the final design of the game, multiple tests have been performed. These tests and their lessons learned will be described briefly and chronologically:

### 3.4.1 TEST 1 – LARGE GROUP - STUDENTS

At the very beginning, the game still consisted of an open world with bridges actually built in the sandbox game “Minecraft”. A trial was tested with a large group of students. Not much of the students got to play the game or some went fully rogue inside the open world game. The instructions and goals of the game were unclear and were not understood.

Lesson 1: clear and concise instructions are vital for players to understand a game’s goal and objectives.

### 3.4.2 TEST 2 – SINGLE PLAYER – NON-EXPERT (PROFESSIONAL)

The second test was more effective, it was played with a non-expert in maintenance decision-making, but a professional in the Asset Management market. This person was acquainted with bridge maintenance experts and knows about their daily job functioning. It seemed that the world of Minecraft did not serve any purpose other than distracting the player from what was actually asked from them: namely to observe information & data and form a decision based on that. Minecraft’s only purpose was to let the player would have to “perform” the right maintenance action within the world of where the bridge was situated and to include loads of fun. Therefore, the sandbox game Minecraft was (unfortunately) disregarded.

Lesson 2: forcefully incorporate fun into a game can work distracting from other aspects. In other words: too much play and too less meaning was the result.

### 3.4.3 TEST 3 – SINGLE PLAYER – MAINTENANCE EXPERT 1

The third test was played by an expert and was very productive. Now, the game was created in Microsoft Office Excel only, and the player would receive scenarios of the bridges one by one by clicking through pages within excel. From this test, it was noticeable that the player could be very much distracted when giving too much information at one time. Of the 40 design points, the participant only performed eight since this already lasted 45 minutes due to the amount of data that was included.

INSPECTION REPORT  
GENERAL BRIDGE INFORMATION

BRIDGE 1

Date last inspection: 01-08-2015

Name: Viaduct Kruisweg

Code: V1

Coordinates: x = 82309 y = 20 z = -44422

Age: 30

Length: 80 Minecraft blocks

Width: 30 Minecraft blocks

Thickness: 2 concrete blocks, 1 asphalt block

Bridge Type: Concrete Highway Girder Bridge

Construction type: T-Type

Slope Angle: 30 degrees

SPECIFICATIONS

VISUAL ASSESSMENT

Previous Check	Last Check
Date: 01-08-2009	Date: 01-08-2015

Checklist - Secondary Elements		
Previous Check	Last Check	Remark
Abutment up to standard?	yes	
Drainage qualitative?	yes	
Electric System working?	yes	
Expansion joint functional?	yes	

Inspection Primary Elements		
Previous Check	Last Check	Remark
ASPHALT		
Surface flat?	yes	
User standards met?	yes	
DECK		
Cracks	None	Yes
Extent	-	Regularly
Severity	-	Minor
Corrosion	-	No
PIERS		
Cracks	None	No
Extent		
Severity		
Corrosion		

REMARKS INSPECTOR

Some minor cracks in the Deck have been found. The best guess of the inspector is that is may have occurred due to the opening of the new part of the A+ highway in 2012.

Include an image of the bridge here:




FIGURE 27. TEST 1: AN INSPECTION REPORT OF THE MINECRAFT BRIDGE



Lesson 3: “less is more”; only incorporate the absolutely necessary information in each design point for an efficient gameplay. Too much detail and information leads to distraction of the player from the core meaning of the game.

### 3.4.4 TEST 4 – SINGLE PLAYER – MAINTENANCE EXPERT 2

Another expert performed the fourth test, this time the game was performed fully and it ended with a discussion on the realism and improvement of the damage types and scenarios. The new data sources and the visual inspection documentation were concise but still clear enough for serving their purpose. Small improvements were made in the definitions and the instructions to reduce possible wrongly interpretations of the players. Finally, it was decided that one last test would be conducted with another expert for full confidence of serving a valid experiment measurement tool.

Lesson 4: No matter how much someone thinks a product is finished, when another person takes a look at it he can mostly find ways to improve it.

### 3.4.5 TEST 5 – SINGLE PLAYER – EXPERT 3

A final test was performed and resulted in direct a “GO” for the game to be played by the other participants. Afterwards, during the debriefing, no large improvements were made other than spelling mistakes. The gameplay lasted slightly more than one hour, which was aimed for. The player was not given notice of this being a test upfront. Therefore, the dataset of this person was included in the total dataset. Finally, success!

Lesson 5: “Better be safe than sorry: perform an extra test!”.

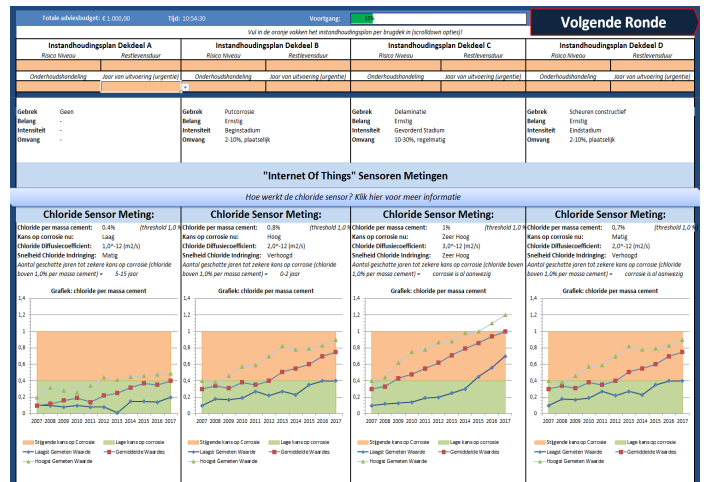


FIGURE 28. TEST 3: TOO MUCH INFORMATION!



## SOME SCREENSHOTS OF THE FINAL VERSION OF THE SERIOUS GAME AND A PHOTOGRAPH OF A PARTICIPANT PLAYING.

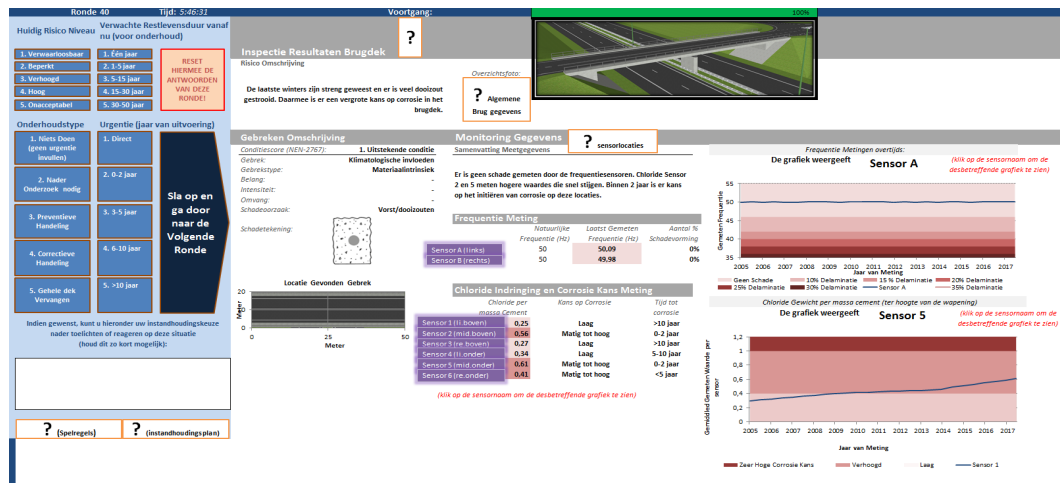


FIGURE 30.SCREENSHOT OF THE FINAL GAME - TREATMENT GROUP 1

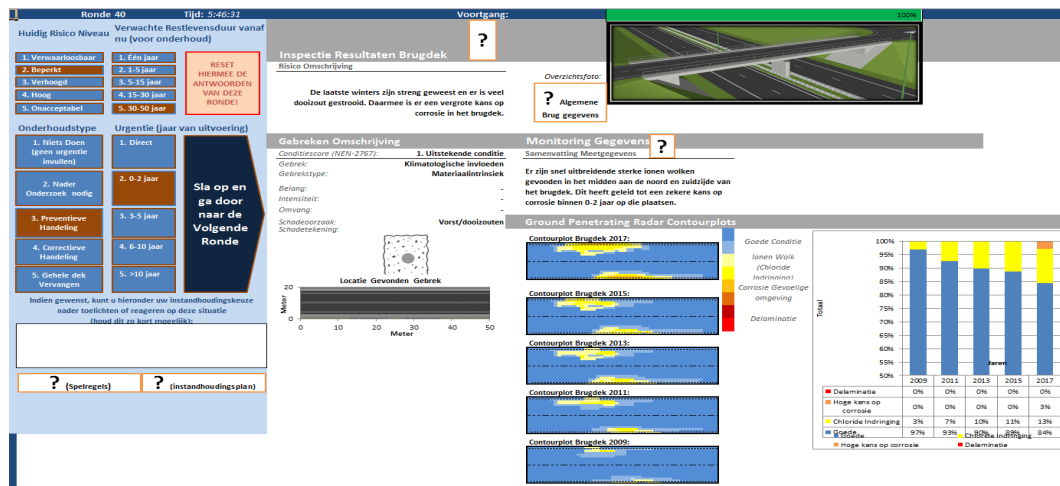
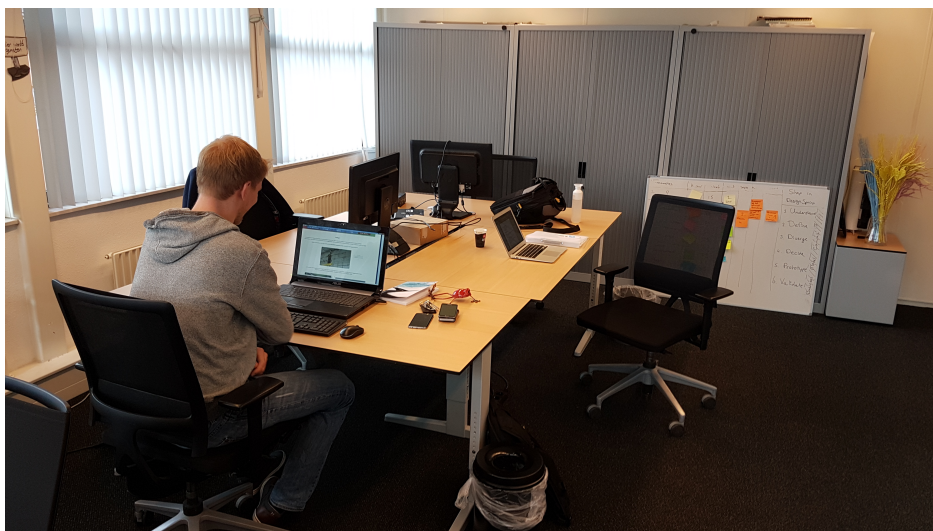


FIGURE 29. SCREENSHOT OF THE FINAL GAME – TREATMENT GROUP 3



## 4 RESULTS

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This chapter will provide an analysis of the obtained results from the experiment game in quantitative and qualitative manners respectively. The chapter starts with some general notes about the experiment, a description of the sample, and the results of the questionnaires to observe if any strange occurrences are expected in the data. Afterwards, the Friedman Test is performed on the outcome data to test the Hypotheses. Then, the debriefing is summarised, the in-game comments and notes of the participants are observed, and the results are summarised. Finally, a post-hoc test is performed for more robustness of the analyses and to exclude other possible results from the measured data. All results form the foundation for the discussion Chapter 5.

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"STATISTICS IS THE GRAMMAR OF SCIENCE." – KARL  
PEARSON

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## 4.1 GENERAL OBSERVATIONS

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### 4.1.1 GENERAL NOTES

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The participants played the game dispersed throughout a timespan of almost two months and were received in a room, or when the researcher visited the participant, it was made sure that a room was available. Upon the start of the meeting, the researcher would set up his computer for the participant to play the game on (or provide the Microsoft Excel game file by USB-stick). The session would start with a small introduction from both persons, after which the researcher insisted to directly play the game before talking about the subject matter since the game and instructions were also included in the document. When the game started, the participant had to finish the pre-questionnaire and instructions before the researcher asked if the participant still had any questions regarding the game. After this, the researcher would leave the room and let the participant play.

Much of the participants did not have any questions before playing; three participants had a question during the playing time. These were left unanswered if these were about the content of the game.

### 4.1.2 SAMPLE DESCRIPTION

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As described, the targeted population exists of knowledgeable experts. Not much organisations are willing to provide multiple experts with a two-hour session for a graduate student. Therefore, a request has been sent towards 42 experts from several organisations. Of the 42 sent invites, 36 responded after two reminders and 19 were willing to participate. Of which two did not make it at the last moment and cancelled. This resulted in a sample size of 17 participants and created a total set of 680 data points for each dependent variable, which results in 170 data points per experiment group per dependent variable. Of the sample, 5 participants are concrete specialised maintenance engineers, 4 participants are (senior) inspectors, 5 participants are concrete structural engineers, 3 participants are asset managers (with previous advisor or technical maintenance expertise). The total years of expertise is 170 years in their current job positions. The shortest period of experience in concrete highway overpass maintenance decision-making was one year but this participant had longer experience with maintenance and concrete structures in general; the longest period of experience was 20 years.

### 4.1.3 OUTCOMES QUESTIONNAIRES

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The sample, mean, standard deviation and median were considered as useful for interpreting the results of these questionnaires, the results are measured on a 5-point scale; 1 being full disagreement and 5 being full agreement (other scales are indicated if these are used). For the outcomes of the questionnaires, SPSS has been used.

	Subject	N = 17	Std.	
			Dev.	Median
PRE-QUESTIONNAIRE	Age in years (ratio scale)	39,1	9,6	39
	Experience in years (ratio scale)	10,0	6,9	9
	Knowledge level of maintenance advice	4,3	1,0	4
	Knowledge level of concrete deterioration	4,4	0,6	4
	Knowledge level on handling with data and reports	4,1	0,9	4
	Understanding of Visual Inspection Data	4,5	0,5	4
	Understanding of Frequency sensor Data	4,3	0,6	4
	Understanding of Chloride sensor Data	4,4	0,5	4
	Understanding of GPR contour plots	4,2	0,5	4
	Expectation of learning something new from the game	3,8	0,8	4
POST-QUESTIONNAIRE	Before-game expectations towards a good score	3,4	0,6	3
	Clarity of the Game Instructions	4,0	0,7	4
	Clarity of the Game Goals	4,1	0,5	4
	Clarity of the Decision Output options	4,2	0,6	4
	Completeness of the in-game Information	3,1	1,1	3
	Realism of the game	3,1	0,8	3
	Actually learned something	3,9	0,7	4
	The game was easier than expected	3,1	0,5	3
	Perceived value of inspection data	3,5	1,0	4
	Perceived value of the frequency sensor data	3,4	1,1	3
	Perceived value of the chloride sensor data	4,2	0,7	4
	Perceived value of the GPR contour plots	3,6	0,9	4
	The level of fun of playing this game	4,4	0,5	4
	After-game expectation towards a good final score	3,1	0,7	3
	Giving a mark to the game (10-point scale)	7,5	0,8	8

TABLE 9. RESULTS OF THE PRE- AND POST-QUESTIONNAIRE

#### OBSERVATIONS PRE-QUESTIONNAIRE:

- The knowledge level of the participants about the maintenance, concrete deterioration mechanisms, and maintenance advice was scored more than sufficient.
- The types of data were understood (a mean above 4 and a median of 4 for every type of data). The participants thus generally scored that they understood what was visualised by all different types of data.
- The expectations towards the learning in the game are higher than the expectation towards the final score (with a mean of 3.8 and 3.4 respectively). The participant seemed conservative in their attitude towards performance.

#### OBSERVATIONS POST-QUESTIONNAIRE:

- The game instructions, goals and decision options were scored as very clear (mean above > 4).
- The perceived realism and completeness of the game information were scored towards neutral (mean of 3.1 for both). This will be addressed during the qualitative debriefing results.

- The participants found that they created insights or learned something by performing the game.
- The game was scored as being not easier than expected, but neutral.
- The perceived values of the data sources were scored all above neutral, with the chloride sensor standing out with a higher mean (above four > 4).
- The game was fun to do, but the expectation after the game towards the final score has lowered compared to the pre-game score expectation averagely.
- The game was graded a 7,5 averagely with an 8 as median.

By means of the general observations and the questionnaires, no highly significant factors were identified that could have a confounding role in the quantitative analysis. This chapter continues with the quantitative analysis.

## 4.2 QUANTITATIVE RESULTS

This paragraph includes the statistical tests that are performed to test the hypotheses. It starts with the Friedman Test and finalises with the Kendall's tau-b test. Note that this alters the chronological order of answering the hypotheses and propositions.

Between the experiment sessions, the researcher performed the statistical tests and it is noteworthy that the results towards the hypotheses tests have not changed significantly after the 10<sup>th</sup> participant when compared to the current results in the quantitative analysis.

By presenting the sample size, mean, standard deviation, and median of the dependent variables per experiment group, differences can be evaluated between the groups. This list is used for answering the direction of which any significant differences are observed during the Friedman Test.

DESCRIPTIVE ANALYSIS	Dependent Var. & Abbreviations	N	Mean	Std. Deviation	Median
0. Control Group	Risk Level E. (Ri0)	170	2,0	1,1	2
1. Treatment Group 1	Risk Level E. (Ri1)	170	2,7	1,0	3
2. Treatment Group 2	Risk Level E. (Ri2)	170	2,6	1,1	3
3. Treatment Group 3	Risk Level E. (Ri3)	170	2,7	1,0	3
0. Control Group	Rest life E. (Re0)	170	4,3	1,0	5
1. Treatment Group 1	Rest life E. (Re1)	170	3,7	1,1	4
2. Treatment Group 2	Rest life E. (Re2)	170	3,8	1,0	4
3. Treatment Group 3	Rest life E. (Re3)	170	3,7	1,0	4
0. Control Group	Maint. Type (MaTy0)	170	2,0	1,1	2
1. Treatment Group 1	Maint. Type (MaTy1)	170	2,7	1,1	3
2. Treatment Group 2	Maint. Type (MaTy2)	170	2,7	1,2	3
3. Treatment Group 3	Maint. Type (MaTy3)	170	2,9	1,1	3
1. Control Group	Urgency (U0)	170	4,1	1,9	4
2. Treatment Group 1	Urgency (U1)	170	3,1	1,6	3
3. Treatment Group 2	Urgency (U2)	170	3,3	1,7	3
4. Treatment Group 3	Urgency (U3)	170	3,1	1,6	3

TABLE 10. DESCRIPTIVE VALUES OF THE EXPERIMENT OUTCOMES.

The statistical results are described below according to the Friedman Test (Hinton et al., 2014). Note that the adjusted significance (Adj.Sig.) is used from the results tables and not the “normal” Significance (Sig.). This is necessary since pairwise comparisons were performed with a Bonferroni correction for multiple comparisons for each dependent variable.

**PROPOSITION 1: NEW DATA SOURCES WILL LEAD TO A CHANGE IN EXPERT JUDGEMENT.**

**RISK LEVEL ESTIMATE – FRIEDMAN TEST**

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Ri0 – Ri1	-1,050	,140	-7,498	,000	,000
Ri0 – Ri2	-,962	,140	-6,868	,000	,000
Ri0 – Ri3	-1,153	,140	-8,234	,000	,000
Ri1 – Ri3	-,103	,140	-,735	,462	1,000
Ri2 – Ri3	-,191	,140	-1,365	,172	1,000
Ri2 – Ri1	,088	,140	,630	,529	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

The Risk Level Estimate was statistically significantly different at the different groups during the exercise intervention,  $\chi^2(2) = 139.132$ ,  $p < .0005$ . Post hoc analysis revealed statistically significant differences in Risk Level Estimate from:

- a) Control Group (Mdn = 2, Mn = 2.0) to Treatment Group 1 (Mdn = 3, Mn = 2.7) ( $p < .0001$ ),
- b) and Control Group (Mdn = 2, Mn = 2.0) to Treatment Group 2 (Mdn = 3, Mn = 2.6) ( $p < .0001$ ),
- c) and Control Group (Mdn = 2, Mn = 2.0) to Treatment Group 3 (Mdn = 3, Mn = 2.7) ( $p < .0001$ ).

But there were no significant differences between Treatment Group 1 and Treatment Group 3, and between Treatment Group 2 and Treatment Group 3 ( $p > .0005$ ).

For the hypotheses, this means the following: there are differences observed when the participants used additional new data sources, when compared to only visual inspection data. Differences between the types of new data sources are not observed.

<b>H1.A: More objective measurement data lead to higher risk level estimates.</b> H1.Null: More objective measurement data do not lead to higher risk level estimates.	NULL REJECTED
H2.A: Globally measured data lead to higher risk level estimates. H2.Null: Globally measurement data do not lead to higher risk level estimates.	NULL NOT REJECTED
H3.A: More frequent measurements lead to higher risk level estimates. H3.Null: More frequent measurements do not lead to higher risk level estimates	NULL NOT REJECTED

## REST LIFE ESTIMATE – FRIEDMAN TEST

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Re0 – Re1	,924	,140	6,595	,000	,000
Re0 – Re2	,824	,140	5,881	,000	,000
Re0 – Re3	,994	,140	7,099	,000	,000
Re1 – Re3	,071	,140	,504	,614	1,000
Re2 – Re3	,171	,140	1,218	,223	1,000
Re2 – Re1	-,100	,140	-,714	,475	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

The Rest Life Estimate was statistically significantly different at the different groups during the exercise intervention,  $\chi^2(2) = 113.278$ ,  $p < .0005$ . Post hoc analysis revealed statistically significant differences in Rest Life Estimate from:

- Control Group (Mdn = 5, Mn = 4.3) to Treatment Group 1 (Mdn = 4, Mn = 3.7) ( $p < .0001$ ),
- and Control Group (Mdn = 5, Mn = 4.3) to Treatment Group 2 (Mdn = 4, Mn = 3.8) ( $p < .0001$ ),
- and Control Group (Mdn = 5, Mn = 4.3) to Treatment Group 3 (Mdn = 4, Mn = 3.7) ( $p < .0001$ ).

But there were no significant differences between Treatment Group 1 and Treatment Group 3, and between Treatment Group 2 and Treatment Group 3 ( $p > .05$ ).

For the hypotheses, this means the following: there are differences observed when the participants used additional new data sources, when compared to only visual inspection data. Differences between the types of new data sources are not observed.

<b>H4.A: More objective measurement data lead to a lower rest life estimates.</b>	NULL REJECTED
H4.Null: More objective measurement data do not lead to a lower rest life estimates.	
H5.A: Globally measured data lead to a lower rest life estimates.	NULL NOT REJECTED
H5.Null: Globally measurement data do not lead to a lower rest life estimates.	
H6.A: More frequent measurements lead to a lower rest life estimates.	NULL NOT REJECTED
H6.Null: More frequent measurements do not lead to a lower rest life estimates.	



**PROPOSITION 3: THE USE OF NEW DATA SOURCES WILL AFFECT MAINTENANCE  
DECISION MAKING.**

**MAINTENANCE TYPE – FRIEDMAN TEST**

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
MaTy0 – MaTy1	-,771	,140	-5,503	,000	,000
MaTy0 – MaTy2	-,835	,140	-5,965	,000	,000
MaTy0 – MaTy3	-,994	,140	-7,099	,000	,000
MaTy1 – MaTy3	-,224	,140	-1,596	,110	,663
MaTy2 – MaTy3	-,159	,140	-1,134	,257	1,000
MaTy2 – MaTy1	-,065	,140	-,462	,644	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

The Maintenance Type was statistically significantly different at the different groups during the exercise intervention,  $\chi^2(2) = 102.475$ ,  $p < .0005$ . Post hoc analysis revealed statistically significant differences in Maintenance Type from:

- a) Control Group (Mdn = 2, Mn = 2.0) to Treatment Group 1 (Mdn = 3, Mn = 2.7)( $p < .0001$ ),
- b) and Control Group (Mdn = 2, Mn = 2.0) to Treatment Group 2 (Mdn = 3, Mn = 2.7)( $p < .0001$ ),
- c) and Control Group (Mdn = 2, Mn = 2.0) to Treatment Group 3 (Mdn = 3, Mn = 2.9)( $p < .0001$ ).

But there were no significant differences between Treatment Group 1 and Treatment Group 3, and between Treatment Group 2 and Treatment Group 3 ( $p > .05$ ).

For the hypotheses, this means the following: there are differences observed when the participants used additional new data sources, when compared to only visual inspection data. Differences between the types of new data sources are not observed.

<b>H11.A: More objective measurement data lead to larger maintenance</b> H11.Null: More objective measurement data do not lead to larger maintenance interventions.	NULL REJECTED
H12.A: More frequent measurements lead to larger maintenance H12.Null: More frequent measurements do not lead to larger maintenance	NULL NOT REJECTED
H13.A: Globally measured data leads to larger maintenance interventions H13.Null: Globally measured data do not lead to different maintenance interventions than locally measured data.	NULL NOT REJECTED

## URGENCY – FRIEDMAN TEST

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
U0 – U1	,785	,140	5,608	,000	,000
U0 – U2	,594	,140	4,243	,000	,000
U0 – U3	,750	,140	5,356	,000	,000
U1 – U3	-,035	,140	-,252	,801	1,000
U2 – U3	,156	,140	1,113	,266	1,000
U2 – U1	-,191	,140	-1,365	,172	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

The Urgency was statistically significantly different at the different groups during the exercise intervention,  $\chi^2(2) = 60.149$ ,  $p < .0005$ . Post hoc analysis revealed statistically significant differences in Urgency from:

- a) Control Group (Mdn = 4, Mn = 4.1) to Treatment Group 1 (Mdn = 3, Mn = 3.1)( $p < .0001$ ),
- b) and Control Group (Mdn = 4, Mn = 4.1) to Treatment Group 2 (Mdn = 3, Mn = 3.3)( $p < .0001$ ),
- c) and Control Group (Mdn = 4, Mn = 4.1) to Treatment Group 3 (Mdn = 3, Mn = 3.1)( $p < .0001$ ).

But there were no significant differences between Treatment Group 1 and Treatment Group 3, and between Treatment Group 2 and Treatment Group 3 ( $p > .05$ ).

For the hypotheses, this means the following: there are differences observed when the participants used additional new data sources, when compared to only visual inspection data. Differences between the types of new data sources are not observed.

<b>H12.A: More objective measurement data lead to more urgent maintenance</b> H12.Null: More objective measurement data do not lead to more urgent maintenance interventions.	NULL REJECTED
H15.A: More frequent measurements lead to more urgent maintenance H15.Null: More frequent measurements do not lead to more urgent maintenance interventions.	NULL NOT REJECTED
H16.A: Globally measured data lead to more urgent maintenance H16.Null: Globally measured data do not lead to different urgency of the maintenance intervention.	NULL NOT REJECTED

**PROPOSITION 2: EXPERT JUDGEMENT HAS A MONOTONIC RELATION WITH  
MAINTENANCE DECISIONS.**

For the remaining hypotheses seven to ten, a Kendall's tau-b correlation was run to determine the relationship between the dependent variables. The test was run for four (hypotheses-based) combinations of the four variables for 17 participants with 680 paired observations.

- a) There was a strong, positive association between Risk Level Estimate and Maintenance Type, which was statistically significant,  $\tau_b = .498, p < .0001$ .
- b) There was a strong, negative association between Risk Level Estimate and Urgency, which was statistically significant,  $\tau_b = -.667, p < .0001$ .
- c) There was a strong, negative association between Rest Life Estimate and Maintenance Type, which was statistically significant,  $\tau_b = -.393, p < .0001$ .
- d) There was a strong, positive association between Rest Life Estimate and Urgency, which was statistically significant,  $\tau_b = 0.510, p < .0001$ .

For the hypotheses, this means the following: there is a monotonic relation observed between expert judgements factors and the maintenance decision factors.

<b>H7.A: Higher risk level estimates are related to larger maintenance interventions.</b> H7.Null: Higher risk level estimates are not related to more maintenance interventions.	NULL REJECTED
<b>H8.A: Higher risk level estimates are related to a higher urgency of the maintenance intervention.</b> H8.Null: Higher risk level estimates are not related to more urgent maintenance interventions.	NULL REJECTED
<b>H9.A: Lower rest life estimates are related to larger maintenance interventions.</b> H9.Null: Lower rest life estimates are not related to larger maintenance interventions.	NULL REJECTED
<b>H10.A: Lower rest life estimates are related to more urgent maintenance interventions.</b> H10.Null: : Lower rest life estimates are not related to more urgent maintenance interventions.	NULL REJECTED

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## 4.3 QUALITATIVE RESULTS

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The qualitative results section presents a summarised description of the findings from the debriefing discussion held after each participant played the serious game. It does so throughout the structured framework of Hoogen et al. (2016). All findings of the debriefing have been written down extensively (in Dutch), this resulted in 60 pages of minutes that are therefore not included in the appendix. All conclusions from these debriefings are described in key points and are included in Appendix V Debriefing Framework and Results.

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### 4.3.1 COOLING DOWN

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Generally, the participants found the experiment fun to do and harder than they expected when hearing about playing ‘a game’ about maintaining bridges. It gave them a good impression of their current decision making process. The level of detail that was included in the experiment astonished some. This astonishment does not reflect in the scoring of realism of the post-questionnaire, it came after explanation of the research model, the intention of the research, and scope of the total research. This made the participants understand better why only the bridge deck and chloride-induced corrosion were chosen.

Much of the participants were also surprised when they saw the differences in output they had given between the experiment groups in their evaluation forms. They did not expect that seeing additional data on top of visual inspection data would deceive them that much. This made a good start for further conversation.

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### 4.3.2 DATA COLLECTION (ASSESSMENT MEASUREMENT VALIDITY)

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The participants knew their role within the game and the instructions were clear (as also presented by the pre- and post-questionnaires). It was clear that the presented deterioration mechanism was chloride-induced corrosion and the types of maintenance were appropriate as decision options. Some participants stated that the answering panel depicted their actual decision-making in practice and that the dependent variables (risk, rest life, type and urgency) were the subjects that were mainly important during actual decision-making. However, the maintenance type variable was not always considered ordinal scaled, since level three (preventive maintenance) and level four (corrective maintenance) were possible to switch position regarding their size of action. This is a serious limitation that will be revised in a Post-Hoc analysis in the discussion chapter. The design decision for using the years as unequal interval (thus ordinal data) is reinforced by the participants; some of them do not use these intervals for planning in actual years but merely for indicative urgencies and prioritisation.

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### 4.3.3 SENSITIVITY (CRUCIAL EVENT DETERMINATION AND OBJECTIVE POSSIBILITIES)

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Much of the participants felt more confident in answering the scenarios along the game progressed. Any lack of confidence was partly caused due to the missing experience with using the new data or by the lack of interaction with other experts to discuss upon the damage and its consequences for the structure. When the participants recalled their decision-making behaviour, the decision type “2. Detailed Inspection” was used a significant amount of times if they were unsure of the presented situation, and most of the

other decisions were largely dependent on the type of damage present in the bridge deck. The participants would not expect large differences in their output values if they would play the game another time, since the damages were clear and the maintenance types were also clear from the start.

Some of the participants did notice some similarities throughout the design points of the game, but due to their random occurrence and other (perceived) small differences it was undoable for them to recall what decision output they had given beforehand. Next to this, the scenarios were presented with different sources of additional data what led to the cause that the participant was forced to observe the scenario from a new perspective (this was mentioned four times). Three participants did not notice large similarities between the scenarios and one was shocked afterwards that he did not notice it at all.

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#### 4.3.4 INTERNAL VALIDITY (HOW DID THE TREATMENT HAVE AN IMPACT, OTHER/CONFOUNDING/ NOISE VARIABLE IDENTIFICATION)

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The most mentioned data elements that were considered as convenient for decision-making were the chloride measurement values, the progression speed of the corrosion, the risk description, and the years to corrosion. The NEN-2767 condition score of the bridge deck was of less interest. Most of the participants used all information that was presented, some of the participants mentioned that they clearly had more focus on the new data sources when these were available and only one mentioned he clearly used the visual inspection data more (because this was more familiar).

More than half of the participants described that the introduction of more (objective) data led to better understanding of the situation and that they had the feeling of being able to determine the right maintenance actions better. They felt more confident upon advising with use of more objective data, but it did not fully eliminate the necessity for expert judgement. Many stated that decision-making remained a form of experience-based craftsmanship, but now enhanced with some additional data.

When asked if the participants took into account the differences in data quality aspects such as the locality of the measured data or the frequency of the measurements, they mentioned that they were aware of these differences but that they were not able to define properly how to decide upon the differences in these aspects. The participants knew about a possible missing information about deterioration due to local measurements from In-Situ data. Nevertheless, they extrapolated the significant deterioration values towards a more global bridge deck area.

Upon asking forward about this they replied that a lack of guidance on how to use the data correctly and no previous experience caused an indifference towards the use of this data. They simply did not have the capacity to know what they should have done otherwise since no practical guidelines from the field were available.

Two participants had previous experience through a test where a GPR system was used and mentioned that during this test they experienced large variability in deterioration values along the bridge span overtime. They concluded that they therefore did not “trust” the In-Situ sensors due to their local measurement and used more detailed inspections during treatment group one (In-Situ) if any deficiencies seemed to occur.

The difference in non-frequent or frequent measurements was considered useful for determining the deterioration progression speed, but it remained difficult to steer on this quality aspect since no clear reference points in the market were available to compare the speed with. Next to this, some participants used the frequency of the measurements rather as a consistency check of the accuracy, reliability, and consistency of the measured data because they did not know if the GPR system would provide reliable data (even though it was clearly stated in the instructions that the data sources were 100% accurate).

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#### 4.3.5 GENERALIZABILITY (IS THIS SAMPLE REPRESENTABLE FOR THE FULL POPULATION)

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The participants expect differences in the maintenance advice per type of professional specialisation, but also expect that the effect that is caused by using new data sources will have similar directions for each participant. They mentioned that the found results more likely grow stronger if significant differences were found based on multiple professions.

The game is, according to the participants, expected to be a good indicator for all types of deterioration that also occur from within a concrete structure and have a time span of several years. This includes carbonation-induced corrosion, alkali-silica reactions, other corrosion related deterioration types, and deterioration through overloading of traffic on concrete girders, columns, or wing walls.

The participants found the content of the game fitted to the research model and to the research question. However, the introduction of bridge components other than only the bridge deck and other types of deterioration would broaden the research model's boundary and thereby increase the generalizability towards the real practice.

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#### 4.3.6 EXTERNAL VALIDITY (IS THE GAME REPRESENTABLE FOR REALITY)

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At this moment during the debriefing, the participants knew the underlying research question and research model. Most of the participants still missed the other interacting bridge components that would have been present in reality but understood that this game was for measuring effect of adding data during decision-making moments, the external validity thereby became defined as high by the participants.

To provide the game of more realism, the following remarks were given: an actual photograph of the deterioration instead of a conceptual image, inclusion of the other bridge components, a budget to operate from, costs & availability criteria of the bridge, less consistency in the presented data (due to dynamic influences from the environment), a possibility of incomplete data (e.g. missing previous inspection data), and more contextual information about the environment of the bridges.

When asked further if these improvements would change the outcome of the experiment, the participants could not define properly what would happen other than the game being more realistic. These changes would not take away the actual on-going deterioration mechanisms at the bridge but only induce more variation in the chances of deterioration, perceived risks, and probabilities during decision-making. The participants thereby expected that the effects of using new data sources were likely to remain apparent.

The descriptions of the scenarios, the deterioration processes, the decision making process and output (answering panel in the game), the data visualisation (numbers, thresholds, and progression speed), and the use of the definitions from NEN-2767 were considered as very realistic in the game and formed a reflection to their current jobs practices.

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#### 4.3.7 PLANNING FOR ACTION

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As answer on the question if the participant can see these new data sources exclude the necessity of visual inspections, much smiles arose among the participants. Most of them see new data sources as great enhancement but they will not provide causal relations between the bridge and its environment. Other participants thought that, if algorithms could detect the cause, it was certainly possible that within the coming ten to twenty years, no more human inspection would be necessary.

One participant also mentioned that current practice is more than good enough, the only innovation or improvement that is needed is the improvement of current documentation and communication methods.

Some participants argued that more objective measurement data will not only affect decision making in the first place, but will have a much greater effect on bringing uniformity in decision making between organisations and even internationally. However, to create uniformity, much more standards and regulations concerning the use of data from new measurement instruments should be defined properly.

Most of the participants also found that expert judgement, even though it is subjective, will always remain in the decision making process. The use of innovative dashboards or data-driven reports will only shift the final verdict of the expert from the assessed object to the office desk. One participant made the comparison with road maintenance and stated that the ARAN system that is used to measure roads has yet to come for bridges. This would create real improvements in all decision-making aspects will.

Finally, some mentioned that they would rather invest in On-Site Systems such as the GPR than in In-Situ systems since hardware and software developments will go so fast, that if In-Situ sensors are finally incorporated in current- long duration- projects they are likely to be outgrown by better and more advanced In-Situ systems.

### 4.3.8 IN-GAME COMMENTS

The comment section did unfortunately not produce any significant new insights that were not explained by the qualitative results or observed in the quantitative results.

Of the 680 measured design points, 113 comments were given (around 17%). The comments seemed to occur randomly within the deterioration phases or deterioration speeds. However, it is noticeable that fewer comments are given during the game progresses:

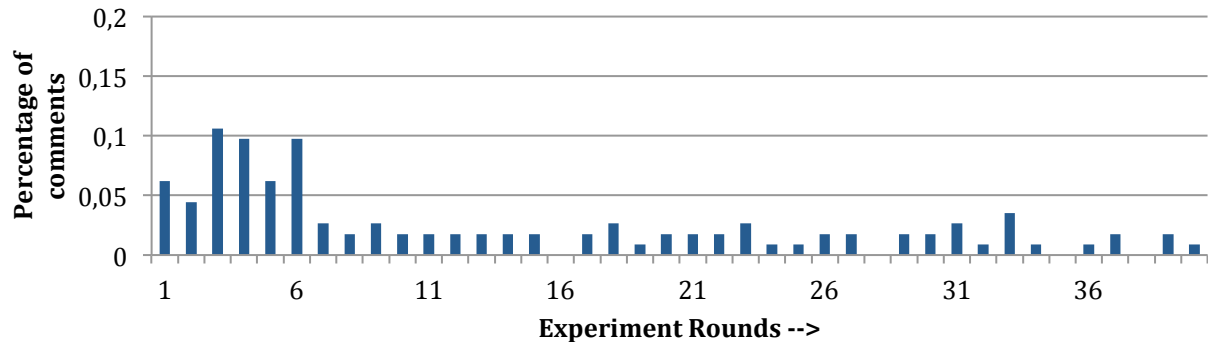


FIGURE 31. COMMENTS PER PLAYED ROUND IN ORDER OF LEFT TO RIGHT

- 47 (42%) of the comments consisted of a description of the situation by the participant and did not add real value to the results.
- 17 (15%) of the comments specified their do nothing maintenance type and explained that they would wait for the next inspection to come.
- 14 (12%) of the comments specified that they wanted their maintenance action to be incorporated into standard asphalt replacement schedule or in the fixed maintenance cycle.
- 14 (12%) of the comments gave explanation of how the advised maintenance action would have to be performed.
- 11 (10%) of the comments gave a direction to the chosen detailed inspection: focus on the chemical properties of the concrete.
- 7 (6%) of the comments gave a direction to the chosen detailed inspection: focus on the physical properties of the concrete.
- 3 (3%) comments indicated that they missed certain data about other bridge components.



## 4.4 RESULTS OF THE ANALYSES

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Three propositions have been tested by 16 hypotheses with a within-subject experiment that was operationalized by a serious game as measurement tool. The propositions are as follows:

*“(P1): New Data Sources will lead to a change in the expert judgement. (P2) expert judgement has a monotonic relation with Maintenance Decisions. (P3) The use of New Data Sources will affect Maintenance Decision Making.”*

### PROPOSITION 1 & 3

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The use of New Data Sources during decision-making have led to a change in expert judgement and affected the maintenance advice, when compared to visual inspection. However, no differences could be observed between the types of different new data sources that were being used. These findings remained consistent and significant for each of the four dependent variables that were filled out by the participants.

It seems that a shift in the data quality from more subjective measurement data towards more objective measurement data has led to larger and more urgent maintenance actions, a higher estimated risk level and lower rest life duration of the bridge deck. However, a shift from local measured data points to globally measured data, or a shift from a single measurement to more frequent measurements has not led to significant changes in the decision making behaviour of the participants.

The post-questionnaire and debriefing endorsed these findings. The participants explained that they used certain indicative deterioration parameters that were quantitatively presented by the new data sources and thereby were better able to anticipate on certain deterioration scenarios. Especially the chloride and corrosion parameters were considered as useful since these values were quite familiar and could be interpreted relatively easy.

No differences in decision making and expert judgement have been found between the categories of new data sources, In-Situ Sensor and On-Site Sensing Systems. This finding is consistent throughout all measured dependent variables.

Explanations from the debriefing show that the participants had no experience with using neither In-Situ Sensor nor On-Site Sensing Systems. This resulted in them handling the data of both sources as similar to each other no matter the locality of the measured data. Even though acknowledging the possibility of finding differences in the deterioration values at different points of the construction, they generalised the deterioration parameter values from locally measured points towards the whole bridge deck. Participants that did have experience with new data sources, namely with GPR, noted that they did behave differently between Treatment group 1 with In-Situ systems and Treatment group 3 with On-Site Systems. They explained that they found the GPR system trustworthy since their previous experience had shown that deterioration can happen very locally and thus can be missed if using only local In-Situ data. The lack of experience and proper methods on how to use these types of data has most probably caused this indifference.

Also, there is no significant difference measured in the participant's maintenance advice when On-Site Sensing Systems have measured once in time or more frequently at every two years.

Most of the participants seemed more focused on the current condition status of the bridge, and in lesser extent on the actual progression speed of the deterioration. Some participants explained that the progression speed of deterioration throughout the data gave them an indication of the deterioration going fast or not, but other used this merely as indication for observing whether the measurement system was consistent and reliable for usage during decision making. Nevertheless, participants were not able to use this data quality aspect optimally due to a lack of proper guidelines; they were not able to determine how fast the deterioration was going without reference point or external written guidelines from standards of deterioration laws, ISO or NEN.

## PROPOSITION 2

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Finally, the measurement that expert judgement has a significant monotonic association with the maintenance that is advised seems sensible according to the participants: if there is more risk and the structure has a lower rest life expectation, a maintenance engineer is likely to adjust his decisions to these by increasing actions and more urgent actions.

Before these results will be discussed in their contextual setting and are reflected on existing theories and literature, a Post-Hoc analysis is performed on the quantitative data. It is presented here since it was raised by discussions or assumptions that were not proposed in the research model, but can increase the robustness of the final conclusions or to exclude the possibility of unnoticed observations from the measured data that could provide for new insights to the final conclusions.

## 4.5 POST-HOC ANALYSIS

During the debriefing and analysis of the results, discussion arose or were found in articles about; the used scale of ordinal data in the maintenance type, about the used methods of statistical tests, and about in which deterioration phases or deterioration speeds the use of new data sources results in having more or less significant effects. A post-hoc analysis will assess per discussion point if such changes in the analysis would influence the outcomes of the experiment.

“STATISTICS DO NOT CONVEY EMOTION. THEY SHOCK US FOR A MINUTE OR TWO, AND THEN WE CLICK AGAIN.” – MADELEIN M. KUNIN

### 4.5.1 ARGUING THE ORDINAL SCALE OF THE MAINTENANCE TYPE VARIABLE

Some of the participants noted that they did not agree upon the order of the ordinal scale of the maintenance type variable. They stated that level three “3. Preventive maintenance” and level four “4. Corrective Maintenance” could be exchanged in size and order. Therefore, a dummy variable is proposed that considers both preventive and corrective maintenance as equal in terms of size of intervening. The dummy variable can thereby be interpreted as the amount of action that is used and if this action intervenes at the condition status of the bridge. The following conversion is used to create the dummy:

Maintenance Type	Amount of action and intervention
1. Do Nothing	1. Nothing (no action and no intervention)
2. Detailed Inspection	2. Small Action but no Intervention
3. Preventive Maintenance	3. Action and Intervention
4. Corrective Maintenance	
5. Replacement	4. Large Action and Intervention

TABLE 11. CONVERSION FROM MAINTENANCE TYPE VARIABLE TO DUMMY VARIABLE.

The results of the Friedman Test with this dummy variable are presented in Appendix VI and are not included here since none of the hypotheses tests were altered by this test. The only observed difference was that the means of the outcomes grew closer to each other, which is likely caused by decrease of levels in the ordinal scale. Nevertheless, all significant differences remained significant. The test had the same sample size as the original Maintenance Type tests.

### 4.5.2 FRIEDMAN TEST AN IMPOSTER? WILCOXON TEST!

Some articles mention that the Friedman Test is an extension of the Sign Test though it is sometimes referred to a being an extension of the Wilcoxon test (Zimmerman & Zumbo, 1993). In general, the Sign Test has less statistical power than the Wilcoxon Test, but they are both used for comparing within subject design experiment group outcomes (Zimmerman & Zumbo, 1993). Due to this discussion, a post-hoc analysis is performed by methods of the Wilcoxon Test throughout the theory of Field (2013, pp. 577 - 581), which describes how pairwise comparison can be singlehandedly performed using Wilcoxon Sign rank tests per paired group (thus testing between every experiment group one by one instead of all in once which the Friedman Test does). It is advised to use this test as well

and to see whether differences occur in the analysis. Again, the results are only presented in Appendix VI since none of the hypotheses tests were altered by the Wilcoxon Sign Rank test. This test included the dummy variable of the maintenance type variable from the previous post-hoc discussion. The test had the same sample size as the Friedman test.

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#### 4.5.3 TESTING PER DETERIORATION PHASE

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Due to the debriefing discussions, an expectation arose that the use of new data sources would have a larger effect in the first deterioration phases than in the later deterioration phases of chloride-induced corrosion due to the deterioration becoming visible for visual inspection. To test this, the data is split into levels of the five deterioration phases; this creates a blocking in the data and affects the sample size that is required for gaining the right power. By performing the resource equation with 17 participants, 5 blockings (the five deterioration phases) and 4 treatments, a dfE of 9 ( $< 10$ ) is obtained, which makes the outcomes of this test not reliable for final conclusions. Therefore, the results of this analysis are not included in the report and are only used as indication to give a direction to future research and cannot be used as reliable statements in the conclusions.

Results of the test show that during the deterioration phases where visual inspection could observe actual deterioration happening (phase three to five), the effects of using new data sources as addition to visual inspection were somewhat less observable than during the phase where visual inspection could not see deterioration happening (especially phase two). Phase one also showed less significant differences between the control group and treatments, it is expected that this has to do with the good condition of the bridge deck irrespectively from what type of data source was presented (thus all groups performing most probably no maintenance).

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#### 4.5.4 TESTING PER DETERIORATION SPEED

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Participants gave notice that, according to them, more frequent measured data only become more valuable than non-frequent measured data when the deterioration speed is higher since it would then be able to identify a more urgent situation. This assumption is tested with the Friedman Test after splitting the data into the levels of the deterioration speed: low (0) and high (1). Now, the sample size is sufficient for concluding upon according to the resource equation since the blocking has only two levels, resulting in a dfE of  $12 > 10$ .

No changes in the results of (all) the hypotheses have been found except for one: at the independent variable urgency at high deterioration speed when comparing treatment group 2 with treatment group 3 (On-Site measured once with On-Site measured two-yearly respectively). All test results are included in the Appendix VI and only the significant one is presented here.

The Urgency was statistically significantly different at the different groups during the fast deterioration speed,  $\chi^2(2) = 50.791$ ,  $p = .009$ . Pairwise comparison revealed statistically significant differences in Urgency from Treatment Group 2 (Mdn = 3, Mn = 3.2) to Treatment Group 3 (Mdn = 2, Mn = 2.6) ( $p = .009$ ), but not when the groups were compared for slow deterioration speeds ( $p > 0.05$ ).

This means that maintenance actions were scheduled more urgent upon seeing high deterioration by more frequent measured data, but not upon seeing low deterioration speed, in that case, more frequently measured data made no difference compared to non-frequent measured data.

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#### 4.5.5 POST-HOC CONCLUSIONS

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The post-hoc analyses have not altered nor changed the final outcomes of the quantitative and qualitative analysis of this research. It has provided a stronger outcome and provided a more detailed view towards the measured results.

It seems that the differences in performing maintenance between visual inspection and the introduction of new data sources still remains significant when both preventive as corrective actions are bundled into one ordinal level. This most likely means that, in most cases, the participants switched their maintenance type decisions from doing nothing to doing something, or from requesting a detailed inspection towards one of the direct actionable maintenance interventions.

Furthermore, the Friedman Test results have been examined by another statistical test with arguably more power, the Wilcoxon Test. No differences were found which means that the results from the original Friedman Test are reliable and can be concluded upon.

Finally, the data has been split into blockings of deterioration phase and deterioration speed to observe if the use of new data sources has different effectiveness for different conditions and scenarios that may occur in the lifecycle of a bridge:

Firstly, there is an expectation that new data sources mostly have an effect when deterioration is otherwise not observable (which makes sense), but this research cannot conclude on these results since a too small sample was available for the many tests that had to be performed out of this dataset. It is advised to perform more research on this topic for further elaboration and validation.

Secondly, the deterioration speed did partly vary the decision making of maintenance engineers upon using new data sources with more frequent data points, but only for the urgency of the maintenance and not the other dependent variables. It seems sensible that being able to observe the speed of deterioration leads to shorter “waiting times/urgencies” for maintenance to be performed when the deterioration speed is faster than slower since the participant was able to observe the speed which he else simply would not be able to. Though, risk level estimation and rest life estimation did not differ significantly, which could also be expected in this case. Again, this could be due to expert judgement within decision-making and the lack of clear guidelines for using new data sources properly. The fact that the maintenance type did not change was expected since the base condition of the bridge deck and the deterioration phase were similar at both deterioration speeds being compared.

## 5. DISCUSSION

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“STORIES CHANGE PEOPLE WHILE STATISTICS GIVE THEM  
SOMETHING TO ARGUE ABOUT.” – BERNIE SIEGEL

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The objective of the research was to assess whether there would be an effect of introducing new data sources during decision-making moments on the decision-making behaviour of maintenance engineers. By means of a theoretical construct research model that was operationalized through measurable variables and hypotheses in a within-subject experiment, data was obtained from real world experts on their decision-making behaviour when new data sources were introduced.

The measured effects are briefly described below per proposition. Hereafter, a reflection of the used literature in this report is performed by comparison with the analysed results.

**Proposition 1 & 3:** It seems that a shift in the data quality from more subjective measurement data towards more objective measurement data has led to larger and more urgent maintenance actions, and a higher estimated risk level and lower rest life duration of the bridge deck. However, a shift from local measured data points to globally measured data, or a shift from a single measurement to more frequent measurements has not led to significant changes in the decision making behaviour of the participants. The participants used indicative deterioration parameters that were quantitatively presented by the new data sources and were better able to anticipate on certain deterioration scenarios. Especially already familiar data types such as the chloride and corrosion parameters were considered as useful since these values could be interpreted relatively easy. **Proposition 2:** when the participants saw more risks by their expert judgement, they tended to increase the maintenance actions and its urgency.

After an extensive literature review, no previous research was found that performed a bridge maintenance decision-making field experiment which used serious gaming as operationalization tool. The discussion of this research is thus not able to compare its results with other found results on similar studies. Therefore, this section elaborates on how the results reflect on the theories from literature presented in Chapter Two.

The results of the experiment seem to be in line with the proposed theory from IBM (2013), which expects maintenance decisions to shift from descriptive to predictive and that it will be performed earlier before failure occurrence. The participants increased the risk level estimate, lowered the rest life estimate, increased the size of maintenance, and performed these more urgent, based on seeing more objective measured data by sensing systems in mostly the first phases of deterioration. The experiment found that the quantitative presentation of certain indicative deterioration parameters increased the levels of the outcome variables by the participants (thus expert judgement and maintenance advice), because the participants were better able to anticipate on the damages. This indicates that preventive measures will be decided upon by maintenance engineers when using new data sources. Though, it depends on the occurring situation whether these preventive measures are always necessary and efficient for that moment. This was not tested by the experiment, but such loss in value is explained by Malings and Pozzi (2016).

Malings and Pozzi (2016) expected that the difference between the observed and actual condition of the bridge component would decrease and thereby also the loss between the impact of the performed maintenance on the bridge condition state and its actual necessity of maintenance. This expectation towards improved maintenance decision-making is mentioned in other literature as well (Ahlborn et al., 2012; Brous et al., 2017; Vaghefi et al., 2012). Unfortunately, this aspect cannot be answered upon by this research throughout definitions of a decrease in loss or by good or bad maintenance decisions.

Maintenance decision-makers seemed to advice upon their maintenance somewhat more conservative when using new data sources, which could lead to either a decrease in loss of the amount of risk in the bridge (good) or an increase in loss of efficiency and effectiveness by too early interventions (bad). This thus solely depends on the given deterioration type, its progression speed, and other influential factors that could occur.

Figueiredo et al. (2013) addressed this problem by mentioning that there is a lack of feedback about current maintenance effectiveness and that more standardised decision-making models must be considered for usage in the market. The findings of the research and the perceived limitation of not being able to measure the 'goodness' of a maintenance decision strongly endorse the statement of Figueiredo et al. (2013). This could bring uniformity in the process of decision making throughout (inter)national markets and improve the effectiveness of the advised maintenance decisions. As additional value, this research found that better maintenance effectiveness determination and improved deterioration threshold identification could also lead to improved identification on how new data sources will influence the maintenance decision making process and thereby create more clarity on their usefulness for the market by more quantifiable or definable indicators of decision-making.

The results do not fully comply with expectations from Zonta et al. (2014), which state that current decision-making is based on subjective and ineffective data from visual inspections and that the use of new data sources could eliminate "guesswork" performed by the decision-makers. Participants mentioned how it felt that they were able to determine how the presented deterioration was affecting the bridge deck better due to the addition of new data sources, but the necessary maintenance type remained difficult to decide upon and remained subjective. The new data sources did not provide any guidance in why the presented deterioration parameter values were apparent at that situation and required the advisor to couple the parameters to possible deterioration causes based on own expertise. It withheld the final decision from being objective by being based on preference and experience, which influences expert judgement. In short: innovative condition assessment mechanisms most probably provide more objective data, but without purposely providing this data in a decision making model or program that provides insights about causal relations between deterioration and its possible cause, the final verdict of the maintenance decision maker is likely to remain subjective.

Furthermore, the experiment results did not agree upon the theory of Mufti et al. (2005), which stated that maintenance engineers would become less conservative and more risk seeking by using new data sources. Though, it could be that this effect only occurs if more experience with using new data sources is obtained by the experts if they are more familiar to seeing deterioration upon these data quality aspects (e.g. more timely, objective). Momentarily, the experts were not familiar with the inclusion of these types of data in their decision information. Most of the times, descriptions are provided about deterioration mechanisms from visual inspectors with possibilities of where the deterioration originated. In-Situ Sensor or On-site Sensing Systems cannot provide these links between failure cause and failure event and require the maintenance engineer to combine the quantified data with the inspection report description from the inspector. They need to determine what these quantified values actually mean in practice, but this remained though since no previous examples were available for the decision-makers. Despite using the arguments for presenting clearly visualised new data sources and meaningful descriptions of this data by Bakht (2005) and Kuckartz and Collier (2016), the



participants still did not know good enough what the data actually represented in reality (in forms of actual deterioration) since they had never used the data before in this way. This could have caused them to fall back in their usual conservative and risk averse decision-making behaviour. As Bakht (2005, p. 321), a professional from the field of using SHM data for monitoring short span concrete bridges, describes this:

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“WHILE THE USE OF THE MOST APPROPRIATE SENSORS TO IDENTIFY THE DEFICIENCY OF A STRUCTURE IS IRREFUTABLE, IT IS ALSO OF PARAMOUNT IMPORTANCE THAT THE DATA COLLECTED FROM THE SENSORS ARE INTERPRETED CORRECTLY.”

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van Riel et al. (2016) used serious gaming to observe how variances in information quality influenced decision outcomes of sewer management engineers. He found that intuitive reasoning and experience are highly present in the sewer maintenance decision-making practice, similar to bridge maintenance decision making. van Riel et al. (2016) explains that for sewer maintenance, the subjective reasoning is caused by the long duration of deterioration mechanisms that disable short feedback cycles which are necessary for increase of effective decision-making. van Riel et al. (2016) does observe in his game that maintenance engineers (when making decisions individually) are able to reduce the amount of failures in sewer systems if they are presented with perfect instead of imperfect data. This could mean that if new data sources create a more true image of the on-going deterioration mechanisms, they could reduce the difference between the observed bridge condition and the actual bridge condition (Malings & Pozzi, 2016). This more complete set of data would therefore likely reduce the amount of failures in the bridge system. This failure reduction is thereby also expected for the bridge maintenance system to happen, since more preventive measures cause more maintenance actions in earlier phases of the deterioration mechanism where current information sources would not result in any intervention. Though, the cost effectiveness of such effect remains unclear.

During the time of this research, another research was performed with a similar objective and experiment method to this research' though it focused on infrastructure road maintenance (Duzgun, 2017). It also conducted a within-subject experiment and it resulted in no measured differences between the use of new data sources and current methods. These results create a contrast with the observations from this research. Explanations for this come from the setup of the data visualisation and the maintenance practice:

Duzgun (2017) research included a deterioration mechanism that was fully measurable and quantifiable by all experiment groups, which was not the case in this research. The treatments of Duzgun (2017) consisted of data parameters that were similar to already known and used data from practice, but were presented throughout the different data quality aspects (objectiveness & timeliness). This research did not use similar data values to practice; it altered the variety of observable deterioration parameter from visual inspection (descriptive) to measured quantified values from In-Situ Sensor and On-Site Systems.

Finally, the methods of how experts assess deterioration and translate these into decisions are different between road maintenance practice and bridge maintenance practice. In road maintenance, the assessment and decision making of maintenance is performed on a

much shorter interval with less decision options to choose from because the deterioration is less complex and less unpredictable than bridge deterioration. Next to this, road maintenance practice is also enhanced by already implemented measurement systems, such as ARAN vehicles which already disrupted the market. Together with the great amount of roads having to be maintained, this technology leap has enabled researchers and engineers to obtain more quantified data points that can be used for more accurate road deterioration models and decision guidelines for road maintenance. In short, it seems that road maintenance decision-making is somewhat more structured than bridge maintenance decision-making by having more knowledge on the deterioration patterns and having a less complex system to decide upon. This more structured practice has most likely led to less observable effects of introducing new data source.

## 6. CONCLUSIONS

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“REASONING DRAWS A CONCLUSION, BUT DOES NOT MAKE  
THE CONCLUSION CERTAIN, UNLESS THE MIND DISCOVERS IT  
BY THE PATH OF EXPERIENCE.” – ROGER BACON

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## 6.1 MAIN CONCLUSIONS

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This research was conducted to assess the effects of using new data sources during maintenance decision-making moments of concrete highway overpass maintenance experts. It presented the current bridge maintenance practice, provided a model of the decision making process of maintenance experts in the field, and explains that decision-making moments of maintenance engineers when determining the advice for maintenance is the main interest of the study. Chloride-induced corrosion within bridge decks of highway overpasses that are situated in the Netherlands was chosen as main deterioration mechanism to focus on. An explanation of the current most used condition assessment mechanism ‘visual inspection’ and other more innovative technology related condition assessment mechanisms that could measure important deterioration parameters from this deterioration mechanism is given. The expected uses of these new data sources were derived from literature review and thereby a testable research model was designed. The research model tests for the propositions between three constructs: new data sources are used as cause of the expected effects and the maintenance decision construct is for observing these effects, expert judgement is the mediator construct between both for additional observation of effects during decision making moments. An experiment method was chosen for testing the proposition and hypotheses in this research model. Through a within-subject experiment design with fractional factorial treatment, four experiment groups were compared that included four types condition assessment mechanisms. The experiment groups are as follows: visual inspection data are used in the control group, In-Situ Sensing Systems with chloride content & corrosion sensor data and frequency-based damage detection data are used as treatment group one, On-Site Sensing System with ground penetrating radar contour plots measured once are used as treatment group two, and On-Site Sensing System with ground penetrating radar contour plots measured every two years are used as treatment group three. The experiment was operationalized by theories of serious gaming in order to simulate the maintenance decision-making moments realistically, meaningfully, and playfully. 17 participants participated in the experiment and were debriefed for explaining the results by reviewing an evaluation form and discussing upon the quality of the experiment.

The main research question and the found results of this experiment are as follows:

*“What is the effect of introducing new data sources during decision-making moments on the maintenance advice from concrete highway overpass experts?”*

The introduction of the more objective new data sources during maintenance decision-making moments of concrete highway overpass experts leads to a significant difference in maintenance advice when comparing this with the use of only less objective visual inspection data. The maintenance decision-moments included different deterioration phases and speeds from chloride-induced corrosion in concrete bridge decks from the Netherlands. The experiment shows that due to the introduction of new data sources, larger and more direct actionable maintenance interventions were chosen, the maintenance was planned more urgent, risks levels were estimated higher, and the rest life was estimated shorter. Maintenance engineers were able to observe the deterioration progression by indicative parameters in earlier phases more quantitatively, and were thereby guided in their expert judgement and maintenance decisions. It seems to have caused them to behave more conscious and conservative in certain situations. The

maintenance decisions were not assessed on their correctness since a lack of decision models that are used in practice made this infeasible.

These findings are expected to be also accountable for similar relatively slow progressing deterioration mechanisms as carbonisation or alkali-silica reactions, as explained by the participated experts, but this has not been examined further in this research.

The introduction of new data sources led to significant differences, but these significant differences were not observed when comparing the new data sources to each other. No significant differences were observed between the outcomes of locally measured In-Situ Sensing System data and globally measured On-Site Sensing System data. Nor differences were observed between non-frequent measured On-Site data and more frequently measured On-Site data, except for one: during faster deterioration progression speed, the urgency of the maintenance grew higher for more frequently measured On-Site data.

The inconsistencies and indifferences between the effects of the new data sources are most likely caused by a lack of experience and a lack of guidelines on how to use these data sources. Participants extrapolated local measured data to the full extent of the bridge area because they did not have previous experience with new data sources and thought this was the 'safest' option. Also, more frequent measurements gave an indication of the progression speed of the deterioration, but the participants sometimes also used the more frequent measurements as consistency check to observe whether the measurement system was reliable (despite being informed that these were accurate, reliable, and consistent during the experiment). When being able to observe faster deterioration through more frequent measurements, the experts did notice the difference and used it as attention point planning the maintenance more urgently.

It seems that the maintenance engineers are generally conservative in their maintenance decision-making behaviour, most likely due to the nature of their daily jobs wherein large negative consequences could result from too risky decisions. When additional deterioration parameters are available during decision-making moments, the experts simply react to these indicators by advising for maintenance interventions immediately without contemplation. It is found that is partly caused by the superficial ability of experts of balancing risks and weighing of decisions, since there is limited knowledge on deterioration and maintenance effectiveness available.

## 6.2 LIMITATIONS OF THE RESEARCH METHOD

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Following from the research model setup, the experiment method, and the serious game design, some limitations were identified that should be kept in mind while considering the conclusion from this research.

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### 6.2.1 LIMITATIONS OF THE RESEARCH MODEL

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There are sometimes vague borders between the data quality aspects, which make some of these not mutually exclusive from one another as they are presented in the research model. As example: more frequent measurements of the data were sometimes not used for the progression speed of the deterioration, but to determine whether the measured values from the sensing systems were consistent in their accuracy and reliability overtime. Thus, the quality aspect that was used as frequency-timeliness related aspect came out as indicator for consistency check of the data, even while the instructions of the game presented that all data was 100% accurate, consistent, and reliable. Therefore, this research concludes by using terms from the data quality aspects in relation with the type of used new data source, simply because a data presentation always includes a perceived form of consistency, reliability, timeliness, and validity to the participants.

Another limitation of the research model is the limited boundary width. The research only tested one deterioration mechanism, while in reality multiple mechanisms could occur or have an simultaneous effect on the bridge. It tested a single bridge component, while in reality the bridge also consists of interactions between bridge components that even could influence the condition of one another. It used singular moments in time where one maintenance engineer was ought to perform decisions, while in reality the decision making is more of a continuous longer lasting process with reviewing moments with multiple experts. This smaller boundary enabled the research to obtain very clearly definable measurements and valid results but it reduced the practical application of these results. Though, it is considered that this decision was appropriate since bridge maintenance decision-making is a complex and relatively unstructured process and should be investigated in a stepwise approach to increasingly include more relevant subjects structurally, especially since no previous research was available to build forth upon.

Finally, new data sources are expected to create more significant effects if they are tested with inclusion of the timeliness aspect over the lifecycle progression of a bridge. More frequent measurements do not only enable the decision-maker to observe deterioration speeds at singular decision moments, but also create shorter measurement intervals. By receiving data on shorter intervals, decision-makers could specify their moment of intervention even better.

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### 6.2.2 LIMITATIONS OF THE EXPERIMENT DESIGN

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During the debriefing, the participants were questioned if they thought they would differ in their maintenance decision making behaviour and expert judgement if they would perform the serious game another time. Almost all participants did not expect any significant changes, but this is a reasonable answer since no expert is likely to question his or hers own consistency in their daily job practice. It is thus not fully reliable to state that the found results would remain consistent under all possible conditions. Another

performed test would exclude this conservative reservation, but this was not performed in this research.

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### 6.2.3 LIMITATIONS OF THE SERIOUS GAMING TOOL

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The data visualisation as presented in the serious game was almost ideal, meaning that it presented the values it was meant to present and did not deceive the participant in any way. In reality, sensing data is much more likely to be influenced by confounding factors and environmental influences. This could create less uniform datasets of the deterioration parameters and likely increases the uncertainty of decision-making. It will most probably require even more knowledge on the interpretation of the data by experts.

Secondly, there was a general consensus from the participants that the currently retained NEN-2767 norm is lacking in clarity of its definitions. They mentioned that the decision to use this method was most probably the best for this experiment since its broad use, but that the content of the NEN-2767 itself is not up to the standards. It leaves descriptions too much open for interpretation; e.g. what does the “final deterioration phase” of a clogged drainage mean? It is expected that more clarity in this documentation standard could lead to more uniform and informed decision-making and lessen the significant differences between visual inspection and new data sources.

Finally, the proposed comment box seemed to be used mostly to describe the situation of the deterioration scenario instead of adding value to the reason why participants chose to perform a certain maintenance option. It is expected that this misinterpretation of the purpose of the comment box was the result of a too broad explanation for it during the game.

## 6.3 IMPLICATIONS OF THE STUDY

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During the research, both practical as theoretical implications were observed. These are described below separately.

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### 6.3.1 THEORETICAL IMPLICATIONS

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New data sources only retrieve quantified data about deterioration parameters, which requires the decision maker to still use his experience and expert judgement capabilities to couple important parameters to possible deterioration causes. This does not eliminate “guesswork” during decision making moments completely, but only provides more data to base this guesswork on which in turn requires also more knowledge on the occurring deterioration mechanisms.

In reality it is expected that much more confounding variables are to be influential in the decision making process. This will most likely make the measurement of any effect of using new data sources on maintenance decision-making less observable and more difficult to define.

The outcomes of this research may also imply that it does not matter what type of information is being presented to maintenance engineers if it’s at least additional data about the on-going deterioration mechanism. It must be stressed that this is an overstatement that cannot be used since other data quality aspects (e.g. accuracy, reliability) are surely present and form influential factors in practice. It is the lack of guidance in decision-making, the lack of knowledge regarding deterioration mechanisms and maintenance effectiveness, and current expert judgement based reasoning that most probably induces the indifference between the used different types of new data sources.

The fact that deterioration mechanisms and maintenance effectiveness are not known ‘optimally’ makes it hard to quantify decision making, which induces not only the subjective expert judgement in decision making but also reduces the ability for new data sources to be better defined or quantifiably expressed in its benefits.

Finally, methods of documentation, data infrastructure, and software technologies used are currently inefficiently organised at organisations. Efficient data management and governance is crucial for facilitating improvements that could make the maintenance practice much more efficient and effective. The focus of improvements has remained mostly on the tangible civil infrastructure and not on the less tangible digital infrastructure, while the ‘era of information technologies’ has already started a more than a decade ago.

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### 6.3.2 PRACTICAL IMPLICATIONS

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There is rather a technology push than a market pull for these types of data measuring innovations for bridge maintenance. Researchers see possible solutions for seemingly problematic occurrences in practice and aim to resolving these problems. However, due to the criticality of the infrastructure within society, and the large costs and risks related to possible failures, research experiments in the real world are difficult, if not infeasible, to perform.



This creates a lack of emerging 'proof of concepts' to bring significant disruption to the market. Most performed tests conclude with large 'ifs' and 'buts' before an technique would become feasible and are only proved throughout small field experiments or laboratory tests. This makes the adoption of innovative and new condition assessment mechanisms similar to the "chicken and the egg" dilemma; the chicken being the currently existing maintenance system entity and the egg a new possible outcome or adoption for new data measuring techniques. More room for adoption is likely created if there are good 'proof of concepts', but good proof of concepts are likely to be created if there is more room for adoption.

Nevertheless, the most straightforward answer in the chicken or the egg dilemma is that the egg came first (Randerson, 2006), which means that in this dilemma the innovations must be given space to be able to improve and adapt to current practices. It requires long term strategic and tactical thinking, it requires cooperation of both researchers as experts from practice, and organisations should not level their expectations on technical innovations bringing the solution to all problems immediately.

Asset owners can facilitate this process by gradually taking baby steps in every tender they put forward and not rush in with too high demands. A safe space needs to be made for technological innovations without applying too much pressure on the direct performance of such systems. They should be used in cooperation and as addition to visual inspections to gradually improve.

Next to this, more thorough cost analyses should be made for new data sources from the 'innovation organisations', as well as descriptions of the impact on current methods and processes. If these innovations have similar costs or fewer costs than current inspection methods, they have a larger chance to be adopted. Such cost analysis can also be improved if there is more focus on creating a feedback loop that considers the effectiveness of the actual performed maintenance interventions.

## 6.4 RECOMMENDATIONS

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To provide a direction to future research and as follow-up research on this topic, the following section provides an overview of the research subjects and possibilities that were encountered during the research.

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### 6.4.1 FOLLOW-UP RESEARCH SUGGESTIONS

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- Firstly, it is recommended that follow-up research should explore a more broadly defined boundary:
  - More deterioration mechanisms with significantly different parameters and characteristics could be incorporated for broader statements about the effects of using new data sources. More new data sources from In-Situ and On-Site Sensing Systems are expected to go paired with this broadening.
  - The full lifecycle of a bridge can be modelled overtime to observe possible effects of continuous monitoring compared to current long interval visual inspection practices. So to include the timeliness aspect.
  - Multiple decision-makers could be used in cooperative decision-making to observe whether effects occur when using more objective data. Such research could observe group dynamics to determine whether more uniform decision-making behaviour occurs or if there is more agreement between participants.
- It is recommended that follow-up research defines the data quality aspects and the enhancement of these by adoption of new data sources more thoroughly. It would increase the insights in where and on what the actual data quality aspects have an influence in the decision-making process and it could give direction towards optimisation of the technological development of new innovative measurement systems. It is envisioned that such research includes experiment treatments where data is presented by multiple levels of accuracy, objectiveness level, or locality. It could be analysed by statistical regression methods (for a within-subject design with ordinal data the generalised estimating equation test could be useful).
- Finally, a simple but effective recommendation would be to perform the experiment again to observe whether the results have remained consistent. This would increase the reliability of the results tremendously.

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### 6.4.2 OTHER RESEARCH SUGGESTIONS

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- To enhance the usability of advanced measurement technologies in current maintenance decision-making, deterioration parameters should be defined more properly in their relation to causes and what values must be used as thresholds for new data sources. There is a large diversity in bridges, environments, usage levels, material types, and construction methods present in the infrastructure market and it is unclear what of these aspects are the main drivers for deterioration to actually happen. Threshold values about when deterioration initiates under different circumstances of combinations of influential factors are currently not defined properly for insightful information. While new data sources are already able to obtain very specific deterioration parameters.

- More research is needed towards a proper method of assessing bridge maintenance effectiveness to enable better decision-making in general and to enable better descriptions of possible influences by new data sources on this process. If more definition could be given to parameters of effective bridge maintenance interventions, and if maintenance interventions would be assessed in their effectiveness in the field, it could enhance the insights of current decision-making by making the performances of maintenance more describable and less a form of craftsmanship. Next to costs and time, other aspects such as risks, aesthetics, durability, and quality should be incorporated into this assessment of maintenance effectiveness.
- Research can be conducted towards creating opportunities within contract-forms, or on how to form a strategy, in order to adopt new data sources more efficiently through cooperation of multiple stakeholders (such as engineer consultancies but also start-ups). Much of the risks and cost-allocations cannot be financed by individual parties, especially not by start-ups, while their contribution to progression, their enthusiasm, and knowledge on innovations is highly important. Special constructs for pilot studies should be made possible by multiple organisations in new forms of more flexible contracts.
- Another suggestion is to define important deterioration parameters and test what their usefulness is in practice if they become available during decision-making; it could define the market's demands better and it could list the current important decision-making parameters used by experts. Current researchers tend to focus on making very sophisticated sensing systems with large technical capabilities to extract as much different deterioration parameters as possible, but thereby create infeasible and unaffordable systems for practice. By defining what deterioration parameters are actually useful in practice, more focused, feasible, and lean sensing systems could be designed.

## 6.5 FUTURE PLANNING AND FINAL NOTES

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The presented game was able to create maintenance advices for 40 bridges relatively easy and fast. The current decision making process could be enhanced by using such structured system that presents condition assessments more interactive, more effective, and can present the visual inspection reports one by one in combination with new data sources (if present) rapidly. It could define crucial bridge components within a larger portfolio on short notice and is regarded as more playful manner of current job practices by the participants.

The game can be used as training device for starters to see whether they have understood their maintenance decision-making courses. It remains difficult to state whether a decision option is good or bad, but with this game, an experienced person can help understand their thinking patterns and adjust these when necessary.

Finally, this tool can be used to question a lot of experts remotely on a large amount of different deterioration mechanisms and damage scenarios. It could follow their thinking patterns and become learning by observation tool, similar to the functioning of Google's image search (which is largely based on people linking tags to photo's). This tool could recognise certain patterns in inspection reports since it is written in NEN-2767 guidelines and therefore is somewhat consistent in definitions for all organisations, and could recognise patterns of deterioration types on photographs. By combining these with new data sources, a Bridge Maintenance Tool can be made for much more efficient bridge maintenance decision-making.

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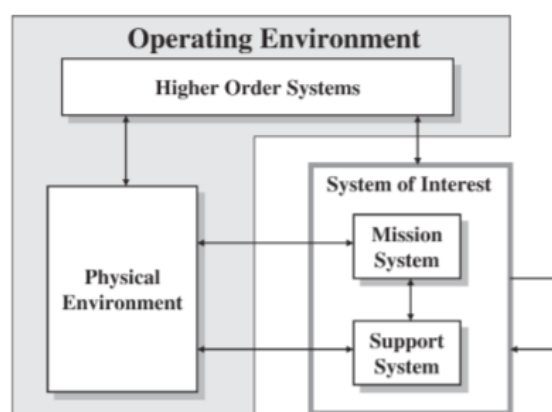
## APPENDICES

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### APPENDIX I BRIDGE MAINTENANCE SYSTEMS ENTITIY EXTENDED VERSION

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By structured methods, an understanding of the complete management system in reality can be made. An interesting and complete method for using such system comes from Charles Wasson (Wasson, 2006), who described this methodology throughout a stepwise guide by defining processes, organisations or other entities as systems with . This methodology is based on some concepts that are relevant for defining a system, which are illustrated in the figure below.



In the first part of his book, Wasson (2005) presents a structured method of defining such system by answering questions that are related to the system entity concept (what is the system), the architecture concept (its form, fit and functioning), the system mission concept (the system's reason for existence), the operation concept (performance based operations and tasks), and finally the capability concept (how to use the integrated set of the system to come to a capability of using).

Maintenance of bridges is a part of the Asset Management of bridges. It includes the following main points: technical knowledge, processes and social interactions, costs, and time. It is a service-based system that includes static concrete highway overpasses and uses allocation of maintenance actions, stakeholders, methods, guidelines, costs, time, and risks to preserve them into safe, functioning, aesthetic, and optimal assets. The mission to do so is to attain the required safety level for the user and minimising risks in the system against as fewer resources as possible. An optimal output is the right maintenance action at the right time. The maintenance system can be divided into different attributes. These attributes are described in the following table:

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#### System Of Interest (SOI)

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##### Personnel

The personnel element consists of all humans with a role within the SOI. They are responsible for accomplishing any performances of the system.

- Asset Managers – decision makers for maintenance actions
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- Engineers – experts on technical specialisations for bridges as assets
- Advisors – experts on specialisations related to bridge deterioration and maintenance
- Inspectors - trained personnel to observe and document the bridge's condition
- Specialised Inspectors – trained personnel that can measure or operate specialised measurement equipment
- Contract managers
- Department Managers – weighing the risks, costs and allocating the resources within an organisation
- Independent Inspection Agencies – engineering consultants
- Personnel of the Contractors – performing the actual maintenance
- Data Analysts
- Data & system administrators of documentation systems

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### **Facilities**

This element consists of all entities that are required to be able to give the SOI a space and location to function.

- Asset owner office
- Engineering consultancy office
- Storage of equipment and maintenance products
- Location of projects (bridges)
- Other equipment locations to secondary system elements (data infrastructure, archives, human resources, office supplies).

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### **Equipment**

The equipment element exists of physical and nonphysical devices that are developed to establish the system's capabilities and performance and are used to operate and maintain the system. It is generally divided into hardware and software devices.

#### *Hardware*

- Inspection Vehicles
- Measurement Equipment (ranging from simple rulers to laser systems)
- Documentation devices (ipad or hardcopy papers)
- Communication devices
- Computers
- Machinery that can help perform a measurement (e.g. concrete core extractors)
- Photo Cameras

#### *Software*

- Bridge Database (e.g. DISK, Bridge Passports, GIS)
- Documentation software (Microsoft Office, pdf-files, dashboards)
- Planning and budgeting tools
- Communications platforms (Forums, E-mail, DISK)
- Illustrative software (Autocad, Revit)
- Modelling and calculating Software
- Specialised Software (risk & probability analysis, 3D-point cloud software, scientific analysis tools for sensors)

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### **Mission Resources**

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The resources consist of all data, consumables and expendables that are required for the *Mission Data Resources*:

The data provides information for the right decision making within the system.

- Design Reports (bridge system documentation)
- Construction Documentation
- Example Projects/Relatable Projects
- Status report of delivery of the bridge
- Status report on the current condition of the bridge (including important deterioration parameters)
- Current Maintenance Plan
- Available Maintenance Options
- Existing Knowledge on deterioration, lifecycles, maintenance effectiveness
- Experience of the Involved Personnel
- Recorded Data (for post-mission performance analysis and assessment)
- Feedback processes and lessons learned (operational, tactical and strategic)
- Post-Maintenance Evaluation data
- Database updates

*Expandable Resources*:

- All products, systems and personnel that can be used and re-used for the SOI to function.
- All types of Personnel
- Equipment, computers, office supplies & vehicles
- Safety equipment

*Consumable Resources*:

- All products or systems (NO PERSONNEL!) that are used within the SOI and thereby also consumed.
- Maintenance Materials (water, cleaning liquids, paint)
- Repair materials (e.g. concrete)
- Energy related resources (fuel, electricity)
- Time
- Money
- Office supplies

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### **Procedural Data**

Procedural data specifies how certain operations and activities can, should, or are to be performed in order to obtain uniform standards, safety, and efficient processes. The most typically used standards and guidelines for bridge maintenance are:

- NEN-2767 (specialised to performing condition assessments)
- Other NEN norms (deterioration parameter threshold values, concrete structures)
- CUR Aanbevelingen 117:2015
- Richtlijnen Ontwerpen Kunstwerken (ROK 1.3:2015)
- ISO55000
- DISK documentation method
- Risk Analysis Frameworks (e.g. RAMS, RAMSSHEEP)

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### **System Responses**

These are the responses that are based on certain events, stimuli or threatening situations that may occur. The responses may be explicit (actions, reports, communications) or

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implicit (perceptions, mental thoughts, behavioural patterns).

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system to support the system mission.

#### *System Behaviour*

The behaviours of the system responses can be strategic, tactical or countermeasures.

- Need for inspection (*strategic*)
- Type of measurement needed (e.g. risk related attention point allocation for inspections) (*tactical*)
- Information Updating and performing re-assessment of risks, future developments, and further deterioration (*strategic*)
- Defining the urgency of the maintenance (*strategic*)
- Defining type of action needed (*countermeasure*)
- Communications between organisations (*strategic, tactical and countermeasure related*)

#### *System By-Products*

- All outputs that cannot be regarded as a system, product or service.
- Communication Documents
- Nuisance & pollution (pollution, noise, time-related, CO2 emissions)
- Unexpected Impacts and events (fire, crash, earthquake)
- Additional (temporary) Constructions

#### *System Services*

- All types of behaviour or other systems that assist the SOI.
- Road Maintenance System
- Traffic Operation System
- National Budget allocating system
- Research Institutes and Organisations

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## **Operating Environment**

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The operating environment is of importance to the observed SOI because this defines higher order systems that may apply forces and directions to the systems functioning and missions. It contains the larger contextual setting with an own solution space and certain amount of influences and significance on the SOI. It can be divided into the higher order domain (other human-made systems) and the physical environment domain (external physical systems).

### **High Order Systems Domain:**

These systems can exist of human made systems, such as organisations or governments with their own goals, missions and rules for operating, and physical or natural laws context systems, such as physics or climates.

#### *1. Roles and Missions*

- The higher order system role and mission is to assure the full functioning and safety of the infrastructure in the Netherlands
  - National and International standards and guidelines for infrastructure
  - International Trade and Climate Goals
  - Independent assessments of other organisations on the bridge condition
  - Road Safety and Functioning
-

- Efficient and Effective Maintenance Execution

## 2. *Organisational Structure*

- National Government
- European Government
- Road Infrastructure Asset Management Organisations
- Contractors

## 3. *Operating Constraints*

- National and International Laws
- Regulations, standards (related to procedural data) and other guidelines
- Subjective output from the inspector during condition assessment
- Hierarchical systems and perceived reliability of advice (between manager and advisors, inspectors and advisors, within organisations and between organisations)
- Contractual demands and regulations
- Stakeholder agreements and preferences
- Organisational and Inter-organisational Budget and time allocations
- Penalty systems for bridge closures
- Black Swans or unexpected events

## 4. *Resources Element*

- National, Organisational, Department budget allocations
- National, Organisational, Department time availability
- National, Organisational, Department personnel (with expertise)
- Available materials
- Measurement devices
- Momentary general knowledge status about deterioration and maintenance types

## **Physical Environment**

### 5. *Human-Made Systems*

- Nearby users or user types of the bridge (agricultural, heavy transport, chemical transport)
- The type of urban environment (neighbourhood, city centre)
- Aesthetic environment
- Existing Economical system and tax payment systems
- Traffic changes in frequency, speed and loads
- Transportation Network Area

### 6. *Natural Environment*

- Location of the asset (geographical)
- The climate zone and conditions of the location
- The average wetting/drying cycle on the bridge
- Protected Archaeological or animal based environments
- Location of the facilities of the system

### 7. *Induced Environment*

- Traffic Load increase
- Use of de-icing agents
- Carbonation effect in the air
- Extreme events such as fires, flooding, earthquakes or long-during extreme weather influences.
- Unbeneficial maintenance procedures by external parties

### 8. *Operating Environment Decision-Making Methodology*

This element is responsible for identifying all operating environment conditions and to described the technical parameters that characterise these, and then making able that



these are incorporated into the performance indicators of the SOI. It can use multiple levels of abstraction to do so, from the part within a bridge system to the fully abstract level of the higher order system domain.

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## **The System Interface**

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The system interface is a crucial part for a system, it is the factor that drives the system's success throughout the interoperability with other external systems in to give protection against threats and it ensures survivability. The system interface is the composition of the system's architecture, which means that it describes the interacting between the elements that are listed in the system's architecture and also how they interact with their operating environment. These interactions have some objectives; to physically link system elements, to adapt incompatible system elements, to buffer the effects of incompatible elements, to leverage human capabilities, and to restrain system elements for their usage (when needed). These interface can take up three forms; active interfaces (responding and interacting in two ways), passive interfaces (only receiving without response), and a combination or active/passive interfaces (such as walkie-talkies where communication is always received, but to respond one has to press a button). There are two types of interfaces; physical and logical. These will be subsequently assessed and elaborated for the SOI.

### **Logical Interfaces**

The logical interfaces represent a direct relationship between two points and under what conditions these relationships or communications occur, and when it occurs.

- From measurement or observation to communication and information document
- Communication from one personnel type to another personnel type
- Communication between similar personnel
- Communication between organisations
- Information processing within and between personnel
- The parameters of the asset parts responding to the influential parameters
- The parameters of the asset parts interacting with each other, resulting in new conditions of the asset
- Relation between the budget, time and risks allocations the and necessary costs, time and most probably obtainable risk levels of the asset.

---

### **Physical Interfaces**

This interface represents how certain elements physically interact with each other or how they have an effect on each other. For bridge Asset Management, these come in many forms, a list is provided below:

- Age of the asset
  - Quality of the study
  - Quality of the structural elements (responsiveness to influences)
  - Frequency, speed and traffic concentration impacts on the construction
  - Reaction on atmospheric falls
  - Earth movements or settlement of the structural elements.
  - Visibility of an occurred damage
  - Chloride attack
  - Frost
  - Carbonation effect
-

- 
- Fire
  - Easiness of the maintenance or construction works
  - Inspection type
  - Routine maintenance works
  - Renewal of anti-corrosion protection
  - State of secondary elements

#### *Mechanical*

- Loads from objects or traffic on the construction (dynamic or static)
- Impacts from objects on the construction
- The construction reacting to weather or environmental effects (thermal shrinkage or expansion)
- De-icing agents contact and ingress into the construction
- Age of the structure

#### *Vehicle functioning*

#### *Electrical Interfaces*

- All electrical devices, digital data transfer
- Measurement devices

#### *Optical Interfaces*

- Measurement devices
  - Human observations of the construction
  - Imagery and videos
  - Chemical
  - Carbonation effect
  - Laboratory tests and measurements
- 

## **Organisational Roles, Missions, and System Applications**

This chapter explains the driving factors for the SOI performance and its mission capabilities. These factors are important for defining what should be and should not be included in the solution space of the SOI and it helps understanding why the system exists and what it does.

### **Strategic Planning**

Strategic planning comes from an organisation mission and vision statement that states what direction the organisation is heading in order to keep clarity towards all stakeholders involved. It is generally a long-term plan. Asset Management is about minimising risks with as less resources (time and costs) as possible. This accounts for almost every organisation within this system. There are generally constrained budgets or defined contractual amounts of money for a certain project (to maintain, inspect, or advice upon a bridge for maintenance) with limited or defined time scopes. All the necessary activities also have to be performed within the operating environment while taking account the user's safety.

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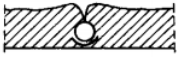
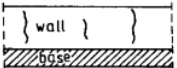
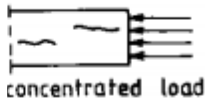
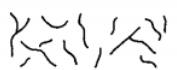
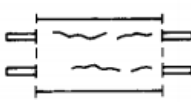
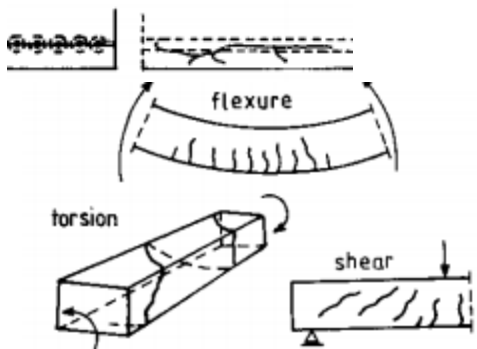
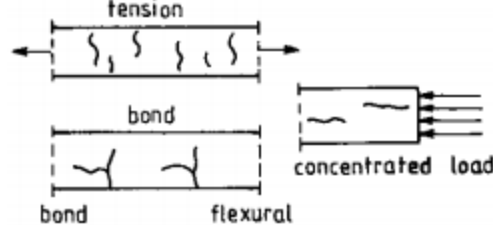
### **Tactical Planning**

The tactical plan brings the strategic plan into more depth by defining how this vision will be established. It is about short term objectives and actions. Some general actions that account for the vast majority of bridge asset management organisations are:

- The best assessment of the most important deterioration parameters to base a decision on
  - Create the optimal decisions that reduce risks as much as possible while being not too costly
  - To increase or withhold enjoyment, fulfilment and welfare throughout all employees.
  - Efficient and effective cooperation within the organisation and between other organisations
  - Increase the value of a company
-

## APPENDIX II DETERIORATION MECHANISMS

There could be several different types of deterioration present that form cracks into concrete. These cracks have their own appearances. A description of these types is included in the table below.

Visualisation	Damage Cause	Time of Formation	Appearance
	Plastic Settlement	First few hours after casting	Cracks along reinforcement
	Thermal Cracks	First few days after casting	Large cracks at joints
	Shrinkage	First few months	Several crack types possible (similar to flexure, torsion or shear cracks)
	Alkali-aggregate reaction	First few years after casting	"Mapping" of cracks along the surface
	Corrosion	Increased chance at older constructions	Cracks along the reinforcement bars (rust staining mostly visible during wet conditions)
	Service Loading	Dependent on the usage	Flexure, torsion or shear cracks, mostly small (large indicate a design fault)
	Restraints	Dependent on the environmental conditions	Tension, bond or flexural cracks, mostly small in size

*Drawings by (Radomski, 2002, p. 22 & 23)*

## APPENDIX III CONDITION ASSESSMENT MECHANISMS

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As a third objective, this research aims to provide a better understanding of the current technological readiness of the new data sources and the available technologies for the bridge maintenance market. The research aims to develop an understanding of possible developments, future processes, and possible future scenario's by experts for more market involvement in these innovations because this subject must not only be spoken of within the walls of already innovating facilities like universities. Such innovations must also be presented to the market for a review for their usefulness and to capture the potential of them. This is why this appendix will follow with a list of found condition assessment mechanisms. All mechanisms will be shortly described below and after each category, a table is given that indicates the capabilities of the sensor or sensing systems when comparing them to the deterioration parameters of concrete bridge components.

### **On-Site Sensing Systems**

1. Radar/Backscatter/Speckle
2. Ground Penetrating Radar (GPR)
3. InSAR (Interferometric Aperture Radar)
  4. Spectral Analysis
  5. Ultrasonic Surface Wave
  6. 3D Optics (3D photogrammy)
  7. Digital Image Correlation
8. EO Airborne and Satellite Images
  9. Optical Interferometry
10. Light Detection and Radar (LiDAR) 3D Laser Scanning
11. Thermal/Infrared Vision and Imagery
12. Streetview style Photography
  13. Acoustics
  14. Impact Echo
  15. Chain Dragging
  16. Electrical Resistivity
  17. Half Cell Potential

### **In-Situ Sensor Systems**

18. Accelerometers
19. Acoustic Emission
20. Automated Laser Total Station
21. Electrochemical fatigue sensing
  22. Electrical Impedance
23. Electrical Resistance Strain Gauges
  24. Fibre Optic Cables
  25. Linear Potentiometer
26. Linear Variable Differential Transformer
27. Linear Polarization Resistance (LPR)
28. Macrocell Corrosion rate Monitoring
  29. Chloride content sensors
  30. Tiltmeters/Inclinometers

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## ON-SITE SENSING SYSTEMS: REMOTE

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### 1. RADAR/BACKSCATTER/SPECKLE (AHLBORN ET AL., 2010)

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Radar is a technique that has a wide range of applications. It comes in different forms with backscatter and speckle techniques. It uses radio waves to receive values from the concrete. Unless the bandwidth is wide and has low emission frequencies, it is mostly valuable for measuring displacement, surface and subsurface characteristics, or vibrations of the construction. It can be sub categorised by different types of radar, of which Ground Penetrating radar and Interferometric Aperture radar are the most commercially common and have the broadest applications.

### 2. GROUND PENETRATING RADAR (GPR) (AHLBORN ET AL., 2010)

---

GPR has a wide bandwidth and low frequency, which makes it more applicable for more global measurements. It detects voids, cracks, chloride contaminated sections, rebar locations, and rebar diameter changes (corrosion). It can extract these deterioration parameters by air-ground interface which means that it also can be equipped onto a vehicle.

### 3. INSAR (INTERFEROMETRIC APERTURE RADAR) (AHLBORN ET AL., 2010)

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InSAR is similar to GPR, it has a slight different bandwidth and is mostly used in earth orbiting satellites for creating images of the surface of the earth. It needs specialised hardware and software by the comparison with previous images from that location the system automatically detects changes in the deterioration parameter values. It does this by comparing pixel-by-pixel differences between images at a time interval. Just as GPR, different wavelengths of radar can be used for different penetration depths and it can be used to detect delamination and cracking of the concrete.

### 4. SPECTRAL ANALYSIS (AHLBORN ET AL., 2010)

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Spectral Analysis is a light based measurement technique (sometimes enhanced with infrared) that detects where at the bridge structural component's surface light is absorbed or reflected. With this set of data, deficiencies can be observed. However, until now, only chemical leaching was observe with confidence and this techniques does not show great promises for further usage since it is also expensive to deploy. It needs shadows and colour differences to detect cracks or deficiencies, which are not always clearly defined or very variable in different weather or environmental circumstances.

### 5. ULTRASONIC SURFACE WAVE TESTING (GUCUNSKI ET AL., 2016)

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Ultrasonic Surface Wave measures the concrete's elastic modulus. It uses a high frequency range that is comparable to spectral analysis. It checks whether the concrete is homogenous in its velocity of the wavelength, if not, it indicates a defect such as delamination by an inconsistency of the elastic modulus.

### 6. 3D OPTICS (3D PHOTOGRAMMY) (AHLBORN ET AL., 2010)

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3D photogrammetry is produced by two cameras making images of the same object under a different angle. The generated models provide insights in the depth and heights of certain structures. It is commercially available and can be equipped onto different types of ground or air vehicles. It is especially useful for locating cracks from top views such from the bridge deck surface, or for expansion joint failures. But views from below have more practical limitations by less lightning and depth estimations of the programs.

### 7. DIGITAL IMAGE CORRELATION (AHLBORN ET AL., 2010)

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This sensing type is also produced with images from photogrammetry. Now, images are compared between two time intervals pixel-by-pixel. The more pixels are available, the more adequate the system can compare the two situations and possibly detect changes. It is also commercially available and can be equipped onto driving vehicles. Though, the images need to be taken from exact same locations thus exact GPS locations are a must. It can observe deficiencies on the deck surface, girder surfaces, or asphalt.

#### 8. AIRBORNE AND SATELLITE IMAGES (AHLBORN ET AL., 2010)

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Aerial images are especially good for providing information about the contextual and environmental setting of the bridge, and possibly for detection of large surface cracks and expansion joint deficiencies. Though, for the latter two, high quality images are necessary which are relatively expensive. Aerial vehicles (manned or unmanned) can fly over relatively lower than satellites and are less expensive in usage. Tests with forest fires indicated that very detailed information could be extracted which could be similar to crack growth at a concrete surface. Early bridge tests provided an accuracy of around 80% with this measurement method of detection surface cracks at a bridge site.

#### 9. OPTICAL INTERFEROMETRY (AHLBORN ET AL., 2010)

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Interferometry is a broad term for wave propagated measuring and is also used at e.g. radar systems. Optically means that it uses visual and thermal images to generate the data. It looks for subsurface features and internal stresses of the system by advanced algorithms that compute these from the taken images. It is a readily and widely available commercial system that can be adapted. Tests provided an explanation that this system was most useful for deck surface measurements and expansion joint deficiencies such as sand in the joint. The resolution of the data is so fine from this technology that cracks at millimetre scales also have been detected. When placed onto a vehicle, its sensitivity becomes lower. When placed onto a static system that focuses on a part of the bridge, it can be even used for determine structural vibrations.

#### 10. LIGHT DETECTION AND RADAR (LIDAR) 3D LASER SCANNING (AHLBORN ET AL., 2010)

---

Light detection and ranging (LiDAR) is performed by a laser that generates a 3D point cloud of surrounding objects through the reflection times of the laser to return to the system. The light spectrum of the laser is around infrared and it can observe objects at large distance. Some researchers claim that the technique can identify cracks and spalls in the concrete. It is especially helpful for fast mapping out of 3D surroundings. It is expected to be used for self-driving vehicles, which makes the technique even more interesting since these vehicles are likely to pass the bridges very frequently in the near future.

#### 11. THERMAL/INFRARED VISION AND IMAGERY (VEMURI & ATADERO, 2016)

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Infrared light is used in several other systems, but thermography uses the surface radiant temperature of an object to see how it differs in this temperature. For concrete objects, this could indicate voids, moisture areas, or delaminated areas in the bridge. It is crucial for this technique that is used at the correct time during the day since contrasts between temperature of the deficiencies and the sound structure can be best observed if the construction is warming up or cooling down. These parts do not transfer heat with the same properties. It seems to be a fairly accurate method by testing.

#### 12. STREETVIEW STYLE PHOTOGRAPHY (AHLBORN ET AL., 2010)

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Streetview style photography is something that is unnoticeably already used for decision making. It is currently best provided by Google maps streetview and Google earth. It provides situational and

environmental photographs and can show a more rough version of the state of the outer layers of a bridge. Especially the upper and downside of the bridge deck, expansion joint, and the abutments can be identified through this method.

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### 13. ACOUSTIC EMISSION (AHLBORN ET AL., 2010)

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Acoustics come in remote form and in contact based form. Remote techniques use acoustic waves to measure certain parameters of delamination that come from this wave emission in the structure. It uses the wave's flight time, frequency, and amplitude to measure these parameters. It is mostly applicable to direct concrete surfaces and measures (internal) cracks and section losses.

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## ON-SITE SENSING SYSTEMS - CONTACT BASED

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### 14. IMPACT ECHO (GUCUNSKI ET AL., 2016)

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Impact Echo is a broadly used technique. The technique was early on performed by knocking with rubber hammers or simply by knocking by hand to detect voids and delamination in the structure through hollow sounds. Nowadays, new contact based systems are available that use other impact sources for creating sound. The oscillation reflections of the bridge structure determine its condition. Such systems are slightly more accurate than the early practice of hand-knocking. The found condition is translated into good, sound, poor, serious or severe, which correspond with the variance of the measured response frequency ranges that are expected from sound concrete.

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### 15. CHAIN DRAGGING (PAILES, 2014)

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Chain dragging is a less advanced technique and is performed by an inspector that drags a chain behind him on top of the deck surface to listen for any inconsistencies that generally have a lower pitch than sound concrete parts. This method detects delamination near the surface of the construction and is only reliable for detecting large scale delamination. It is very easy to use and to deploy, but is dependent on the hearing expertise of the inspector.

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### 16. ELECTRICAL RESISTIVITY (PAILES, 2014)

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Electrical resistivity is a technique that measures the concrete by how it passes electrical currents. It thereby shows areas that have a beneficial environment for corrosion to happen. It needs at minimum two contact points between which the electrical current moves. The output values need to be calibrated since the system is influenced by moisture, chlorides, and temperature. Of which the chloride content is mostly the most influential parameter. The output is stated as risk of corrosion.

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### 17. HALF CELL POTENTIAL (PAILES, 2014)

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Half-cell potential is capable of identifying active corrosion environments because it uses the electrical current between the reinforcement steel and the concrete. It shows how fast ions can pass between the two and thereby identifies the speed progression of corrosion. It needs a contact point with the reinforcement steel which makes it an imposter in the non-destructive evaluation techniques. Though, sometimes a contact point is provided externally with the reinforcement by an open space to the reinforcement at some pre-stressed bridge types. It is also influenced by multiple factors as moisture, temperature, oxygen, and ion contents.



## ON-SITE SENSING SYSTEM DETERIORATION PARAMETER RELATION TABLE

The following table presents the explained condition assessment mechanisms in relation to the bridge components and deterioration mechanisms. This particular table is specified to On-Site mechanisms, another table for In-Situ mechanisms is presented afterwards. The systems (top rows per column) are scored per type of damage that can they can measure or assess at the bridge.

Bridge Component & Deterioration Mechanism		REMOTE										CONTACT-BASED							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Visual Inspection	Radar	GPR	InSAR	Spectral Analysis	Ultrasonic SurfaceWave	3D Optics	DIC	EO Airborne imagery	Optical Interferometry	LiDAR	Thermal Imaging	Streetview Style	Acoustics	Impact-Echo	Chain Dragging	Electrical Resistivity	Half-Cell Potential
Global Metrics	Bridge Length																		
	Bridge Settlement																		
	Bridge Movement																		
	Surface Roughness																		
	Vibration																		
Deck Surface	Expansion Joint																		
	Map Cracking																		
	Scaling																		
	Spalling																		
	Delamination																		
Deck Subsurface	Expansion Joint																		
	Delamination																		
	Scaling																		
	Spalling																		
	Corrosion																		
Girder surface	Chloride Ingress																		
	Steel Cracking																		
	Concrete cracking																		
	Steel Section Loss																		
	Paint																		
Girder Subsurf.	Concrete Loss																		
	Concrete cracking																		
	Concrete Loss																		
	Strand Breakage																		
	Corrosion																		
	Chloride Ingress																		

Table is partly based on literature from (Ahlborn et al., 2010)

ON-SITE SENSING SYSTEM DETERIORATION PARAMETER RELATION TABLE (CONTINUATION)

Bridge Component & Deterioration Mechanism		REMOTE										CONTACT-BASED							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Visual Inspection	Radar	GPR	InSAR	Spectral Analysis	Ultrasonic SurfaceWave	3D Optics	DIC	EO Airborne imagery	Optical Interferometry	LiDAR	Thermal Imaging	Streetview Style	Acoustics	Impact-Echo	Chain Dragging	Electrical Resistivity	Half-Cell Potential
Drainage	System Clogging	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Good	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
	Paint	Good	Not Applicable	Not Applicable	Medium	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
Light system	Light	Medium	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Medium	Not Applicable	Medium	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
	Guardrail Movement	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
Guardrail	Guardrail Cracking	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Medium	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
	Grass	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Medium	Medium	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
Abutment	Slope movement	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Good	Medium	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	
	Erosion	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Medium	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Good	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	

Table is partly based on literature from (Ahlborn et al., 2010)

Index:

Good	Good Measurement Capability
Medium	Medium Measurement Capability
Low	Low Measurement Capability
Not Applicable	Not Applicable

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## IN-SITU SENSOR SYSTEMS:

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### 18. ACCELEROMETERS (GASTINEAU ET AL., 2009)

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Accelerometers are broadly used as devices all over multiple fields of practice. They can provide direct measurements on the natural frequency, deflection, vehicle load, or other properties that induce vibrations on the structure. It needs proper calibration before data readings become valuable. It is sensitive to environmental influences, though, complex algorithms are being investigated that could identify and filter important deterioration values from the data. It is expected that tremendous advances will be made in the coming years, and it is advised to use vibration data in combination with other data sources to form a more elaborate image on the bridge condition status.

### 19. ACOUSTIC EMISSION (GASTINEAU ET AL., 2009)

---

Acoustic Emission is a sensor node based technique that 'listens' to changes in the structure. If a crack forms or a reinforcement bar loses a section, a small amount of energy is released from this point which can be detected through using multiple sensors in a combination. This combination, in cooperation with software, can determine the location of the originated sound and thereby specify where the deterioration is happening. Tests are performed on concrete structures, but most successes come from steel structures.

### 20. AUTOMATED LASER TOTAL STATION (GASTINEAU ET AL., 2009)

---

A laser station is a location based system that keeps track of the displacement of a certain specified point from a distance. The laser must be pointed to a receiver which can be placed anywhere. Most similar systems are used in laboratories and are highly accurate.

### 21. ELECTROCHEMICAL FATIGUE SENSING (GASTINEAU ET AL., 2009)

---

Electrochemical fatigue sensors are not applicable to concrete but can be used for the steel bearings of the bridge structure. It uses electrical current fluctuations to observe fatigue and crack growth in the steel. It can only observe specific parts of the bridge and does not identify global values. Care must be taken where to apply these systems.

### 22. ELECTRICAL IMPEDANCE (GASTINEAU ET AL., 2009)

---

Electrical Impedance is used on post-tensioning tendons that are located in concrete structures. It measures the resistivity between parts of the concrete, comparable with On-Site Electrical Resistivity systems, from a singular location. Any lowered resistance value indicates a possible ingress of chlorides or moisture and thereby indicates also that corrosion is almost surely forming. It is a relatively simple and commercially available system.

### 23. ELECTRICAL RESISTANCE STRAIN GAUGES (GASTINEAU ET AL., 2009)

---

Electrical resistance strain gauges measure changes in distances on a relatively small span width. They are mostly used to monitor existing cracks because they need to be placed after the cracks are formed. They are cheap and easy to install, but do not have a long endurance in outdoor environments.

### 24. FIBRE OPTIC CABLES (GASTINEAU ET AL., 2009)

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Fibre optic sensors are embedded or applied long span small cables that use several characteristics of light fractioning to monitor deterioration parameters. There are multiple principles that could be used which consist of; interferometry, polarisation, spectroscopy and the intensity of the light. By

combining these principles, much parameters have been found during research. Settlement, temperature, load intensities, acceleration, corrosion, cracks, section losses, and strain are one of these. These cable systems are highly multifunctional but need calibration from a temperature cable. Though, the cables are small and easy to bundle during construction. External (not embedded) cables are tested for application to existing bridge structures, though these are sensitive to vandalism.

#### 25. LINEAR POTENTIOMETER (GASTINEAU ET AL., 2009)

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The linear potentiometer is a spool with a wire attached to another location and is used to measure displacement. If there grows a distance between the spool system and the attached location, the spool rotates which can be measured. Dynamic measurement spools can also measure the speed of this displacement.

#### 26. LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (GASTINEAU ET AL., 2009)

---

A Linear Variable Differential Transformer (LVDT) sensor measures displacement by a cylindrical magnet that moves along a coil. An electrical current can measure the resistivity between the coil and the magnet and calculate the distance travelled. It is highly accurate in different environmental conditions.

#### 27. LINEAR POLARIZATION RESISTANCE (GASTINEAU ET AL., 2009)

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Linear Polarization Resistance is the equivalent of Half-Cell potential at a single location. It measures the electrical current between the reinforcement steel and the concrete to observe if, and how fast, corrosion is happening by speed activity of the current.

#### 28. MACROCELL CORROSION RATE MONITORING (GASTINEAU ET AL., 2009)

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Macrocell Corrosion Rate Monitoring measures and indication of the corrosion in the concrete by having an 'own' piece of identical reinforcement steel as anode to measure and to monitor how the corrosion is progressing in that piece.

#### 29. CHLORIDE CONTENT SENSORS (GASTINEAU ET AL., 2009)

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Measurements of electric potential of electrodes in concrete give the owner an indication of the possible risk of corrosion. It is mostly used as indication of the chloride content in the structure.

#### 30. TILTMETERS/INCLINOMETERS (GASTINEAU ET AL., 2009)

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Tiltmeters and inclinometers measure the inclination of a certain bridge component. It is mostly used to measure columns and vertical objects. It mostly requires multiple sensors to observe the full behaviour of a structure and it is a relatively easy, cheap and commercially available method to use.

**IN-SITU SENSOR SYSTEM DETERIORATION PARAMETER RELATION TABLE**

	18	19	20	21	22	23	24	25	26	27	28	29	30
	Accelerometers	Acoustic Emission	Automated Laser Total Station	Electrochemical fatigue sensing	Electrical Impedance	Electrical Resistance Strain Gauges	Fiber Optic Cables	LPR	Linear Potentiometer	LVDT	Macrocell Corrosion Monitoring	Chloride content Sensors	Tiltmeters/Inclinometers
<b>Deterioration Parameter:</b>													
<i>Acceleration</i>													
<i>Climatic Conditions</i>													
<i>Curvature</i>													
<i>Displacements</i>													
<i>Load</i>													
<i>Tilt/Slope</i>													
<i>Corrosion</i>													
<i>Cracking</i>													
<i>Delaminations</i>													
<i>Strain</i>													
<i>Tensions in rebar</i>													
<i>Chloride Ingress</i>													

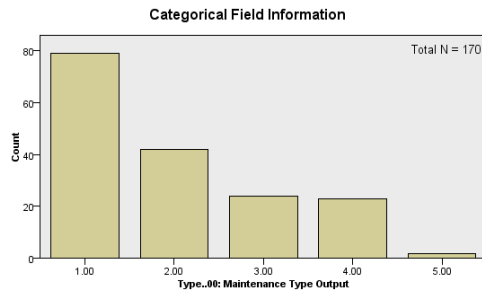
Index:

	Measurement Capability
	Not Applicable

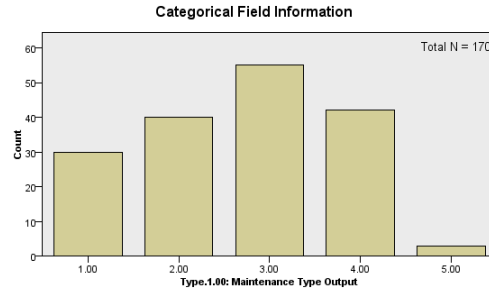
## APPENDIX IV QUANTITATIVE OUTCOME DISTRIBUTIONS SPSS

The Friedman test comes with more output than only the significance test. This appendix shows the full test results obtained from SPSS per outcome variable of the experiment.

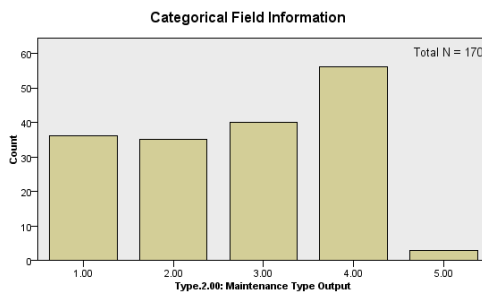
### MAINTENANCE TYPE OUTCOMES:



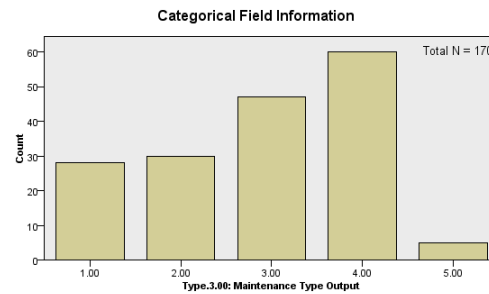
Type.00: Maintenance Type Output field is ordinal but is treated as continuous in the test.



Type.1.00: Maintenance Type Output field is ordinal but is treated as continuous in the test.

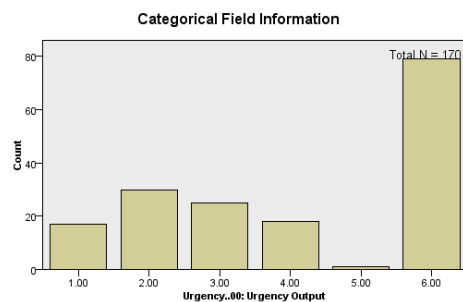


Type.2.00: Maintenance Type Output field is ordinal but is treated as continuous in the test.

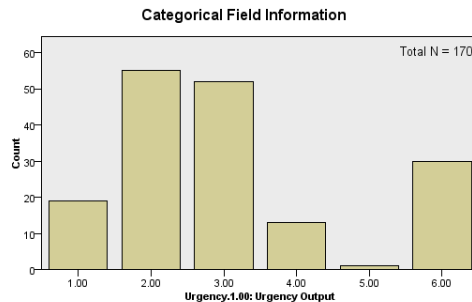


Type.3.00: Maintenance Type Output field is ordinal but is treated as continuous in the test.

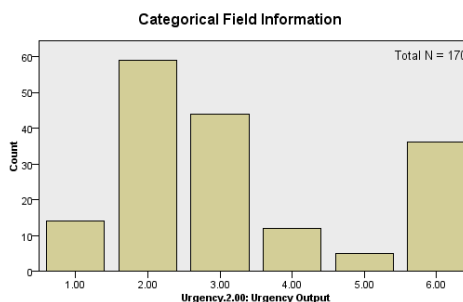
### URGENCY OUTCOMES:



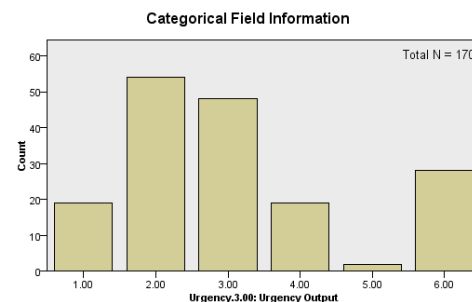
Urgency.00: Urgency Output field is ordinal but is treated as continuous in the test.



Urgency.1.00: Urgency Output field is ordinal but is treated as continuous in the test.

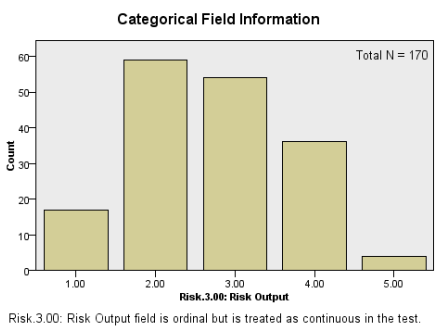
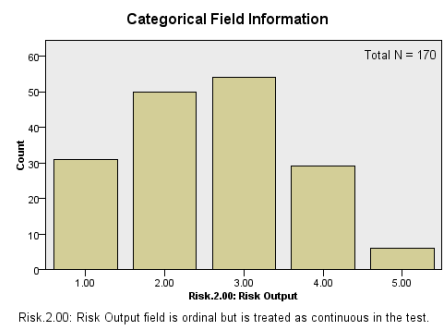
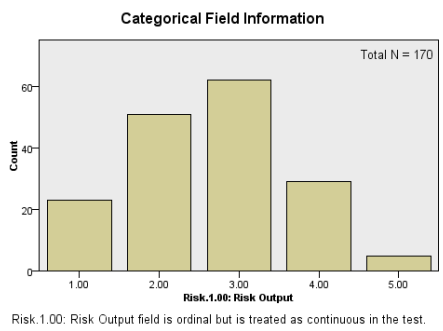
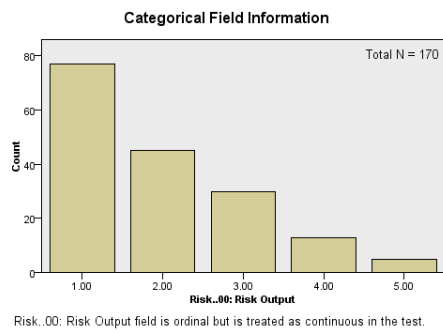


Urgency.2.00: Urgency Output field is ordinal but is treated as continuous in the test.

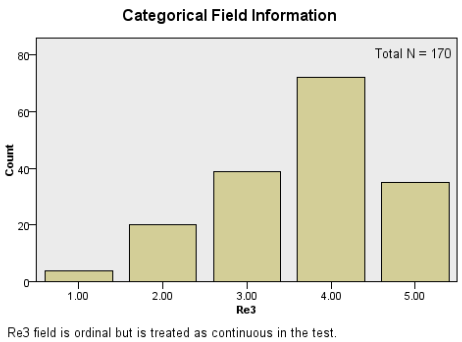
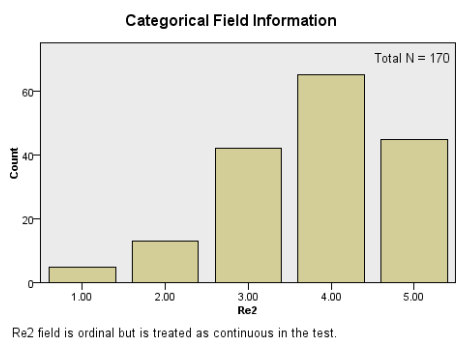
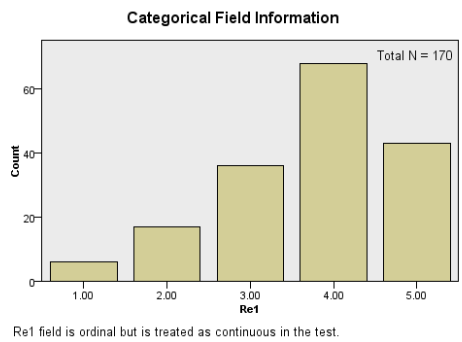
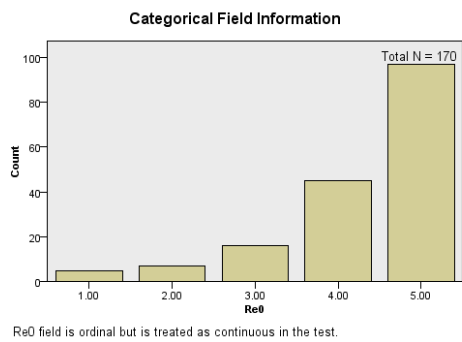


Urgency.3.00: Urgency Output field is ordinal but is treated as continuous in the test.

RISK LEVEL ESTIMATES



REST LIFE ESTIMATES



## APPENDIX V DEBRIEFING FRAMEWORK AND RESULTS

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### DE-BRIEFING QUESTIONS – SERIOUS GAME

---

- A. *Cooling Down (observations and game experiences)*
  - 1. Hoe vond je het spel, de hele ervaring?
- B. *Data Collection (assessment measurement validity)*
  - 2. Wat is er allemaal gebeurd?
  - 3. Kon je jezelf genoeg uitten met de handelingen waaruit je kon kiezen? Had je meer of minder vrijheid gewild, en waarom?
  - 4. Heb je opmerkingen geplaatst om jezelf verder te specificeren?
- C. *Sensitivity (crucial event determination and objective possibilities)*
  - 5. Wat heb je gedaan bij specifieke situaties en waarom? (verder gaan op scenario's)
  - 6. Als je het spel nogmaals zou spelen, wat zou je dan anders doen?
- D. *Internal Validity (how did the treatment have an impact, other/confounding/noise variable identification)*
  - 7. Wat was jouw ervaring met het verschil tussen de datatypes? (& wat deed je met deze verschillen?)
  - 8. Waarop baseerde je je keuzes voornamelijk?
  - 9. Leercurve: heb je bepaalde scenario's hetzelfde geantwoord omdat ze herkenbaar waren?
- E. *Generalizability (is this sample representable for the full population)*
  - 10. Verwacht je verschillende antwoorden/effecten bij andere personen? (constructeurs, adviseurs, inspecteurs, asset managers, beheerders).
  - 11. Hoe geldig is dit spel voor andere bruggen of voor andere schades?
  - 12. Denk je dat ik met dit spel kan beantwoorden of nieuwe databronnen handig zijn in brugmanagement?
  - 13. Denk je dat, als er verschillen uit de analyse komen, het generaliseerbaar is voor de hele brugmarkt?
- F. *External Validity (is the game representable for reality)*
  - 14. Om het spel nog realistischer te maken, wat zou jij toevoegen qua spel elementen?
  - 15. Zou dit dan ook tot andere keuzes leiden?
- G. *Robustness (what impact does other/further innovation have)*
  - 16. Hoe zie jij deze innovaties in de werkelijkheid voor je, is hier ruimte voor?
  - 17. Wat voor andere innovaties spelen een rol in het hele brug onderhoudsproces?
- H. *Planning for Action (follow-up research determination)*
  - 18. Stel, we zouden met deze technologieën verder gaan. Er komen steeds meer verschillende soorten data bij vanuit andere type sensoren of systemen. Hoe zie jij dit voor je qua implementatie en bruikbaarheid, waar voorzie jij knelpunten?
  - 19. Zouden deze databronnen alleenstaand kunnen werken, zonder inspecties of bezoek aan de brug? Welke databronnen zouden dit wel kunnen?
- I. *Protection (what can or cannot be fed back into the world)*
  - 20. Wat zou je uit de spel absoluut WEL en NIET kunnen linken aan de realiteit?
  - 21. Stel ik zou een tweede spel maken, wat zou dan zeker anders moeten? Meer info? Meer tijd? Andere brugscenario's?



---

## DEBRIEFING RESULTS

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The results of the debriefings with all participants have been written down in Dutch. The most important findings and keynotes have been included in the table below per discussed item.

---

### COOLING DOWN

---

#### 1 WHAT DID YOU THINK OF THIS EXPERIENCE?

Fun to do!  
Harder than expected.  
Good game for fresh insights into current processes.  
Very impressive that this was built by one person.  
Very much (new) Information in one experience.  
Good Quality and realistic game.  
Nicely Scoped game, very clear what needed to be done.

---

### DATA COLLECTION (ASSESSMENT MEASUREMENT VALIDITY)

---

#### 2 WHAT HAS HAPPENED?

Chloride Induced Corrosion mechanism was clear  
A difference in role between competences of inspector, constructor, advisor, and asset manager.

#### 3 WERE YOU ABLE TO SPECIFY YOURSELF THROUGHOUT THE DECISION OPTIONS?

Realistic Answering Panel  
Corrective and Preventive can lie close to each other  
Very representable for daily job

#### 4 DID YOU FURTHER SPECIFY YOURSELF IN THE BLANK BOX?

NEN is an inefficient method

---

### SENSITIVITY (CRUCIAL EVENT DETERMINATION AND OBJECTIVE POSSIBILITIES)

---

#### 5. WHAT DID YOU DO AT CERTAIN SCENARIOS AND WHY?

During the game, I felt more confident in answering  
My Answer was mostly dependent on the type of damage  
Much Detailed Inspection Used  
Life Expectation is a vague estimate value  
Missing of interaction with other experts  
I Expect that I decided more extreme values than others due to my large amount of experience

#### 6 IF YOU WOULD PLAY THE GAME AGAIN, WOULD YOU DO THINGS DIFFERENTLY?

No different answer expected when playing another time

---

### INTERNAL VALIDITY (HOW DID THE TREATMENT HAVE AN IMPACT, OTHER/CONFOUNDING/NOISE VARIABLE IDENTIFICATION)

---

#### 7 HOW DID YOU PERCEIVE THE DIFFERENT TYPES OF DATA?

With more data, one can specify his actions better/more directly

To be able to observe the speed progression was valuable  
 I feel that sensors can be used best as trigger  
 Frequency sensor was a nice indicator and useful due to its speed-time indicator  
 I had the feeling that the data was realistic  
 Frequency sensor was not useful due to only intensity presentation and not extent  
 T1 presents the severity and speed progression  
 T2/3 measures the extent of the damage  
 More objective measurements will bring uniformity into decision making  
 The contour plot was not useful (due to only top deck observation)  
 It is unclear how new data MAY be used in an organisation, and how one can deal with the data.  
 T3 was most useful of all  
 More objective measurements will have an impact by determining the status of an component  
 It is very hard to conclude on all the data at one time efficiently  
 Chloride Data was useful as indicator  
 The use of data will be more of an "to be sure" measure than actual data for decision making  
 I think that contour plot data can be used as detailed inspection

#### 8 WHAT DATA DID YOU FIND IMPORTANT FOR DECISION MAKING?

Similar focus on data or inspection  
 Deterioration Speed  
 Damage Description  
 Less value to condition score itself  
 More focus on Data  
 Years to corrosion  
 More focus on Inspection

#### 9 DID YOU RECOGNISE SIMILARITIES THROUGHOUT THE GAME, AND DID YOU ANSWER THESE SIMILAR?

Recognisable scenario, but due to the data a different view was given. Therefore, differences were expected.  
 Similarities but did not know the answer due to randomisation  
 Did not recognise the similarities; thought that everything was different

### GENERALIZABILITY (IS THIS SAMPLE REPRESENTABLE FOR THE FULL POPULATION)

#### 10 DO YOU EXPECT DIFFERENT ANSWERS BY DIFFERENT PERSONS?

Yes, due to knowledge based background. (which is; inspectors focus more on deficiencies of the outside and perform direct actions, constructors check if the damage is critical and if material loss is prohibited in that area, asset managers reason more from costs and planning perspective)  
 Subjectivity and interpretation of data plays a role between experts  
 Yes, experience with maintenance types and preferences play a role

#### 11 IS THIS GAME REPRESENTABLE FOR OTHER TYPES OF DETERIORATION?

For every concrete bridge component  
 If the differences between data and inspection are comparable, this is very representable  
 Mostly for other (slow & similar) deterioration types  
 In most cases, the construction warns before it fails. When this warning can be observed earlier, this research is valid.

#### 12 IS THE GAME ABLE TO ANSWER THE RESEARCH QUESTION?

Yes, this principle must count for other bridges or data sources.

Expectation of reality is less concise data due to external influences

Most of the times, you advice to do certain maintenance actions or detailed inspections in combination with other maintenance interventions, such as asphalt. When sensors are used, you can know beforehand if you need this operation space during asphalt replacement.

My organisation always does a little extra that is not asked from them.

The decision making of bridge maintenance is very unsure and especially no science. There is no good or bad. Most of the times, experts do not even thoroughly analyse scenarios before making up their decision. I would consider it even guesswork.

#### 13 CAN THE ANSWERS FROM THE GAME BE GENERALISED TO OTHER BRIDGE TYPES?

Yes, definitely.

Only on slow deterioration mechanisms, no sudden events.

Especially the short term and speed progression will be of value and is representable for what is going to happen.

### EXTERNAL VALIDITY (IS THE GAME REPRESENTABLE FOR REALITY)

---

#### 14 & 15 WHAT SHOULD BE INCLUDED TO IMPROVE THIS GAME? AND WOULD THIS LEAD TO ANOTHER DECISION?

A photograph of the damage - but no change in decision making expected. Only for better image in mind and sureness of the situation. It would not lead to different effects between the experiment groups, but between the scenarios.

No improvement comments

Information about the other elements

A photograph of the damage - but no change in decision making expected. Only for better image in mind and sureness of the situation.

Costs and availability as scoring elements

Contextual information about the location and environment

Reality of the sensing data (less uniform and robust --> with mistakes and contrasts in them)

A guideline for decision making

More into depth per case, and less cases in total. (quality up, quantity down).

### ROBUSTNESS (WHAT IMPACT DOES OTHER/FURTHER INNOVATION HAVE)

---

#### 16 HOW DO YOU SEE THESE INNOVATIONS HAPPENING IN REALITY, IS THERE AN AVAILABILITY FOR THIS?

Proof of concepts are highly needed right now.

If it becomes affordable, then it will be used.

It is difficult to estimate up front what the actual usefulness will be of a sensing mechanism

It will not be initiated by RWS and Owners because they prefer traditional methods.

Data infrastructure is a serious obstruction

Deterioration is mostly slow and not that significant. Current methods will suffice.

Combinations of sensors are needed, but that is expensive.

It must be initiated and steering by RWS and Owners, only then will contractors listen.

The first contractor that has a valuable proposal regarding these innovations will definitely be ahead of the rest of the market.

Data Sources will bring ease to inspection moments, organisations can now decide better when inspections are necessary. They are a trigger.

The timeliness of sensing data is extremely valuable, no need for difficult planning of investigations anymore.

It will proceed, but with baby steps

Asset Owners already provide innovation space by broadening guidelines for inspections and data interpretation.

I would say; fully focus on the contour plots and dynamic systems because sensing systems will grow old very fast.

It is a strange thought that I won't be necessary anymore in 20 years.

17 WHAT OTHER INNOVATIONS DO YOU KNOW OR PLAY A ROLE IN THE MAINTENANCE DECISION MAKING PROCESS?

No direct knowledge about it.

Interested in new methods

GPR

Liquid levelling

Cathodic Protection

Trustworthiness is a great issue (in the field, not the experimental setting)

Mostly larger companies work with it and are busy with it.

Material intrinsic research is most valuable currently, concrete material innovations.

Chloride Sensor is familiar, from other companies that work with it.

Engineers can be very excited about new stuff and innovations, however, asset owners just want verification and a opportunity cost of capital calculation.

Optic Fibres are known

The understanding of relations between environmental or inner factors and the structural durability and capacity

PLANNING FOR ACTION (FOLLOW-UP RESEARCH DETERMINATION)

18 WHAT IF WE CONTINUE WITH SUCH NEW DATA SOURCES, WHERE DO YOU FORESEE ANY BOTTLENECKS IN THE ADOPTION PROCESS?

I would want to have a neat oversight of the monitoring and sensing possibilities at this moment.

It is highly important to know how to interpret the data from each sensing mechanism.

Money is one of the greatest issue

Current innovations and improvements (e.g. sustainability projects) are always performed at a very low practical level. This type of innovation cannot be implemented that small and requires good cooperation between parties.

The sensors need to last long enough for a contractual period.

Sensing mechanisms for highway overpasses are too expensive. Most of the time, the construction will remain for a longer time. Much more crucial civil infrastructures will have a preference over maintenance with data.

Current processes just need to be improved and better documentation is the most important issue.

The financing of these innovations will not be done by asset owners at pilot projects, but small startups will not have the capacity to backup an insurance finance for if something goes wrong themselves.

19 CAN THESE DATA SOURCES EXCLUDE THE CURRENT VISUAL INSPECTION METHODS?

New Data Will provide triggers and can delay for timely inspection

New Data will improve insights in the structural condition but will not provide causal relations between the bridge and its environment (e.g. a farm nearby with heavy agricultural tractors, conditions of impactful elements like the abutment, expansion joints, asphalt --> concrete only damages if these things do not work, flexibility of the observations --> from leaking joint to not

properly cleaned drainage system).

Yes, it can work fully (but in the far future and programs and algorithms will have to be able to process everything)

Data must be translated into understandable information before being processed.

Expert judgement remains necessary for indicating cause-effect relations at damages.

There is no ARAN for bridges yet, unfortunately.

There should be a focus on bringing the expert opinions into one line and thus decreasing subjectivity. However, by introducing the data, the level of expert judgement can just move up one point higher in the process.

Data can be very convenient for checking the quality of works of the contracting party.

#### PROTECTION (WHAT CAN OR CANNOT BE FED BACK INTO THE WORLD)

---

#### 20 WHAT DID YOU ABSOLUTELY NOT FIND REALISTIC AT THIS GAME?

The lack of the full system

No photograph of the damage

Abstract Level (total game)

Damage existent since longer than 5 years and no plan for it

The uniformity of all data about the damage (no contrasting data, everything was just right)

More types of deterioration is possible

#### 21 WHAT DID YOU ABSOLUTELY FIND REALISTIC AT THIS GAME?

Descriptions of the scenarios (deterioration)

Deterioration Process

Decision Process - Gameplay

The requested output fields

NEN method

#### 22 WHAT SHOULD BE INCLUDED IF YOU COULD REMAKE THIS GAME?

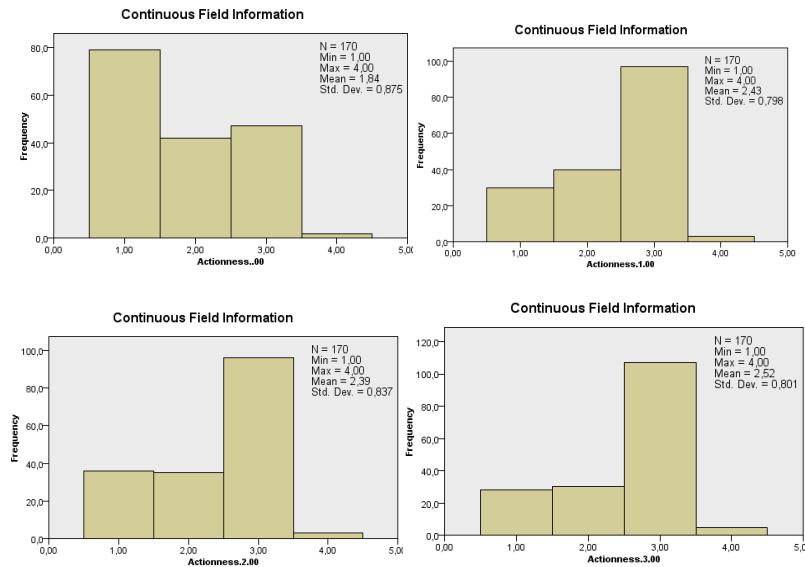
Life cycle costing included

Check for uniformity in everyone's decision making and which decision is the best one.

## APPENDIX VI POST-HOC RESULTS

In the discussion chapter, some Post-Hoc tests were performed. The results from these tests that are not included in the discussion chapter itself are presented below.

### MAINTENANCE TYPE DUMMY VARIABLE: SIZE OF ACTION AND INTERVENTION



	Mean	Std. Deviation	Median
<i>Actionness..00</i>	1,8	0,9	2
<i>Actionness.1.00</i>	2,4	0,8	3
<i>Actionness.2.00</i>	2,4	0,8	3
<i>Actionness.3.00</i>	2,5	0,8	3

The Friedman test was performed with a Bonferonni correction. The results are as follows:

The results were statistically significantly different at the different groups during the exercise intervention,  $\chi^2(2) = 110.986$ ,  $p < .0005$ . Post hoc analysis revealed statistically significant differences in the Maintenance Type based dummy variable; size of Action and intervention from:

- Control Group (Mdn = 1,8, Mn = 2.0) to Treatment Group 1 (Mdn = 3, Mn = 2.4) ( $p < .0001$ ),
- Control Group (Mdn = 1,8, Mn = 2.0) to Treatment Group 2 (Mdn = 3, Mn = 2.4) ( $p < .0001$ ),
- Control Group (Mdn = 1,8, Mn = 2.0) to Treatment Group 3 (Mdn = 3, Mn = 2.5) ( $p < .0001$ ).

But not between Treatment Group 1 and Treatment Group 3, and between Treatment Group 2 and Treatment Group 3 ( $p > .05$ ).

### CORRELATIONS RISK & REST LIFE VERSUS SIZE OF ACTION AND INTERVENTION

For the remaining hypotheses seven to ten, a Kendall's tau-b correlation was run to determine the relationship between the dependent variables. The test was run for four (hypotheses-based) combinations of the four variables for 17 participants with 680 paired observations.

- a) There was a strong, negative association between Rest Life Estimate and size of Action and intervention, which was statistically significant,  $t_b = -.352, p < .0001$ .
- b) There was a strong, positive association between Risk Level Estimate and size of Action and intervention, which was statistically significant,  $t_b = .446, p < .0001$ .

For the hypotheses, this means the following: there is a monotonic relation observed between expert judgements factors and the size of Action and intervention.

## FRIEDMAN TEST RESULTS PER DETERIORATION PROGRESSION SPEED

Pairwise comparison shows that all differences between the control group (0) and the treatments (1, 2, or 3) are significant. All pairwise comparisons except for one remained not significant. This one is the urgency between treatment group 2 and 3.

Report

Deterioration Speed		Risk.2.00	Risk.3.00	Restlife.2.00	Restlife.3.00	Type.2.00	Type.3.00	Urgency.2.00	Urgency.3.00	Actionness.2.00	Actionness.3.00
,00	Mean	2,5529	2,4824	3,8118	3,9176	2,6471	2,6824	3,2706	3,5529	2,3412	2,3765
	Std. Deviation	1,02940	,93365	,94484	,90253	1,15166	1,16713	1,65031	1,58494	,82452	,85880
	Median	3,0000	2,0000	4,0000	4,0000	3,0000	3,0000	3,0000	3,0000	3,0000	3,0000
1,00	Mean	2,6118	2,9412	3,7412	3,4235	2,8235	3,1294	3,2353	2,6235	2,4353	2,6706
	Std. Deviation	1,13488	,99227	1,09276	1,05081	1,20689	1,07779	1,65937	1,37993	,85143	,71361
	Median	3,0000	3,0000	4,0000	4,0000	3,0000	3,0000	3,0000	2,0000	3,0000	3,0000

Pairwise Comparisons

Deterioration Speed	Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
,00	Risk..00-Risk.1.00	-,918	,198	-4,634	,000	,000
	Risk..00-Risk.3.00	-1,035	,198	-5,228	,000	,000
	Risk..00-Risk.2.00	-1,153	,198	-5,822	,000	,000
	Risk.1.00-Risk.3.00	-,118	,198	-,594	,552	1,000
	Risk.1.00-Risk.2.00	-,235	,198	-1,188	,235	1,000
	Risk.3.00-Risk.2.00	,118	,198	,594	,552	1,000
1,00	Risk..00-Risk.1.00	-1,182	,198	-5,971	,000	,000
	Risk..00-Risk.3.00	-1,271	,198	-6,416	,000	,000
	Risk..00-Risk.2.00	-,771	,198	-3,891	,000	,001
	Risk.1.00-Risk.3.00	-,088	,198	-,446	,656	1,000
	Risk.2.00-Risk.1.00	,412	,198	2,079	,038	,226
	Risk.2.00-Risk.3.00	-,500	,198	-2,525	,012	,069

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Pairwise Comparisons

Deterioration Speed	Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
,00	Restlife.2.00-Restlife.3.00	-,124	,198	-,624	,533	1,000
	Restlife.2.00-Restlife.1.00	,176	,198	,891	,373	1,000
	Restlife.2.00-Restlife..00	1,018	,198	5,139	,000	,000
	Restlife.3.00-Restlife.1.00	,053	,198	,267	,789	1,000
	Restlife.3.00-Restlife..00	,894	,198	4,515	,000	,000
	Restlife.1.00-Restlife..00	,841	,198	4,248	,000	,000
1,00	Restlife.2.00-Restlife..00	,629	,198	3,178	,001	,009
	Restlife.3.00-Restlife.1.00	,088	,198	,446	,656	1,000
	Restlife.3.00-Restlife..00	1,094	,198	5,525	,000	,000
	Restlife.1.00-Restlife..00	1,006	,198	5,079	,000	,000
	Restlife.3.00-Restlife.2.00	,465	,198	2,347	,019	,114
	Restlife.1.00-Restlife.2.00	-,376	,198	-1,901	,057	,344

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

Pairwise Comparisons

Deterioration Speed	Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
,00	Type..00-Type.1.00	-,718	,198	-3,624	,000	,002
	Type..00-Type.2.00	-,924	,198	-4,664	,000	,000
	Type..00-Type.3.00	-,924	,198	-4,664	,000	,000
	Type.1.00-Type.2.00	-,206	,198	-1,040	,299	1,000
	Type.1.00-Type.3.00	-,206	,198	-1,040	,299	1,000
	Type.2.00-Type.3.00	,000	,198	,000	1,000	1,000
1,00	Type..00-Type.1.00	-,824	,198	-4,159	,000	,000
	Type..00-Type.2.00	-,747	,198	-3,772	,000	,001
	Type..00-Type.3.00	-1,065	,198	-5,377	,000	,000
	Type.1.00-Type.3.00	-,241	,198	-1,218	,223	1,000
	Type.2.00-Type.3.00	-,318	,198	-1,604	,109	,652
	Type.2.00-Type.1.00	,076	,198	,386	,699	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

Pairwise Comparisons

Deterioration Speed	Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
,00	Urgency.2.00-Urgency.1.00	,182	,198	,921	,357	1,000
	Urgency.2.00-Urgency.3.00	-,318	,198	-1,604	,109	,652
	Urgency.2.00-Urgency..00	,841	,198	4,248	,000	,000
	Urgency.1.00-Urgency.3.00	-,135	,198	-,683	,494	1,000
	Urgency.1.00-Urgency..00	,659	,198	3,327	,001	,005
	Urgency.3.00-Urgency..00	,524	,198	2,644	,008	,049
1,00	Urgency.2.00-Urgency..00	,347	,198	1,753	,080	,478
	Urgency.1.00-Urgency..00	,912	,198	4,604	,000	,000
	Urgency.3.00-Urgency..00	,976	,198	4,931	,000	,000
	Urgency.3.00-Urgency.1.00	,065	,198	,327	,744	1,000
	Urgency.3.00-Urgency.2.00	,629	,198	3,178	,001	,009
	Urgency.1.00-Urgency.2.00	-,565	,198	-2,852	,004	,026

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2-sided tests) are displayed. The significance level is ,05.

## WILCOXON SIGN RANK TEST RESULTS

The Wilcoxon Sign Rank Test is used as verification of the Friedman test because it is said that this has more power. The significance that needs to be reached is  $p < 0,008333$  by Bonferonni correction.

### Pairwise Comparisons

	Z	Asymp. Sig. (2-tailed)
Risk.1.00 - Risk..00	-7,984	0
Risk.2.00 - Risk..00	-8,486	0
Risk.3.00 - Risk..00	-8,480	0
Risk.3.00 - Risk.1.00	-0,865	0,387
Risk.3.00 - Risk.2.00	-2,179	0,029
Risk.2.00 - Risk.1.00	-1,274	0,203
Restlife.1.00 - Restlife..00	-7,345	0
Restlife.2.00 - Restlife..00	-7,134	0
Restlife.3.00 - Restlife..00	-7,849	0
Restlife.3.00 - Restlife.1.00	-0,952	0,341
Restlife.3.00 - Restlife.2.00	-1,814	0,07
Restlife.2.00 - Restlife.1.00	-0,779	0,436
Type.1.00 - Type..00	-6,508	0
Type.2.00 - Type..00	-7,059	0
Type.3.00 - Type..00	-7,850	0
Type.3.00 - Type.1.00	-2,095	0,036
Type.3.00 - Type.2.00	-1,970	0,049
Type.2.00 - Type.1.00	-0,424	0,672
Urgency.1.00 - Urgency..00	-6,902	0
Urgency.2.00 - Urgency..00	-6,061	0
Urgency.3.00 - Urgency..00	-6,570	0
Urgency.3.00 - Urgency.1.00	-0,111	0,912
Urgency.3.00 - Urgency.2.00	-1,657	0,098
Urgency.2.00 - Urgency.1.00	-1,593	0,111
Actionness.1.00 - Actionness..00	-6,756	0
Actionness.2.00 - Actionness..00	-6,977	0
Actionness.3.00 - Actionness..00	-7,478	0
Actionness.3.00 - Actionness.1.00	-1,171	0,241
Actionness.3.00 - Actionness.2.00	-2,124	0,034
Actionness.2.00 - Actionness.1.00	-0,839	0,401



## APPENDIX VII GAME INPUT DATA

### NEN2767 - INSPECTION REPORT DATA PER SCENARIO

Scenario	Conditie Score	NEN inspectie	Gebrek	Schadebeeld	Belang
1	1. Uitstekende con	Niks (risico gebied)	Klimatologische invloeden	Geen	-
2	1. Uitstekende con	Niks (risico gebied)	Klimatologische invloeden	Geen	-
3	1. Uitstekende con	Niks (risico strenge winters)	Klimatologische invloeden	Geen	-
4	1. Uitstekende con	Niks (risico strenge winters)	Klimatologische invloeden	Geen	-
5	1. Uitstekende con	Corrosie (risico plasvorming)	Plasvorming	Geen	Serieus
6	1. Uitstekende con	Corrosie (risico plasvorming)	Plasvorming	Geen	Serieus
7	2. Goede conditie	Uitlekkend	Wapeningscorrosie	Putcorrosie	Ernstig
8	3. Redelijk conditie	Uitlekkend en hol klinkend	Delaminatie	Putcorrosie	Ernstig
9	3. Redelijk conditie	Scheur klein en langzaam	Scheur, constructief	Scheuren constr	Ernstig
10	4. Matige conditie	scheur groter en snel (uitlekken)	Scheur, constructief	Scheuren constr	Ernstig
Scenario	Intensiteit	Omvang	Schadeoorzaak	Gebrekestype	
1	-	-	Klimatologische invloeden	-	-
2	-	-	Klimatologische invloeden	-	-
3	-	-	Vorst/dooizouten	Materiaalintrinsiek	-
4	-	-	Vorst/dooizouten	Materiaalintrinsiek	-
5	Beginstadium	-	Plasvorming/Afwatering	Materiaalintrinsiek	-
6	Beginstadium	-	Plasvorming/Afwatering	Materiaalintrinsiek	-
7	Beginstadium	<2%, incidenteel	Lekkage	Constructief primair	-
8	Gevorderd Stadium	2-10%, plaatselijk	Lekkage	Constructief primair	-
9	Eindstadium	2-10%, plaatselijk	Roestende wapening	Constructief primair	-
10	Eindstadium	10-30%, regelmatig	Roestende wapening	Constructief primair	-

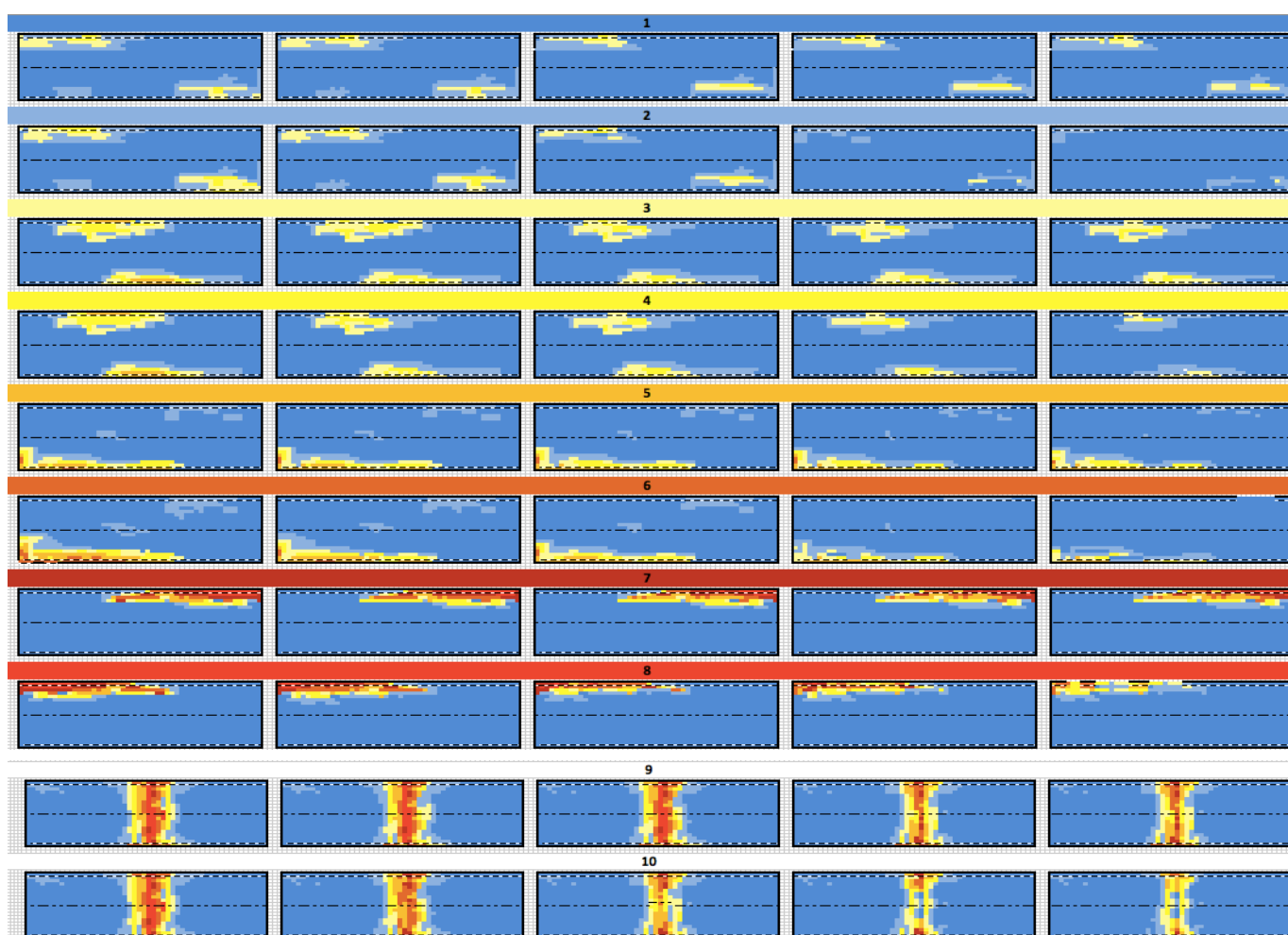
### FREQUENCY SENSOR DATA PER SCENARIO

	(Aanduidin	Natuurlijke Frequentie (Hz)	Laatst gem	Grootte van de Delaminatie intern(%)
Sensor A	11	50	49,91	0%
Sensor B	12	50	50,09	0%
Sensor A	21	50	50,03	0%
Sensor B	22	50	50,01	0%
Sensor A	31	50	49,96	0%
Sensor B	32	50	50,03	0%
Sensor A	41	50	50,09	0%
Sensor B	42	50	49,98	0%
Sensor A	51	50	47,52	5%
Sensor B	52	50	50,05	0%
Sensor A	61	50	47	6%
Sensor B	62	50	50,03	0%
Sensor A	71	50	49,98	0%
Sensor B	72	50	46,23	8%
Sensor A	81	50	43,7	13%
Sensor B	82	50	50,06	0%
Sensor A	91	50	42,03	16%
Sensor B	92	50	41,99	16%
Sensor A	101	50	39,03	22%
Sensor B	102	50	39,1	22%

# CHLORIDE & CORROSION SENSOR DATA PER SCENARIO

Scenario	Sensor	Start	Chloride M	Diffusie N	Diffusieco	A (constan	Dekking	Seconden in een jaar	Tijd tot corrosi	Leeftijd Br	Tijd tot cor	Kans op Corrosie
11	Sensor 1	0,2	0,37739	1,7	1,7E-12	1,85	0,0025	31536000,00	25,2065119	20	5-10 jaar	Laag
12	Sensor 2	0,09	0,23041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	>10 jaar	Laag
13	Sensor 3	0,08	0,22041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	>10 jaar	Laag
14	Sensor 4	0,03	0,17041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	>10 jaar	Laag
15	Sensor 5	0,1	0,24041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	>10 jaar	Laag
16	Sensor 6	0,13	0,30739	1,7	1,7E-12	1,85	0,0025	31536000,00	25,2065119	20	5-10 jaar	Laag
21	Sensor 1	0,05	0,34	3	3E-12	1,85	0,0025	31536000,00	14,2836901	20	5-10 jaar	Laag
22	Sensor 2	0,05	0,20977	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	>10 jaar	Laag
23	Sensor 3	0,05	0,19041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	>10 jaar	Laag
24	Sensor 4	0,05	0,20977	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	>10 jaar	Laag
25	Sensor 5	0,05	0,22739	1,7	1,7E-12	1,85	0,0025	31536000,00	25,2065119	20	>10 jaar	Laag
26	Sensor 6	0,05	0,36	3	3E-12	1,85	0,0025	31536000,00	14,2836901	20	5-10 jaar	Laag
31	Sensor 1	0,21	0,32902	1,4	1,4E-12	1,85	0,002	31536000,00	24,4863259	25	>10 jaar	Laag
32	Sensor 2	0,3	0,44041	1,5	1,5E-12	1,85	0,002	31536000,00	22,8539041	25	<5 jaar	Matig tot hoog
33	Sensor 3	0,15	0,26902	1,4	1,4E-12	1,85	0,002	31536000,00	24,4863259	25	>10 jaar	Laag
34	Sensor 4	0,2	0,26846	1,2	1,2E-12	1,85	0,002	31536000,00	28,5673802	25	>10 jaar	Laag
35	Sensor 5	0,3	0,45977	1,6	1,6E-12	1,85	0,002	31536000,00	21,4255351	25	<5 jaar	Matig tot hoog
36	Sensor 6	0,2	0,34041	1,5	1,5E-12	1,85	0,002	31536000,00	22,8539041	25	>10 jaar	Laag
41	Sensor 1	0,21	0,24815	1,1	1,1E-12	1,85	0,002	31536000,00	31,1644147	25	>10 jaar	Laag
42	Sensor 2	0,3	0,56	2,8	2,8E-12	1,85	0,002	31536000,00	12,2431629	25	0-2 jaar	Matig tot hoog
43	Sensor 3	0,15	0,26902	1,4	1,4E-12	1,85	0,002	31536000,00	24,4863259	25	>10 jaar	Laag
44	Sensor 4	0,2	0,34041	1,5	1,5E-12	1,85	0,002	31536000,00	22,8539041	25	5-10 jaar	Laag
45	Sensor 5	0,3	0,61	2,9	2,9E-12	1,85	0,002	31536000,00	11,8209849	25	0-2 jaar	Matig tot hoog
46	Sensor 6	0,2	0,40837	1,9	1,9E-12	1,85	0,002	31536000,00	18,0425559	25	<5 jaar	Matig tot hoog
51	Sensor 1	0,1	0,16846	1,2	1,2E-12	1,85	0,0025	31536000,00	35,7092252	20	>10 jaar	Laag
52	Sensor 2	0,2	0,35977	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	>10 jaar	Laag
53	Sensor 3	0,3	0,33815	1,1	1,1E-12	1,85	0,0025	31536000,00	38,9555184	20	>10 jaar	Laag
54	Sensor 4	0,4	0,54041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	0-2 jaar	Matig tot hoog
55	Sensor 5	0,4	0,54041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	0-2 jaar	Matig tot hoog
56	Sensor 6	0,1	0,21902	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	>10 jaar	Laag
61	Sensor 1	0,1	0,21902	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	>10 jaar	Laag
62	Sensor 2	0,2	0,31902	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	>10 jaar	Laag
63	Sensor 3	0,2	0,35977	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	5-10 jaar	Laag
64	Sensor 4	0,4	0,71896	3	3E-12	1,85	0,0025	31536000,00	14,2836901	20	Aanwezig	Matig tot hoog
65	Sensor 5	0,34	0,65896	3	3E-12	1,85	0,0025	31536000,00	14,2836901	20	Aanwezig	Matig tot hoog
66	Sensor 6	0,3	0,3952	1,3	1,3E-12	1,85	0,0025	31536000,00	32,9623617	20	<5 jaar	Laag
71	Sensor 1	0,1	0,21902	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	>10 jaar	Laag
72	Sensor 2	0,4	0,4815	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	Aanwezig	Matig tot hoog
73	Sensor 3	0,6	0,75977	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	Aanwezig	Matig tot hoog
74	Sensor 4	0,2	0,31902	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	5-10 jaar	Laag
75	Sensor 5	0,3	0,3952	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	<5 jaar	Laag
76	Sensor 6	0,3	0,3952	1,3	1,3E-12	1,85	0,0025	31536000,00	32,9623617	20	<5 jaar	Laag
81	Sensor 1	0,4	0,8	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	Aanwezig	Matig tot hoog
82	Sensor 2	0,4	0,8	3	3E-12	1,85	0,0025	31536000,00	14,2836901	20	Aanwezig	Matig tot hoog
83	Sensor 3	0,2	0,34041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	5-10 jaar	Laag
84	Sensor 4	0,2	0,31902	1,4	1,4E-12	1,85	0,0025	31536000,00	30,6079073	20	5-10 jaar	Laag
85	Sensor 5	0,2	0,34041	2,6	2,6E-12	1,85	0,0025	31536000,00	16,4811809	20	5-10 jaar	Laag
86	Sensor 6	0,29	0,3852	1,3	1,3E-12	1,85	0,0025	31536000,00	32,9623617	20	<5 jaar	Laag
91	Sensor 1	0,2	0,34041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	>10 jaar	Laag
92	Sensor 2	0,7	0,87739	1,7	1,7E-12	1,85	0,0025	31536000,00	25,2065119	20	Aanwezig	Matig tot hoog
93	Sensor 3	0,3	0,33815	1,6	1,6E-12	1,85	0,0025	31536000,00	26,7819189	20	5-10 jaar	Laag
94	Sensor 4	0,3	0,33815	1,1	1,1E-12	1,85	0,0025	31536000,00	38,9555184	20	5-10 jaar	Laag
95	Sensor 5	0,7	0,85977	1,2	1,2E-12	1,85	0,0025	31536000,00	35,7092252	20	Aanwezig	Matig tot hoog
96	Sensor 6	0,2	0,2952	1,3	1,3E-12	1,85	0,0025	31536000,00	32,9623617	20	>10 jaar	Laag
101	Sensor 1	0,2	0,34041	1,5	1,5E-12	1,85	0,0025	31536000,00	28,5673802	20	5-10 jaar	Laag
102	Sensor 2	0,4	0,8	3	3E-12	1,85	0,0025	31536000,00	14,2836901	20	Aanwezig	Matig tot hoog
103	Sensor 3	0,3	0,33815	3,2	3,2E-12	1,85	0,0025	31536000,00	13,3909595	20	5-10 jaar	Laag
104	Sensor 4	0,3	0,33815	1,1	1,1E-12	1,85	0,0025	31536000,00	38,9555184	20	5-10 jaar	Laag
105	Sensor 5	0,4	0,75	1,2	1,2E-12	1,85	0,0025	31536000,00	35,7092252	20	Aanwezig	Matig tot hoog
106	Sensor 6	0,2	0,2952	1,3	1,3E-12	1,85	0,0025	31536000,00	32,9623617	20	5-10 jaar	Laag

## GPR CONTOUR PLOT DATA PER SCENARIO



Scenario	Groep	2017	2015	2013	2011	2009
1	Goed	93%	93%	94%	94%	95%
1	Chloride	8%	7%	6%	6%	5%
1	Corrosie	0%	0%	0%	0%	0%
1	Delaminatie	0%	0%	0%	0%	0%
2	Goed	88%	92%	95%	99%	100%
2	Chloride	12%	8%	5%	2%	1%
2	Corrosie	0%	0%	0%	0%	0%
2	Delaminatie	0%	0%	0%	0%	0%
3	Goed	84%	85%	89%	90%	90%
3	Chloride	13%	15%	11%	10%	10%
3	Corrosie	3%	0%	0%	0%	0%
3	Delaminatie	0%	0%	0%	0%	0%
4	Goed	84%	89%	90%	93%	97%
4	Chloride	13%	11%	10%	7%	3%
4	Corrosie	3%	0%	0%	0%	0%
4	Delaminatie	0%	0%	0%	0%	0%
5	Goed	90%	90%	90%	92%	92%
5	Chloride	7%	6%	7%	6%	6%
5	Corrosie	4%	4%	3%	3%	2%
5	Delaminatie	0%	0%	0%	0%	0%
6	Goed	86%	89%	90%	92%	93%
6	Chloride	6%	6%	6%	6%	5%
6	Corrosie	8%	5%	4%	2%	2%
6	Delaminatie	0%	0%	0%	0%	0%
7	Goed	83%	84%	84%	86%	86%
7	Chloride	7%	6%	6%	7%	7%
7	Corrosie	8%	8%	9%	6%	6%
7	Delaminatie	3%	2%	1%	1%	1%
8	Goed	83%	84%	86%	88%	90%
8	Chloride	7%	6%	7%	7%	7%
8	Corrosie	8%	9%	6%	4%	2%
8	Delaminatie	3%	1%	1%	1%	0%

9	Goed	76%	78%	80%	82%	84%
9	Chloride	9%	9%	8%	8%	7%
9	Corrosie	7%	6%	6%	5%	5%
9	Delaminatie	8%	7%	6%	5%	4%
10	Goed	70%	76%	82%	88%	94%
10	Chloride	12%	10%	8%	6%	4%
10	Corrosie	8%	6%	4%	2%	2%
10	Delaminatie	10%	8%	6%	4%	0%



The current practice of bridge maintenance decision-making is informed by subjective visual inspection data with long time intervals between inspections. This creates inefficiencies and possible loss of value in the maintenance process. New opportunities from technology-related innovations for measurement devices are available for better informed decision-making. Even though this is acknowledged, the adoption and use of these opportunities seems to be disregarded by the market. The main focus of innovating organisations is mostly on the technology development of these systems and not on their levels of use within practice. This thesis presents a study towards the effects of using technology-related opportunities on maintenance decision-making from a user-centric perspective. A serious gaming experiment was performed wherein bridge maintenance decision-making professionals were questioned to set up a maintenance advice based on different types of data.

