Developing a framework for the specification of Structural Health Monitoring for concrete bridges using the key driver method

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Master thesis

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Preface

Currently, in front of you is the thesis titled: 'Developing a framework for the specification of Structural Health Monitoring for concrete bridges using the key driver method' This thesis forms the conclusion of my master's in Construction Management and Engineering at the University of Twente. The graduation research was carried out for Antea Group. Hopefully this research will contribute to the maturing of Structural Health Monitoring.

I would like to thank my supervisors for their supervision and support throughout this research. First, I want to thank Giel Klanker of Antea Group for the daily supervision. Next to the suggestions and the critical reflections for improving my research, I learned a lot about asset management in general and working at an engineering firm. This will be beneficial in my further career. Secondly, I would like to thank Robin de Graaf, Farid Vahdatikhaki and Osama Hegeir for their critical feedback during my research process. Thirdly, I want to thank all experts, that I interviewed for this research. I am grateful that everyone was willing to share their knowledge with me. It really helped me with my research. Fourthly, I want to thank all my colleagues of Antea Group.

Finally, I want to thank my family, friends and fellow students, who supported me during my life as a student and especially during this research. I would like to express a special word of thanks to my grandmother, who offered me a place to live during the research. Despite her illness, she always was interested and caring.

Sander Smit

Samenvatting

Veel betonnen bruggen in Nederland zijn gebouwd in de jaren zestig en zeventig van de vorige eeuw. Veel van deze bruggen bereiken in de komende decennia hun verwachte technische einde levensduur. Daar komt bij dat de verkeersintensiteit over de bruggen sterk aan het toenemen is, wat leidt tot een hogere belasting over de bruggen. Deze ontwikkelingen zorgen ervoor dat Nederland een grote renovatie- en onderhoudsuitdaging heeft in de komende decennia. Deze uitdaging vraagt om een efficiëntere onderhoudsstrategie. Een manier om de onderhoudsstrategie efficiënter te maken, is door te schakelen naar een risico gestuurde onderhoudsaanpak. Dit betekent dat onderhoudskeuzes gemaakt worden op de actuele conditie van de brug en de mogelijke risico's die de brug loopt. Structural Health Monitoring (SHM) is een snel ontwikkelende techniek, die de asset manager een beter inzicht kan geven in de huidige conditie van de brug en de mogelijke risico's. Structural Health Monitoring is gedefinieerd als het real-time monitoren van een in-gebruik zijnde brug, met gebruik van een reeks of netwerk van sensoren om data te verzamelen, die de verandering van de conditie van een brug weergeeft over tijd. De data wordt gecommuniceerd over een netwerk en data algoritmes kunnen worden gebruikt, wanneer mogelijk, voor schade lokalisering, classificering en beoordeling, maar ook voor levensduurvoorspelling.

SHM wordt met name door marktpartijen gepusht. De asset manager is echter niet de gebruiker van het SHM systeem. Een expert met constructieve kennis moet de data van het SHM systeem namelijk interpreteren om tot een goede indicatie van de conditie van de brug te komen. Daarnaast heeft de asset manager vaak geen verstand van de SHM technieken zelf. Dit zorgt ervoor dat het voor de asset manager lastig is om te evalueren of een SHM systeem, dat gepusht wordt door de markt, geschikt is voor zijn project. Daarnaast kan de asset manager vaak niet goed verschillende SHM systemen met elkaar vergelijken. Een manier om te kunnen evalueren of een systeem geschikt is, is door te kijken of het systeem aan bepaalde systeemeisen voldoet. Het probleem dat centraal staat in dit onderzoek is dat er geen framework beschikbaar is voor een asset manager om tot een specificatie van een SHM systeem te komen.

De doelstelling is daarom om een framework te ontwikkelen die aan de asset manager laat zien hoe systeemeisen opgesteld moeten worden, zodat het SHM systeem zal bijdragen aan de doelstellingen van de asset manager. Hierbij wordt gefocust op de doelstellingen: hoge veiligheid van de brug, weinig hinder voor de bruggebruiker en lage life-cycle kosten voor de brug. Om deze doelstelling te halen de volgende onderzoekvraag zal beantwoord moeten worden:

Hoe kunnen asset managers systeemeisen stellen aan Structural Health Monitoring systemen, zodat de asset manager in staat is om te controleren of aangeboden SHM systemen zullen bijdragen aan de doelstellingen van de asset manager voor het onderhouden van betonnen bruggen?

Dit onderzoek is een exploratief onderzoek. Met behulp van de key driver methode is geprobeerd om tot een framework te komen die systeemeisen kan stellen aan een SHM-systeem. De key driver methode is een doelgerichte specificatie methode. De key driver methode deelt hoofddoelen op in subdoelen, totdat het mogelijk is om systeemeisen aan de subdoelen te stellen. Er is gekozen voor deze methode omdat een doelgerichte specificatie methode ervoor moet zorgen dat een SHM-project niet alleen maar laat zien wat het SHM-systeem kan, maar ook daadwerkelijk bijdraagt aan de doelstellingen van de asset manager.

Het onderzoek start met een literatuuronderzoek en expertinterview om erachter te komen waarom betonnen bruggen onderhouden moeten worden en hoe dat gedaan is in het huidige beleid van de asset managers. Dit is gedaan om de beperkingen van het huidige beleid en de mogelijkheid voor SHM te bekijken. Dit geeft een beeld van de mogelijkheden hoe SHM het huidige onderhoudsbeleid kan verbeteren. Uit het literatuuronderzoek bleek dat asset managers verplicht zijn om aan te tonen dat de brug veilig gebruikt kan worden. Er is geen verplichte manier om dit te doen. Op dit moment, wordt de veiligheid vooral gewaarborgd met visuele inspecties en constructieve berekeningen. Daarnaast is het mogelijk om extra onderzoek uit te voeren.

Toen de huidige aanpak bekend was, is er gekeken naar de doelstellingen die gehaald kunnen worden met SHM-systemen. Dus, welke doelen kunnen behaald worden met SHM. Hierbij lag de focus hoe SHM-systemen kunnen bijdragen aan de hoofddoelen van de asset manager: hoge veiligheid van de betonnen brug, weinig hinder voor de brug gebruiker en weinig life cycle kosten van de betonnen brug. Een literatuuronderzoek en expertinterviews zijn uitgevoerd om een algemeen key driver diagram te maken. Dit diagram laat de relatie zien tussen hoofddoelen, subdoelen en systeemeisen. Vervolgens is een framework ontwikkeld, die laat zien hoe het algemene key driver diagram gebruikt kan worden en eventueel uitgebreid kan worden.

Dit framework is gevalideerd op twee manieren. Deze validatie is uitgevoerd om te controleren hoe het framework scoort op de criteria: degelijkheid, compleetheid, begrijpelijkheid, gemak van gebruik, mogelijkheden om de specificatie aan te passen voor elke betonnen brug en verifieerbaarheid. De eerste validatie sessie focuste op het resultaat van het framework. Dit is gedaan door het framework toe te passen voor twee cases. Het resultaat is geëvalueerd met de projectleider van de case. De tweede validatiesessie focuste op het hele framework. Twee experts zijn gevraagd om het framework te beoordelen op de genoemde criteria.

De uitkomst van de validatiesessies was dat de experts, op enkele kleine details na, vonden dat het framework de juiste systeemeisen genereert. Daarnaast vonden de experts dat de key driver diagrammen duidelijk weergeven waarom een systeemeis werd gesteld. De experts hadden echter wel hun twijfels over de compleetheid van de specificaties, maar vonden het lastig om aan te geven welke eisen er misten. Daarnaast was het ontwikkelde framework moeilijk te begrijpen en konden verschillende experts verschillende ideeën hebben bij sommige doelen of subdoelen. Daar komt bij dat het begrijpen en doorlopen van het framework veel tijd kost. Ten slotte gaven de experts ook aan dat het niet altijd nodig is om zo een uitgebreid diagram te maken voor een specificatie.

Dus, het ontwikkelde framework is nog niet gebruiksvriendelijk voor in de praktijk. Echter, het overzicht van de gespecificeerde systeemeisen en de overwegingen tijdens het specificatie zijn nuttig voor de asset manager. In appendix G, een lijst met system eisen en overwegingen tijdens het specificatieproces zijn gepresenteerd. De volgende subdoelen moeten worden behandeld in het specificatieproces van een SHM-systeem:

- Correct data verzameling
- Correct presentatie van data
- Betrouwbaarheid data
- In staat zijn om data in de toekomst te gebruiken
- Lage investeringskosten SHM-systeem
- Lage datamanagement kosten
- Lage onderhoudskosten SHM-systeem
- Robuust SHM-systeem
- In staat zijn om te blijven functioneren onder omgevingsfactoren

- Weinig hinder veroorzaakt door het SHM-systeem
- Geen onveilige situaties veroorzaakt door het SHM-systeem

Tijdens de validatiesessie was daarnaast ook gediscussieerd hoe de specificatie gebruikt kan worden in de praktijk. De specificatie kan ervoor zorgen dat een asset manager kan controleren of een SHM-systeem geschikt is. Daarnaast is het ook mogelijk om de specificatie te gebruiken om verschillende SHM-systemen met elkaar te vergelijken. Er zijn echter vraagtekens bij de toepasbaarheid van zo'n gedetailleerde specificatie voor de aanbesteding van een SHM-systeem. Een gedetailleerde specificatie zorgt voor minder vrijheid van de markt. Daarnaast, zullen SHM-systemen vaak aanbesteed worden in combinatie met andere analyses en inspecties/ onderzoeken.

Abstract

A lot of concrete bridges in the Netherlands were built in the sixties and seventies of the previous century and are expected to reach their technical end of life in the coming decades. Next to that, the traffic intensity is increasing, which results in higher loads on the bridge. This causes the Netherlands to have a big maintenance and renovation challenge in the coming decades. This challenge asks for more budget for maintenance or a more efficient maintenance strategy. A possible way to improve the efficiency of the maintenance policy is by switching to a more risk-based maintenance approach. This means that maintenance decisions are based on the actual condition of the bridge and the actual risk of failure. Structural Health Monitoring (SHM) is currently developing fast and can present to the asset manager what the current condition of the bridge is. The definition of SHM is the real-time monitoring of in-service structures using an array or network of sensors to collect data that can be used to represent changes in the condition of a structure over time. The data is communicated over a network, and data processing algorithms may be used, if possible, for damage localization, classification and assessment, as well as residual life prediction. This shows that SHM can be beneficial for an asset manager.

Asset managers want to have more information about the condition of the bridge, but the SHM system will only give data. The asset manager does not use the SHM system itself and is in most cases not familiar with the SHM techniques. This results that an asset manager cannot specify what they want from a SHM system.

A way to check whether a system is suitable is by checking if it meets the system requirements in the specification. The objective of this research is to develop a framework that presents to asset managers how an asset manager should define system requirements, such that the asset manager is able to evaluate if proposed SHM solutions contribute to his objectives. To achieve this objective, the following research question should be answered.

How can asset managers set system requirements to Structural Health Monitoring systems, such that the asset manager is able to check if proposed SHM systems will contribute to the asset managers' goals for the maintenance of concrete bridges?

The research is an explorative research that tries to develop a framework that comes up with a specification for a SHM system. This is tried by using the key driver method. This is a goal-oriented approach. The key driver method splits up main goals in more detailed sub-goals until it is possible to link system requirements to the sub-goals. The hypothesis before the research was that the objective to use SHM influences the specification of the SHM system.

The research started with a literature research and expert interviews to identify the need of maintenance of concrete bridges and the current maintenance approach. This is done to find the shortcomings of the current approach and opportunities for applying SHM. The literature research showed that asset managers are obliged to ensure that their bridge can be used safely. There is no compulsory approach to prove this safety. In the current approach, asset managers prove in several ways that their bridge is safe. First, the bridge is inspected visually. Secondly, the safety of the bridge can be assessed by doing structural calculations. Furthermore, it is possible to do additional research.

When the current state of the affair was clear, there was researched how SHM systems could contribute to this maintenance approach. So, there was tried to identify what goals should be achieved with applying a SHM system on a bridge, whereby is focussed how SHM systems could contribute to the main objective of asset managers: high safety of the bridge, low life cycle costs of the bridge and low hindrance to the bridge user. A literature research and expert interviews were executed to develop

a generic key driver diagram. This diagram split up the main goals in sub-goals until it was possible to link system requirements to the sub-goals. Furthermore, a framework was developed that shows how an asset manager can develop a case specific key driver diagram: a diagram that shows the link between the main goals he wants to achieve in his project and the system requirements that he should set to the SHM system.

The framework was validated in two ways. These validations were executed to check how the framework scored on the criteria: soundness, completeness, understandable, ease-to use, ability to tailor the specification for an individual case and verifiability. The first validation focussed on the outcome of the framework. This was done by applying the framework for two cases. With the project leader of the case was evaluated how the specification scored on these criteria. Secondly, two experts were asked to evaluate the complete framework itself.

The outcome of the validation sessions was that the experts, except some minor details, thought that the framework generates correct system requirements. The system requirements that are presented in the specification in the case and in the generic key driver diagram are logical. Next to that, the experts found that a key driver diagram presents in a clear way why specific system requirements are set. So, the experts were also satisfied with the verifiability of the framework. The experts had doubts about the completeness of the framework but found it hard to explain what system requirements were missing. Furthermore, the developed framework scored less on the criteria ease-to-use. The experts explained that they found it difficult to understand how the framework works and running through the framework costs a lot of time and stated that it is not always necessary to develop a complete key driver diagram for a specification. Finally, the experts think that the understandability of the framework can be improved.

So, it is hard to apply the framework directly in practice. However, the overview of the developed system requirements and considerations during the specification process can be beneficial for the asset manager. It can show, about what aspects should be thought. In appendix G, a list of system requirements and considerations during the specification process are presented. The following sub-goals should be achieved with the specification of the SHM system:

- Correct data gathering
- Correct presentation of data
- Reliable data
- Able to use data in future
- Low capital investment SHM system
- Low data management costs
- Low maintenance costs SHM system
- Robust system
- Able to deal with environmental threats
- Low hindrance caused by SHM system
- No unsafe situations caused by SHM system

During the validation was also discussed when a specification could be used. The specification of a SHM system can be used to compare different SHM systems or to check whether a SHM system is suitable for a project. But the experts have doubts if it is necessary to have such a comprehensive and detailed specification for the tendering of a SHM system. The more detailed the specification, the less freedom for the market. Next to that, SHM system is often tendered most of the time in combination with an analysis or other inspections / researches.

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List of abbreviations

A1 - A8	Activity 1 – Activity A8 of the developed framework
AM	Asset manager
AM1 – AM3	Expert with knowledge of asset manager, who is interviewed in this research
ASR	Alkali silica reaction
GE1	Expert with general knowledge about Structural Health Monitoring and asset management, who is interviewed in this research
MA	Maintenance advisor
pH	Unit that indicates how acidic or basic a material is
Q1 – Q5	Question 1 – Question 5 of the developed framework
RBK	Guideline assessment asset (Dutch: Richtlijn beoordeling kunstwerken)
RE	Requirement engineer
SD	Structural health monitoring / data specialist
SE	Structural Engineer
SE1 – SE3	Expert with knowledge of structural engineering, who is interviewed in this research
SHM	Structural health monitoring
SHM 1 – SHM 3	Expert with knowledge of structural health monitoring, who is interviewed in this research
VI1 – VI2	Expert with knowledge of visual inspections and damages on concrete bridges who is interviewed in this research

1 Introduction

1.1 Background

The Netherlands is a country with many rivers and lakes. To enable the transport of people and goods to cross these waters, many bridges have been built in the last centuries. Rijkswaterstaat is the executive agency of the Ministry of Transport and Water Management and is responsible for the national highways, waterways and water system (Paulissen, Es, & Peelen, 2019). Rijkswaterstaat is responsible for 1052 bridges, consisting of 167 movable bridges, 103 static steel bridges and 782 static concrete bridge (Rijkswaterstaat, 2019). Other bridges are maintained by other governments, like municipalities or provinces. For this transportation it is important that all bridges are available and safe.

1.1.1 Bridge problem

According to the Dutch minister of Infrastructure and Water Management, the Netherlands currently faces the largest renovation challenge for bridges and tunnels in the history (Verlaan, 2019). In Figure 1, the year of construction of concrete bridges in the Netherlands are presented. What can be noticed is that in the seventies many concrete bridges were built. These bridges are maintained by Rijkswaterstaat and are expected to reach their technical end-of-life in the coming decades (Rijkswaterstaat, 2007). This can be caused not only by the deterioration of the structures, but also by the more intensive use of the bridges. The Dutch infrastructure is used to a higher extent. The number of vehicles and the weight of the trucks are increasing (Paulissen et al., 2019). The amount of vehicle kilometres of trucks and cars has increased from 60.4 billion in 2005 to 71.1 billion in 2017(Verlaan, 2019).

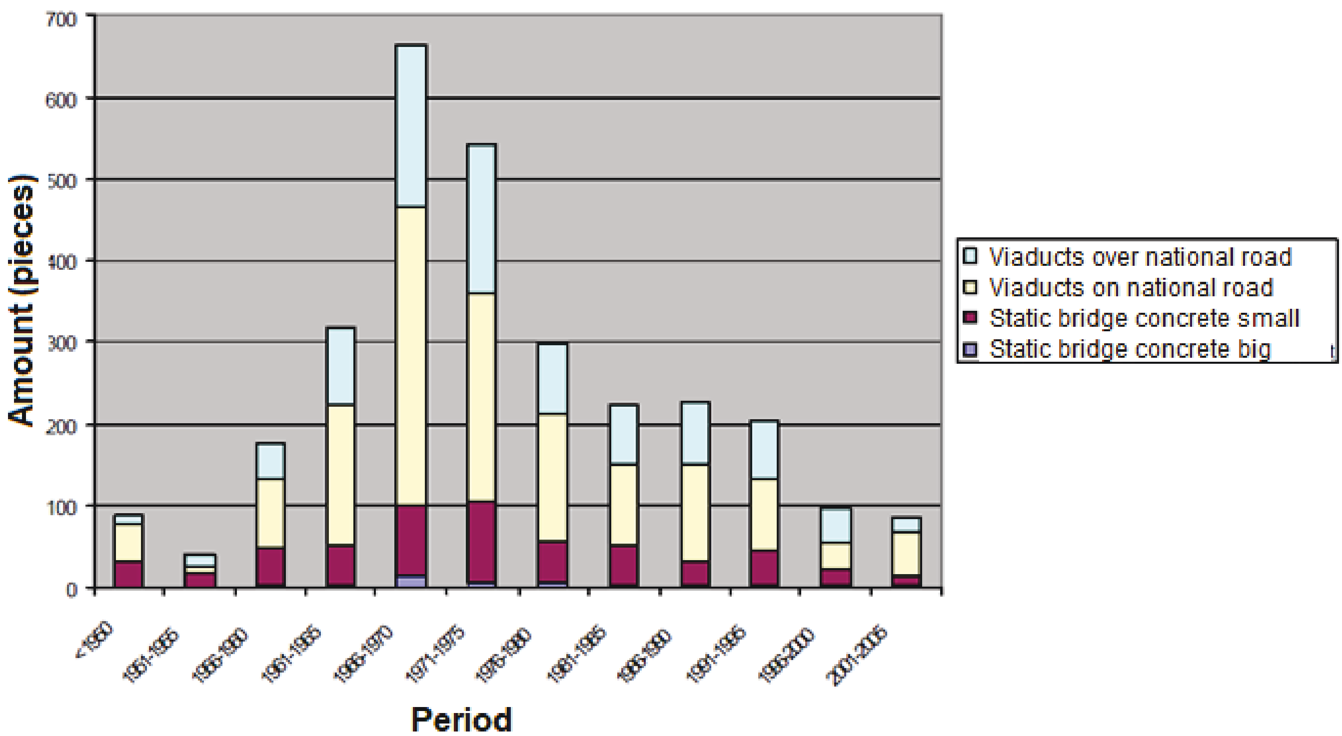


Figure 1 Year of construction concrete bridges in the Netherlands (Rijkswaterstaat, 2007)

The challenge, described before, demands for extra budget for replacements and renovation of existing bridges or / and a more efficient strategy. Because of the economic crisis of 2008, the government had had lower investments in the maintenance and rehabilitation of the Dutch infrastructure. Since a few years, the investments in the maintenance and rehabilitation of infrastructure increased again (Kerkhof, Lamper, & Fang, 2018). In Figure 2, the prognosis of the budget needed for replacing aging infrastructures is presented. HWS, HVWN, HWN means respectively main water system, main inland shipping network and main road network. Paulissen et al. (2019) predicts the time of replacement in three ways. First, predictions of replacements, which are based on visual inspections. These predictions focus on the short term (<10 years) and are stated as projects. Secondly, there are issues that are predicted based on characteristics of similar bridges. These focusses on the medium long term (10-15 years). Thirdly, the time and costs of replacement can be predicted based on the statistical end of life. This focusses on the long term (>15 years). The statistical end of life is determined based on the age of the object and on issues that are expected based on the known problems with groups of similar assets. What can be seen is that the total replacement costs will increase in the coming decades for the total amount of infrastructure. The costs for the replacement of concrete bridges is not mentioned specifically in this graph. However, the share in the replacement budget of different infrastructure assets is presented in Figure 3. What can be seen, is that concrete bridges are responsible for a significant part (14% of the total replacement budget) of the of the total replacement costs in the future.

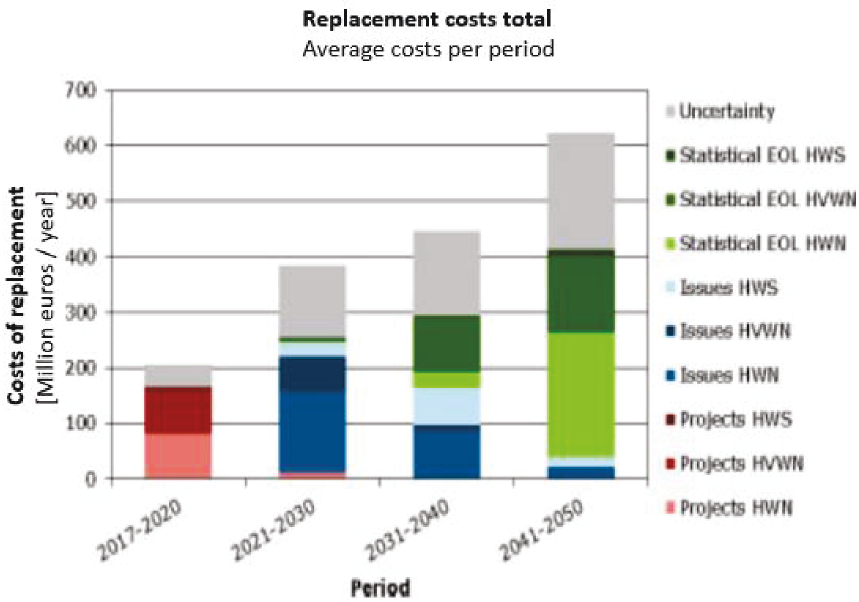


Figure 2 Expected budget needs for the replacement (Paulissen et al., 2019)

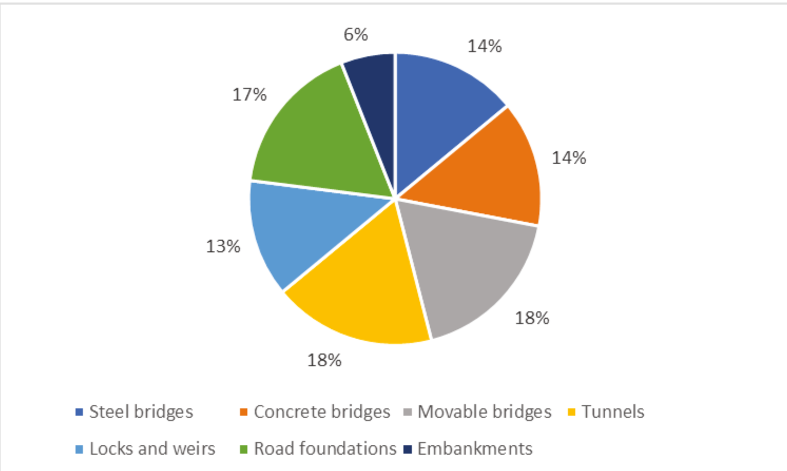


Figure 3 Share in the replacement budget prognosis for every category of infrastructure assets (Kerkhof et al., 2018)

1.1.2 Asset management

Like stated before, the Netherlands is facing a challenge with aging infrastructure. On the one hand, the asset manager must deal with a critical demand for the safety and functionality of its infrastructure. On the other hand, the budget of the asset manager is limited. In Figure 4 is schematized how the functioning of an infrastructure is threatened. Asset managers have to deal with increasing performance requirements, limited budget, higher legal requirements and less public acceptance (Wijnia & Herder, 2009).

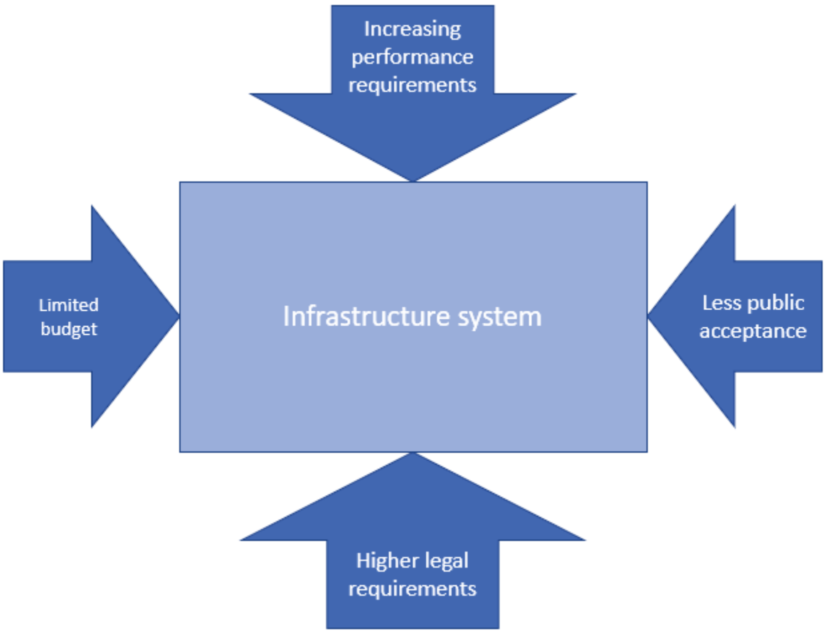


Figure 4 Pressure on infrastructure systems (Wijnia & Herder, 2009)

To cope with those conflicting aspects, many infrastructure owners have introduced asset management. Asset management is an integrated approach to balance costs, performance and risks. An efficient strategy means that more assets can be maintained and controlled with a similar or lower budget. Asset management is a widely used approach that tries to balance performance and (limited) budget with acceptable risks. According to the ISO 55000, the definition of asset management is: the coordinated activity of an organization to realise value from assets. Where an asset is an item, thing or entity that has potential or actual value for an organization and realization of value involves the balancing of costs, risks, opportunities and performance benefits (IAM, 2015).

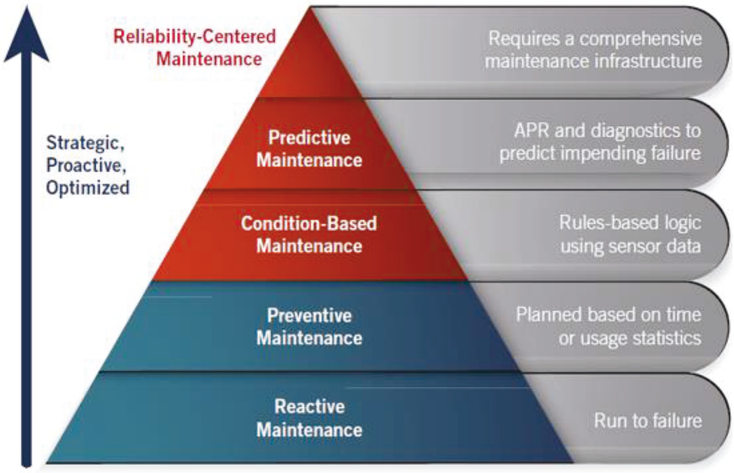


Figure 5 Maintenance maturity pyramid (Custeau, 2015)

In Figure 5, different categories of maintenance strategies are presented. The difference between the categories is the level of optimization of the maintenance. The amount of optimization is explaining if the bridge is maintained on time (not too early, not too late). By implementing asset management, infrastructure organizations try to have a more strategic, proactive and optimized maintenance policy in the past, infrastructure assets were especially maintained reactively. This means that assets were maintained when a failure occurred. By having a better insight in the risks of failure or a prediction of the expected lifespan, it is possible to maintain the structure on the right time(Custeau, 2015). This means that costs can be saved by scheduling the maintenance more efficiently and on the other hand unsafe situations can be prevented. However, only better insight in the condition of the bridge does not result in a more effective maintenance policy. Effective asset management requires an interdisciplinary approach, in which good collaboration should exist between different disciplines, like: accounting, engineering, finance, logistics and information systems technologies (Ahmadi-Echendu, Brown, Willet, & Mathew, 2010).

1.1.3 Structural Health Monitoring

A way to gather more information about the current condition of a bridge is using Structural Health Monitoring. Gastineau et al (2009) reviewed several definitions of SHM and defined SHM as follows: Structural health monitoring is the real-time monitoring of in-service structures using an array or network of sensors to collect data that can be used to represent changes in the condition of a structure over time. The data is communicated over a network, and data processing algorithms may be used, if possible, for damage localization, classification and assessment, as well as residual life prediction. SHM techniques have been developed in the last decades. Chang (1999) defines that the goal of SHM is to gain continuous knowledge about the integrity of structures that are in use.

The advantage of SHM in comparison with periodic inspections is that it offers continuously information about the structure and it is less costly in terms of extensive labour and downtime (Chang, 1999). SHM projects can differ per case in size and complexity from systems. There can be periodic, short term but also long-term monitoring. Furthermore, there can be chosen to measure one component, multiple components or the entire structure. Finally, it is possible to measure many different parameters of the structure, depending on the purpose of the monitoring. This shows that SHM projects can differ significant from each other(Gastineau, Johnson, & Schultz, 2009). SHM is currently developing fast. Reasons for the rapid development and advancement of SHM system are(Dong, Song, & Liu, 2010):

- Recent advancements in sensor technology

- Developments in communication technologies, (internet use and wireless technologies)
- Development of powerful data transmission and collection systems, and data archiving and retrieval systems; and advances in data processing, including damage detection models and artificial intelligence algorithms.

Although Structural Health Monitoring (SHM) is developing and has been an interesting topic in major international research during the last 20 years, the implementation of SHM systems on bridges is still no common practice, while it can deliver some serious benefits for the asset manager. Wenzel (2019) presented several obstacles that explain why SHM is not used very often. According to Wenzel (2019) these are the most important ones:

- Specific data needs are not defined;
- Standards do not exist;
- Each bridge is unique;
- SHM systems are still expensive;
- SHM systems are unproven;
- Bridge owners are not convinced of value;
- SHM is not required by law

1.1.4 Demand specification

In previous sections, the challenge of asset managers in the Netherlands and their need for a more efficient strategy to maintain their assets are presented. More information about the current condition of their asset can help the asset manager with maintaining their assets more effectively. Next to that, there is a rapid development and advancement of SHM systems. These new techniques are very promising and can contribute to the challenges of the asset manager.

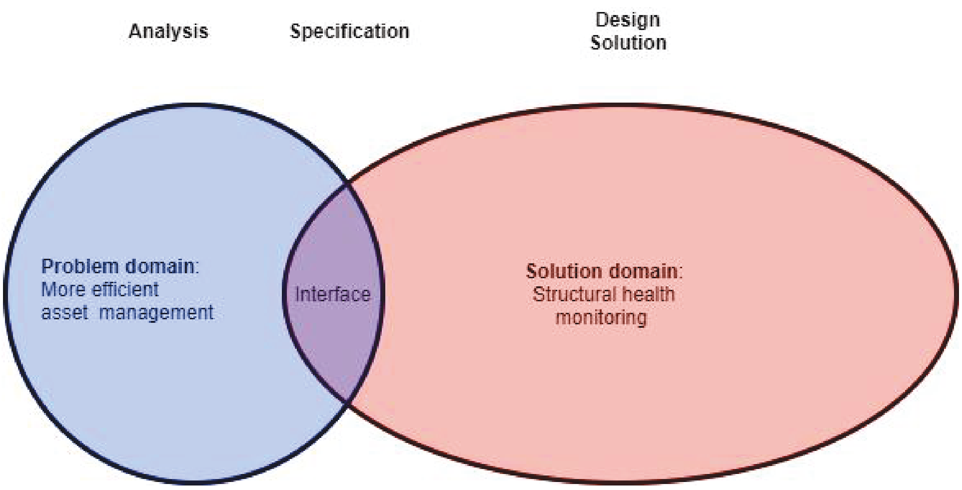


Figure 6 Ideal situation problem and solution domain

Two domains can be distinguished in the design process: the problem domain and the solution domain. The problem domain is the domain in which a system is going to be used (Dick, Hull, & Jackson, 2017). A system should enable the user to do something. In the case of managing bridges, the asset manager wants to be able to make decisions how to maintain their assets. In the solution domain, designers and engineers use their knowledge and expertise to solve problems (Dick et al., 2017). In this case, SHM should deliver input for the decision making. In the ideal situation, SHM systems can directly benefit to the maintenance policy of the asset manager, see Figure 6. The interface between the problem domain and the solution domain is the specification. A specification describes abstractly what a system should do to meet the requirements of the stakeholder and avoid references to any particular design (Dick et al., 2017). A specification is a set of system requirements for a product.

Defining requirements is an iterative process and is not determined in once. In Figure 7 is presented how requirements are derived in several levels of details. For every layer the requirements engineer should:

- Communicate with the customer, and improve mutual understanding of the system to be developed;
- Analyse the system to ascertain the presence of desired emergent properties (and the absence of undesirable ones);
- Determine how to satisfy the requirements by deriving new requirements at the layer below.

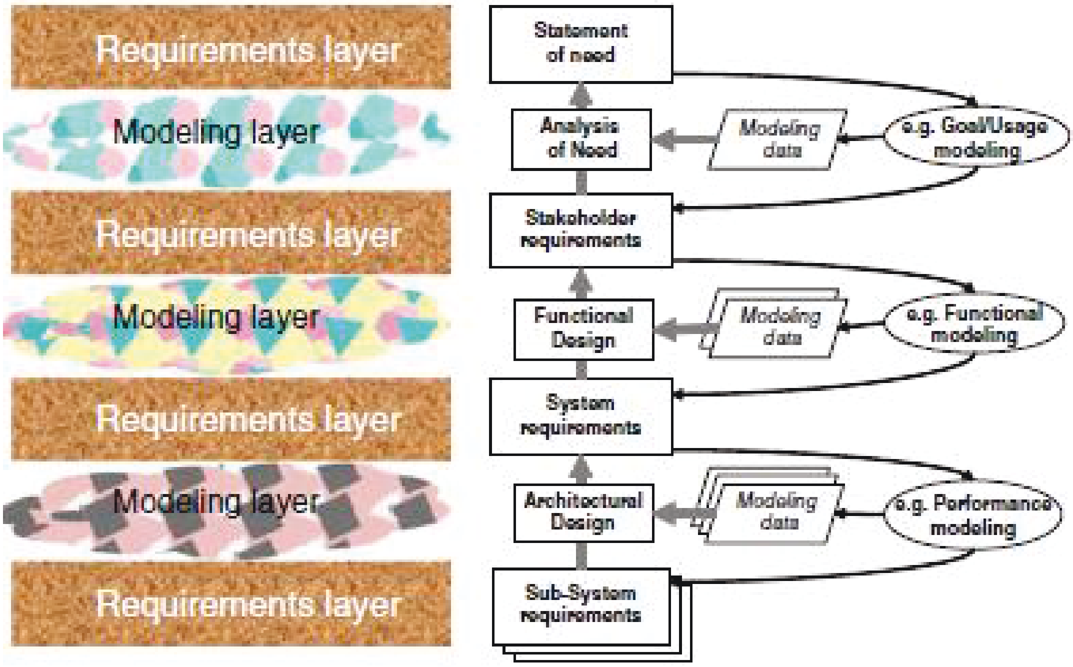


Figure 7 Different layers of requirement engineering (Dick et al., 2017)

In the begin of the specification process, the requirements (statement of need and the stakeholder requirements) are still in the problem domain. There should only be mentioned what problem should be solved by the system. System requirements are the first layer that enters the solution domain. The system requirements describe what the system needs to do to solve the problem, without referring to any solution. The system requirements must be created at an appropriate level of abstraction such that it encompasses(Dick et al., 2017):

- Internal functionality that the system must exhibit; this must concentrate on what the system must do rather than on how it should be done to avoid pre-empting the design;
- Functionality necessary to enable the system to interact with other systems in its environment;
- Functionality necessary to enable people to successfully interact with it;
- Functionality to prevent the system from malfunctioning due to the presence of other systems (threats) in its environment.

1.2 Problem statement

Like presented, SHM systems can deliver data about the current condition of a bridge. This can contribute to a more efficient and pro-active maintenance policy of the asset manager. In Figure 8, the process for making maintenance decisions based on the output of SHM systems is presented from left to right. The supply side of SHM systems is presented on the left-hand side. The output of a SHM systems is data. The data needs to be interpreted, which is not done by the asset manager, but by an expert with knowledge of structural engineering. Next to that, asset managers have in general not much knowledge about the SHM techniques itself. Therefore, it is difficult for the asset manager to specify what the SHM system should look like and what the SHM system should do. This results that asset managers cannot compare or evaluate delivered SHM solutions of market parties.

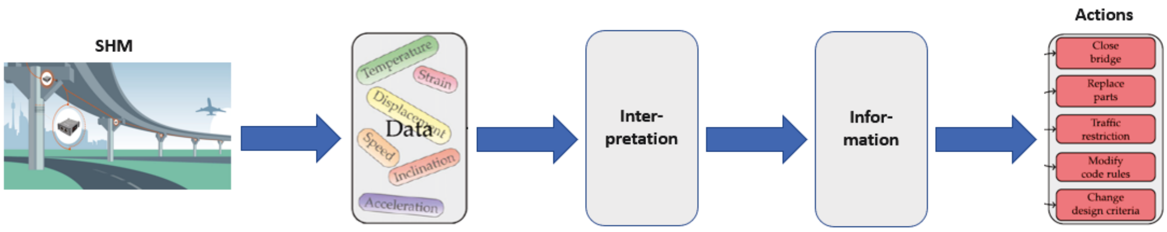


Figure 8 Process from SHM system to actions

The problem that is tried to be solved in this research is that:

No framework or standard is available how different knowledge disciplines need to be integrated to identify system requirements for SHM systems. Which makes it hard for asset managers to come up with a complete list of system requirements to evaluate if a SHM system is suitable for his project.

1.3 Problem owner: Antea Group

Antea Group sees many possibilities in SHM of assets and does not only want to operate on the demand side, but also on the supply side. Antea Group developed several SHM systems for asset managers. In all projects, Antea Group proposed the solution to the asset manager. However, Antea Group also wants to advise the asset manager with the selection of the right SHM system for his project.

Antea Group is an internationally operating engineering and consultancy firm with over 3100 employees worldwide. Antea Group works especially in the field of environment, soil, infrastructure, management, safety and spatial development (Antea Group, 2019). Furthermore, they deal with issues like energy transition, smart cities, smart mobility, circular economy and sensor technology. Antea Group has six business lines:

- Management and realization
- Construction and realization,
- Contracts and Permit,
- Infrastructure
- Environment and safety and
- Space and Water.

This research is executed for the advice group asset management. Asset management is a new advisory group within the business line Infrastructure. The asset management group focusses on public space and infrastructures. Antea Group operates on the strategic, tactical and operational level. From strategy to concrete approach.

1.4 Research objective

Since the required knowledge for the design of a SHM system is fragmented, the asset manager is not able to evaluate or ask for a SHM system that contributes to their objectives. The knowledge of several disciplines is required for the drafting of a specification for a SHM system. Antea Group wants to assist the asset manager with his demand specification such that the asset manager can evaluate proposed SHM systems.

The objective of this research is to develop a framework that presents to asset managers how a complete list of system requirements should be defined, such that the asset manager is able to evaluate if proposed SHM solutions contribute to his objectives for the maintenance of concrete bridges.

The following criteria can be used to check if the framework meets the research objective (adapted from: Beecham, Hall, Britton, Cottee, & Rainer (2005))

- Sound; The framework should derive only system requirements that contribute to the objectives of the asset manager
- Complete; The framework should come up with a complete set of system requirements. All solutions that meet these system requirements, benefit to the goals of the asset owner.
- Tailorable for every concrete bridge; The framework must be structured so that it can be extended and tailored to every concrete bridge.
- Verifiable; The framework should make it possible for asset manager to check why specific system requirements should be set to the SHM system
- Understandable; All users of the framework should have a shared understanding of the process
- Ease to use; Users should quickly understand the framework and it should not take long to come up with a specification. Over-complex frameworks are unlikely to be adopted as they require extra resources and may be too challenging for the user to interpret without extensive training.

1.5 Research questions

To achieve the research objective, it will be necessary to answer the main research question. The main research question is subdivided into several sub questions. These sub questions provide structure in this study and safeguard the validity of this research. In this research a goal-oriented approach will be used, that splits up main goals in sub-goals, until it is possible to link system requirements to the sub-goals. The first two sub-questions are asked to get an idea what goals could be achieved with SHM. Answering the third and fourth sub-questions should present how these goals can be met and answering the fifth sub-question should explain how system requirements can be linked to those goals.

Table 1 Overview of the main research question and sub-questions

Main research question	**How can asset managers set system requirements to Structural Health Monitoring systems, such that the asset manager is able to check if proposed SHM systems will contribute to the asset managers' goals for the maintenance of concrete bridges?**
Sub questions	1. Why do concrete bridges need to be maintained? 2. How do asset managers in the Netherlands currently maintain their concrete bridges? 3. How can SHM systems contribute to the asset managers' goals for the maintenance of concrete bridges according to literature? 4. How can SHM systems contribute to the asset managers' goals for the maintenance of concrete bridges in practice? 5. How can asset managers link system requirements for a SHM system to those goals?

1.6 Scope of research

The scope of the research is important to ensure that the correct focus is maintained throughout the research to in the end answer the research questions. The following aspects are within the scope of the research.

1. The framework will use the key driver approach of Muller et al. (2006) to derive system requirements. Other specification approaches are not considered in this research. The key driver method is a goal-oriented approach, which means that system requirements will be derived from goals. This research focusses only on the main goals of the asset manager: safety of the bridge, availability of the bridge and life cycle costs of the bridge. Since safety, functionality and costs are the main drivers of asset management (Vardenga, 2016). Life cycle costs are considered as the total costs during the lifetime of the bridge. This includes amongst others, the costs of maintaining the bridge, costs of implementing SHM and costs of inspecting the bridge.

2. The framework should be useful to elicit system requirements for SHM system for existing concrete bridges. Inaudi (2016) presented that it can also be beneficial to use SHM system for new structures including innovative aspects in the design, construction procedure, or materials used and for new structures with unusual associated risks or uncertainties. However, these new structures are not considered during this research. Also structures from other materials, like steel or wood are not considered.

3. The framework presents how system requirements can be derived from main goals. Requirements can also be specified until sub-system requirements. This level of detail will not be reached in this research. System requirements state abstractly what the system will do to meet the client requirements, without reference to a particular design(Dick et al., 2017). There is decided to use this level of detail, since system requirements can be used for the procurement of the system and for the evaluation of different solutions.

4. This research is an explorative research. The framework that is developed in this research tries to enable the asset manager to evaluate if a proposed SHM system is suitable for his project or not. The evaluation process of different SHM solutions or the method to request for SHM solutions will not be researched. The framework will not come up with a complete demand specification for the tender of a SHM system.

1.7 Outline

This research is structured in the following way:

Chapter 2: This chapter contains the method of the research. A description is given of the activities that are executed in the research.

Chapter 3: This chapter describes the current approach of asset managers concerning the maintenance of bridges. A description is given why concrete bridges need to be maintained and how asset managers do this in the current approach.

Chapter 4: This chapter describes in general how SHM can contribute to the main objectives of asset managers and what system requirements could be defined in order to meet those objectives. This is presented in one big diagram: the generic key driver diagram.

Chapter 5: This chapter contains a framework that describes how a case specific key driver diagram can be made. A case specific key driver diagram presents to what objectives the SHM system should contribute and which system requirements should be set. This framework consists of two parts:

- Description how the generic key driver diagram can be used
- Description how the generic key driver diagram can be elaborated

Chapter 6: The validation of the framework is presented in this chapter. The framework is validated with a case study and an expert panel.

Chapter 7: This chapter contains the discussion of the research method and the results

Chapter 8: The conclusions and recommendations from this research are presented here.

2 Methodology

The objective of this research is to develop a framework for the specification of Structural Health Monitoring systems for concrete bridges. To achieve this there is chosen to use the key driver method of Muller et al (2006) as specification method. This is a goal-oriented approach, which means that main goals of the asset manager are split up in sub-goals until it is possible to link system requirements to a sub-goal. There is chosen for this method, because SHM projects are now often projects that show what SHM systems can do, rather than really be valuable for the asset manager(Vardanega, Webb, Fidler, & Middleton, 2016). By using the main goals of an asset manager as starting point, there is tried to make sure that the SHM system will be beneficial for the asset manager. Several activities will be executed in this research to achieve the research objective, see Figure 9. In the following paragraphs, the activities in the research will be described in more detail.

2.1 Literature study

A literature study has been executed to have a good starting point for the expert interviews. The literature research is executed to three topics. First, a literature research is conducted towards damages and structural risks of concrete bridges in the Netherlands. This gives an idea why and when a bridge needs to be maintained. Scientific articles are used as input for this analysis. Secondly, there will be looked at the current maintenance policies of asset managers in the Netherlands. Regulations, guidelines and scientific articles are used as input. Thirdly, a literature study is conducted towards goals and requirements of structural health monitoring systems. There will be looked how SHM can be beneficial for the maintenance policy of the asset managers. Input for this activity are scientific articles.

2.2 Expert interviews

Experts were interviewed to elaborate and validate the information of the literature research. All interviews were semi-structured interviews. This implies that a set of questions was prepared, but that is was also possible to ask follow-up questions. The interview protocol is presented in Appendix B. In this appendix can be read how the interviews were structured.

The interviews addressed three topics:

- Topic 1: Risks and damages of concrete bridges in the Netherlands
- Topic 2: Current approach of maintaining concrete bridges by asset managers in the Netherlands
- Topic 3: Benefits of SHM in the current approach of maintaining concrete bridges in the Netherlands and the specification of such a system.

The questions towards Topic 1 and 2 remained the same for all experts (SHM experts were not asked about Topic 1 and 2, since this is not their expertise). The questions towards Topic 3 differed per interview. This has to do with new insights based on the output of previous interviews. The objective of the questions towards topic 3 is to get an insight in all possibilities how SHM can benefit to the main goal of the asset manager (high safety of the bridge, low hindrance for bridge users and low life cycle costs of the bridge). This is done by dividing these main goals in sub-goals until it is possible to define system requirements. Two techniques were used to define the goals, sub-goals and system requirements: refining and eliciting and scenario-based reasoning. Both techniques were used sequentially. First the refining and eliciting technique will be used. When the experts have problems with defining system requirements with this method, the scenario-based reasoning technique will be used.

Refining and eliciting

Once some goals and sub-goals are identified, the aim is to refine them in more detailed sub-goals(Muller, Somers, Yuan, & Heemels, 2006). This process is done by asking the HOW-questions (How do you want to achieve this goal?) and refining goals through AND/OR refinements (Is there another way to do this? / Is this the only goal you want to achieve?). A similar technique is the process of eliciting more abstract goals from these already identified by asking WHY these goals exist (Why do you want to achieve this?). This is done to elicit more abstract goals.

Scenario based reasoning

Another method that can be used to identify goals and system requirements is scenario-based reasoning. Muller et al. (2006) state that scenario-based reasoning from a customer perspective is very helpful in defining goals and system requirements. Stakeholders often have problems with expressing their needs in terms of goals. They are often more comfortable when they talk about the interaction with the system. To induce higher level goals, it can be useful to collect scenarios. A scenario is defined as “a temporal sequence of interactions among different agents in the restricted context of achieving some implicit purpose”(Lapouchnian, 2013). Scenarios are examples of real-world experience, expressed in natural language. The most common form being examples or stories grounded in real world experience. There will be asked how the stakeholders wants to interact with the systems in specific situations.

2.2.1 Expert selection

Webb (2016) presented three key players that should deliver input during the specification of a SHM project: the SHM operator, the structural engineer and the asset manager. In this research, also visual inspectors are interviewed. Visual inspectors have knowledge about damages of concrete bridges. The SHM operator, the structural engineer and the visual inspector can assist the asset manager with maintaining their assets:

- **Asset managers**; who aim to fix issues identified by the SHM system if empowered to act once informed that a trigger value or limit has been reached. They want to have maximum performance of their bridge at minimum cost.
- **SHM operators;** who should provide a system to produce measurement data from a structure and quantify the expected level of accuracy and error rates.
- **Structural engineers**; who aim to provide appropriate structural models and data interpretation techniques along with meaningful ‘trigger values’ that have a sound technical basis.
- **Visual inspectors**; who aim to provide appropriate advice to the asset managers concerning damages to bridges.

In Table 2 is presented which experts were interviewed and why this expert was selected.

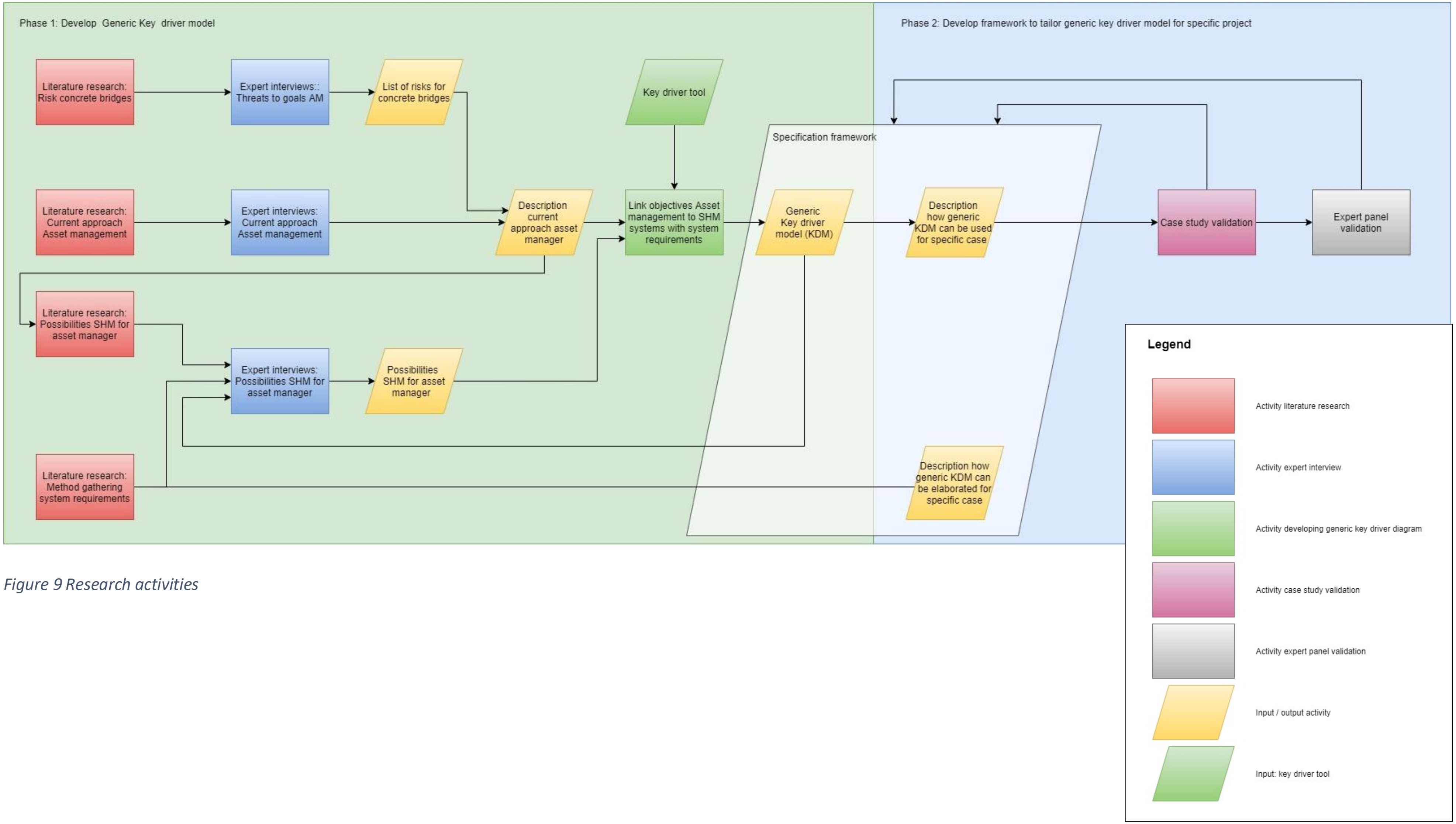


Figure 9 Research activities

Table 2 Interviewed experts

Nr.	Referred to as	Expertise	Reason for selection
1	General expert 1 [GE1]	Innovation in Infrastructure (current maintenance approach / SHM)	Responsible for knowledge development and application of new techniques for infrastructure
2	Asset manager 1 [AM1]	Asset management	Asset manager for Rijkswaterstaat. Experience with SHM projects
3	Asset manager 2 [AM2]	Asset management	Asset manager for big municipality in the Netherlands. Experience with SHM projects
4	Asset manager 3 [AM3]	Asset management	Senior advisor asset management. Good overview of the maintenance and rehabilitation policies of different asset managers
5	Structural Engineer 1 [SE1]	Structural Engineering	Senior engineer and experience with analyses of concrete structures
6	Structural Engineer 2 [SE2]	Structural Engineering	Senior engineer and experience with analyses of concrete structures
7	Structural Engineer 3 [SE3]	Structural Engineering	Senior engineer and experience with analyses of concrete structures
8	SHM specialist 1 [SHM1]	Structural Health Monitoring systems	Involved in SHM project. Experience with SHM techniques
9	SHM specialist 2 [SHM2]	Structural Health Monitoring systems	Involved in SHM project. Experience with SHM techniques
10	SHM specialist 3 [SHM3]	Structural Health Monitoring systems	Involved in SHM project. Experience with SHM techniques
11	Visual inspector 1 [VI1]	Visual inspector	Senior inspector and experience with inspection and analyses of concrete structures
12	Visual inspector 2 [VI2]	Visual inspector	Senior inspector and experience with inspection and analyses of concrete structures

2.2.2 Developing the generic key driver diagram using the key driver method

In the literature research and the expert interviews, data was gathered about how SHM can contribute to the main goals of the asset manager. To be able to analyse the data, the data will be presented in a structured way by using the key driver method of Muller et al. (2006). The key driver method is a tool to analyse and present data in a structured way. The key driver method presents how three to six main goals of a stakeholder can be split up in sub-goals in a diagram, see Figure 10. These sub-goals are split up, as well. This continues, until it is possible to define system requirements. In this research is only focussed on the main objectives of the asset manager.

The key driver method presents the customers objectives and couples it to the system requirements (Muller et al., 2006). This goal-oriented approach provides a common language for analysts and stakeholders. This makes it easier for the requirements analyst to communicate with the stakeholders in the language they are comfortable and familiar with. The requirement analysist is the person that guides the specification process and gathers the requirements. Furthermore, the key driver method enhances the understanding between the project leader and his developers. It gives a good insight why some system requirements are a must and why others are less important. A final benefit is its support in making sound trade-offs between the requirements of a product.

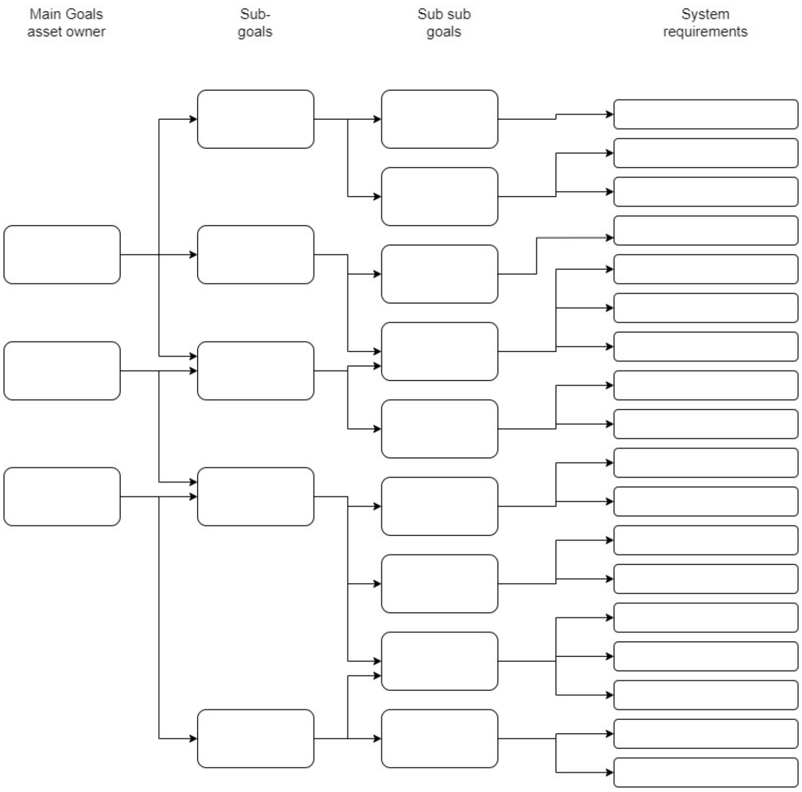


Figure 10 Template key driver diagram

The key driver method will be used to build a big diagram, the generic key driver diagram, that presents the relation between the goals of the asset manager, sub-goals and system requirements. This diagram can be used to see why specific system requirements should be set.

The generic key driver diagram is not made in once. The first version of the diagram will only be based on literature. The expert interviews are executed to elaborate and validate the diagram, see Figure 11. The diagram can be used to see what data is already known and what data is missing. New interview questions are prepared to gather this missing data. The development of the key driver diagram started with a literature research, see appendix A. In this literature research is investigated, how SHM can be beneficial for asset managers according to the literature. This literature is used to build the first version of the generic key driver diagram. In the expert interviews, the findings of the literature research are evaluated and elaborated. To explain how this is done, an example will be given:

Webb (2014) distinguished five categories of SHM projects: Anomaly detection, threshold check, model validation, damage detection and SHM deployment studies. Model validation will be taken as example. The experts were asked: “Why do you want to validate a model?” and “How can you validate a model?”. Why-questions lead to more abstract goals and How-questions lead to more detailed goals. A more abstract goal in this example is: “Reduce conservatism in the models”. The follow-up question was: “Why do you want to reduce conservatism in models?” This led to the more abstract goal: “able to postpone maintenance”. Then again was asked: “Why do you want to postpone maintenance”. This led to the main objectives “Reduce the costs” and “Prevent hindrance by replacement of the bridge”. In the same way it is possible to find more detailed goals, but then was asked “How do you want to achieve this sub-goal”. The link between these goals and sub-goals are presented in the generic key driver diagram. After every expert interview, the key driver diagram was updated.

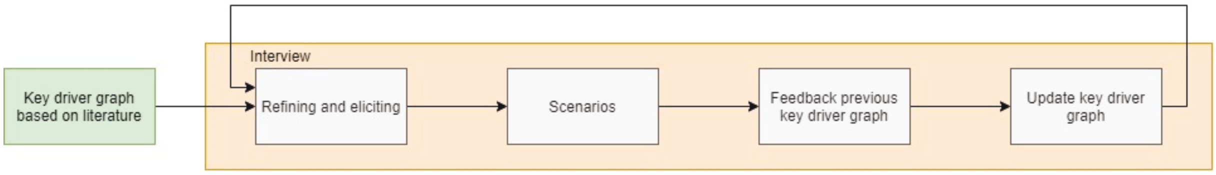


Figure 11 Process of the development of the generic key driver diagram

2.3 Develop the framework

The objective of this research is to develop a framework that can specify a SHM system that contributes to the main objectives of the asset owner for a specific case. Therefore, should be described how the generic key driver diagram can be used for a case specific specification. It might be necessary to only select several system requirements or to add more system requirements. In the framework will be presented which activities needs to be taken, in order to come up with case specific system requirements that contributes to the main objectives of the asset owner.

The framework will consist of three parts:

- The generic key driver diagram, that is developed with help of the literature and expert interviews
- Description how the generic key driver diagram should be used
- Description how the key driver diagram can be expanded for a specific case. This is based on the techniques that are found in the literature research (eliciting & refining and scenario-based reasoning)

2.4 Validation

This research is an explorative research, which means that it is unlikely that the developed framework scores well on all criteria that are mentioned in the research objective: soundness, completeness, ability to tailor for a specific project, verifiability, understandability and ease of use. The validation is executed to see how the developed framework scores on these criteria. This research is a qualitative research, which makes it more difficult to state that the results are valid. In theoretical research, validation often refers to testing the plausibility, credibility and trustworthiness of the results. Higher plausibility, credibility and trustworthiness makes that results can be defended better(Johnson, 1997). The validation in this research is especially used to look for strengths and weaknesses of the framework. The framework will be validated in two ways:

- First, the framework will be applied in two real life cases. By applying the framework in cases, you can show if the framework is applicable in real life context. This validation focusses especially on the output of the framework. Does the framework deliver the right specification? The validation should show strengths and weaknesses of the result.

- Secondly, the framework will be validated by using expert reviewing. Two experts will review the complete framework. This validation is less detailed as the case validation but is focussed on the strengths and weaknesses of the complete framework.

2.4.1 Case validation

The developed framework will be applied in two cases. In this activity is validated if the framework can be applied in real life cases. The validation focusses especially on the outcome of the framework. There will be executed if the output is relevant.

This activity starts with applying the framework in the two cases. There will be specified to what goals SHM should contribute and what system requirements should be set to solutions. This is done by executing the steps of the framework with the involved project experts (asset manager, structural engineer and SHM specialist). The result of this activity is a case-specific key driver diagram. This diagram will be evaluated with the project leader of the SHM project. First, the diagram will be presented and introduced to the project leader. Secondly, the project leader will be asked to answer questions related to the criteria, see appendix E. Finally, the answers on the questions will be discussed with the project leader in a skype meeting.

2.4.2 Expert panel validation

In the case validation is especially focussed on the framework itself. Two experts of different disciplines will be asked to evaluate the framework. This is done by evaluating the framework with the criteria, that are mentioned above. There will be looked what the strengths and weakness are of the framework. First, the framework will be presented and introduced to the experts. Secondly, the project leader will be asked to answer questions related to the criteria, see appendix F. Finally, the answers on the questions will be discussed with the expert in a skype meeting.

3 Maintenance approach of concrete bridges in the Netherlands

To get an idea why asset managers want to apply SHM and to what goals SHM could benefit, there is first looked at the current maintenance approach of concrete bridge in the Netherlands. This is done to have an idea about the limitations in the current approach and to understand how SHM can contribute to the maintenance approach. In other words: to what goals SHM could benefit. These goals are used as starting point of the generic key driver.

An asset manager in the Netherlands does not have to follow a general approach for maintenance and control of their assets. No inspections or analyses are obligatory. However, the asset manager must prove that an asset can be used safely [SE2][1]. This is stated in several laws:

Civil Code article 6:174: Risk liability (Dutch: Burgerlijk wetboek artikel 6:174 Risicoaansprakelijkheid) shows the responsibility for the safe use of the bridge: "*The owner of an asset (dikes, bridges, roads, bicycle roads, road sides, locks, tunnels etc.) who does not meet the requirements, which may be set according to the circumstances, where there is a risk to a person or property, is liable. Unless, he did not make a mistake, if he knew the risk on the time of its origin*."

According to Civil Code article 6:162 Guilt liability (Dutch: Burgerlijk wetboek artikel 6:162 Schuldaansprakelijkheid):

1. *He, who commits an unlawful act against another, which is imputable to him, is obliged to compensate the damage that the other person suffers as a result*
2. *An unlawful act is considered: an infringement of a right and an act or omission in violation with a legal duty or with that according to unwritten law in society subject to the presence of a justification.*
3. *An unlawful act can be attributed to the perpetrator if it is due to his fault or to a cause for which, under the law or prevailing opinions are for his account coming.*

3.1 Structural risks and damages of existing concrete bridge in the Netherlands

A new built bridge can be considered structural safe, since the design must meet the regulations of the building code. If it does not meet the regulations of the building code, no building permission will be given [SE1]. So, unless mistakes are made during the construction phase, a bridge can be considered safe after construction. Mistakes can come to light several years after construction. SHM can be used to identify these mistakes, but this is not part of the scope of this research, because the research focusses on older bridges.

In this research is focussed on the maintenance approach of concrete bridges. Concrete is a very durable material and does not deteriorate very fast [AM1]. In general, the steel of the reinforcement is normative for the strength of the bridge [SE1]. When no concerns were identified in this period, the asset manager should only look at the durability of the structure. The structural safety should be assessed again, when damages are determined during visual inspections, loads changed and / or regulations changed. For older concrete bridges several damages and risks should be identified.

There are different reasons how the structural safety of a concrete bridge can be threatened. For an asset manager it is important to keep track of these phenomena, since this can cause unsafe situations or even collapses. This are the most common threats of the safety of concrete bridges in the Netherlands:

- Higher loads are crossing the bridge than was considered during the design process.

[1] Reference to expert interview

    - The risk for collapse by shear forces increases
    - The risk for collapse by fatigue increases
- Subsidence of the structure;
  The loads are distributed differently in the structure. This can lead that components should bear higher loads than they were designed for. This can lead to failure of this component.
- The bearing capacity decreased, because the reinforcement bars were affected. This could have several reasons:
    - Chloride intrusion
    - Carbonatation
    - Alkali Silica Reaction
    - Cracks

3.1.1 Higher loads

Bridges are used in a higher extent in comparison with the expected use during the design. This is caused by a bigger increase in the weight and number of vehicles. Higher loads on the bridge can increase the severity of several structural risks. First, the shear forces on the concrete bridge will increase. Secondly, the moment in the bridge will increase as well. This can increase the risk of fatigue.

3.1.1.1 Collapse caused by Shear strengths

Shear strength is an important risk for older concrete bridges, because the structure does not 'warn' with cracks but has a ductile failure. A shear force is a force that tends to produce a sliding failure on a material along a plane that is parallel to the direction of the force. The reason why many old concrete bridges face this problem is because the standards about reinforcement bars for shear stresses, was less strict in the past. This means that all concrete bridge that were built before 1976, have too less reinforcement bars according to the current standards. The increasing loads on the structures increase the severity of this. It is only possible to identify this risk by doing structural calculations [SE1, SE2, SE3]. Rijkswaterstaat controlled the risk by doing calculations for all concrete bridges from before 1976 and replace or strengthen the bridges [AM3].

3.1.1.2 Collapse caused by fatigue

Fatigue in material occurs when the material subjected to rapidly fluctuating and cyclic stresses. In bridges this is caused by passing traffic over the bridge. Fatigue can best be explained with the example of bending a paperclip. You can bend, a paperclip several times without breaking it, but when you bend it too often it will break. This phenomenon is also applicable to bridges. In concrete structures, fatigue loading leads to fractures, cracking, and eventual collapse/failure because the structure will likely fail before it reaches its yield point. Fatigue can be determined by looking at the cracks in the bridge, but also determining the stiffness of the structure, by looking at the deflection related to applied loads.

3.1.2 Subsidence of bridge

Subsidence of a bridge can have serious consequences for the safety of the bridge [SE1]. When the bridge does not sag equally, the loads can be divided different over the components. A component can face bigger loads, than it is designed for. This can lead to failures of these components. The subsidence of the bridge can have different causes, for example weak sub soil.

3.1.3 Damages of concrete

The steel of the reinforcement bars is normative for the strength of the structure. The reinforcement steel in concrete is protected by the alkalinity of the pore water. If the pH (pH > 12 à 13) is high enough, then there is a thin oxide layer on the steel surface. This passivation layer prevents that iron-ions can solve, such that the corrosion process stops. There are different damages that can affect the bearing capacity of the reinforcement bars.

3.1.3.1 Carbonatation

Carbonatation is the intrusion of CO_2 from the air in the porewater in concrete. The air consists for 0.04 % out of CO_2. The gas solves in the water and produces a weak acid. This process reduces the pH level in the concrete. The lower pH can reduce or remove the passivation layer. In a moisty environment, this can lead to corrosion of the reinforcement bars. In a constant dry or wet environment, carbonatation would not occur(Soen, 2007).

3.1.3.2 Chloride intrusion

Free chloride-ions are very harmful to the reinforcement bars. They penetrate to the passivation layer and react with iron towards the easy to solve iron chloride ($FeCl_2$). During the follow up reaction the iron-chloride ($FeCl_2$) reacts with OH^- ions. The amount of OH^- ions are decreasing by this reaction, which will cause that the pH level of the concrete will decline. The chloride-ions are not used up by this reaction and are available for new reactions. This can cause that the reinforcement steel is damage very locally. This is called pitting corrosion(Soen, 2007).

3.1.3.3 Cracks

Cracks are characteristic for concrete structure. Cracking is normal and even required for the reinforcement steel to work well. When the tensile force of the concrete is exceeded and the concrete is cracking, the reinforcement steel will start working. In comparison to structures from other material, concrete structure are characterized that material is 'damaged' before the structure will collapse(Braam & Lagendijk, 2011). Therefore, cracks can work as warning mechanism. Cracks can have different causes.

However, cracks can also be risky. The concrete cover protects the reinforcement bars against aggressive substances. When cracks are too big, those substances can easily penetrate to the reinforcement bars [AM3]. This can lead to corrosion of the reinforcement bars. The volume of corrosion is much bigger than the volume of steel, which can push away the concrete cover. Furthermore, the surface of the reinforcement bar intersection will decline, which lead to a lower capacity of tensile forces.

3.1.3.4 Alkali silica reaction (ASR)

ASR in concrete is a reaction of alkalis and water with reactive silica, that can be present in aggregates. Alkalis can be present in the pore water of concrete. The product of the reaction is a gel, that can absorb a lot of water. The gel will swell up and compressive forces in the concrete will be built up. When the forces are too high, the concrete can crack. The reaction is very slow, and damage occurs after many years. ASR is visible by craquelure (fine pattern of dense cracking) and white tarnish. The sensitivity for ASR can be reduced by selecting the right cement(Soen, 2007).

3.2 Current maintenance policy of asset manager in the Netherlands

The presented risks can cause damages to the bridge that the bridge needs to be repaired. Not all asset managers have the same maintain and control strategy [AM3]. Rijkswaterstaat, most provinces and the bigger municipalities have a risk-based approach [AM3]. This means that the decision to maintain their assets depends on the risks the asset faces. Smaller municipality have a more reactive strategy. This means that they react, when damage happened [AM3]. In general, the safety of bridges is guaranteed by executing condition inspections and executing calculations (structural assessment and verification calculations). This can be complemented by extra research to specific properties or by monitoring a risk.

Condition inspections are the first assessment of the of the condition of a bridge. The visual condition is the input for other analyses, like risk analysis, recovery advise and multi-year maintenance planning

[VI1, VI2]. Furthermore, it can warn for structural insecurities. A condition inspection works in general: The inspection is executed by two inspectors. They begin with a desk study and start up meeting. The history of the bridge is analysed, and the process of inspecting is discussed, including safety aspects. Secondly, they start the inspection and assess all components on the bridge for damage. One person makes pictures and the other one writes down the results. All components should be checked visually from approximately one meter. Afterwards, the inspection, the inspectors have a meeting to check whether the same issues were identified and check if everything is assessed. Sometimes, boats or aerial platforms are required. The result of a visual inspection is a report with damages and possible structural insecurities [VI1, VI2]. The report will be analysed by the inspectors and there will the causes, effects and possible measures.

When damage is detected, loads are changed or regulation is changed, the structural safety should be assessed again with calculations. The Eurocodes, NEN 8700 series and the Richtlijn Beoordeling Kunstwerken (RBK) are used for structural calculations [SE3]. The norms are conservative to deal with uncertain situations. The first calculation is the structural assessment. This assessment is used to get a quick underpinned judgement of the feasibility to determine the structural safety of the construction(s). When the bridge does not pass this assessment, it is possible to do a more detailed verification calculation. Costs, time and expected benefits should be considered before a more detailed calculation is made [SE1, SE2, SE3]. More detailed calculations require more information about the structure and its material properties. In the standards a specific load distribution is presented, which should be used in the calculation.

More detailed information about the structure and its material can be identified by doing extra material research. This can be done with for example: concrete samples (concrete compressive force) and steel samples (steel tensile force). It is also possible to monitor a specific risk. The goal of monitoring is to gather insight in the development of a specific property, stability or failure mechanism of the construction(SBR-CUR, 2015). It consists of a technical research on location, based on periodically measurements or samples, combined with an analysis of the result. Monitoring can be executed visually or with SHM systems.

When a bridge is not safe according to the verification calculation, there are different measures that can be used to improve the structural safety during the rest of its life span(Rijkswaterstaat, 2013):

- Reduction of the permanent loads
- Reduction of the traffic loads
- Reduce or prevent the deterioration of the condition
- Strengthening
- Replacement

Reason to replace or strengthen a bridge is not only caused by the conditional state of the bridge. Other aspects of consideration are costs for the measure, disturbance to the road user, user safety, what still can be done with the structure, functional requirements in future and other projects in the environment [AM1, AM2]. The condition of the bridge is input in the decision making. Big maintenance and rehabilitation project should be planned in programs. These programs are made by policy makers and consists of multiple projects in the coming years [AM1, AM2].

4 Generic key driver diagram

In the previous chapter, the current maintenance approach is explained. By executing a literature research and expert interviews is tried to develop a generic key driver diagram, which shows how SHM can contribute to the maintenance approach of the asset manager. This is done by linking the main objectives of the asset manager to sub-goals until it is possible to link system requirement to a SHM system that should be implemented.

An asset manager is responsible for the safety and functionality of the bridge. Furthermore, asset managers in the Netherlands have in general a limited budget (Vardanega et al., 2016). The three main goals of the maintenance approach of an asset manager are in general:

- High safety of concrete bridges
- Low hindrance for bridge users
- Low life cycle costs of concrete bridge

Those three objectives are the starting point for the development of the generic key driver diagram. The reason to start with such high-level goals is that no sub-goals should be missed. Missing sub-goals could lead that system requirements that follow from these sub-goals are not presented in the diagram. The relations between the goals, sub-goals and system requirements are presented in one diagram.

4.1 How to read the key driver diagram

The generic key driver diagram is one big diagram. Because of the readability of the diagram, the diagram will be presented in parts. In Figure 12, the overview of the different parts is presented. In Figure 13, the legend of the diagram is presented. The lines in the diagram have different colours to improve the readability of the diagram.

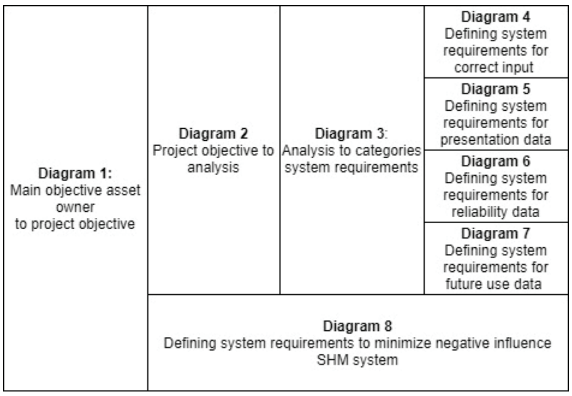


Figure 12 Composition of generic key driver diagram

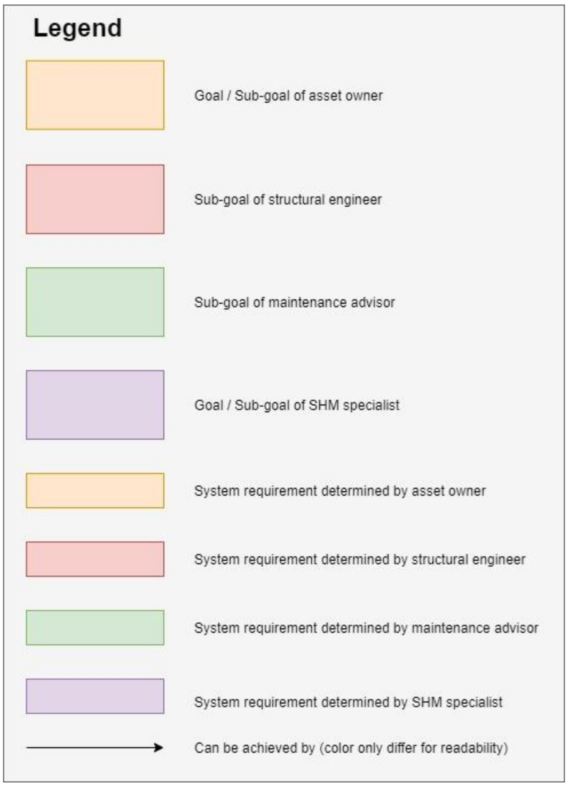


Figure 13 Legend generic key driver diagram

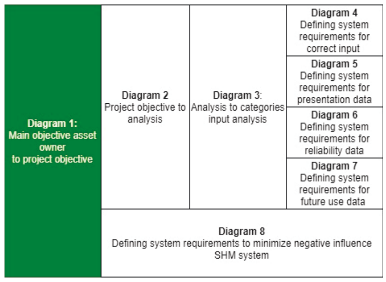
The key driver diagram consists of three elements(Muller et al., 2006):

- The three main objectives of the asset manager (key drivers): high safety of concrete bridge, low life cycle costs of the concrete bridge, low hindrance to the bridge user. These main goals explain what the asset managers want to achieve.
- Sub-goals (application drivers), the main goals of the asset manager are divided in sub-goals. These sub-goals explain how the main objectives can be achieved. The sub-goals are divided in more detailed sub-goals etc.
- System requirements; Detailed (often quantitative) specifications of the product or its subsystems. The system requirements describe how the SHM system will contribute to the sub-goals. By contributing to the sub-goals, there will also be contributed to the main goal. The system requirements only focus on the systems or components of the system.

The generic key driver diagram can be read in two ways:

- From left to right: every link means: **How can this be achieved?**
- From right to left: every link explains: **Why should this be achieved?**

4.2 Diagram 1: Main objective asset owner to project objective



In Diagram 1 is presented how SHM can contribute to the main objectives of the AM. The main goals (low life cycle costs, high safety of the bridge and low hindrance for bridge users) are split up in sub-goals. These sub-goals are goals that should be achieved by a SHM project. What can be noticed is that SHM can be beneficial by taking away the shortcomings of the activities in the current approach. In the current approach, the maintenance decisions are made on basis of the outcome of visual inspections (condition inspections and visual monitoring) and structural calculations.

The first disadvantage of visual inspections is that the condition of the bridge is only assessed occasionally. This can lead that damages are determined too late or that it is hard to get insight in the process of deteriorating [AM1]. Determining damage too late, can cause that the impact worsens, and that maintenance is more expensive [SE1]. Another disadvantage is that visual inspections are expensive and can cause hindrance for the bridge user [VI1]. Visual inspections are labour intensive and can require boats or aerial platforms. Next to that, it can be hard to access several spots of the bridge [AM1]. SHM can be used to get a continuous insight in risk and can be used to replace aspects of visual inspections (assess hard accessible spots or monitor a specific risk).

The disadvantage of structural calculations is that the standards include a lot of conservative values [SE1]. These values are used to make sure that all bridges are safe. Based on these decisions can be decided that the bridge is not safe anymore and actions should be taken (repair bridge, limit traffic load etc.). However, there is a difference between the strength in practice and in theory [VI2]. SHM can be used to get a better insight in the actual condition and proof that these actions are not required. This can save costs and hindrance.

Predicting the lifespan is also mentioned as a project objective [SHM2]. However, this objective is not included in the key driver diagram. The reason to not include this, is that there is a lot of uncertainty in the life span prediction. Predicting the lifespan for a short period can be done by keeping track of a normative indicator [AM1]. In Diagram 1 this is mentioned as ‘able to keep track of severity of risk’. When you want to predict the lifespan of a bridge for a longer period, there are many uncertainties that influence the lifespan [AM3].

SHM does not only have advantages. Implementing a SHM system on a concrete bridge can also negatively influence the life cycle costs, availability of the bridge and safety of the bridge [AM3]. This impact should be limited. Therefore, sub-goals are also: low life cycle costs of the SHM system, high safety SHM system and low hindrance caused by SHM system.

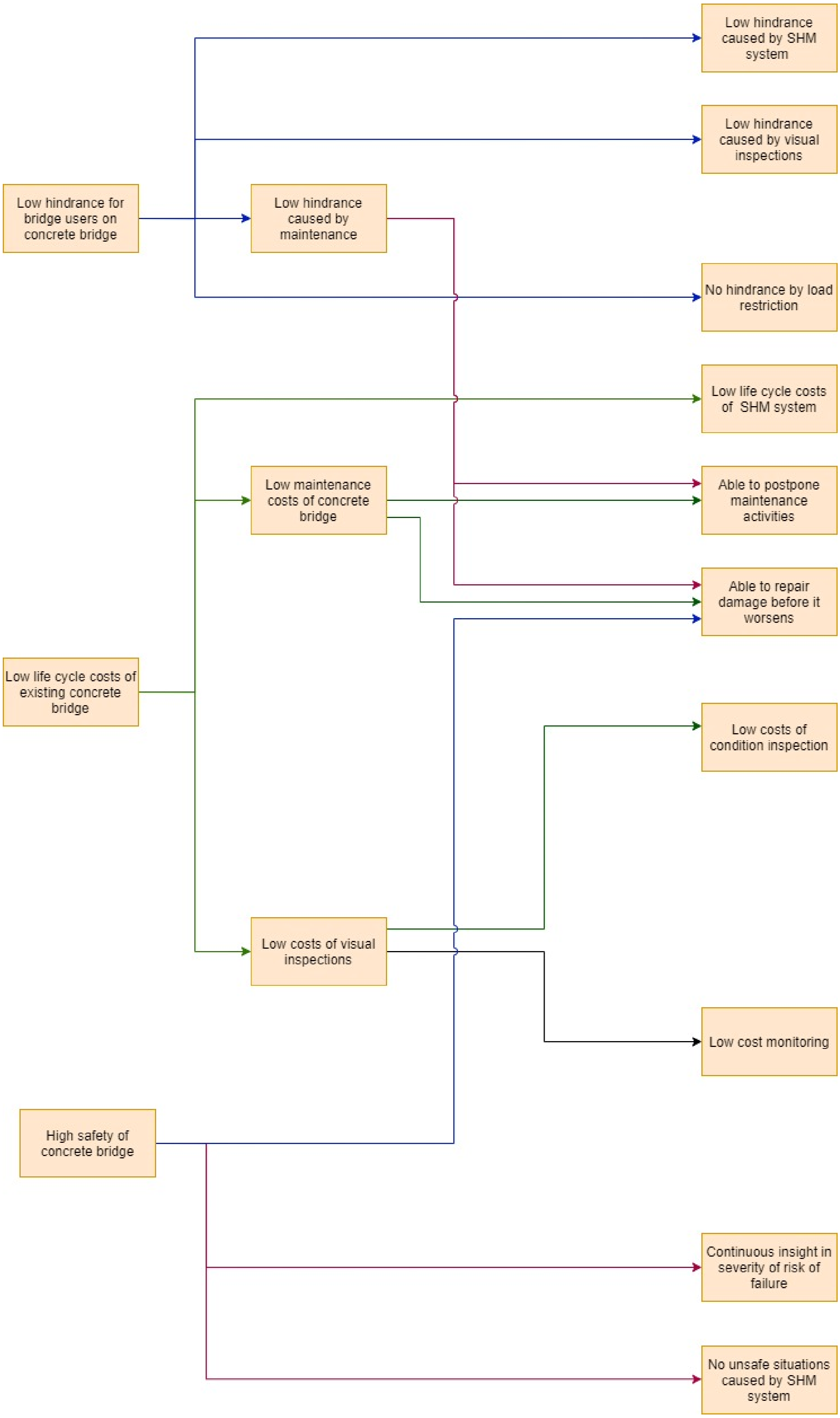
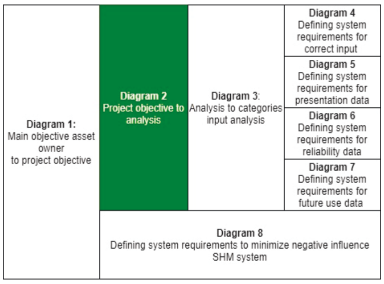


Diagram 1 Main objective asset owner to project objective

4.3 Diagram 2: Project objective to analysis



In Diagram 2 is presented how the project objectives of the asset manager can be linked to a required analysis. The objectives 'low hindrance caused by SHM system', 'low life cycle costs of SHM system' and 'No unsafe situations caused by SHM system' are not presented in diagram but are linked to other sub-goals in diagram 8.

A SHM system delivers data and not information. Asset managers are not able to make maintenance decisions, based on the data that a SHM system produces [AM1]. For example: the asset manager is not capable to make decisions based on the amount of deflection of the bridge deck. The structural engineer should advise the asset manager and describe what the influence of this deflection is on the safety of the bridge.

For determining which analysis should be executed, knowledge is required about structural engineering and/or damages. The exact completion of the analysis should be determined by a structural engineer. This is the case, because a general analysis cannot be used for every bridge. Every bridge is unique, and it is important that the structural engineer understands properties of the bridge, before he identifies what analysis he wants to execute. Therefore, it might be necessary to execute different pre-analysis first, before it is possible to identify which SHM system should be applied on the bridge. The analyses that are presented in Diagram 2 are based on the presented risks in Chapter 4.

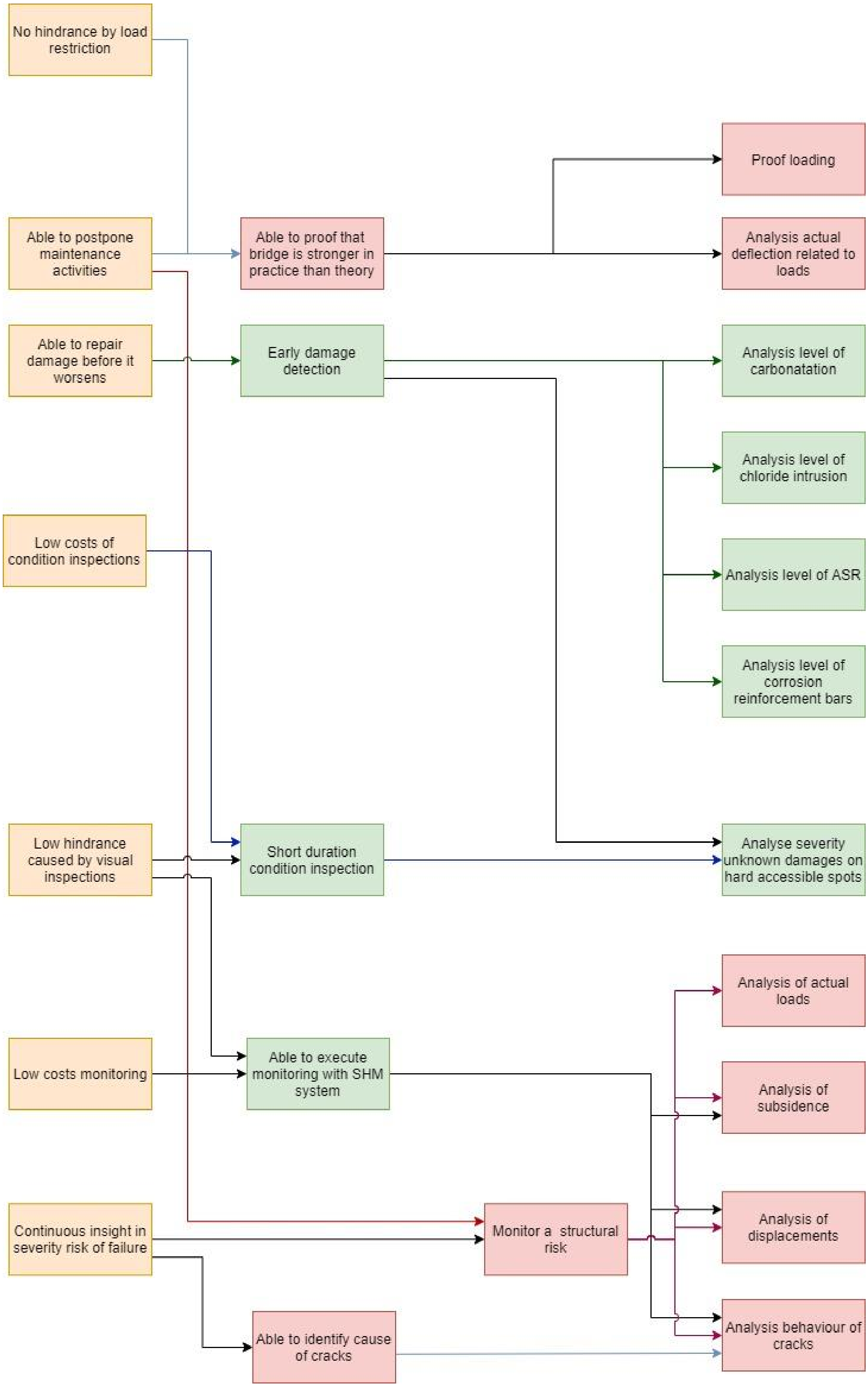
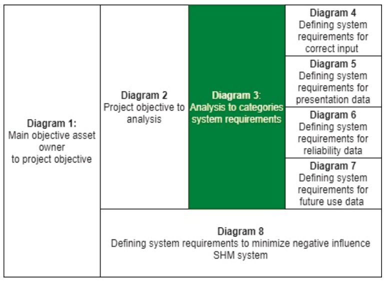


Diagram 2 Project objective to analysis

4.4 Diagram 3: Analysis to categories of system requirements



In Diagram 2, different analyses are presented on the right-hand side. In this diagram is presented what sub-goals should be achieved by the SHM system, such that the analysis can be executed. Other sub-goals, like 'correct execution of the analysis' are not included in this diagram. Four sub-goals, related to the specification of a SHM system, can be defined.

- Correct data gathering (Diagram 4)
- Correct presentation of the data (Diagram 5)
- Reliable data (Diagram 6)
- Able to use the data in the future (Diagram 7)

What was noticed during the development of the generic key driver diagram was that despite other analyses should be executed, the sub-goals that should be achieved by the SHM system remained the same. To explain this, an example of two analyses will be given: analysis 1: analysis of chloride intrusion and analysis 2: analysis of deflection. For both analyses it is important that the SHM system measures the correct data. The only difference is that for analysis 1, the correct data of the chloride intrusion should be measured, while for analysis 2 the correct data of the deflection should be measured. This is also the case for the sub-goal 'clear presentation of the data', 'reliable data' and 'able to use the data in the future'. To prevent that the eleven analyses will lead to 44 sub-goals, there is chosen to use a generic formulation. In the following diagrams, templates should be filled in based on the analysis that should be executed.

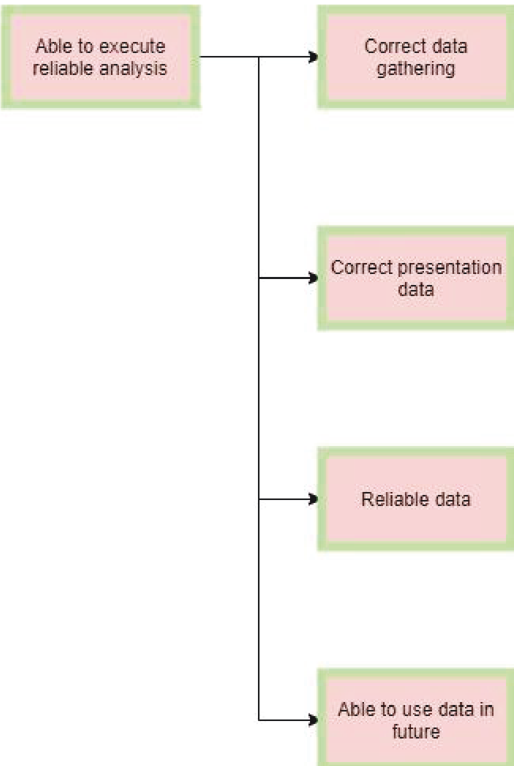
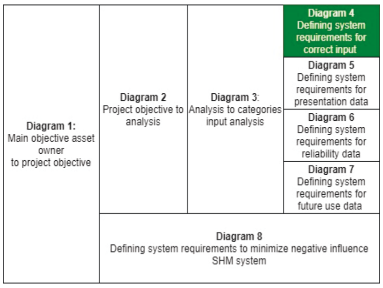


Diagram 3 Analysis to categories system requirements

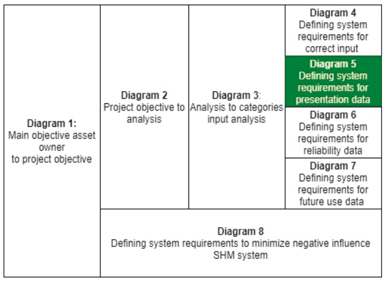
4.5 Diagram 4: Defining system requirements for correct data gathering



In Diagram 4, system requirements are defined, such that the SHM system will gather the correct data. The structural engineer should determine what data he needs, such that he is be able to execute the analysis and give an advice to the asset manager [SE2].

In the diagram is presented what system requirements should be set. The structural should determine if the SHM system should only measure the main principle or that also conditions during the measurements should be measured. For example: if you want to analyse the behaviour of a crack, it is also necessary to identify the influence of the temperature on the behaviour. Otherwise, you cannot say what causes the behaviour of the crack.

4.6 Diagram 5: Defining system requirements for correct presentation of data



The data that is measured by the SHM system should be presented to the structural engineer. However, it is not always necessary to present all data. So, first there should be determined what data should be presented and if it is required to process the raw data. Secondly, should be determined how the data should be presented. This can be done in different ways, like tables or graphs. Finally, it can be important to specify the format of the results. It can be possible that the outcome of the SHM systems should be used in specific software. Therefore, the data should be compatible with this software.

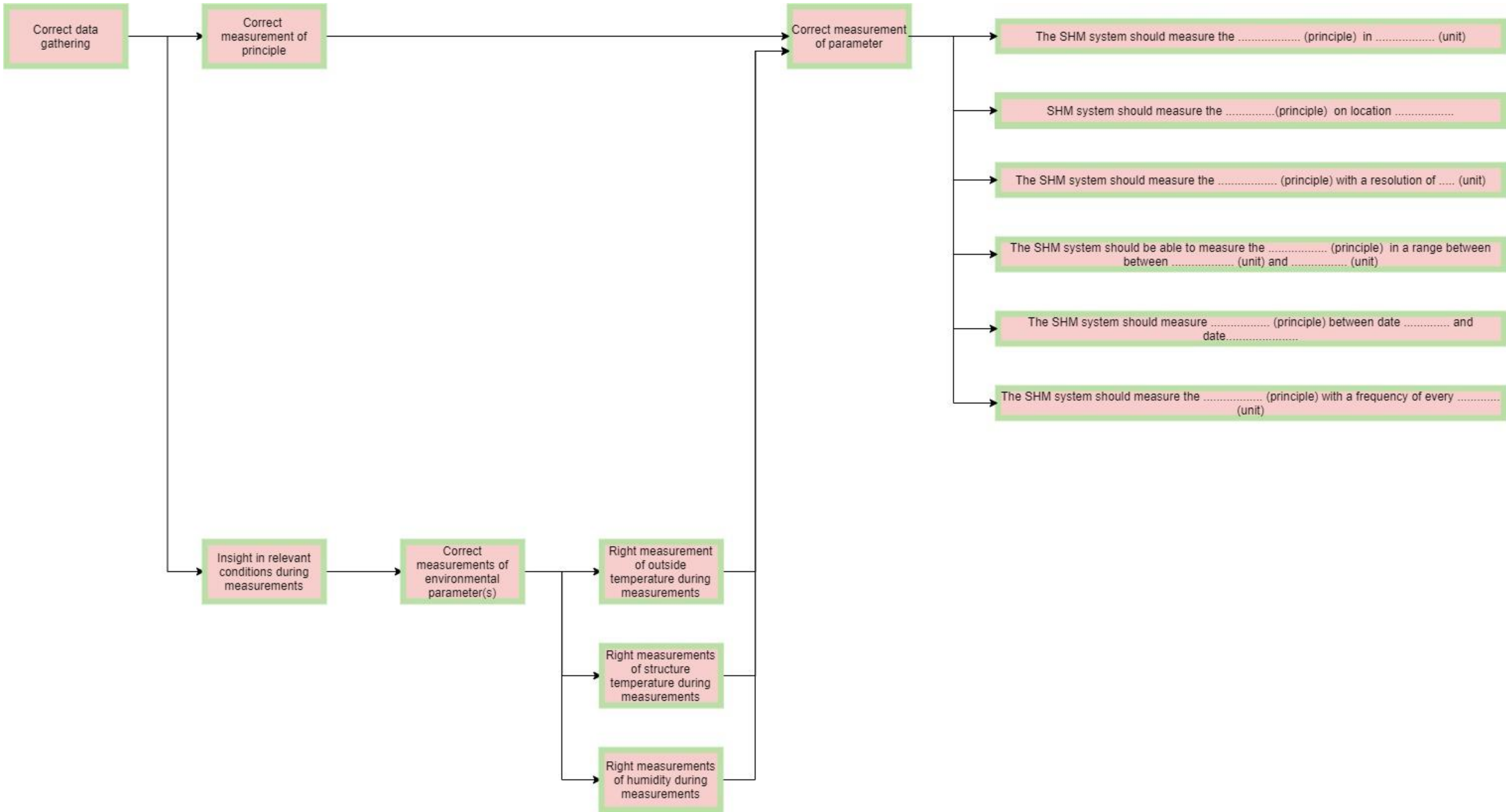


Diagram 4 Defining system requirements for correct data gathering

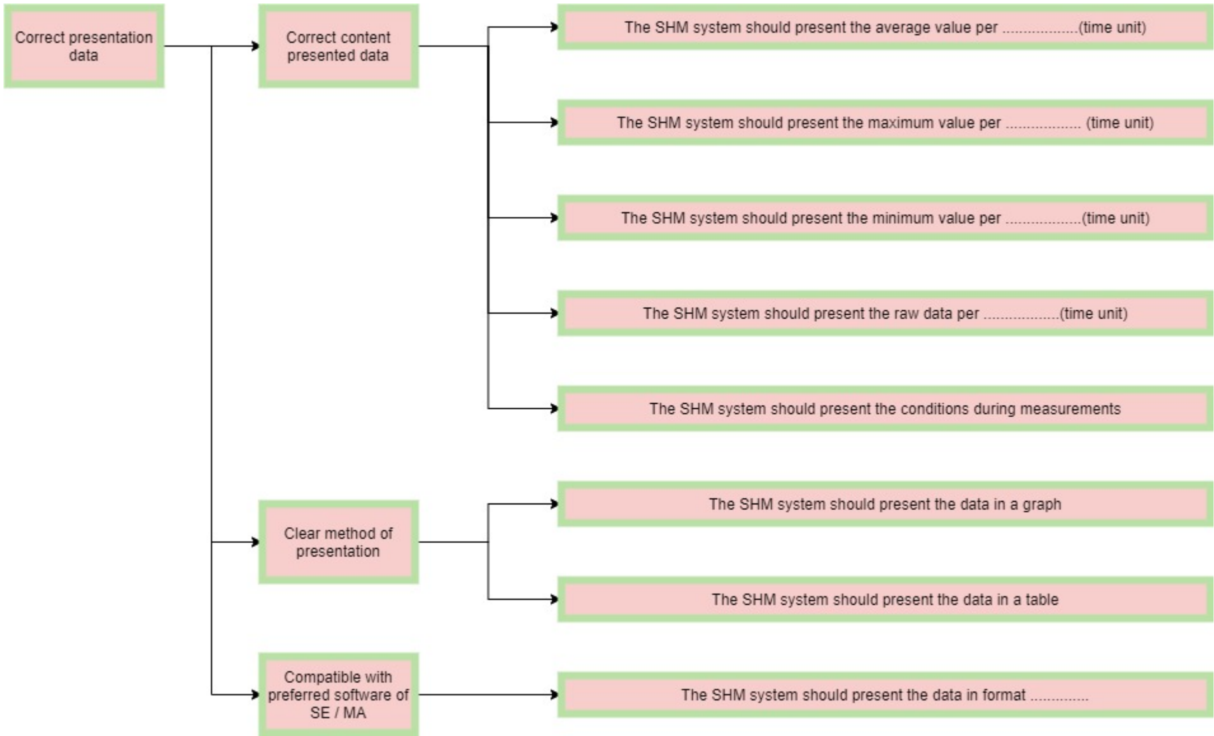
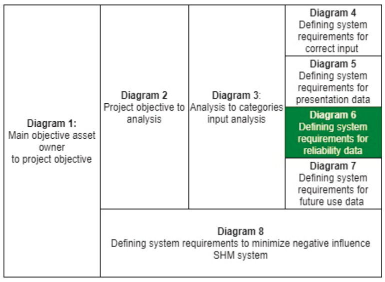


Diagram 5 Defining system requirements for correct presentation of data

4.7 Diagram 6: Defining system requirements for reliable data gathering



Reliability of the data means the level of trust that the structural engineer can have that the gathered data is correct. A distinction is made between reliability directly after installation and reliability in the longer run. The reliability of the data can be assured after installation by using reliable components. Furthermore, it is possible to verify data by compare the data with other data. This can be done by comparing data of different sensors or by comparing data from different sensing techniques.

The reliability of the data can be affected over time. Influences that can influence the measurements are weather conditions, human influences, technical disruptions, etc.. It is important that the SHM should be able to keep performing, despite these threats. This is especially important for long term measurements.

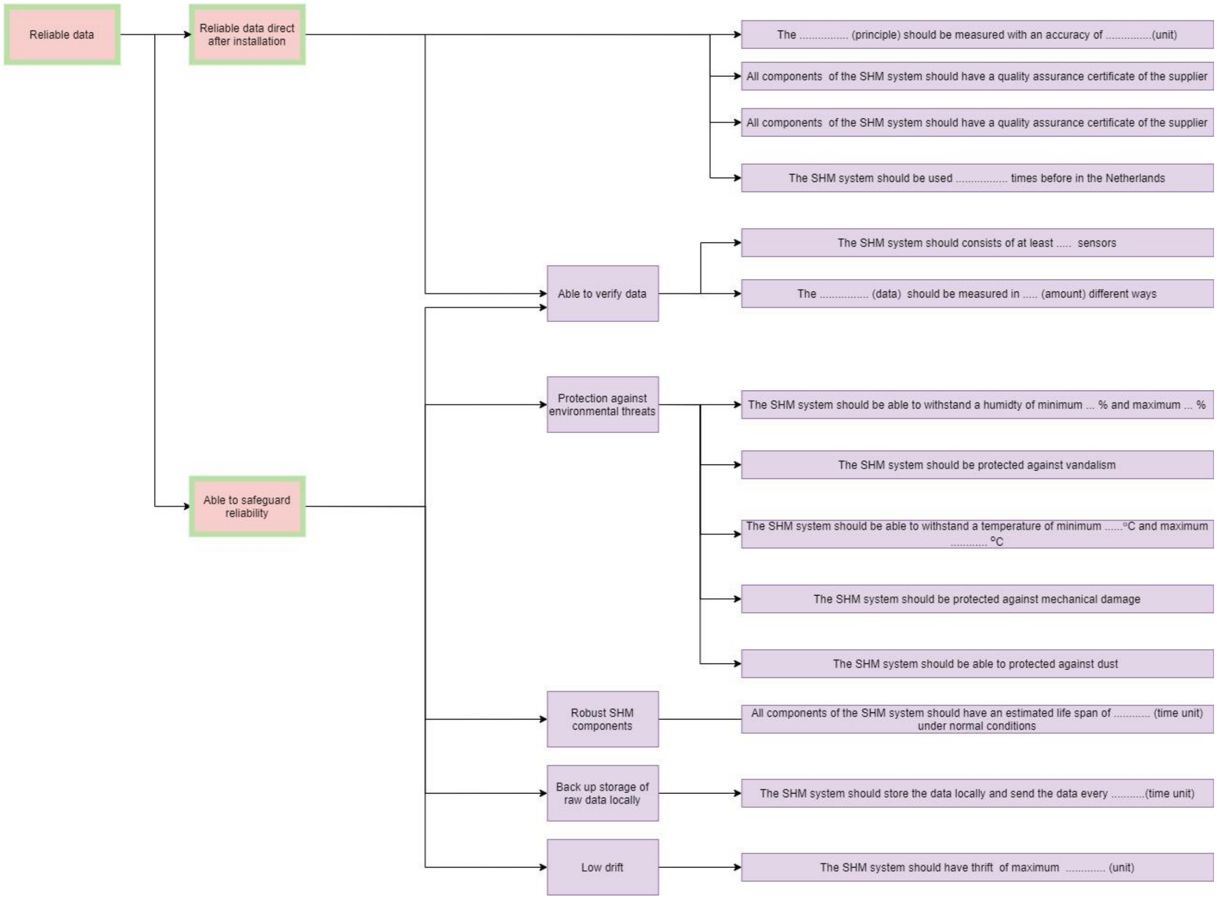
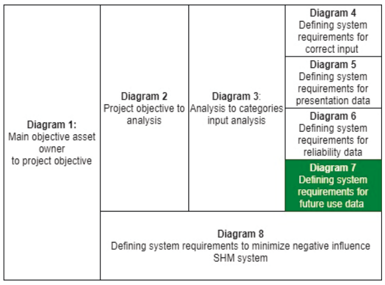


Diagram 6 Defining system requirements for reliable data gathering

4.8 Diagram 7: Defining system requirements to future use of data



Data should be stored in order to make sure that the data can be used later. Data can be beneficial to see trend in the measurements, to verify if the data is processed in the right way or to do other analysis. Data can be very valuable. Also, for purposes that are unknown yet [SHM1]. The storage of a big amount of data is not a big issue anymore. Data can be stored in clouds and this storage is not very expensive[SHM3]. Finally, it can be necessary to secure the data, such that not everyone can use this data. However, data from SHM systems is general not very sensitive for cyber-crime.

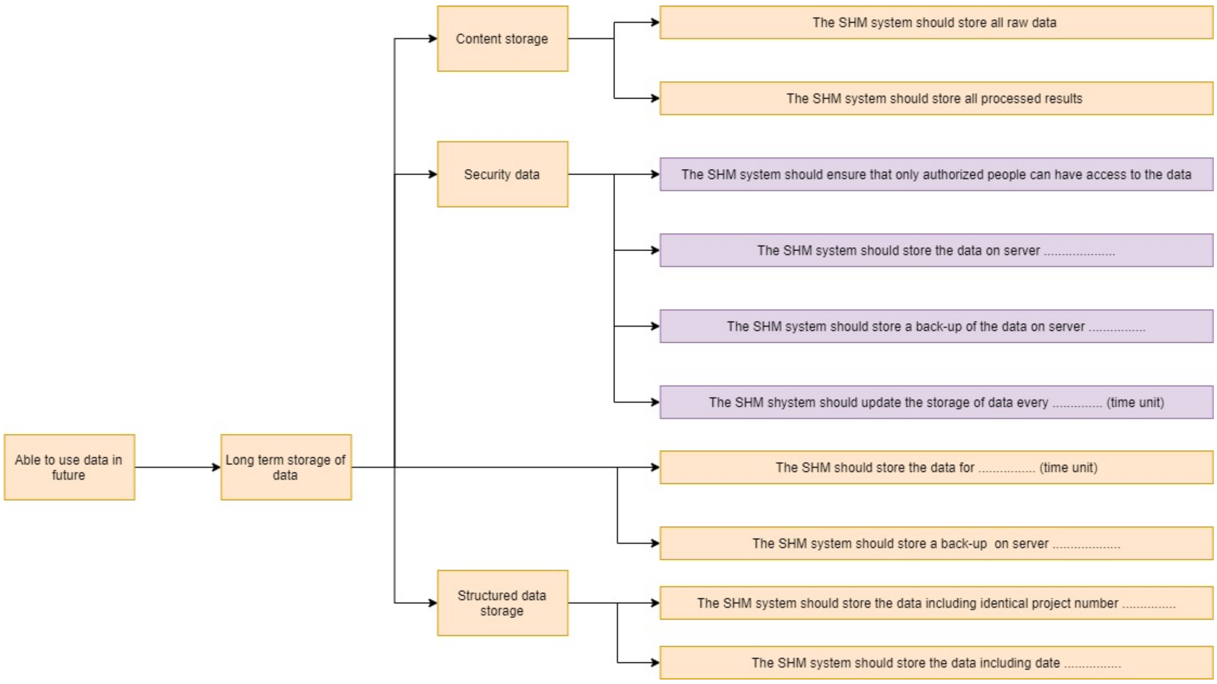
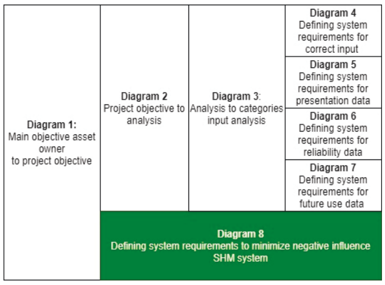


Diagram 7 Defining system requirements to future use of data

4.9 Diagram 8: Defining system requirements to limit negative impact SHM system



Like described before, the implementation of SHM is not only beneficial for the main objectives of the asset manager, there are also disadvantages of implementing SHM systems. Applying SHM can increase the total costs of the bridge, since the installation of the SHM system, purchasing of the SHM system, maintenance of the SHM system, storage and interpretation of data costs money. Furthermore, the installation and maintenance of the SHM system can also cause hindrance to the bridge users. Furthermore, the SHM can cause unsafe situations to the bridge. These negative influences on the main objectives of the asset manager should be limited.

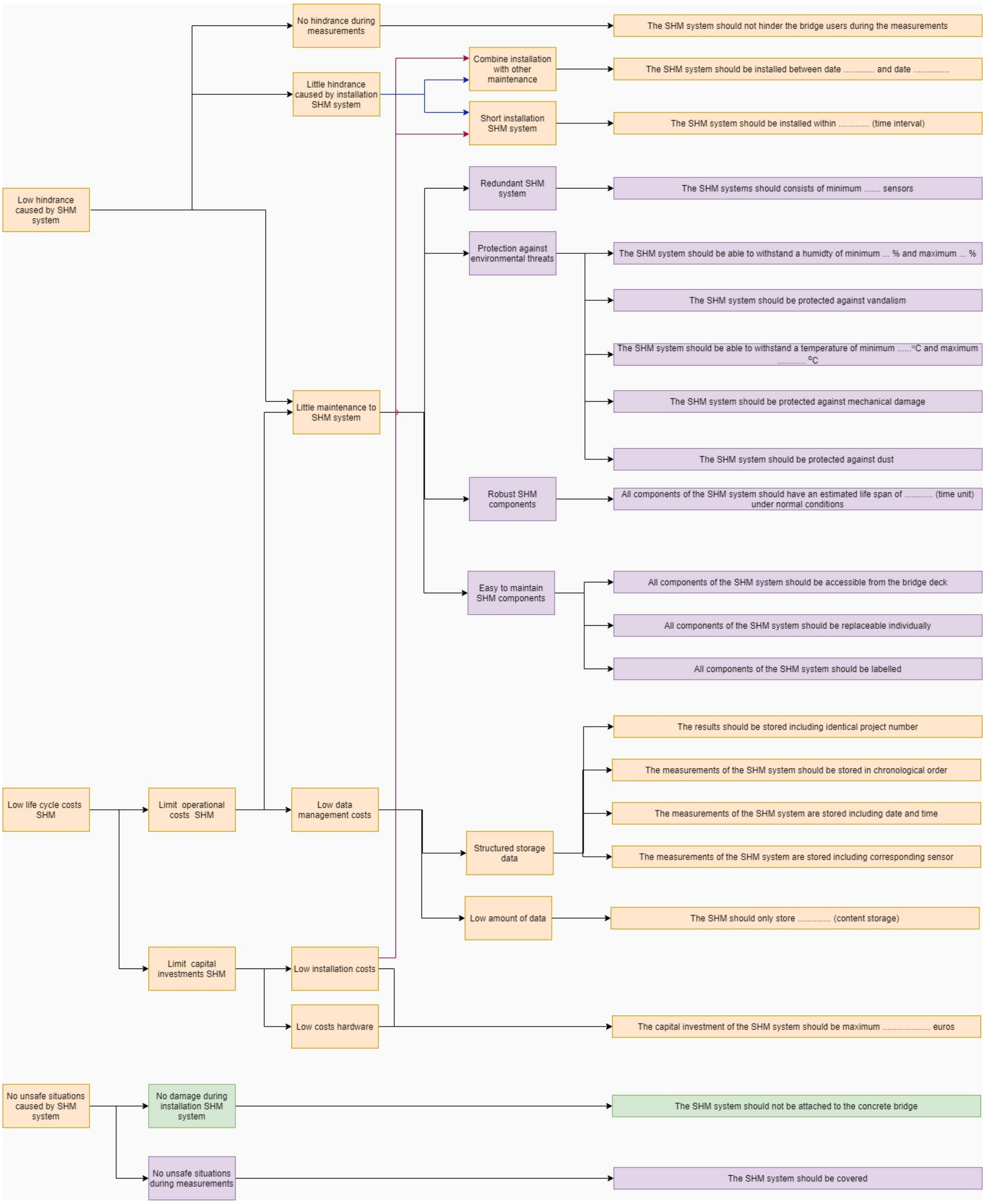


Diagram 8 Defining system requirements to limit negativity impact SHM system

5 Framework for developing a case specific key driver diagram

Many aspects can differ per bridge: the construction, the subsurface, the damages, the loading, the environment etc. All these aspects might influence the type of SHM system that should be placed on the bridge and therefore the specification of the SHM system. For a specific SHM project, the asset manager does not need to achieve all goals, sub-goals and system requirements, that are mentioned in the generic key driver method. Therefore, the asset manager should select several goals, sub-goals and system out of the generic key driver diagram. Next to selecting goals, sub-goals and system requirements from the generic key driver diagram, the asset might need to add other (not mentioned) goals, sub-goals and system requirements, that were not considered in the generic key driver diagram. In this chapter, a framework is presented, that should show the asset manager how a specification could be made. There should be noticed, that this framework will be evaluated for the criteria: soundness, completeness, ability to be tailored for every concrete bridge, verifiability, understandability and ease of use.

5.1 Involved experts

For the execution of this framework several experts should collaborate. The following people are involved in the specification activities:

- **Requirements engineer (RE)**: The requirement engineer guides the specification process and is responsible that the framework is used in the correct way. Furthermore, he is responsible for the correct documentation of the specification.
- **Asset manager (AM):** The asset manager is responsible for the safety of the bridge and he should define the objectives for the SHM project. He is responsible for clearly expressing what he wants to achieve with the SHM project and setting constraints to the SHM project. The asset manager can be advised by other disciplines.
- **Structural engineer (SE);** The structural engineer has knowledge about the structural safety of concrete bridges. He is responsible for the specification of the right data, that should be gathered by the SHM system. Next, to that the Structural engineer needs to analyse the data of a SHM system and advising the asset manager about the structural safety of the bridge and what measures the asset manager can do to safeguard the structural safety.
- **Maintenance advisor (MA)**; The maintenance advisor has knowledge about damages of concrete bridges and basic knowledge about the structural safety of concrete bridges. He is responsible for the specification of the right data, that should be gathered by the SHM system. Next, to that the maintenance advisor is responsible for interpreting of data of a SHM system and advising the asset manager about the damages and what measures the asset manager can do to control the damages.
- **SHM / data specialist (SD)**; This person has knowledge about SHM systems and has an overview of the possibilities of SHM systems. He is responsible for setting the requirements for the installation of the SHM system, the reliability of the SHM system, the maintainability of the SHM system and the storage of data.

5.2 Result of the framework

The result of the framework is a case specific key driver diagram. In a case specific key driver diagram is presented to what main objectives the SHM should benefit, what sub-goals could be set, and which system requirements should be set to the SHM system. This is presented in the same way as the generic key driver diagram. The advantage to present the specification in this way, is its conceptual simplicity and the clear visibility of the trade-offs(Muller et al., 2006). To get an idea about the outcome, the outcome of two cases are presented in Appendix D.

5.3 Framework

An overview of the framework is presented in Figure 14. The framework describes how the AM, the SE, the MA and SD should collaborate to make a case specific key driver diagram and how the RE should support this. The framework consists of several activities:

- The AM should determine the project objective (A1) and/ or project exceeding objectives (A2)
- The AM and the SE should determine which analysis should be executed and which information this should deliver (A3).
- The SE should specify what data the SHM system should gather (A4) and how the data should be presented (A5), such that it is possible to execute the analysis.
- The SD and the SE should specify how the reliability of the data is ensured during its lifespan, such that the data can be translated in reliable information(A6).
- The AM, SE and the SD should consider how the SHM can ensure that it is possible to use the data in the future.
- The AM, SE and SD should specify how the negative influence (higher costs, lower safety and more hindrance) by the SHM system can be limited(A9).
- The AM, SE, SHM should evaluate critically if the specification is correctly executed.

Between the different activities, several conditions are set. On these points should be considered if there should be continued with the specification process or that the defined sub-goals / system requirements should be reconsidered.

- How could the generic key driver diagram (presented in Chapter 4) be used in this activity?
- How could the generic key driver diagram be elaborated for this part?
- How should the case specific key driver diagram be built?

In the following sections, the activities and conditions are described in more detail.

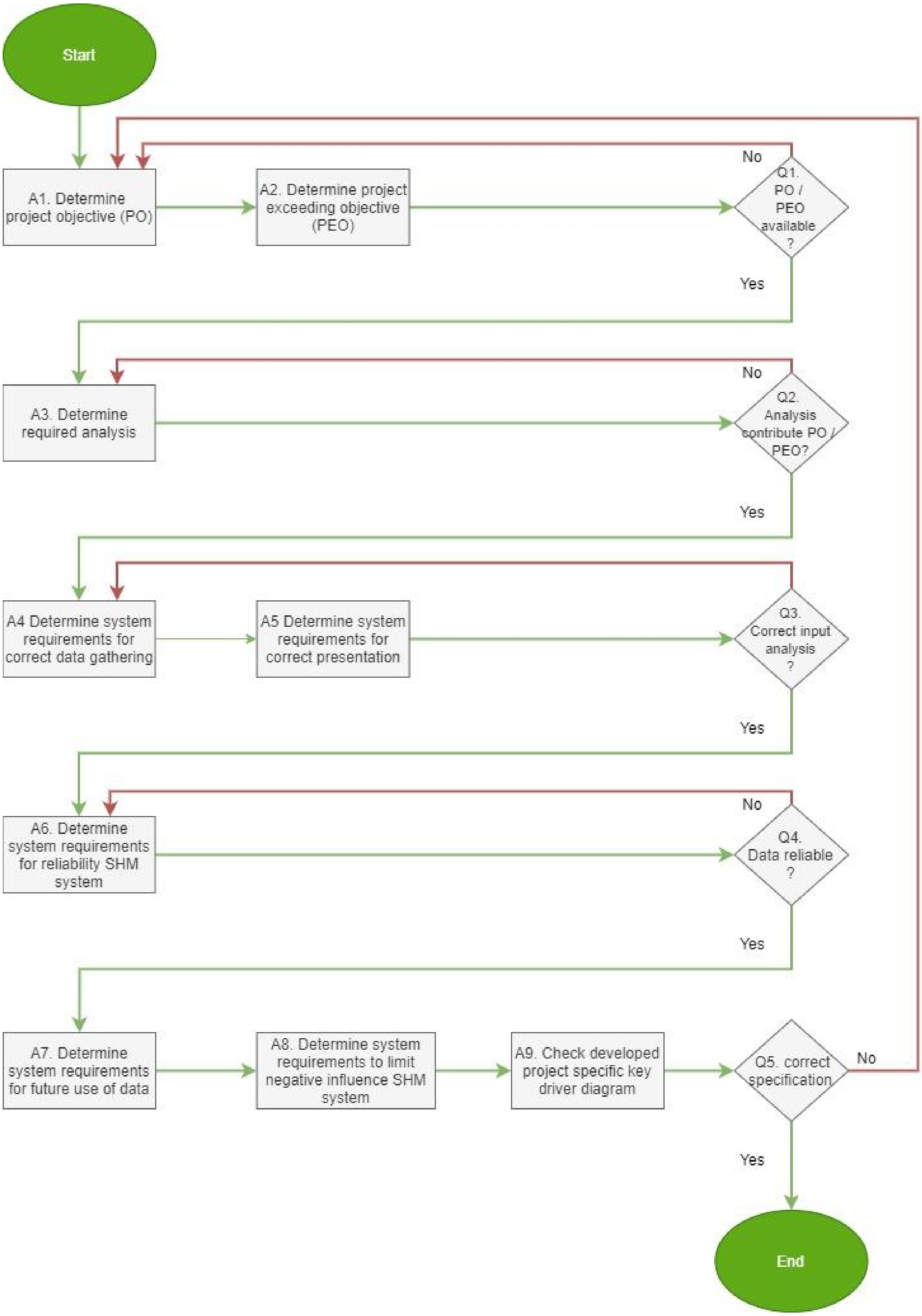


Figure 14 Overview framework

A1: Determine project objective

A project objective describes how the SHM project will contribute directly to the main objectives of the asset owner. An example of a project objective is getting insight in the risk of fatigue. This project will contribute to the main objective: high safety of the concrete bridge. The project objective can be determined in two ways. It is possible to have multiple project objectives.

Use Diagram 1 of the generic key driver diagram

- The AM determines to what main objective(s) the implementation of a SHM system should contribute:
    - High safety of the bridge
    - Low life cycle costs of the bridge
    - Low hindrance to the bridge users
- The AM selects a sub-goal that he wants to achieve in his project on the right side of the Diagram 1, that is linked with the selected main objective. (low life cycle costs of SHM system, no unsafe situations caused by the SHM system and low hindrance caused by SHM system do not count as project objective)
- The AM makes the project objective more detailed for his case i.e.
    - Able to postpone maintenance activities → Able to postpone rehabilitation for 3 years
    - Continuous insight in severity of risk → Continuous insight in risk of chloride intrusion

Determine another project objective (If project objective is not included in diagram 1)

If the expected 'project objective of the AM is not presented in the diagram, it is possible to use the refining and eliciting technique, that is presented by Muller (2006)

- The AM describes: <u>What do I want to achieve with the SHM project?</u>
- The RE asks the AM multiple times: "<u>Why do you want this?"</u> to elicit more abstract goals, until the AM answers with a main goal of the asset owner (I.e. higher safety of bridge, lower life cycle costs, etc.).
- The RE asks the AM several times: <u>How can you achieve this with a SHM system</u>? until the AM answers with a sub-goal that tackles a clear problem of the asset manager, that can be solved by a SHM system. If the SHM system solves this problem, the project is a success. This is the project objective.

Start developing a case specific key driver diagram

The RE should present the link between the main objectives of the asset owner and the project objective. This should be structured like presented in Figure 15. It presents why a specific project objective is beneficial to the asset manager.

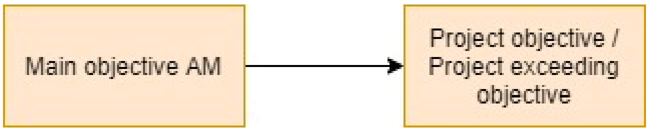


Figure 15 Result A1

A2. Determine project exceeding objective

A project exceeding objective is an objective that cannot be met with one SHM project but requires multiple SHM projects. For example: the measurements of loading over one bridge will not change the regulations, but it can contribute to new regulations if loading is measured in more projects. It is only possible to check whether the SHM project **can** contribute to the project exceeding objective. However, many factors influence if the project exceeding objective can be reached. It is not required to have a project exceeding objective.

Select a project exceeding objective from Table 3

- The AM selects a project exceeding objective from Table 3
- The AM determines how the project exceeding objective will contribute to the main objectives
- The AM makes the project exceeding objective more specific for the case:
    - Develop degradation model → Develop degradation model for carbonatation in concrete
    - Contribute to less conservative regulations → Contribute to load standard for regional bridges

Table 3 Project exceeding objectives

Project exceeding objectives	Explanation	Can contribute to the main objective
Develop or improve degradation models	It is beneficial for the asset manager to learn about the behaviour of a concrete structure. Getting more information about how material degrades, can be useful for the AM for several reasons. First, the AM can predict better when maintenance is required. Secondly, the design of new structures by learning from the degradation process.	• Low life cycle costs • Low hindrance • High safety of the bridge
Deliver input for new regulations	Like presented, the current standards include a lot of conservative values. These conservative values are used to make sure that all bridges are safe. However, by gathering data from many bridges, asset managers can prove, that the standards are too strict for category of bridges and that less strict values can be applied. This prevents that bridges are maintained when it is not necessary.	• Low life cycle costs • Low hindrance
Improve SHM techniques	Asset managers see potential benefit in SHM techniques. However, the application of SHM is not common yet. To improve SHM techniques, it can be beneficial that the SHM techniques are tested in real life.	• Low life cycle costs • Low hindrance • High safety of the bridge

Define other project exceeding objectives

This can be done in the same way as in activity A1.

Start developing a case specific key driver diagram

This can be done in the same way as in activity A1.

Q1. Is a project objective or project exceeding objective available?

The asset manager should consider if a clear project objective is identified in activity A1 and / or A2. There can be two scenarios.

Situation 1: No project objective or project exceeding objectives is determined in activity A1 and A2:

- When there is no objective for the SHM project, you cannot check whether the SHM project is a success or not. This can lead that the SHM project will only be a presentation of what the SHM system can do. In this situation, the asset manager should reconsider what he wants to achieve with the project.

Situation 2: One or multiple project objectives and/or project exceeding objectives are determined in activity A1 and A2:

- AM should consider if the project objective(s) contributes to the main objectives of the asset owner.
- If the selected project objective is considered correct, there should be looked what analysis is required to deliver information that contributes to this project objective. This is done in activity A3.

A3. Determine required analysis

The required analysis can be determined in two ways:

Use Diagram 2 of the generic key driver diagram (if the selected project objective is mentioned in Diagram 1)

- The SE select one of the analyses on the right-hand side, that is linked to the project objective, that is determined in A1.
- The SE / AM should make the analysis more specific for his project i.e.
  - Analysis level of chloride intrusion → Analysis of chloride intrusion near the joints
  - Analysis of displacements → Analysis of displacement of the top of the abutments

Define other analysis

- The SE should first look at the project objective or project exceeding objective of the AM and determine What information does the AM need, to achieve this objective?
- The SE should determine: How can this information be gathered?

Elaborate the case specific key driver diagram

The RE should make add link in the key driver diagram. The project objective or the project exceeding objective of the AM should be linked to the required analysis. The link shows that executing the analysis should contribute to the project objective or project exceeding objectives.

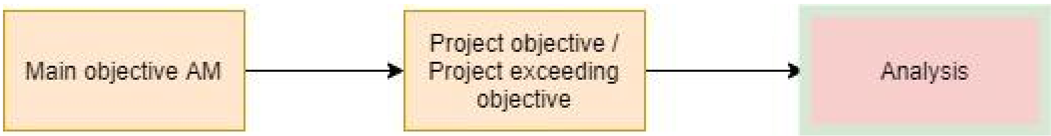


Figure 16 Result A3

Q2. Does the analysis contribute to the project objective or project exceeding objective of the AM?

Project objective(s) are determined in activity A1 and/or A2. To achieve these objectives, the AM wants to get information about the condition of the bridge. The AM and SE should consider if the selected analysis of A3, will deliver the right information to achieve the project objective and if SHM is required for this analysis. There are two scenarios.

Situation 1: No analysis can deliver information that contributes to the project objective or the project exceeding objective of the AM or SHM is not required for this analysis.

- When the analysis does not result in information that contributes to the objective of the AM, the SE should reconsider if the right analysis is chosen.

Situation 2: An analysis can deliver information that contributes to the project objectives of the AM and SHM is suitable for this analysis.

- If the analysis delivers the right information, there should be specified that the SHM system
    - Gathers the correct data (A4)
    - Presents the data correctly (A5)
    - Gathers reliable data (A6)
    - Enables users to use data in the future (A7)

A4. Determine system requirements for correct data gathering

To be able to execute the analysis, input data is required from the SHM system. In this activity will be specified what the SHM system should do or should be able to do, such that the input data can be gathered.

Use Diagram 4

- The SE should determine what main principle(s) the SHM should measure, such that he can gather the information.
- After this, the templates of the six system requirements on the right-hand side of diagram 4 should be filled in by the SE for this principle(s).
- Thirdly, the SE should determine which conditions can influence the outcome of the measurements (example: temperature);
- Thirdly, the structural engineer should determine if these conditions should be determined with the SHM system or with another source; If the SHM system should determine the conditions, the same six templates on the right-hand side of diagram 4 should also be filled in for this condition parameter.

Define other system requirements for correct gathering of data

- The SE should look what information the AM wants and check what analysis will be executed
- The SE should check: What data is required for the analysis?
- The SE should define: How can the SHM system gather the data that is needed for the analysis?
- The SE should determine: What conditions can influence the measurements of the pre-defined parameter
- The SE should define: How can the SHM system measure the condition?

Elaborate the case specific key driver diagram

The RE should add a link between the analysis and the system requirements for the correct gathering of the data. The system requirements should not include references to solutions. The following formats can be used for formulating the system requirements.

- The system should …..
- The system should be able to ……

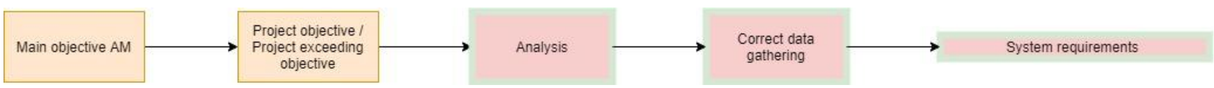


Figure 17 Result A4

A5. Determine system requirements for presentation of data

The data that is gathered by the SHM system should be presented to the SE/AM. The measurements can result in a big amount of data. When it is not presented in a structured way, it is not possible for the SE/AM to interpret the data. Therefore, system requirements should be set for the presentation of the data.

Use Diagram 5 for determining system requirements for the presentation of data

- The SE should determine how the raw data should be processed and what data should be presented to him.
- The SE should check what sub-goals for the presentation of data are applicable in the case. When the sub-goal is applicable in the case, linked system requirements from diagram 5 could be selected. There should be considered if the

Define other system requirements for presentation of data

- The SE / MA should check what data is gathered and what information should be determined
- The RE should ask the SE / MA: How should the data be presented?
    - What content should be presented?
    - What method of presentation should be used?
    - In what format should the data be presented?

Elaborate the case specific key driver diagram

The RE should make a link between the analysis and the system requirements for the presentation of the data. The system requirements should be linked, like presented in Figure 19. It can be possible to add sub-goals between 'correct presentation data' and the system requirements in order to structure the diagram more. The system requirements should not include references to solutions. The following formats can be used for formulating the system requirements.

- The system should .....
- The system should be able to ......

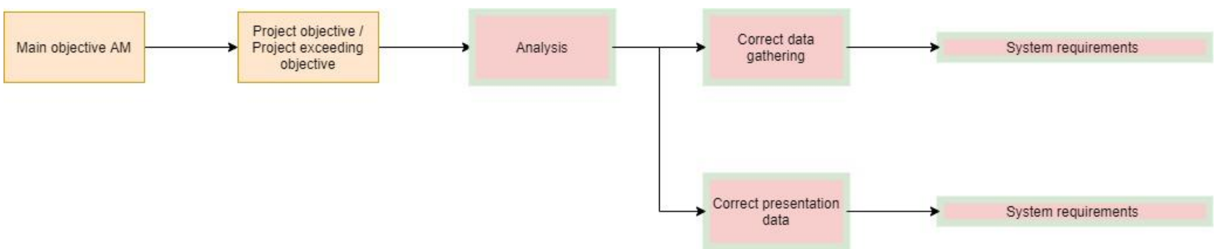


Figure 18 Result A5

Q3. Able to deliver right information based on this data?

In A4. and A5 is determined what data the SHM system should gather and how it is presented. There should be critically determined if this data can be translated in the right information. There are two scenarios:

Scenario 1: The SHM system cannot deliver the right data, that should be used in the analysis

- When the SHM system cannot gather the correct data or the data cannot present in the correct way, it is hard / impossible to execute the analysis. Therefore, the SE should reconsider the system requirements that are set in activity A3 and A4.

Scenario 2: The SHM system can deliver the right data, that should be used in the analysis

- If the correct data is gathered by the SHM system and the SHM system presents the data in the correct way, the SD should specify how the reliability of the data can be guaranteed. This is done in A5.

A6. Determine system requirements for reliability SHM system

Making sure that the data is reliable consists of two parts. First, the SHM system should deliver reliable data direct after installation. This assures the structural engineer that the results that are gathered by the SHM system are correct and can be used for the analysis. Secondly, the reliability of the data should be safeguarded for the required duration of the measurements. The system requirements for the reliability can be determined in two ways:

Use diagram 6 to determine the system requirements for reliability of the SHM system

- First, the SD should determine if the reliability should be ensured only direct after the installation of the SHM system or also for the entire lifespan of the SHM system.
- Secondly, SD should set system requirements for the reliability directly after the installation. This can be done by deciding which system requirements that are linked to the sub-goal 'reliable data direct after installation' should be defined in the project Systems requirements
- Thirdly, the system requirements should be determined to safeguard the reliability of the data for the required lifespan (if required). This can be done by selecting system requirements that are linked to the sub-goal 'able to safeguard reliability data gathering'.

Define other system requirements for reliability

- The SD and SE should discuss: <u>How reliable should the data be, to be able to execute the analysis</u>
- The SD should define system requirements by asking: <u>How can be assured that the SHM system delivers reliable data directly after installation?</u>
- The SD should consider <u>how the reliability of the SHM system can be affected over time</u>:
  - I.e. Weather conditions
  - Human influences
  - Technical disruptions
- The SD should define system requirements <u>how the SHM system can cope with these external threats</u>

Elaborate the case specific key driver diagram

The RE should make a link between the analysis and the system requirements for the reliability of the data. The system requirements should define such that the SHM system gathers reliable data for the analysis. The system requirements should be linked, like presented in Figure 20. It can be possible to add sub-goals between 'reliable data' and the system requirements for reliable data, for example: "reliable data direct after installation" and "able to safeguard reliability of data". The system requirements should not include references to solutions. The following formats can be used for formulating the system requirements.

- The system should …..
- The system should be able to ……

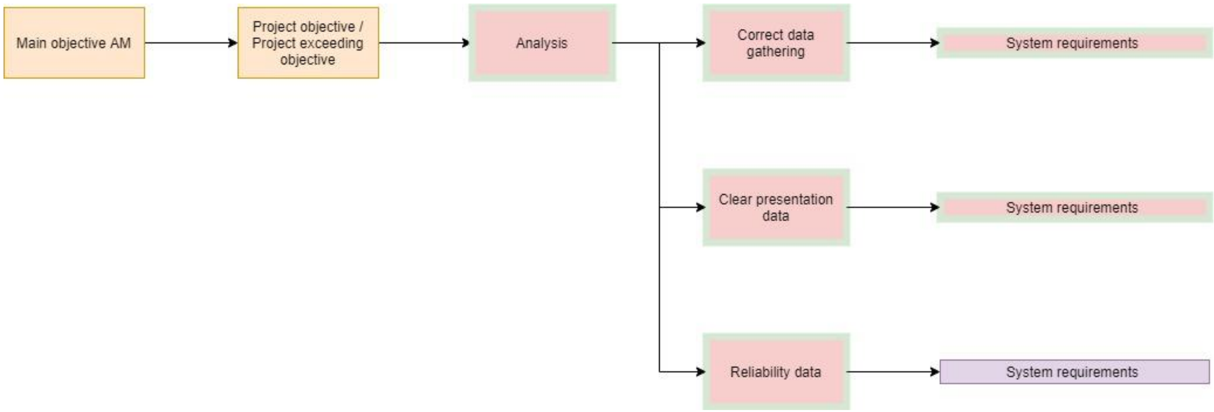


Figure 19 Result A6

Q4. Reliability safeguarded for its entire lifetime?

The SD and the SE should consider if the right system requirements are set to the reliability of the SHM system. Data can never be 100% reliable. However, the SE needs a level of reliability in order to translate the data in reliable information for the AM. Since, there is no SHM system yet, the SD should estimate, based on the system requirements, if the SHM will deliver reliable data or not. There can be two scenarios

Scenario 1: The SD expects that data that is gathered by the SHM system is not reliable enough

If the SE cannot trust the data, the SE cannot make reliable conclusions out of the data. When the SD does not trust that the SHM system will deliver reliable data, the system requirements that are set in activity A6 should be adapted.

Scenario 2: The SD expects that data that is gathered by the SHM system is reliable

- Although the data is considered reliable, it is important that the SE has a good insight about the reliability of the data and what consequence this has for the information that he is giving to the AM; This should be considered during the analysis.
- When the right system requirements are set to the reliability of the SHM system, system requirements should be defined, such that the data can also be used in the future. This is done in A7.

A7. Determine system requirements for data use in future

Data should be stored in order to make sure that the data can be used later. Data can be beneficial to see trend in the measurements, to verify if the data is processed in the right way or to do other analysis. Data can be very valuable. In this activity will be specified what the SHM system should do such that users are able to use the data in the future.

Use diagram 7 to determine the system requirements for future use of data

- The AM, SE, MA and SD should determine why the gathered data should be used in the future. The SD should determine what the SHM should do, such that the involved parties are able to use the data.
- System requirements can be defined by selecting system requirements from diagram 6.

Define more or other system requirements for future use of data

- The AM, SE, MA and SD should determine: Why should the gathered data be used in the future?
- The AM, SE, MA and SD should determine: How do you make sure that the SHM system makes it possible that people in the future are able to use the data?
  - What data should be stored?
  - How do you make sure that the data stays available?
  - How do you make sure that future users are able to interpret the stored data?

Elaborate the case specific key driver diagram

The RE should make a link between the analysis and the system requirement for the future use of data. The system requirements should define such that the SHM system enable users to use data in the future. The system requirements should be linked, like presented in Figure 20. It can be possible to add sub-goals between 'correct data gathering' and the system requirements for future data use, for example: "correct content storage" and "secure data storage".

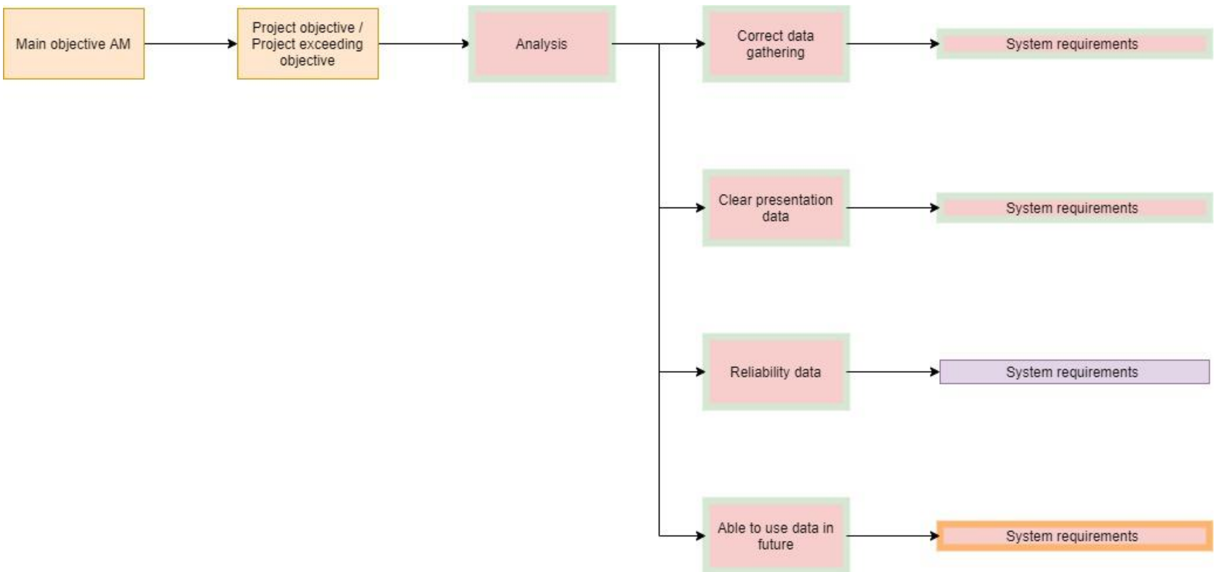


Figure 20 Result A7

A8. Determine System requirements to limit negative influence of SHM system

Like described before, the implementation of SHM is not only beneficial for the main objectives of the asset manager, there are also disadvantages of implementing SHM systems. Applying SHM can increase the life cycle costs the bridge, cause hindrance to the bridge users and cause unsafe situations. System requirements to limit the negative influences of the SHM system on the main objectives can be set in two ways.

Use diagram 8 to determine the system requirements for constraints of SHM

- The AM should determine for which main objectives he wants to limit the negative influence of implementing a SHM system, i.e. limit hindrance for bridge users.
- The AM can set system requirements to limit the negative impact by selecting system requirements on the right-hand side of the diagram.

Determine other system requirements for the constraints of SHM

- The AM should determine for which main objectives he wants to limit the negative influence of implementing a SHM system, i.e. limit hindrance for bridge users.

1. **<u>Limit life cycle costs of the SHM system</u>**

- The SD and AM should determine how the life cycle costs can be reduced. This can be done by asking the following questions:
    - The SD should determine: <u>How can costs for installation be limited?</u>
    - The SD should determine: <u>How can the costs of hardware be limited?</u>
    - The SD should determine: <u>How can the costs of maintenance be limited?</u>
        - <u>How can the amount of maintenance to the SHM system be limited?</u>
            - <u>How do you make sure that the SHM system is robust?</u>
            - <u>How do you make sure that the SHM system is able to withstand threats from the environment?</u>
        - <u>How can the maintenance be executed more easily?</u>
    - The SE / MA should determine: <u>How can the costs for interpreting the data be limited?</u>

2. **<u>Limit hindrance for bridge users caused by the SHM system:</u>**

- The AM and SD should determine: <u>How can the hindrance during the installation be limited?</u>
- The SD should determine: <u>How can the hindrance during the measurements be prevented?</u>

3. **<u>Prevent unsafe situations by the SHM system:</u>**

- The SD should determine: <u>How can be prevented that the SHM system cause unsafe situations during installation?</u>
- The SD should determine: <u>How can be prevented that the SHM system cause unsafe situations during measurements?</u>

Elaborate the case specific key driver diagram

The RE should make a link between the main objective and system requirements that are set to limit the negative influence of implementing a SHM system. This is presented in Figure 21.

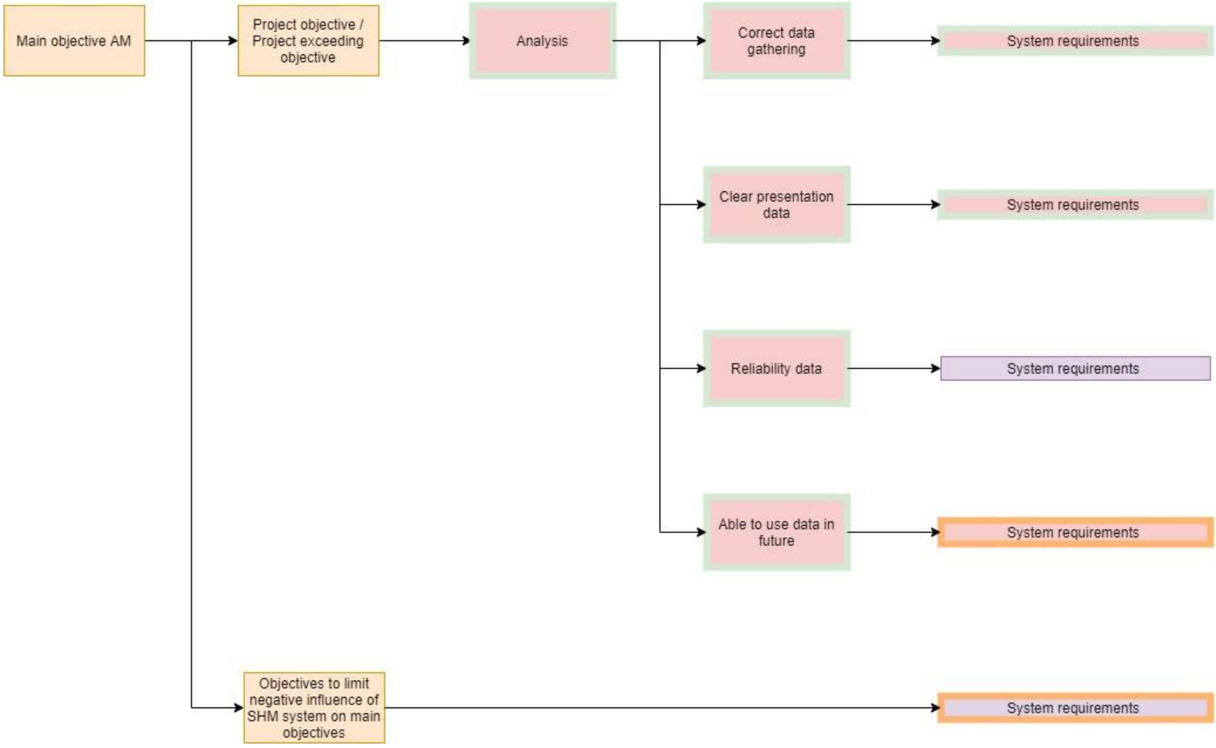


Figure 21 Result A8

A9. Verify if the SHM system still contributes to the main objectives

By executing activities A1 until A8, the RE created a case specific key driver diagram. In this activity should be discussed with all involved experts if the relations between the goals, sub-goals and the system requirements are presented correctly.

- Does the project objective really contribute to the main objectives of the asset owner?
- Does the result of the analysis really contribute to the project objective?
- Are the right system requirements set such that the SE or MA can execute his analysis?
    - Will the correct data be gathered?
    - Will the data be presented in the correct way?
    - Is the data reliable?
    - Can the data also be used in the future?
- Is the negative influence of the SHM system be limited?

Q5: Correct case specific key driver diagram

In the previous activity, the case specific key driver diagram is evaluated with all involved experts. There can be two scenarios.

Scenario 1: The case specific key driver diagram is not formulated correctly

- When one or several components of the key driver diagram are not presented correctly or the link between different components are not presented correctly, the key driver diagram should be adapted. The key driver diagram is not presented correctly, if the link between goals, sub-goals and system requirements do not logically follow each other. The framework should be run through again to check if it is possible to make some modifications.

Scenario 2: The case specific key driver diagram is formulated correctly

- The case specific key driver diagram is finished. A correct key driver diagram can help the asset manager in two ways:
  - To check if a proposed SHM system is suitable for his project
  - To help him evaluating several proposed solutions.

6 Validation of framework

The objective of this research was to develop a framework that presents to asset managers how SHM can contribute to the objectives of the maintenance policy for concrete bridges and how they should define system requirements, such that the asset manager is able to evaluate if proposed SHM solutions contribute to his objectives. In Chapter 5, the developed framework is presented. This framework is validated in two ways. These validations are used to check what the strong and weak points are of the developed framework. The first validation is executed by applying the framework in two cases. The result of the framework is evaluated with the project leader. The second validation focussed on the framework itself. Three experts from different disciplines evaluated the framework. The evaluation focusses on the six criteria that are presented in the project objective:

- Soundness
- Completeness
- Understandability
- Ease of use
- Ability to tailor specification for every concrete bridge
- Verifiability

6.1 Case study validation

This validation focusses on the result of the framework. This is done by applying the framework for two cases. The first case focussed on a bridge that is in the centre of a Dutch city. The asset manager wants to have a better insight in the remaining lifespan of the bridge, such that he can check if it is possible to postpone the replacement of the bridge, that is currently planned for 2043. Postponement of the replacement can save money for the asset manager. The second case focussed on a regional bridge. During a recalculation is concluded that the bridge should be strengthened. This will be done in 2022. Furthermore, a crack is identified on a location where also shear force cracks are located. The asset manager wants to prove that the crack is not caused by shear force. In this way the asset manager wants to prove that the bridge can be used safely until 2022.

6.1.1 Applying the framework in the cases

The framework has been run through for both cases. This is done with help of the experts that are also included in the real-life cases: the asset manager, the structural engineer and the SHM / data specialist. For the validation will be acted as if no decisions are made about a SHM system.

A1: Determine project objective

The framework started with an interview with the asset managers of both cases to determine the project objective. First the asset managers were asked to use diagram 1 of the generic key driver diagram to identify the project objective of the case. Afterwards, there was asked if more project objectives were identified.

- The asset manager of case 1 explained that safety of the concrete bridge is the most important main objective for this project. The generic key driver diagram was presented to the asset manager. The asset manager explained that he wants to achieve this by keeping track of the risk of fatigue. In previous analyses, there was determined that this is the normative factor for safety of the bridge. Furthermore, there was asked if the asset manager wants to achieve more. He explained that he wants to get a more accurate life span prediction, since he expects that the current calculations are too conservative. When there was asked why he wants to achieve this, he explained that a delay of replacement can save the asset manager much money. So, the main objective is to reduce costs.

- The asset manager of case 2 explained that safety is the main objective for him. The asset manager explained that the safety was first guaranteed with visual monitoring. He explained that he wants to use SHM, because this is less expensive, and it gives a continuous insight in the behaviour of the crack. A continuous insight in the behaviour of the crack is preferred, because it can show if the bridge faces the risk of shear force.

A2. Determine project exceeding objective

The asset managers were asked if there were also project exceeding objectives. First, there was asked if one of the project exceeding objectives, that is presented in Table 3, were applicable in the case. Afterwards, there was asked if the asset manager wants to achieve more with the project.

- The asset manager of case 1 stated that he also wants to contribute to new regulations. He explained that he expects that many bridges in city centres face lower loads than assumed in the regulations. The asset manager wants to store data about the actual loads that went over the bridge. Categories of loading per type bridge should be made. In this way the loads that are used in the safety calculations is closer to reality. This prevents that measures should be taken, when it is not necessary. This can reduce costs and hinder in the future.
- The asset manager of case 2 stated that there are no project exceeding objective in this project.

Q1. Is a project objective or project exceeding objective available?

In both cases, several project objectives were determined:

- For case 1 the following project objectives were identified:
    - Get insight in the risk of fatigue
    - Predict the lifespan more accurately
    - Contribute to new regulations regarding load categories

- For case 2, the following projects were identified
    - Replacement visual monitoring
    - Continuous insight in risk of shear force

A3. Determine required analysis

The structural engineers that were involved in the cases were interviewed to determine the analyses that should be executed to meet the objectives of the asset manager. First, the relation between the main goal and the project objective, documented in activity A1 and A2 by the asset manager, are presented to the structural engineer. Secondly, diagram 2 of the generic key driver diagram was presented to the structural engineer. Thirdly, the structural engineers were asked what information they wanted to derive and how they want to gather this information. Fourthly, the analysis was linked to the project objectives of the asset manager.

- For case 1, the structural engineer linked the following analysis to the objectives:
    - Get insight in the risk of fatigue: The deflection of the bridge will be determined in relation to the loads over the bridge. When the deflection with the same loads increases over time, it gives an indication of a change in the level of fatigue.
    - Predict the lifespan more accurate; the structural engineer explained that the lifespan currently is determined based on the regulations. Different parameters in the model can be adapted, such that the model is closer reality. The SHM model should give input such that the parameters can be adapted. There will be looked at the actual loading,

the actual deflection and the actual load distribution over the different beams. The lifespan will be determined on the extrapolation of the measurement data.
  - Contribute to new regulation regarding load categories; The SHM system should give an overview of the number of vehicles over the bridge including their weights.

- For case 2, the structural engineer linked the following analysis to the objectives:
  - The objectives of replacement of visual monitoring and continuous insight in risk of shear forces resulted in one analysis. The analysis of the behaviour of the crack with a SHM system. During visual inspection a crack is identified. When the crack only grows due to temperature changes, there is no risk of shear force. When the crack grows independent from the temperature, there is another cause for the crack growth. Measures should be taken directly, when this happens.

Q2. Does the analysis contribute to the objectives / project exceeding objectives?

The asset manager and the structural engineer were mailed if the analysis contributed to the objectives. Both agreed with this.

A4. Determine system requirements for correct data gathering

With the structural engineers of both cases, system requirements were defined for correct data gathering. First, there was asked what principles should be measured to be able to execute the analysis. Secondly, the six templates of diagram 4 were filled in by the structural engineer. Thirdly, there was asked what conditions can influence the measurements of the results. Fourthly, the six templates on the right-hand side of diagram 4 were filled in for these conditions. Fifth there was asked if more system requirements should be identified to make sure that the correct data can be gathered. Both structural engineers explained that no more system requirements should be set. Finally, the system requirements were linked to the analysis in the case specific key driver diagram.

- For case 1, the structural engineer identified that the loading and the deflection should be measured. For both principles the templates were filled in. The structural engineer explained furthermore, that the construction temperature influences the measurements. Also, for this principle, the templates of the system requirements were filled in.
- For case 2, the structural engineer explained that the crack width should be measured. The templates of diagram 4 were filled in by the structural engineer. Furthermore, the structural engineer explained that the air temperature influences the outcome of the crack width measurements. Also, for this principle, the templates of diagram 4 were filled in.

A5. Determine system requirements for the presentation of data

First, there was asked to the structural engineer how the data should be processed and what data should be presented to him. Diagram 5 was presented to the structural engineer. The structural engineer checked if system requirements were applicable in their case. Thirdly, there was asked how the data should be presented? With the follow-up questions: what content should be presented, what method of presentation should be used and in what format should the data be presented? The system requirements that followed from these activities are linked to the analysis that was identified in activity A3.

- In case 1, the structural engineer explained that the SHM system should present different results. First of all, the structural engineer wanted that the system was able to present: all raw data, deflection related to the loading and construction temperature, a distribution of all loading that went over the bridge and the SHM system should be able to only presented of vehicles with a loading above a specific amount of loading. The structural engineer did not set system requirements to the method of presentation and the format of the data presentation.

- In case 2, the structural engineer explained that the SHM system should be able to present all raw data, a relation between the crack width and the outside temperature over time. The structural engineer wished that the SHM system presents the data in a graph with an open format.

Q3. Able to deliver right input based on this data?

In this step, the structural engineer considered if they expect that the SHM system will gather and present the right data, based on the key driver diagram that is developed in the previous step. Both structural engineers expected that the analysis could be executed, based on the system requirements that were derived in step A4 and A5.

A6. Determine system requirements for reliability of SHM system

First, there was asked to the SHM system if only system requirements should be set for the reliability on the short term or also for the long term. Secondly, diagram 6 of the generic key diagram was presented to the SHM expert. There was asked which system requirements were applicable in their case. Thirdly, there was asked if more system requirements are necessary to safeguard the reliability of the SHM system and such that the SHM system can deal with external threats.

- In case 1, the SHM explained that the reliability should be ensured for a longer time (at least 5 years). The SHM system set several system requirements based on diagram 6 and several by answering the questions that were mentioned in activity A6.
- Also, in case 2, the SHM explained that the reliability should be ensured for a longer time (at least 3 years). The SHM system set several system requirements based on diagram 6 and several by answering the questions that were mentioned in activity A6. The SHM expert mentioned that external threats were not available in this case, since the SHM system should be placed inside the bridge tube.

A7. Determine system requirements for future data use

First, diagram 7 of the generic key diagram was presented to the SHM expert. There was asked which system requirements were applicable in their case. Secondly, the SHM expert was asked why the data should be used in the future and how he wanted to make sure that this is possible.

- The SHM specialist of case 1 explained that he wants to store all data (raw and processed), because he does not know how the data should be used in the future. Furthermore, the SHM experts does not want to set too much system requirements about the future use of the data. The only requirements are that the data should be stored on the correct server.
- The SHM specialist of case 2 explained that he wants to store all data (raw and processed), because he thinks data can always be useful and you never know why you can use it in the future. Furthermore, the SHM experts defined several system requirements by answering the questions: how you make sure that the data can be used in the future.

A8. Determine system requirements to limit negative influence of the SHM system

First, there was asked to the SHM specialist if applying a SHM system will negatively influence the safety, life cycle costs or hindrance to the bridge users. Secondly, diagram 8 was presented to the SHM expert and there was asked which system requirements were applicable in his case. Thirdly, the questions that are presented in activity A8 of the framework were asked to the SHM specialist.

- The SHM expert of case 1 stated that the SHM system influences the life cycle costs, hindrance and the safety. Several system requirements were defined by selecting them from the diagram 8. Others were defined by answering the questions that are stated in activity A8.
- The SHM specialist of case 2 stated that the SHM will only affect the life cycle costs. The SHM system will be placed inside the tube. This will not give much hindrance to the bridge users. Also, unsafe situation caused by the SHM system are not expected. Several system requirements were defined by selecting them from the diagram 8. Others were defined by answering the questions that are stated in activity A8.

A9. Verify if the SHM system still contributes to the main objectives

In steps A1 until A8 the case specific key driver diagram is developed. In this activity the outcome is verified with the SHM expert. The framework describes to execute this activity with all involved experts, but in this validation session it was not possible to arrange this. The SHM expert of the case is used as representative for the group of experts.

- The SHM expert of case 1 agreed in general with the outcome. He proposed several modifications how goals and sub-goals were written down.
- The SHM expert of case 2 also agreed with the outcome.

Q5. Correct case specific key driver diagram

Both SHM experts agreed with the developed case specific key driver diagram. This meant that the specification process is finished. The result of the process is a case specific key driver diagram, which are presented in appendix D. These case specific key driver diagram should be used for the evaluation of a SHM system in their case. The result (the key driver diagram) will be discussed with the project leader of the project.

6.1.2 Evaluating the case specific key driver diagram with the project leader

In the previous steps, a case specific key driver diagram was developed for both cases. The project leader of the cases was asked to evaluate this diagram. This is done by sending a questionnaire to the project leader. The results of this questionnaire were later discussed in an interview. The case specific diagram was evaluated based on the criteria: soundness, completeness, understandable, ease to use and verifiability.

Soundness

This criterion focusses if the right goals, sub goals and system requirements were defined and if the link between these elements were correct. The results differed per case.

The project leader of case 1 thought that the framework defined logical goals, sub-goals and system requirements and the links between the components. However, he had several comments about the diagram. First, the link between goals and sub-goals are not always one-on-one links. For example: the link between 'efficient budgeting based on accurate prediction of the life span' does not always lead to 'low life cycle costs of the bridge'. He explains that the costs only decrease if it is possible to prove that the replacement of the bridge can be postponed. This is not always the case. The SHM system can also show that the bridge should be replaced earlier. Secondly, the project leader is not completely convinced that this specification will lead that the correct data will be gathered. He explains that there is no experience with the analysis that should be executed. Which makes it difficult to specify the required data in front. In the current design process, they use sometimes trial and error to see if a method is possible. The project leader explains that some setbacks cannot be predicted in front. For example, they want to measure the weight of vehicles, but this can be difficult when vehicles are overtaking on the bridge in a specific way.

The project leader of case 2 was though that the defined goals, sub-goals and system requirements were correct. The only comment was that several sub-goals could have been combined. He mentioned that the sub-goals to have “low life cycle costs for the SHM system” and “low costs for monitoring” are related.

Completeness

The key driver diagram presents the relation between the main goals and the system requirements. Both project leaders explained that the specification of the SHM system was comprehensive but found analyse if system requirements were missing. The project leader of case 1 states that the diagram does not present how the analysis is executed and what information will be the result of the analysis. Because this information is missing in the result, it is hard for the asset manager to check if the analysis will really result in information that contributes to the project objective. The project leader of case 2 agrees with this statement. However, he states that this problem is less important for his case since the analysis is not that difficult.

The project leader of case 1 also misses system requirements how the SHM system processes the raw data. Now, is only stated, “the loads and deflection should be presented per vehicle”. It is not clear how this should be done and to check if one solution can do this better than the other.

Understandable

Both project leaders stated that it was easy to understand how the key driver diagram works. The reasoning of the specification is presented in a clear way, and it did not take long to understand what considerations were made in the process. One point of discussion is that there can be some confusion about the formulation and structuring of goals and sub-goals. Both project leaders stated that they would have structured the diagram differently but can understand the line of thought. This was not a problem for the project leader, since they are familiar with the project.

Ease to use

Although, the criteria ‘ease to use’ especially focusses that the framework can be used easily, this validation also checked whether the result of the framework can be used easily. For this criterion was asked if the diagram can be used for:

<u>Evaluating if a proposed SHM solution is suitable for the project</u>

Both project leaders confirmed that this diagram can help by evaluating if a solution is suitable. The SHM solution can simply be tested by checking if they meet the system requirements.

<u>Comparing different SHM solutions</u>

Both project leaders confirmed that such a diagram can help with comparing different solutions. Project leader of case 2 explains: “I would take the list of system requirements and check for the proposed solutions how they score for the system requirements. The sub-goals can explain why the system requirements are set.

Tendering the SHM system

Both project leaders confirmed that the specification can be used for the tendering of such a system. Project leader of case 1 states that the system should not be tendered alone. The analysis and pre-analyses and explanations should also be part of the tender. The project leader of case 2 explains that there are several forms of tendering, which can differ in level of detail. A tender that includes such specific system requirements are possible, but it is more likely that there will be chosen for a less detailed specification. It is more likely that a service will be asked instead of specifying a product.

Verifiable

Both project leaders stated that it was in general clear why specific system requirements were defined. The diagram gives a good overview why specific system requirements are set. Project leader of case 1, mentioned that he would have presented several links differently, but that he was able to follow the line of thought. A point of attention is that the values of the system requirements cannot be verified in the diagram. It is therefore not possible for the asset manager to check why there is chosen for a specific value. It is hard to identify mistakes or wrong quantifications of the system requirements. Furthermore, it is not possible to check if the right analysis is chosen. The reasoning for a specific analysis is not presented. Project leader of case 1 states that the diagram not shows why fatigue is chosen as normative indicator for the lifespan prediction. The project leaders explained that it was possible to verify why specific system requirements were set, but it is not possible to verify if the goals and sub-goals can be met, since this depends also on more aspects.

6.2 Validation with expert panel

This validation is executed to evaluate the complete framework itself. Two experts were asked to evaluate the framework, based on the criteria that were mentioned in the objective. This validation is executed with help of two experts: an expert with knowledge of structural engineering (expert 1) and an expert with knowledge about asset management (expert 2). Unfortunately, it was not possible to interview an expert with knowledge of structural health monitoring. The validation has three parts. In the first part, the generic key driver diagram and the framework was presented and explained to the expert. Afterwards, a questionnaire was sent to the expert. The experts filled in this questionnaire independently. The questionnaire is presented in Appendix F. The experts were asked to evaluate the different parts of the framework based on the criteria. Diagram 1 till 8 of the generic key driver diagram are evaluated for the criteria soundness, completeness and understandable. The total framework was evaluated on the criteria: soundness, completeness, understandable, ease to use and verifiable and ability to tailor for a specific project.

6.2.1 Soundness

This criterium focusses if the generic key driver diagram consists of the right goals, sub-goals and system requirements and if the right activities should be executed in the framework.

Expert 1 states that not all project goals are correct identified in the generic key driver diagram. He explains that: able to repair damage before it worsens and able to postpone maintenance activities are the most important goals for SHM projects. There should be found a kind of optimum between those goals, such that the bridge is maintained on the right time. SHM can help with this but should collaborate with other inspections to achieve this. This collaboration between SHM and other inspections/researches are not presented in the generic diagram. Expert 1 states that correct analyses are presented, but does not understand why some analysis are categorized under early damage detection and others on keeping track of a risk of failure. Expert 1 and 2 explains both that the goals, sub-goals and system requirements that are presented in the generic key driver diagram are in general good. The experts understood why these system requirements could be set to a SHM system.

Both experts stated that the activities in the framework are very comprehensive for a specification of a SHM system. It is not required to develop such a comprehensive diagram to make a specification. Expert 1 explains that he preferred a kind of checklist of system requirements over a framework that explains how a complete key driver diagram should be built.

6.2.2 Completeness

This criterium focusses if the generic key driver diagram is complete and if the framework will result in a complete specification.

First, expert 2 stated that an asset manager can have more main goals. Important main goals of asset managers are currently sustainability and circularity. SHM systems can be applied on the bridge to check whether components are still strong and can be used in the future. Including the main objective 'sustainability' can also cause that more system requirements will be defined, think about the energy use of the SHM system.

Expert 2 states also that he has doubts about the completeness of the specification. The quality of the analysis depends on the quality of the data. Furthermore, no requirements are set about the processing of the data. Expert 2 states that only requirements are set to the results that should be presented. It is also possible that the SHM system should process the data in a specific way. One system might do this better than other systems. So, expert 2 advises to add this to the framework.

More points that should be added according to Expert 1 are:

- Accessibility and transferability of the data for users also influences the management costs of the SHM system. This is not included in the system
- De-installation of the SHM system can also cause hindrance to the bridge users, this is not included in the system
- For the influence of the SHM system on the safety of the bridge is only focusses how the SHM system can possibly damage the bridge. There is not focussed on how the SHM system can affect the bridge user or the people that should work with the SHM system.

6.2.3 Able to tailor the specification for every concrete bridge

This criterion focusses if the framework can come with a specification, that is tailored to the specific project.

Both experts stated that it looks likes it is possible to make a specification for every concrete bridge. However, the experts find it difficult to evaluate, since they did not use the framework, themselves. Expert 1 wants to emphasize that specification can never be copied directly.

6.2.4 Understandable

This criterium focusses if all users have the same understanding of the generic key driver diagram and the framework.

Both experts had problems to completely understand the generic key driver diagram. This had to do with the formulation of several goals and sub-goals and the link between several components of the diagram. Both experts stated that they did understood why several decisions were made, but they should formulate other sub-goals. For example: expert 2 states that the quality of the data depends amongst others on the accuracy, completeness, accessibility and consistency of the data. These aspects are included in the current generic key driver diagram included in other sub-goals. Both experts also had problems with evaluating if the framework was applicable in practice.

6.2.5 Ease to use

This criterion focusses if it was easy to use the generic key driver diagram and if it was easy to run through the framework.

Both experts stated that the generic key driver diagram was not easy to use. It took some time to understand the link between goals. Especially, the links between the main goals, the project objectives and the analyses were not always easy to understand. The link between the system requirements and the sub-goals were easier to understand. Furthermore, the framework that is presented in chapter 5 is too comprehensive and takes a lot of time to understand and run through. Expert 1 states that he would use the generic key driver diagram to identify which system requirements could be set and which system requirements are applicable in his case. Next to that, he said that there should be made a kind of checklist for categories of system requirements. Such that, the asset manager can check if the specification is complete. Both experts stated that it is not necessary to build a complete case specific key driver diagram to make a specification.

6.2.6 Verifiable

This criterium focusses if the reader of the generic key driver diagram can verify why specific goals, sub-goals and system requirements were set.

Both experts explained that the key driver diagram gives a good presentation why a specific system requirement is set. Reading the diagram from right to left makes it clear why the system requirements are defined. However, when the diagram is read from left to right, components are left out. This is done, because the aspects are not related to the specification of the SHM system. However, by leaving out these aspects, it is not possible to check if the main goals and sub goals will be achieved. This caused troubles reading the generic key driver diagram.

7 Discussion

The method, that is chosen in this research, has influence on the outcome of the research. The influence of the limitations of the research method will be discussed per activity.

7.1.1 Literature research

The literature research was executed to find information about the current approach of maintenance of concrete bridges in the Netherlands, the need why concrete bridges need to be maintained and to give an overview how SHM can be beneficial for asset managers and what system requirements should be set to these systems. The first limitation of this literature research is that all asset managers can have different maintenance approaches. It is not possible to discuss all these approaches and therefore, there was looked for the general approach. The same limitation applies to the need for maintenance. Every concrete bridge is unique: the structure, the environment, the stakeholders etc. can be different for every bridge. Therefore, it is hard to give a complete overview of all reasons why concrete bridges need to be maintained. This resulted that the framework could not be very detailed. To cope with these limitations, the results of this part of the literature research is validated with the experts. These experts also explained on which aspects should be focussed. Another limitation about the literature research is that many researches about SHM focusses on new SHM techniques, which are not commonly applied, yet. This makes it difficult to estimate if the SHM technique can be beneficial in practice or not. Next to that, there were some guidelines about how SHM systems should be designed and applied in real life cases. However, these guidelines did not focus on the Dutch market. Finally, SHM techniques are developing fast. This can result that the articles are already outdated and that SHM can have more possibilities, yet.

7.1.2 Expert interviews

Expert interviews were used to gather information about the current approach of maintenance, how SHM systems can benefit to the maintenance policy of asset manager and what system requirements should be set to the SHM system. Twelve expert interviews were executed to gather this information.

The first limitation of the expert interviews is that only twelve experts were interviewed. Whereby, there was tried to get a good overview of the goals, sub-goals and requirements from the perspective of different disciplines. More expert interviews could have let to new insights, whereby more or other sub-goals and system requirements could have been gathered.

Secondly, there was tried to bias the outcome of the research as less as possible. This was done by starting with general questions, like: “How can SHM be beneficial for the asset manager?”. However, the expert was not always able to answer these questions. Therefore, the experts were helped, by asking more detailed questions. Which can lead that the expert was steered in a direction.

Furthermore, SHM is a new development and not all experts have a complete insight in what the possibilities are of the new techniques. This can lead that experts are only focussing on the part of SHM, that they are familiar with. Therefore, an incomplete overview of the possibilities of SHM can be given. Next to this, most experts have worked for years with traditional manner of maintenance. The culture and processes are especially focussed on the traditional ways of assessing the bridge. Therefore, the experts can have only focussed on the application of SHM systems that fit in the current maintenance approach. However, it might be possible that SHM can be even more beneficial if processes and culture changes.

7.1.3 Key driver method

Like presented in the research framework, the key driver method of Muller et al. (2006) plays a central role in this research. It does not only influence how the data is presented, but it also influences how the data is gathered in the literature research and the expert interviews. The presentation of the relation between the main goals and the system requirements are presented in a schematic way. Whereby the goals, sub-goals and system requirements are only presented in a view key words. The limitation of this method of presentation is that the goals or sub-goals can be interpret in different ways.

Muller et al. (2006) advised to use two techniques to gather input for the key driver diagram: refining and eliciting technique and scenario-based reasoning. These techniques are used in the expert interviews. The focus in this approach is especially focussed on goals. Whereby, the purpose was to get a clear insight in the relation between the maintenance policy and the system requirements of a SHM system. However, in this research is not investigated if this specification technique is the best method for the specification of a SHM system. The use of other specification techniques can lead to more or other system requirements.

7.1.4 Case study validation

In the case study validation, there was investigated if the framework can be applied for two real life cases. There are several limitations to the approach of this validation. First, the framework is only tested for two cases, which does not prove that the framework is applicable on every concrete bridge. In other cases, the context can be different. By applying the framework in more cases, more accurate conclusions can be drawn about the applicability of the framework. Secondly, SHM systems were already applied on the bridges. Although, there was tried to act like no SHM system was applied, experts could be biased and trying to specify their own solution, instead of making a solution free specification. Next to that, the experts are already familiar with the project and already thought of several issues during the design process of the SHM system. This makes it easier for them to specify a system, than when a SHM system should be specified from scratch. Another important limitation of this case study validation is that it was not possible to meet the experts in real life due to the Covid-19 virus. All interviews were held with skype. Finally, not all experts were available for multiple interviews. Therefore, additional questions should often be asked by email.

7.1.5 Expert panel validation

The expert panel validation is only executed with help of two experts: an expert with knowledge of structural engineering and an expert with knowledge of asset management. There was tried to let an expert with knowledge of SHM evaluate the framework. Unfortunately, this was not possible within the timeframe of this research. A second limitation of this approach is that the experts were only available for approximately three hours. This means that it was not possible to let the experts apply the framework for a case. Furthermore, it was not possible to let the experts evaluate at a very detailed level. Both experts stated that three hours is much for such a session. This could have led that the experts could have evaluated the framework less thorough than was hoped. Thirdly, the interviews during the validation session were kept with skype. Due to the Covid-19 pandemic it was not possible to interview them in real life. This meant that the framework was explained via a presentation via skype. Fourthly, the validation was only quantitative. The decision to let not the experts rank aspects based on the criteria is made, based on the expected value of such a ranking. Only two people should rank the components. Next to that, the ranking should be interpreted. There was decided that qualitative questions were more efficient to find the strong and weak points of the framework.

8 Conclusions and recommendations

Based on the literature research, expert interviews and validation sessions, several conclusions can be drawn from this report. The limitations of the research are hereby considered. Furthermore, there will be given several recommendations for further research.

8.1 Answers to sub-questions

In the introduction of this research, main questions and sub-questions were derived. Now, the research is finished it is possible to give answers to these questions.

Sub-question 1: Why do concrete bridges in the Netherlands need to be maintained?

Asset managers have the duty to proof that his bridges can be used safely. This is stated in the Civil Code article 6:174 and 6:162. The asset manager is liable when damages or casualties happen. A concrete bridge is tested after construction and can be considered safe, when the bridge does not deteriorate too much, the loads do not increase, and the regulations do not change due to new insights. This are the most important reasons that the safety of concrete bridges in the Netherlands decline:

- Higher loads are crossing the bridge than was considered during the design process.
    - The risk for collapse by shear forces increases
    - The risk for collapse by fatigue increases
- Subsidence of the structure; The loads are distributed differently in the structure. This can lead that components should bear higher loads than they were designed for. This can lead to failure of this component.
- The bearing capacity decreased, because the reinforcement bars were affected. This could have several reasons:
    - Chloride intrusion
    - Carbonatation
    - Alkali Silica Reaction
    - Cracks

Sub-question 2: How do asset managers in the Netherlands currently maintain their concrete bridges?

The safety of the bridge is in general assessed with visual inspections and structural calculations. It can be possible that more detailed information about the structure is required. Therefore, it can be possible to execute additional researches, for example by using concrete or steel samples. Furthermore, it is possible that an aspect is monitored visually. This means that visual inspectors check a specific aspect of the bridge over a time. The disadvantage of visual inspections is that the condition of the bridge is only assessed occasionally. Next to that, visual inspections can be expensive and cause hindrance to the bridge users. Finally, there can be spots on the bridge which are not or hard accessible. An advantage of visual inspection is that it gives a good insight in the general condition of the bridge. A disadvantage of structural calculations is that these calculations should be based on standards, that include a lot of conservative values. This can lead that the safety in practice is not the same as in theory.

Sub-question 3: How can SHM systems contribute to the asset managers' goals for the maintenance of concrete bridges according to literature?

According to Vardanega et al (2016) the objective of an asset manager is that the bridge functions with maximum performance at minimum costs. Samco (2006) presented that SHM can be beneficial for the asset manager by giving a better understanding of in-situ structural behaviour, detecting damage earlier, assuring the structures strength and serviceability, reducing down time and improving maintenance and management strategies. Whereby, there can be made a distinction between different categories of SHM projects (Webb, 2014):

- Sensor deployment studies
- Anomaly detection
- Model validation
- Threshold check
- Damage detection

Furthermore, an overview was given what properties could be measured from a concrete bridge: loads, deformations, strains, temperature, acceleration, wind speeds and pressures, curvatures, displacements, scour, corrosion, cracking, location of rebar and delamination, tension and environmental parameters (Gastineau et al., 2009).

Sub-question 4: How can SHM systems contribute to the asset managers' goals for the maintenance of concrete bridges in practice?

SHM can contribute to the three main objectives of the asset manager: high safety of the concrete bridge, low hindrance to the bridge user and low life cycle costs of the concrete bridge. SHM projects can have the following project objectives:

- Low hindrance caused by visual inspections
- No hindrance by load restrictions
- Able to postpone maintenance activities
- Able to repair damage before it worsens
- Low costs condition inspections
- Low costs monitoring
- Continuous insight in severity of risk

Sub-question 5: How can asset managers link system requirements to the objectives of SHM systems?

In this research, a framework is developed to set system requirements to a SHM system, such that the system will contribute to the goals of the asset owner. This is done by splitting up the main objectives in sub-goals. First, the asset manager should determine the project objective. Secondly, the structural engineer or the maintenance advisor should determine which analysis should provide the right information to the asset manager. The structural engineer, maintenance advisor and the SHM / data specialist should set system requirements for the correct data gathering, correct presentation of the data, reliability of the data and future use of the data. Finally, the asset manager and the SHM/data specialist should define system requirements such that the negative influence of the implementation of the SHM system will be limited (low life cycle costs SHM system, low hindrance to bridge users, high safety of the SHM system). The goals, sub-goals and system requirements will be linked and are presented in a diagram. System requirements can be set in two ways: using the generic key driver diagram or by answering questions that are mentioned in the framework.

8.2 Conclusions

In the introduction, the following research question was asked:

Main research question: How can asset managers set system requirements to Structural Health Monitoring systems, such that proposed SHM systems will contribute to the asset managers' goals for the maintenance of concrete bridges?

This research was an explorative research, whereby was tried to develop a framework that comes up with a sound, complete, easy to use, understandable and verifiable specification. This was tried by splitting up the main goals of the asset manager in sub-goals, that the asset manager wants to achieve with a SHM system. To see, what asset managers want to achieve, there was first investigated why a bridge needs to be maintained and how this is done in the current approach. There was assumed that the objective to place a SHM system influences the sub-goals that should be achieved and therefore the system requirements that should be set to the SHM system. However, every analysis requires that the SHM system gathers the correct data, presents the data correctly, makes sure that the data is reliable and that the data can be used in the future. Other sub-goals were derived by limiting the negative influences of implementing a SHM system.

During the validation of the framework came to light that the developed framework does not meet all criteria. The expert was in general satisfied about the system requirements that were presented in the generic key driver diagram. The experts understood why the specific system requirements were defined. Furthermore, the most detailed sub-goals were good starting point for defining new system requirements by asking how these sub-goals can be achieved. However, the developed framework in chapter 5 is not complete yet, can be ambiguous and can take long to run trough. Next to that, the experts explained that for making a specification it is not required to make a complete key driver diagram.

In appendix G, a list of system requirements and considerations during specification are presented. The following sub-goals should be achieved with the specification of the SHM system:

- Correct data gathering
- Correct presentation of data
- Reliable data
- Able to use data in future
- Low capital investment SHM system
- Low data management costs
- Low maintenance costs SHM system
- Robust system
- Able to deal with environmental threats
- Low hindrance caused by SHM system
- No unsafe situations cause by SHM system

The key driver method was used in this research to develop a specification. This technique is a structured method to develop a specification, based on objectives. The key driver method is a good method to present why specific system requirements were defined. The key driver diagram can be understood quickly for a specific case. However, in this research a generic key driver diagram was developed with many layers of sub-goals. Achieving the high-level goals did not only depend on the choosing the right system. This confused many readers of the diagram. So, it is preferred to only include sub-goals that are related to the specification of the system.

Another point that was discussed during the validation session is the applicability of a specification of SHM system. The specification of a SHM can be used to compare different SHM system or to check whether a SHM system is suitable for a project. But the experts have doubts if it is necessary to have such a comprehensive and detailed specification for the tendering of a SHM system. The more detailed the specification, the less freedom for the market. Next to that, SHM system is often tendered most of the time in combination with an analysis or other inspections / researches.

8.3 Benefits research for Antea Group

Antea Group is an engineering firm, who advises asset managers amongst others with their maintenance policy. Next to that, Antea Group also develops in collaboration with suppliers several SHM systems for projects.

In this research, was tried to develop a framework that comes up with system requirements that should make sure that the SHM system contribute to the goals of the asset managers. Different criteria were set to this framework. Like discussed before, the developed framework did not meet all criteria. Therefore, it is hard to use the framework in practice. The experts stated during the validation session, that the system requirements, that were derived, were correct. However, there are doubts about the completeness of the framework. Additionally, the experts were not satisfied with the understandability and ease to use of the framework. In Appendix G, a list of system requirements and considerations during the specification are presented. Antea Group can use these lists for two things:

- When Antea Group advises asset managers, this list can be useful for Antea Group to help the asset manager evaluate if a proposed SHM system is suitable or not.
- When Antea Group works on the supply side, these lists can be used to check if during the development of a SHM system is thought about several important aspects.

A by-catch of this research is that the generic key driver diagram presents several objectives that can be met in a SHM project. This overview can be used to find opportunities for implementing SHM systems in new projects.

8.4 Recommendations

The research presents a framework for the asset manager to set system requirements to a SHM system. Like explained in the discussion, there are several points of improvement for the framework. Therefore, several recommendations for further research will be advised.

Firstly, more research can be done to improve the criteria ease to use and understandable and completeness of the specification method. Several experts explained that the specification method that is described in chapter 5 takes a lot of time. Although the development of a key driver diagram can explain to the asset manager why specific system requirements are defined, the experts stated that they think that it is not always required to develop such a comprehensive diagram. More research should be done to find a quicker method for this process. The developed generic key driver diagram can be used as starting point, to have an idea about what system requirements could be set and to what goals the SHM system should contribute.

Secondly, more research can be done to elaborate or adapt the generic key driver diagram. The research is currently executed with only twelve experts. Increasing the number of interviews can result that an overview of more system requirements will be developed. When the generic key driver diagram includes more system requirements, asset manager have a more complete insight which system requirements can be set to the SHM system. Additional interviews could also change the way that goals, sub-goals and system requirements are structured and formulated. During the validation, the experts explained that different people can have different ideas about this should be done. Executing more interviews can increase the support of the structuring and formulating.

Thirdly, additional research can be done to the comparison of different SHM systems in a project. In this research, different system requirements are presented that give an indication if a SHM system is suited for a project. However, the research does not present how an asset manager should evaluate which SHM system is more suitable for his project. This can help the asset manager in making an underpinned decision with selection a SHM system from different market parties.

Fourthly, more research can do about how the asset manager could use a specification for the tendering of a SHM system. Experts stated during the validation session that there can be different ways of tendering a SHM system. Sometimes SHM systems will be tendered in combination with other analyses or inspections. Next to that, the experts doubt if it is required to have such a detailed specification in the tender phase, because it declines the design freedom from the market.

Fifthly, additional research should be executed how SHM should be included in the maintenance policy of the SHM system. The focus should be on the collaboration between SHM and other analyses and inspections. What is noticed during the expert interviews is that asset managers see SHM as a replacement of current analyses / inspections, but it might be better to integrate SHM in the current approach.

9 References

Ahmadi-Echendu, J. E., Brown, K., Willet, R., & Mathew, J. (2010). *Definitions, concepts and scope of engineering asset management*.

Aktan, A., Catbas, F., Grimmelsman, K., & Pervizpour, M. (2002). Development of a model health monitoring guide for major bridges. *Highway Administration Research and Development*, (June), 2002. Retrieved from http://www.di3.drexel.edu/DI3/Events/SAMCO03/4 EXE Sum of FHWA HM Model Guide.pdf

Antea Group. (2019). About us. Retrieved June 16, 2019, from https://www.anteagroup.nl/nl/artikel/over-ons-0

Beecham, S., Hall, T., Britton, C., Cottee, M., & Rainer, A. (2005). Using an expert panel to validate a requirements process improvement model, *76*, 251–275. https://doi.org/10.1016/j.jss.2004.06.004

Braam, C. R., & Lagendijk, P. (2011). *Constructieleer gewapend beton* (Seventh).

Chang, F. k. (1999). What is Structural Health Monitoring? *CRC Press*, 1062.

Custeau, K. (2015). Making enterprise asset performance management work for your plant. Retrieved February 28, 2020, from https://www.plantservices.com/articles/2015/making-enterprise-asset-performance-management-work-for-your-plant/

Dalia, Z., Bagchi, S., Sabamehr, A., Bagchi, A., & Bhowmick, A. (2018). LIFE CYCLE COST-BENEFIT ANALYSIS OF SHM OF I-35 W ST . Anthony falls bridge, (October).

Deventer, G. (2015). Eisenboom voor civiele kunstwerken Gemeente Deventer Opdrachtgever Eisenspecificatie Auteur (s).

Dick, J., Hull, E., & Jackson, K. (2017). *Requirements engineering* (Fourth). Springer.

Dong, Y., Song, R., & Liu, H. (2010). Bridges Structural Health Monitoring and Deterioration Detection-Synthesis of Knowledge and Technology. *Final Report. Fairbanks*, (December), 1–182. https://doi.org/10.1038/srep20054

Gastineau, A., Johnson, T., & Schultz, A. (2009). Bridge Health Monitoring and Inspections Systems - A Survey of Methods.

IAM. (2015). Asset Management – an anatomy Asset Management – an Anatomy, (December), 1–84.

ISIS. (2013). *Guidelines for Structural Health Monitoring*. *Handbook of Technical Diagnostics*. https://doi.org/10.1007/978-3-642-25850-3_27

Johnson, R. B. (1997). Examining the validity structure of qualitative research. *Education*, *118*(2), 282. https://doi.org/Retrieved from http://www.nova.edu/ssss/QR/QR4-3/winter.html

Kerkhof, R. M. van de, Lamper, L., & Fang, F. (2018). Maintenance voor de Nederlandse Infrastructuur.

Lantsoght, E. O. L. (2018). *Field assessment of a concrete bridge*. *Eco-efficient Repair and Rehabilitation of Concrete Infrastructures*. https://doi.org/10.1016/B978-0-08-102181-1.00009-5

Lapouchnian, A. (2013). Goal-Oriented Requirements Engineering : An Overview of the Current Research Goal-Oriented Requirements Engineering : An Overview of the Current Research by Alexei Lapouchnian Department of Computer Science, (December).

Lipol, L. S., & Haq, J. (2011). Risk analysis method : FMEA / FMECA in the organizations. *International Journal of Basic & Applied Sciences*, *11*(5), 1–9. Retrieved from https://pdfs.semanticscholar.org/c933/f98700fa61900d6f42a86df98c268740c490.pdf

Muller, G. J., Somers, L., Yuan, Z., & Heemels, W. P. M. H. (2006). The key driver method, 27–42.

Paulissen, J. H., Es, S. H. J. Van, & Peelen, W. H. A. (2019). Information requirements for effective management of an ageing transport network, 1671–1677.

Rijkswaterstaat. (2007). Inventarisatie kunstwerken, (september), 32. Retrieved from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/kamerstukken/2007/10/03/br-53977-bijlage-1-inventarisatie-kunstwerken/br-53977-bijlage-1.pdf

Rijkswaterstaat. (2013). Richtlijnen Beoordeling Kunstwerken.

Rijkswaterstaat. (2019). Bridges Rijkswaterstaat. Retrieved June 5, 2019, from https://www.rijkswaterstaat.nl/wegen/wegbeheer/bruggen/veelgestelde-vragen.aspx

SAMCO. (2006). SAMCO Final Report 2006, 1–54. Retrieved from www.samco.org%5Cnwww.isiscanada.com

SBR-CUR. (2015). *CUR aanbeveling 117: Inspectie en advies kunstwerken*.

Soen, H. H. M. (2007). *Praktische betonkennis* (First). Cement&Beton centrum.

The University of North Carolina. (2011). Measurements and Error Analysis. *College Physics Labs Mechanics*. Retrieved from http://www.webassign.net/question_assets/unccolphysmechl1/measurements/manual.html

Vardanega, P. J., Webb, G. T., Fidler, P. R. A., & Middleton, C. R. (2016). Bridge monitoring. https://doi.org/10.1016/B978-0-12-800058-8.00029-3

Verlaan, J. (2019). Onvoldoende geld voor renovatie bruggen en sporen. *NRC*. Retrieved from https://www.nrc.nl/nieuws/2019/05/28/onvoldoende-geld-voor-grootste-vervangings-en-renovatieopgave-in-de-geschiedenis-a3961823

Vesterinen, A., & Andersen, J. E. (2006). Structural Health Monitoring Systems, 1–128.

Wang, M. L., Lynch, J. P., Sohn, H., & Advanced, K. (2014). *Introduction to sensing for structural performance assessment and health monitoring*.

Webb, G. (2014). *Structural health monitoring of bridges*.

Wenzel, H. (2019). *Health Monitoring of bridges*.

Wijnia, Y., & Herder, P. M. (2009). The state of asset management in the Netherlands, (January), 0–9. https://doi.org/10.1007/978-0-85729-320-6

Appendix A: Data from literature review for first version key driver diagram

In this appendix is presented how SHM system can be beneficial for asset managers, according to the literature. This literature study is executed as starting point for the development of generic key driver diagram. This data is validated and elaborated during the expert interviews.

Objectives of SHM

According to Vardanega et al (2016) the objective of an asset manager is that the bridge functions with maximum performance at minimum costs. The function of a bridge is to make it possible for traffic to cross a waterway in a safe and comfortable way(Deventer, 2015). The SHM system should contribute to this function. Samco (2006) also defines the key benefits of SHM for infrastructure as the decreased ongoing inspection and maintenance and rehabilitation costs, increased structural safety and an improved understanding of the behaviour and durability of the monitored structure. More specific benefits of SHM are(SAMCO, 2006):

- Improved understand of in-situ structural behaviour; the behaviour of a bridge is currently often modelled. However, the results of a model do not always match with reality. SHM can provide a wealth of information on how real structures behave when subjected to actual structural and environmental loads.

- Early damage detection; Damage can be detected earlier with the use of SHM. Early detection of structural damage can ensure that asset managers can prevent the structure from having to sustain loads for an extended period while in a damaged state. Furthermore, early damage detection can make sure that damage can be repaired before it drastically worsened. This can save in maintenance costs. Furthermore, costs can be saved by the decrease of site visits and manual investigations by maintenance workers.

- Assurances of a structure’s strength and serviceability; For long span bridges, it might be impossible or inadequate for determining a bridge’s safety with visual inspection. The SHM can then be used for the inspection of the structure. Furthermore, when the bridge is nearing the end of its service life, SHM can be used for providing confidence of its satisfactory performance.

- Reduction in down time; Down time is defined as the time that a bridge cannot fulfil its function. Down time can be caused during structural repair or upgrade works. This led to high social costs that are hard to quantify. Early damage detection and an improved understanding of structural behaviour result in a reduction in down time for structures which may require repair or strengthening.

- Improved maintenance and management strategies for better allocation of resources; SHM systems reduce the requirement for field inspection and enable the development of large-scale infrastructure condition databases which can be automatically updated. Decision makers can formulate better strategies to effectively deal with infrastructure deterioration and allocate shrinking budgets and scarce resources more efficiently.

SHM can be beneficial by providing information about the issues like the serviceability, safety and durability of a structure. According to ISIS (2013), SHM can contribute to(ISIS, 2013):

- real-time monitoring and reporting
- reducing time
- improving safety and reliability, while reducing maintenance costs

Categories of SHM projects

Different categories of SHM projects can be identified (Webb, 2014). Webb (2014) distinguished the following five classes:

- **Sensor deployment studies**: SHM systems are used to demonstrate new sensor or communication technologies
- **Anomaly detection**: SHM systems used to detect that something has changed, or that something is changing over time
- **Model validation**: SHM systems used to compare the performance of a structure with the performance that is predicted by structural analysis models
- **Threshold check**: SHM systems that compare key parameters against thresholds which are usually derived from a structural model to warn of potential problems
- **Damage detection**: SHM systems that aim to detect and locate damage using advanced techniques such as structural identification and modal analysis

According to Webb (2014), sensor deployment studies and anomaly detection do not have direct relevance for an asset manager. While model validation is of moderate relevance and threshold check and damage detection are of big relevance. There should be mentioned that damage detection and threshold system can become complex. Within the category 'damage detection' four levels can be distinguished. This is also presented in Figure 11. The following levels are(SAMCO, 2006):

- Level 1: the SHM system can detect damage in a structure, but the location of the severity of the damage is not identified.
- Level 2: This is more sophisticated as level 1. In this level the location of the damage is also provided.
- Level 3: In this level damage can be detected and pinpointed and can provide an indication of its severity.
- Level 4: This is the most sophisticated level and can provide detailed information on the presence, location, severity of the damage and it is able to use this information to evaluate the safety of the structural system.

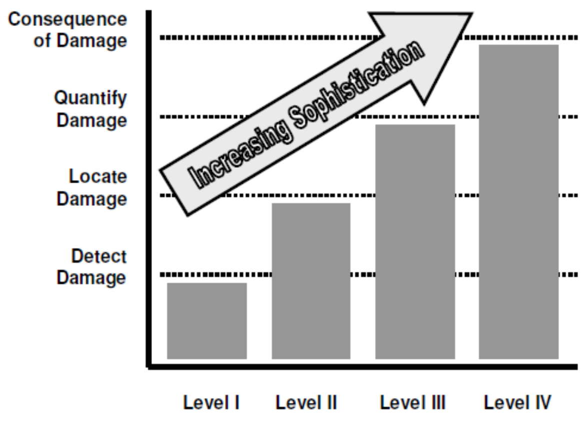


Figure 22 Classification of SHM systems for damage detection(SAMCO, 2006)

Components of structural health monitoring

Structural Health Monitoring systems can come in different forms. However, In general a structural health monitoring system consists out of the following components: sensing modules, portable and/or fixed data acquisition system, data communication system, data processing and control system, user interface, maintenance tools and interface to external systems (Vesterinen & Andersen, 2006). These components are described briefly in the following sections.

Sensing modules
Sensing modules or sensors are important components in the structural health monitoring system. A sensor interacts with the bridge/material to sense the physical process. This physical process will be converted into a detectable signal form (e.g., an electrical voltage). A property of sensors is that they convert kinematic, kinetic, or thermal information to a measurable and controllable quantity, such as a voltage or current. The voltage or current are then processed, either in hardware or software, to obtain information that supports decision-making (Wang, Lynch, Sohn, & Advanced, 2014). There are many different sensors available for SHM systems, that can almost measure any conceivable parameter. In addition, research are still developing and improving the sensing techniques to get more reliable, accurate and cost-effectiveness measurements(Aktan, Catbas, Grimmelsman, & Pervizpour, 2002). Sensors can be divided in sensors which concentrate on the monitoring of local properties like material and in sensors that look at the entire structure. Some sensors are included in the structure and others are placed on the surface of the structure. Deformation, strain, force, weight, dynamic parameters, temperature and durability parameters are most measured.'

The output of a sensor is in common electrical (voltage, current, etc.) or mechanical energy. This can be in the form of an analog or digital signal. An analog signal is continuous in both magnitude and temporal (time) or spatial (space) content. Digital signals provide a discrete representation of the measurand. Analog sensor cannot be read, analysed or stored by a computer. Therefore, a DAU needs to convert it to a digital form.

Data acquisition system
The data acquisition system collects, processes and transmits some physical principle and generates information. The sensing module is part of the total data acquisition system. The acquired information is used for analysis and interpretation. In the Figure 4, a schematic overview is presented of this phenomenon. Sensors measure a physical variable and translate this in an analog or digital signal. Like described before one of the tasks of the data acquisition unit (DAU) is to convert the data in the right format.

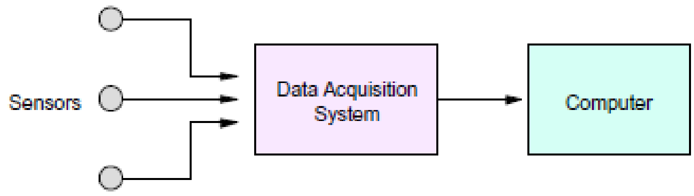


Figure 23 Schematic overview of a data acquisition system (Vesterinen & Andersen, 2006)

Data acquisition systems have in general three components (Vesterinen & Andersen, 2006):

- Data acquisition hardware: this consists of number of electronic components that collect, condition, covert and transmit sensor signal to the computer. Most of the times the following components are available: signal conditioner, analog-to-digital converter, controlling circuitry, memory, communications interface or device and power supply.
- Data acquisition peripherals: this includes cables, terminal blocks and connectors, enclosures and junction boxes to physically connect the sensors to the data acquisition hardware and to protect components from exposures to the elements.
- Data acquisition software: this enables the user to communicate and manipulate the data that is gathered. Driver software and application software are the two general types of software that are required. Driver software facilitates communication between the data acquisition hardware, the computer and the application software. The application software is the link between the user and the data acquisition system.

Data communication
The sensing/acquisition/digitization components can be physically separated or all-in-one. The architecture design of the SHM components and the selection of the components are site specific. The layout is often based on aspects like the size of the infrastructure, modality and dimension of required information, accessibility, and expected lifespan of the monitoring system. The component selection step follows from the layout requirements and is based on parameters such as cost and redundancy.

Data processing and control system
The master screen of the SHM system is developed for the SHM system operator. The master screen can be displayed in different ways, but it should have three functions:

- Provide overall control of the DAU's regarding data acquisition and processing, data transmission and filing control, data archiving and backup and all display and operational control.;
- Post processing and analysis of the collected data
- Generation of instant monitoring reports

SHM system can differ in size. Big systems with many sensors and permanently monitoring can lead to big amount of data that should be processed and stored. Humans do not have the capability to process this data and therefore statistical pattern recognition methodologies need to be introduced into the procedure(Wenzel, 2019). The procedure scrutinizes the incoming data and informs the operator of unusual events, but it will only be as good as the specification of what is meant by unusual. It is therefore necessary to keep the raw data in order to allow reassessment after improvement of the methodology (Wenzel, 2019)It depends on the purpose of the monitoring system strategy what data should be stored. It is possible to store (Webb, 2014):

- <u>No data</u>; For small monitoring systems only support the user safety of the bridge, there can be decide only to save alarms and warnings when a threshold values is passed.
- <u>Ad hoc reports aperiodic / periodic</u>**;** This presents only the results of the analysis of the data.
- <u>Statistical data</u>**:** when it is not certain what information is required in the expected lifetime, it can be useful to store the statistical data.
- <u>All raw data</u>**;** especially in complete innovative projects it might be useful to collect the raw data. Later, can be decided what should be done with this data.

Presentation and decision criteria
The structural health monitoring system is also responsible for the presentation of the data. This can be done on a local workstation, but also on a universal standard based web interface. The data that is measured should be presented in order to make subsequent decisions. A monitoring system should only present the data that is meaningful and easy to understand. Next to the presentation of the results of the measurements, the system should also give an indication of the status of the SHM system itself. The end user of the system should be involved in determining what is displayed and what is not. Alarms can also be part of the presentation of data. An alarm should indicate that some behaviour has exceeded a value.

Maintenance tools
It is important to make sure that the SHM system can be inspected and maintained during its lifetime. There should be looked how the sensors, DAU's, cables etc. can be accessed.

SHM systems interfaces
It can be possible that the SHM system interacts with other management and control system software. This can be used for an overall management of tasks and events related to operation and maintenance

of the bridge. It is also possible to exchange information between the bridge operator for connected highways, railways and the authorities. In common, this interaction will be provided via the control room and not directly.

What can be monitored?

In this research, the focus is on concrete bridges. Therefore, monitor metrics of for example steel or masonry are not included. This section is included to present what is possible to measure and what is not. There should be noted that SHM is a fast-developing industry and new techniques are developed quickly.

Table 4 Measurands and their need to measure (Gastineau et al., 2009)

What?	How can it be used?
Load	Using this data, engineers can determine if the loads on a structure are as expected, or if it is subjected to greater (perhaps damaging or dangerous) loads. SHM can also be used to learn how the various loads are distributed within and supported by the structure. Loads can be static or dynamic.
Deformation	Excessive deformation, or deformation in unexpected places, might signal deterioration or changes in structural condition and can be used to assess the need for rehabilitation or upgrade.
Strain	Strain is a measure of the intensity of deformation of a structural component. Strains can be used to gain a wealth of information about the behaviour and ongoing performance of a structure;
Temperature	Changes in temperature cause materials to expand or contract because of thermal expansion. Repeated cycles of heating and cooling can cause damage to structures through repeated cycles of deformation or thermally induced loads. By incorporating temperature measurements, an SHM system can provide information on how temperature changes affect a structure, and whether the temperature-induced loads and strains are as expected. Temperature may also affect the readings of certain sensors or sensing equipment used in SHM systems.
Acceleration	SHM can be used to determine exactly how a structure is responding to accelerations and the resulting loads via determination of the modal response parameters.
Wind Speeds and Pressures	For tall buildings and long-span bridges, wind can be a governing design criterion and should be recorded at various locations in an SHM system.
Curvature	This is the rate of change of slope along the length of a flexural member and produced by transverse loading (i.e., normal to the longitudinal axis).
Displacements	the overall linear movement (i.e., translation) of a bridge either in relation to its original position or on a global scale
Scour	the removal of soil around the piers of bridges due to fast moving water currents during flooding. Removal of soil can lead to instability of piers.
Corrosion	It is possible to determine whether the steel reinforcement embedded in concrete is at risk of depletion from attack of chloride or carbon dioxide. Some corrosion monitoring techniques determine the probability of corrosion occurring, while others determine the approximate corrosion rate.
Cracking	Cracks of concrete surfaces can be characterized by the width, length and the amount. Small-scale cracking (i.e., few, short, narrow cracks) is expected to take place in all concrete; however wider, longer and/or more cracks are not expected and can influence the safety of a structure.
Location of rebar / delamination	The location of reinforcement in concrete structures can be used to identify if concrete delaminate above or below the reinforcement.

Tension (in rebar / tendons)	In post-tensioned systems, the tension in the cables is important to the overall strength of the concrete structure. Also, if delamination occurs in reinforced concrete, the concrete cannot transfer forces to the rebar causing a reduction in stress. Thus, tension measurements can be used to assess the overall health of the structure.
Environmental parameters	Other environmental parameters, like humidity can also be measured. These values can be used to find influences of this parameters on other measurements.

Design process SHM system

Inaudi (2016) developed a seven-step process to design a monitoring process. This process consists of the following steps:

1. **Identify structures needing monitoring**

Inaudi (2016) presented six categories of structures that needs monitoring. Since this research focusses on aging bridges the following categories are relevant:

- Structures that are critical at a network level, since their failure or deficiency would have serious impact on the rest of the network
- Structures which is representative of a larger population of identical or similar structure. Information might be extrapolated to other structures
- Existing structures with known deficiencies or very low rating results from visual inspection
- Candidate for replacement or major refurbishment works. SHM can be used to identify the real need such action.

2. **Risk / Uncertainty / Opportunity analysis**

According to Inaudi (2016), the SHM operator and engineers are responsible for the structural assessment, but the owner should identify the risks, uncertainties and opportunity he wants to investigate. Risks are possible events and degradations that can possibly affect the structure, for example: corrosion and loss of pre-stressing. Uncertainties refer to unanswered questions about the structural conditions and performances, for example the performance of construction materials. Opportunities refer to parameters and performance indicators that might be better than expected or assumed for example better properties of structural materials or bearing capacity.

3. **Responses**

For each risk, uncertainty and opportunity should be considered what the corresponding response is. This response should then be measured. For example, corrosion will produce a chemical change, but also a section loss. These parameters can be measured.

4. **Design SHM system and select appropriate sensors**

Now, a system should be developed that measure the expected responses and suit in the environment where it should function. Aspects that should be considered in this stage are amongst others: budget, redundancy and complementary. These different aspects should be balanced. The result of this step is a design document, that includes a list of sensors, installation and cable plans, installation procedure and schedule as well as a budget.

5. **Installation and calibration**

It is important that the system is installed and calibrated in the right way, such that the measurements are more reliable. The installation and calibration should be conducted with care.

6. **Data acquisition and management**

When the SHM system operated, data should be acquired and stored in a database. Aspects to keep in mind are appropriate backup and access authorization. Documents of interventions should also be stored, to explain change in data.

7. Data assessment

This is the most important and complex step. By analysing the responses of the structure, it is required to identify any of the foreseen risks or degradations. The asset manager should be able to respond on the analysis. This can be different. The results can be placed in a yearly report, but it is also possible that the asset manager directly decide to close the bridge.

Costs and benefits of SHM system

Life cycle cost analysis (LCCA) is a method to derive all costs over the lifetime in order to compare different various alternatives directly. So, not only the initial costs are considered but also the costs over the entire service life, this includes for a bridge typically maintenance, major rehabilitation, component or element replacement and user costs. The costs of SHM self can also be divided in initial costs (capital investment) and operational costs. The following costs can be distinguished(Dalia, Bagchi, Sabamehr, Bagchi, & Bhowmick, 2018):

- Capital investment
  - SHM design costs, including integration with structure
  - Hardware costs, i.e. sensors, data loggers, data management hardware, communication hardware
  - Installation costs
  - Costs for as-built documentation and system manuals

- Operational costs
  - System maintenance, spare parts, consumables, energy, communication costs
  - Data management costs
  - Data analysis, interpretation and reporting costs

Benefits can be divided in two categories: hard benefits and soft benefits(Dalia et al., 2018). Hard benefits can be expressed in economic value, while soft cannot. An example of a hard benefits is cost saving due to postponed maintenance. Soft benefits cannot be quantified directly, but the asset manager is willing to pay a price for it. Examples are reduction of perceived risk, better image and adherence to standards.

Properties sensors

An important component of the SHM system are the sensors, which measure properties of the bridge. For the selection of the right sensor, there are three general categories of characteristics that should be considered: sensor performance characteristics, environmental constraints and economic considerations.

- Sensor performance characteristics; This describes the way a sensor behaves under typical use conditions; Sub criteria are:
  - Sensitivity
  - Resolution
  - Discrimination
  - Range
  - Linearity
  - Hysteresis
  - Accuracy

- Repeatability
- Stability
- Response time
- Frequency response

- Environmental constraints; these constraints should be considered to make sure that the sensor works in the environment; The following aspects are often considered;
    - Temperature range
    - Humidity range
    - Size
    - Packaging
    - Isolation
    - Thermal effects
- Economic considerations; the economic criteria to select a specific sensor are:
    - Costs of sensor
    - Availability of the sensor on the market
    - Ease of installation
    - Associated data acquisition needs

Uncertainty in measurements

There is always uncertainty in measurements. Every measurement has some amount of uncertainty in it. These uncertainties can have different sources. It is important to have an estimate about the uncertainty in your measurements, otherwise it is hard to make judgements on your results(The University of North Carolina, 2011).

Measurement = (best estimate +/- uncertainty) units

There are two types of errors: random errors and systematic errors. The different types are described briefly and different sources for those errors are presented(The University of North Carolina, 2011). Some errors can be random and systematic.

- Systematic error are reproducible inaccuracies that are consistently in the same direction. These errors are difficult to detect and cannot be solved by using statistics.
    - <u>Incomplete definition</u>: it is not clear what should be measured precisely. Therefore, two people can measure different values
    - <u>Environmental factors</u>: The measurements are influenced by aspects from the environment, like vibrations, change in temperature etc.
    - <u>Calibration</u>: the sensor should be compared with a known accurate value. Calibration errors are usually linear
    - <u>Zero offset</u>: When a relative value is measured it is important that the zero-offset is correct. Otherwise, you will always have a value that is too high or low
    - <u>Instrument drift</u>: the reading of the most electronic instruments drift over time.
    - <u>Lag time</u>; Sometimes measuring devices require time to reach an equilibrium
    - <u>Hysteresis</u>; An instrument readings lag and there is still influence from an occasion a moment back.
    - <u>Personnel errors</u>; these are

- Random errors are statistical fluctuations in the measured data due to the precision limitations of the measurement devices.
    - Incomplete definition, environmental factors and personnel errors can be systematic and random;

- Instrument resolution; all measurements have a finite number of precisions.
- Physical variations;

Appendix B: Interview protocol

The experts that were interviewed were selected based on their knowledge domain. The knowledge domains that were used are: asset managers, structural engineers, visual inspectors and SHM system operators. Twelve experts were interviewed: one general expert, three asset managers, three structural engineers, two visual inspectors, three SHM system operators. The interviews were semi-structured. A list of fixed questions was prepared to gather the required information. When required follow questions were asked to clarify and answer or to elaborate an answer. The interviewee consists of three parts: questions about the current maintenance and control approach, questions about the risks of concrete bridges and questions about goals, sub goals and requirements of SHM systems.

There was paid attention to the following aspects:

- Start with warm-up questions (questions that are easy to answer), such that the interviewee feels more comfortable.
- There is furthermore started with open end questions, so it is possible to form some impression about the overall situation. For example: How are concrete bridges controlled and maintained in the Netherlands? Later, more specific questions about the maintenance and control of concrete bridge were asked. During the interviews, notes were made to make sure that new subjects could be clarified.
- When there were doubts if the interviewee was understood correctly, the answer was summarized shortly and asked if this was what they meant.

The interview questions were not the same for every expert. The questions depended on the knowledge domain of the expert and the gathered information from previous interviews. Information from previous interviews was verified or elaborated on in next interviews. The interview protocol is presented in Table B1. The interview of Structural Engineer 1 is taken as example.

Table B1: Interview protocol

Phase	Activity	Description
Introduction	Introduce yourself and objective of research	• Introduce yourself and your study • Introduce the concept of SHM • Present the objective of the research
	Introduce Objective of interviewee	• Present what you expect from the interviewee. • Example Structural Engineer: "The objective of this interview is (1) to get an overview of the current maintenance and control policy of concrete bridges in the Netherlands, (2) to get an overview of the damages and risks of concrete bridges in the Netherlands and (3) to identify how SHM systems can benefit to the objective of the asset manager and understand what the role of structural engineers is in this process."
	Confidentially statement	Explain that the results cannot be traced back to the expert and there will be referred to him as "Structural engineer 1" in the report.
	Ask permission to record	Explain that you want to record the interviewee, such that you can use the record for elaborating the results. Ask if they allow this. The findings of the interview will be summarized and send back to the interviewee for verification.

	Explain time limit	The interview will take approximately 1 hour and 30 minutes
	Ask for introduction of interviewee	Ask the interviewee to introduce himself (including experiences)
Questions	Questions about current maintenance and control policy of asset owners	<u>Examples of fixed questions</u> • How is the safety of a concrete bridge guaranteed in the current approach (without SHM systems)? • What is the role of structural engineers in the safety provision of the Netherlands? • Explanation of different inspections and analyses. Questions to reason for execution, input and result of activity. • Questions about differences in policies between asset managers Follow up questions can be asked to clarify or elaborate answers
	Questions about damages and risks of concrete bridges	<u>Examples of fixed questions:</u> • When should a bridge be maintained? • What are the biggest risks of a concrete bridge? • What are smaller risks of a concrete bridge? • What damages can occur on a concrete bridge? • How do the risks / damages differ per type of concrete bridge? • What is the result of a risk / damage? Follow up questions can be asked to clarify or elaborate answers
	Questions about possibilities of SHM systems for asset managers	This part is used to develop the key driver diagram. Many how- and why-questions are asked. There is often asked how and why a driver or system requirements is set. <u>Examples of fixed questions:</u> • When should you decide to use SHM system for a concrete bridge? • How can SHM systems benefit to the safety / availability and life cycle costs to the bridge? • Why do you want to validate your structural model? How can you validate your structural questions? <u>Follow-up question:</u> • When the interviewee gives a (sub)goal or system requirement there will be asked why he wants this and how he wants to achieve it?
Scenarios	Scenario based reasoning	Scenarios when SHM can be beneficial (based on previous interviews) are presented to the interviewee. Pictures of a specific type of concrete bridge are presented to explain the context. Example: The asset manager wants to identify the cause of a crack with SHM systems. The following answers were asked: • Do you recommend this to the asset manager? Why/ why not? • How could SHM systems be beneficial during this analysis?

		• Who should install the SHM system? • How should the SHM system be installed? • What are the advantages of using SHM systems over normal visual inspection? • What should be measured by the SHM system? • How should this be measured? • What should be the result of the SHM system? • What will be done with the results? • How can you identify the result based on the gathered data? • What requirements do you set to the result? • Who should work with the output? • Wat should he do with the output • When is the SHM system a success? • What results should be stored? How well? • How should the results be stored? • How do you make sure that the results can be used later by other people? A picture of another concrete bridge was presented afterwards. There was asked what changes in the new situation. The pictures are presented on the next pages.
Feedback on previous key driver diagram	Asking for feedback on previous key driver diagram	• Present the key driver diagram • Explain the graph • Asks if the interviewee agrees with the links, should adapt or add goals or system requirements and agrees with the required knowledge domains

Figure 24 Example scenario: Concrete bridge in Amsterdam

Figure 25 Example scenario Cortenoeversebrug N348 Zutphen

Figure 26 Example scenario Pijlebrug N371 Diever

Appendix C: Interviews

In this appendix, the summaries of the conducted interviews are presented. The following experts were interviewed:

- General Expert 1
- SHM and data specialist 1
- Asset manager 1
- Structural Engineer 1
- Visual inspector 1
- Asset manager 2
- SHM / data specialist 2
- Structural engineer 2
- SHM / data specialist 3
- Structural engineer 3
- Visual inspector 2
- Asset manager 3

Expert 1: General expert 1

General expert 1 is working for TNO. He focusses currently on smart infrastructures. The objective of TNO is to increase the innovation-rate of governments and market parties. They help the government with writing norms, develop and apply knowledge for questions that clients have. Furthermore, they help developing different sensor technologies, i.e. Optic fibres and acoustic techniques.

Findings:

- According to general expert 1, there is a transition going on, from conservative norm-driven infrastructure to more specific norms. Norms often includes high safety margins for bridges. Nowadays, several problems occur with bridges which does not meet the norms anymore. This does not mean that these bridges are unsafe. The norms are created for the total amount of bridges. If you look for case-specific project, it can happen that the bridge is still safe. There is a difference between the assessment of a model-bridge safety and real safety. The model includes a lot of safety factors to cover the uncertainties in the calculations. The actual bridge is, therefore, stronger than calculated. Therefore, it is useful to measure the actual performance of a bridge.

- General expert 1 states that asset managers are not always able to identify what they want to measure and that is not a bad thing. According to General expert 1, it is better that the governments focus on the maintenance policy. How do they want to manage their assets? This leads to information need. Asset managers should focus on the end-of-life and the physical condition of their assets. They need market parties and knowledge organizations to determine KPI's that should give insight in the performance of the bridge. Part of this KPI identification can be done with sensors.

- General expert 1 distinguishes two classes: infrastructure with no concerns and infrastructure with concerns. Bridges with no concerns are bridges that meet the requirements of the NEN 8700.

  - When the bridge is safe according to this norm, you should only look at the deterioration of the bridge and load increases. If you keep track of those factors and they do not change a lot, then the bridge stays safe. You should only look at the durability of the bridge. This is currently done by visual inspections, but it can be useful to use other techniques, for example with video footage where you can determine the cracks and the size of cracks. Getting more information about the durability phase is worth the effort. Costs can be saved, and the quality of the maintenance policy can be increased.
  - There are no unsafe bridges, because these will be closed. But there are bridges that does not pass the first safety tests. You can do two things. First, it is possible to evaluate the norms. The norms are conservative and are applicable for the total population of bridges but should be applied for one bridge. If you look at one specific bridge, the norms can be adapted. TNO does this regularly. The norms are applied on the specific bridge and this means that some safety margins can be decreased. It is also possible to use measurement data to decrease uncertainty and therefore the safety factor. This can result in the fact that the bridge does meet the safety norms, finally. This is normal in the Netherlands.

- Monitoring projects are currently one-of projects. Unless, visual inspections are also labelled as monitoring projects. There is collaboration between different visual inspections.

- General expert 1 states that the most important thing is that the asset managers get the right information. Information is something different as measurement data. Measurement data are Key Performance Indicators (KPI's). If he has the right KPI's, the asset manager should know what he wants to do with it, how he should use it and what the result of the monitor project will be. That is the role of the asset manager. In the specification, he should ask for information. For example: what is the rest life of the bridge? If this is too hard, he should ask for more specific information.,

- General expert 1 states that it is not durable to have a detailed specification for a SHM system, especially if you want to use more monitoring-systems in the future. However, this is the current practice. The KPI's are requested sometimes with three number after the decimal point. The information that you request should be linked to your maintenance processes.

Expert 2: SHM / data specialist 1

SHM / data specialist 1 works for a company that makes software services for the architecture, engineering, construction, manufacturing, media, education, and entertainment industries.

Findings:

- SHM / data specialist 1 explains that sensors are currently placed for a longer period on infrastructure assets. Sensors have been placed on bridges for a longer period, but the difference is that the whole lifecycle of the asset is not assessed often. SHM / data specialist 1 explains that long term SHM brings new challenges. The system should be able to stay on the structure.

- SHM / data specialist 1 explains that the storage of data is not really a problem anymore. Data can easily be stored in a cloud. Data can be stored for a long time. It is hard to predict what the total costs of saving the data in the long term is.

- SHM / data specialist 1 states that data can be valuable as a commodity. You can learn from the behaviour of the structure. The data should not be filtered too much, because you can learn from it. Even the noise in the signal can say something. That is why most projects are research projects.

- SHM / data specialist 1 explains that damages are hard to measure. Damages often occur in the last phase of the life span of the bridge. Furthermore, damages can occur very locally.

- SHM / data specialist 1 states that data is only valuable if it is processed in the right way. So, you must prove the possible benefits for the asset manager.

- SHM / data specialist 1 states that SHM projects are often initiated because asset managers do not agree with the building code. Sometimes the code is too conservative and sometimes not enough. Too codes can be too generalized. Many assumptions are included in the code.

Expert 3: Asset manager 1

Asset manager 1 works for Rijkswaterstaat. He is responsible for the tendering of big maintenance projects. His department works with the challenge of the replacement of big infrastructural projects in the coming decades. Their first task is to predict what kind of maintenance can be expected in the coming decades and how much budget should become available. Furthermore, there should be made an inventory about the expected actions the coming years based on inspections. Big maintenance decisions are not made by them but by the policy makers. This department only advises the policy makers.

Findings in interview:

- Rijkswaterstaat consists of different divisions that have their own responsibilities:
  - Department “Centrale informatie voorziening”(English: Central information facility) is responsible for the ICT services
  - Department “Project programma’s en onderhoud’ (English: Project programming and maintenance) is responsible for regular maintenance of infrastructures and often works with performance-related contracts.
  - Department “Grote projecten en onderhoud’ (English: Big project and maintenance) is responsible for the bigger maintenance contracts.
- Risks are determined based on Failure Mode, Effects & Criticality Analysis (FMECA). FMECA is a methodology designed to identify potential failure modes for a product or process before the problems occur, to assess the risk(Lipol & Haq, 2011). First a desk study about the object is conducted. Then visual inspections are conducted and if required more specified research will be done to the object. Control measures are determined based on this analysis. This can mean recalculation of the bridge or more detailed research.
- Most important risk of concrete bridges are caused by shear forces, because this can lead to brittle collapse. Before 1976, there were less strict standards about shear stresses. Less reinforcement was placed in the bridge in comparison with the newer bridges. This can lead

that these bridges do not meet the current standards anymore. Especially with the increasing traffic loads.

- Overloading by bending is also a risk for concrete bridges. However, this does not occur very often.
- Asset manager 1 states that concrete does not deteriorate very fast. Therefore, it is not necessary to assess concrete frequently.
- Asset manager 1 explains that fatigue is of less importance for concrete bridges. For steel bridges it more beneficial to measure.
- Big maintenance decisions (including prioritizing) are made by policy makers and are especially based on:
  - Structural condition of the bridge
  - Costs
  - Disturbances to the road user
  - Safety
  - What can still be done with the structure
  - What do we want in the future?
  - Other activities in the environment

  The results of SHM activities can be used as input for the maintenance decision making.

- Asset manager 1 explains that the measurement of loads is of most interest for Rijkswaterstaat. This is not only done on bridges, but also on other parts of the road network. Loads do not only say something about the safety of the bridge, but also about traffic patterns.

- According to Asset manager 1, Rijkswaterstaat is also interested in SHM that can be used to replace visual inspections. Advantages for the asset manager to use SHM instead of visual inspections are:
  - Objective information
  - Continuous information
  - Reduce costs and hindrance by visual inspection
  - Possible earlier detection of damage
  - Come to places where humans cannot come

- According to Asset manager 1, disadvantages of using SHM systems instead of visual inspection is that you look at a specific location, while visual inspection are used to have an overall indication of the condition of the bridge, detect damage and possible risks that need further identification.
- For Rijkswaterstaat it is hard to work with monitoring systems with a threshold, because the asset managers do not know what the reason of the alarms are and how to deal with these alarms. Next to this, too strict safety threshold causes that there is often a false alarm, which can lead that the asset manager can be less attentive when it is necessary. The policy makers do not have the knowledge to deal with alarms. They can be falsely worried or reassured.

- According to Asset manager 1, model validation is of big interest for Rijkswaterstaat. Rijkswaterstaat really likes to know if the assumptions that they made are correct. Is the bridge really, as strong as they expect? Furthermore, it is beneficial to check if the bridge is stronger than expected, such that strengthening, rehabilitation or replacement can be postponed. This can save costs.

- Asset manager 1 explains that for the prediction of the life span of a bridge, there should be looked to at a normative indicator.

- It is interesting for Rijkswaterstaat to assess a bridge if this is a representative for a bigger areal or conclusion can be made about more bridges.

- If you measure for a longer period, it is important that the right phenomena are measured. This seems logical but it can happen that the sensors are moved or that the measured parameter is not representative for the risk it should identify.

- All raw data should be saved as much as possible. The operational choices should be made with the processed data, but the raw data should be used as back up. When mistakes are identified in the processing or other insights in processing are available later, the raw data can be used to do new analyses. Furthermore, raw data might have value for other purposes. It is therefore important that the asset manager gets the property rights of the data. This data will then be publicly available. Unless there are cybersecurity issues with the data, but this is not expected.

- According to asset manager 1, SHM systems can reduce costs for the asset manager by:
    - Less and more efficient inspections
    - Make longer use of the bridge
    - Postpone or prevent renovations and / or strengthening

- Rijkswaterstaat is interested in experiments to develop or improve new technologies of SHM.

Expert 4: Interview with structural engineer

Expert 4 is a senior structural engineer of an engineering firm.

Findings:

- Structural engineer explains that in principle, the structural safety of a concrete bridge is ensured with norms. Every asset manager has calculations that proved that the construction is safe. Based on these calculations, a permit is given. This is all included in the building code. If the bridge is proved to be safe and nothing did happen to the bridge (no higher loads or damage etc.), the bridge should be considered safe.

- Structural engineer 1 explains that a structural engineer use 2d and 3d finite element models or just hand calculations for the safety calculations of bridges. This depends on the level of detail that is required by the asset manager. Level of detail is related to calculation costs and time. The input of these models are drawings, technical information in combination with information from inspections.

- According to the code, the life span of a bridge is considered 100 years. In the calculations a rest life span of 30 years is always used (according to the RBK). The steel in the construction is normative for the safety of the bridge. If you want to assess a concrete bridge you should focus on the reinforcement in the structure.

- Structural engineer 1 states that structural engineers are responsible for the assessment of the safety of bridges. They should balance safety and costs. It is economically not possible to strengthen and/or replace every bridge, but unsafe situations should always be prevented. It is sometimes hard for a structural engineer to explain to an asset manager that a bridge is theoretically unsafe, while you do not see much damage outside. But on the other hand, sometimes a bridge with big cracks can still be considered safe. The asset managers will be advised with reports. Sometimes, a bridge can become safe with small adjustments. This need to be done in discussion with the asset manager. Asset manager are responsible for the bridge and should make the final maintenance decisions. The structural engineer tries to advice with their technical background

- Structural engineer 1 explains that conservative values (based on the year of construction) can be assumed in calculations, when nothing is known about the strength of the structure. This is the worst-case scenario. You rather use information from material research.

- The reinforcement strength is normative for the strength of the bridge. Except for the shear force problems, then the concrete strength is normative. The concrete strength can be determined, based on documentations or concrete sample cores. Concrete is getting stronger over time. How much better depends on the pouring process and the type of concrete that they used.

- Structural engineer 1, states that the biggest risk of old concrete beam bridges is the shear force, because of the shortage of reinforcements in the construction. The reinforcements bars are not long enough, such that they can be pulled out of the concrete. Shear forces can lead to brittle collapses. It is hard to measure the effects of the shear force risk.

- According to Structural engineer 1, there is a big discussion going on about the norms for loads on bridges. The norms changed: Before 2007, three load classes were used for bridges: 30-ton bridges, 45-ton bridges and 60-ton bridges. Nowadays, the Eurocodes changed, and every bridge needs to meet the 60 tons standard. This means that every bridge should be able to withstand 60 tons. Many bridges do not meet this new standard. Currently, they are trying to make some revisions to deal with this problem. Several reduction factors can be used if you can prove that the amount of trucks per year is limited. This can be measured with SHM systems. However, it is also possible to do this with traffic census.

- Structural engineer 1 states that the strength of your concrete bridge is related one-on-one to the strength of the reinforcement bars. If you have corrosion in the middle of the bridge, the amount of corrosion is the decrease of capacity of a concrete bridge. The decrease of reinforcement bars is relevant for the structural engineer. Corrosion is a continuous process. So, you know that it is this much today, and it can only be less next day. So, the first step is when you know that you have corrosion, make sure that it stops. Corrosion is always caused by too less concrete on your reinforcement. You can remove the concrete, clean the reinforcement and place new concrete on top.

- Expert 4 states that cracks itself are no problem, only the growth of the cracks is relevant. The length and the width of the cracks are interesting to know. These factors also depend on the temperature. The influence of temperature should be considered. Cracks can cause water intrusion, which can lead to corrosion of the reinforcement bars.

- Prestressed reinforcement bars are more sensitive for corrosion. If this starts to corrode, it can go fast. If you lose your prestress in your structure, you lose your strength and the bridge will no longer meet the standards.

- Pre-stressed concrete constructions are less sensitive for fatigue than not prestressed structures. This is caused by the fact that the stress differences by traffic loading is low in comparison with the present stress. Not pre-stressed concrete bridges are sensitive for fatigue. Steel bridges are even more sensitive for fatigue. Fatigue can be detected by cracking.

- Another possible risk for concrete bridges is the attendance of Alkali – Silica Reaction (ASR), according to expert 4. ASR takes place when the alkali in the cement reacts with silica that is present in some aggregates. The product of ASR is a gel. The gel will expand, when it meets moisture. This expansion causes internal stresses in the concrete. If these stresses exceed the tensile strength of the concrete, cracking will result. In particular, the shear capacity of elements with ASR-damage is subject to discussion, as the cracking reduces the tensile strength of the concrete (Lantsoght, 2018). You can see ASR with white rash on the outside.

- Structural engineer 1 explains that soil settlement can lead to much higher loads and moments on components, which can lead to failures. Therefore, it is important to keep track of the settlement of the bridge.

- Structural engineer 1 states that measuring vibrations is not interesting for concrete bridges. The influence of external loading is very low, because of the high own weight of the bridge. Modern lightweight concrete bridges have a much lower own weight, this increases the risk of vibrations.

- Structural engineer 1 explains that threshold checks with alarms are not very useful for structural engineers, because they are too late. The only thing you can do is measuring the loads and when a truck is too heavy, it can get a fine.

- According to Structural engineer 1, the input of load measurements can be used as input for new regulations. In the current regulations it is not allowed to use lower loads in your calculations. Structural engineer 1: “Who says that if you have measured the loads for one year and no heavy trucks did pass the bridge, this truck would not pass, next year. If you measure this heavy truck, it is already too late”. That is why you are not allowed to deviate from the standards. As asset manager you can say that the bridge is only used by trucks under a specific limit of loads, but then he should also bear the risk.

- Structural engineer 1 states that everything that ensures that you do not have to replace, strengthen or maintain the bridge is a cost reduction. Maintenance or replacement activities can be postponed.

- Structural engineer 1 states that the only way to assess the risk of shear strength is by executing a proof load test. In a proof load test, a load is applied to the bridge. If the bridge can withstand the applied load without signs of distress, it is shown that the bridge can carry the prescribed loads to a satisfactory level. It does not give insight into the ultimate capacity of the tested structure, but only that the bridge can resist an specific amount of loading

(Lantsoght, 2018). Proof load testing is risky, because too heavy loads can damage the bridge and it would lose its capacity.

- Structural engineer 1 states SHM systems can be used to validate a structural model. You can determine the deflection related to a specific load. If the bridge deflects less than the model predicted. The bridge is stronger than expected, or the model is not correct.

- Structural engineer 1 states that corrosion can be often detected at your abutments because the joints are broken and not watertight anymore. Water with salts can damage the concrete on those places. Also, bearings of concrete bridges are critical components.

Expert 5: Visual inspector 1

Visual inspector 1 is a visual inspector and senior advisor at an engineering firm in the Netherlands.

Findings:

- Visual inspections are used as first indication of the condition of the bridge. The general approach of a traditional visual inspection consists of the following steps: The inspection is executed by two inspectors. They start with a desk study to identify what type of bridge it is, what the wishes of the asset manager are, etc. Secondly, the inspectors have a toolbox meeting on location. They identify what the risks are, on which aspects they should focus, what the safety issues are, and the tasks are divided. Thirdly, they start the actual inspection and assess all components on the bridge for damage. One person makes pictures and the other one writes down the results. Afterwards, they have a meeting to check whether the same issues were identified and check if everything assessed. Sometimes, boats or aerial platforms are required. The results are later written down in a report.

- There is no regulation how often a bridge should be inspected visually. This depends on the policy of the asset manager. According to Visual inspector 1, some type of bridges or component of bridges should be assessed more often than others. For example: mechanical parts should be inspected approximately every year. Also, components that influence the direct safety of the user (i.e. barriers or asphalt layer) should be inspected annually. On the other hand, a concrete structure does not deteriorate much over time. Therefore, time between inspections of concrete components can be several years. Every asset manager should make their own decision how and how often the safety of all components is assessed.

- Visual inspections can have different results.
  - A condition assessment can be executed. Every component gets a grade from 1 to 6. 1 is good and 6 is very bad. This gives an indication about the safety of the bridge and can be used for prioritizing maintenance activities. This is often be done for a big amount of bridges.
  - A more detailed assessment is also possible. The condition of the bridge is described more in depth. The damages are described in detail. Based on this report, an asset manager can go to a contractor and explain what kind of maintenance he should do. This gives a better indication of the costs of maintenance.
  - There are also very detailed inspections, which are used to also identify the causes for damages. An example is: crack monitoring. Questions like: How does the crack look like and why is it growing over time.

- Visual inspections are used to assess the condition of the bridge. If no structural concerns are noticed during this inspection, the bridge is considered structural safe and only a maintenance program for the coming years should be made. If structural concerns are noticed during the visual inspection, the asset manager should prove that the structure is still safe. This can be done by executing a recalculation. Visual inspections can be used as input for these calculations. Unknown aspects that are required for the calculation should be identified.

- If a bridge does not meet the first structural safety calculation, it does not mean that the bridge should be strengthened or replaced directly. It is also possible to do a more detailed calculation, where fewer conservative values are used. It is also possible to monitor (with or without SHM systems) the bridge and see if the identified damage is really that bad as expected. This makes it possible to keep track of the risk.

- Visual inspector 1 believes that it is possible that SHM systems replace or assist visual inspections in the future. Visual inspector 1 expects that drones with cameras can help the inspector during the inspections. Drones can speed up the inspection. Furthermore, less people are required during the inspection and the safety of the inspector is improved. A disadvantage of drones with cameras in comparison with traditional visual inspection is that you cannot hear, feel and smell anything. Visual inspector 1 expects that inspectors still must go to the bridge sometimes, to verify the findings of the SHM system.

- The inspector will still be responsible for the analysis of the results, since this depends on many factors. Visual inspector 1 does not think that this can be done complete automatically.

- The advantage of using SHM systems instead of visual inspection is according to expert 5:

    - Lower costs; Visual inspector 1 expects that costs can be reduced because less people are required for the inspection, no extra tools (i.e. boats or aerial platforms) are required and the inspections can be speed up.
    - Safety of the inspector is improved; in the current approach two inspectors must walk over a bridge in use. There should be paid attention to the safety of the inspectors. When the inspectors do not have to be physically on the bridge, unsafe situations can be prevented.
    - More accurate assessment of the bridge; Visual inspector 1 expects that bridges can be inspected more frequently with SHM systems. Therefore, beginning damages can be identified earlier and repaired before they got worse. Furthermore, real time monitoring gives a better indication of the condition of the bridge.
    - Reduced the down time of a bridge, Sometimes, lanes of a bridge should be closed during visual inspections. When the bridges are assessed with SHM systems, this can be prevented.

- According to Visual inspector 1, the result of a visual inspection with SHM systems should be the same as for traditional visual inspections. This is an advice to the asset manager what activities he needs to execute (recalculation, more in-depth research, maintenance etc.) The SHM systems should deliver a movie or pictures to the “inspector”. The inspector should be able to analyse the result and draw conclusions from them. On every movie or picture, the coordinates of the component, the date and the time should be stated. Furthermore, it is important that all components are assessed and that the pictures or movies are clear and sharp.

- Visual inspector 1 gave several examples that are interesting to monitor with SHM systems instead of visual inspections:
  - Crack growth: it is interesting to measure the length and the width of a crack with a SHM system. This can also be measured during visual inspection, but an SHM can give a continuous insight in the size of the crack. This can give a better idea of the cause of cracking and the trend of the growing. Temperature influences should be considered
  - Visual inspector 1 states that it is interesting to measure the amount of chloride intrusion. Chloride intrusion damages first the concrete. If the chloride reaches the reinforcement bars, the capacity of the bridge can decrease. It is therefore useful to identify the chloride intrusion before it researches the reinforcement. Such that severe damage can be prevented. This will reduce the maintenance costs. However, visual inspector 1 states that he is not aware that this can be measured with sensors.

- Visual inspector 1 sees also benefits in automatically damage detection with image-based learning. However, he states that this is very complicated, and the technique should be improved significantly. Damages can be very different; it is therefore very hard for a system to identify every damage and draw conclusions from them.

Expert 6: Asset manager 2

Asset manager 2 is asset manager of a big municipality in the Netherlands. He is responsible for the inspections of all assets and the analysis of those inspections. Furthermore, he is data owner of all the data that the municipality gets. He decides which data should be gathered and where should it be stored.

Findings:

- Asset manager 2 states that the municipality does not only have a replacement challenge, but also a maintenance challenge. They have a lot of bad bridges. This has two reasons: first, the traffic loads are getting higher and on the other hand, too less maintenance were executed in the recent years, due to cuts in the maintenance program.

- The municipality has several blanket orders (Dutch: Raamcontract). Four contractors are responsible for the inspections of all assets. For visual inspections the municipality uses three blanket orders (Dutch: Raamcontract). The municipality want to see want to see every asset, every three years.

- According to Asset manager 2, the heavier traffic loads is one of the most important risk of concrete bridges.

- Asset manager 2 states that the deterioration of the foundation is an important risk, as well.

- The municipality of asset manager 2 has an own inspection portal. In this portal, all types of inspections are stored. Every bridge gets a condition rating from 1 till 6. Every bridge gets a colour on a map. In this way it is easy the asset manager has a clear overview of the condition of the total areal.

- Asset manager 2 states that SHM is currently often used for reactive monitoring, but he sees a development to a more preventive approach.

- Asset manager 2 states that SHM systems can decrease the maintenance costs in several ways:

    - Better insight in the degradation of the concrete structure
    - Preventive maintenance planning: This can reduce the costs in two ways:
        - You can repair damage before it worsens.
        - Predict maintenance better. Direct replacement or maintenance activities is much more expensive. When you know you must maintain or replace a bridge, several years in front, it is possible to combine this project with other projects. This can decrease costs, but also the hindrance for traffic.
    - Another way to reduce costs by postponing maintenance, strengthening or replacement of the bridge, by proving that the bridge is not as bad as predicted.

- Asset manager 2 states that it can be beneficial to ask for new SHM techniques, because you can help shaping the techniques, such that it meets your wishes. However, he says that the technique should be beneficial for the asset manager on the short term.

Expert 7: SHM / data specialist 2

SHM / data specialist 2 is responsible for the structuring of SHM projects of a Dutch engineering firm. Furthermore, he helps developing new innovative sensor projects. So, he does not only focus on structural health monitoring.

Findings

- SHM / data specialist 2 expects the most value of SHM for asset management by estimating the remaining life span of a bridge and give a better indication of a risk. He explains that you can plan your big maintenance better and it might be possible to postpone these activities, which can save money. He expects that SHM for daily maintenance is not useful, since the SHM systems are too expensive for such routine jobs.

- SHM / data specialist 2 believes that SHM systems on many bridges can be used to improve or create deterioration models. These models can be used to predict deterioration of a structure better in future.

- SHM / data specialist 2 explains that there are several difficulties with placing sensor systems on an in-use bridge. In common, sensor suppliers test their sensors with real life conditions. However, it is not possible to test a system for years. For example, they did not test how dust built up over time and how this can damage the system. Although sensors try to simulate real conditions, it is not always possible. In real life projects, the environment can be dirty, the weather conditions can be challenging (high or low temperature, high or low humidity etc.). Furthermore, you must deal with traffic users and other maintenance activities. Also, vandalism can influence the measurements.

- SHM / data specialist 2 states that a SHM system is a complex technical system and that you should accept that technical failures will happen (electricity is down, cables are not connected anymore etc.). There are several things that can be done, to prevent this. First, robust components should be used. Secondly, a SHM systems could have several back-ups. Think about:

  - Batteries, in case electricity is down.
  - Multiple sensors, in case one sensor does not work
  - Local storage of data, in case it is not possible to send the data from the sensor to the computer
  - Etc.

However, SHM / data specialist 2 explains that a structural engineer does not always need data of every day for his analysis. Therefore, it is not always required to build a very robust system. This depends on the objective of the asset manager and the budget.

- The location of sensors should be determined in consultation with the structural engineer. For the analysis, the structural engineer needs data of the right locations. However, there are also some practical issues that can influence the location of the sensors. It is very beneficial to place the sensors near cable boxes. Electricity is already available, and you can place the cables of the SHM system in these boxes. Furthermore, SHM / data specialist 2 explains that he prefers to place sensor systems under the bridge, because there is no traffic and it is drier, less dirty, less windy etc.

- SHM / data specialist 2 explains that there are several aspects that should be paid attention to during the installation of the SHM system. First, you should not damage the bridge, when the system is attached to the bridge. So, you cannot always drill into the bridge. Furthermore, the attachment of the system should not influence the measurements. Thirdly, there should be paid attention to the correctness of the measurements. The supplier of the sensor has most of the time a quality assurance. Furthermore, a calibration should be done in the beginning. Moreover, it is also possible to test the SHM system in a test set up. Finally, multiple sensors can be used to check if the sensors are installed correctly. Fourthly, SHM / data specialist 2 explains that he should install the SHM systems always during other maintenance activities. This can save costs and hindrance.

- SHM / data specialist 2 explains that you can never be 100% sure that the measurements are correct. SHM systems always have a specific accuracy. Furthermore, sensors drift over time. The amount of drift is known by the supplier and is included in the specification of the sensor. Furthermore, there can be measurements fault. Impossible values should always be filtered. It is also possible that a sensor does not measure the correct values anymore. This can have different causes, for example the sensor moved. SHM / data specialist 2 states that it is, therefore, always preferable to have multiple sensors. Sensors from different suppliers or batches are also favourable, because these have different properties.

- SHM / data specialist 2 states different aspects that could be used for comparing sensors from different suppliers. He mentions that sensors are never the same. First, there should be identified if the sensor can measure in the right range and with the right accuracy. Secondly, the sensor should be able to measure in the environment (weather influences, other systems in the neighbourhood, dirt, traffic). Another aspect that can be used for the comparison is costs of the system.

- SHM / data specialist 2 states that the asset manager should also pay attention to the ownership of the SHM system and the data. Who is responsible for the technical SHM system and who is responsible for the storage of the data? How does this change when the contract with a SHM contractor is over? Who gets the data and the SHM system? There should also paid attention, what the SHM contractor can do with the data.

- SHM / data specialist 2 states that the SHM system should always be designed in consultation with the structural engineer. He should be able to work with the data. He should present, what type of data of information he wants. (i.e. monthly averages, every second measurements etc.). The structural engineer should also present how he want to receive the data.

- SHM / data specialist 2 explains that data should be stored by different parties. Also, back-ups should be required to make sure that the data would not be lost. Suppliers could go bankrupt. There should be prevented that all data is lost. Furthermore, expert 7 states that it is important that the data is stored in a structured way, such that it can be easily found back.

- According to SHM / data specialist 2, there are different costs:

    - Hardware costs and installation of the system
    - Preparation of the system
    - Maintenance to the monitoring system
    - Data storage
    - Analysis of the data (biggest costs)

- SHM / data specialist 2 states that the most data of SHM is not critical. However, it is still necessary to make sure that only the right people have access to the data.

Expert 8: Structural engineer 2

Structural engineer 2 is a senior structural engineer at a Dutch engineering firm.

Findings:

- Structural engineer 2 states that there is no obligation for the asset manager to prove that all bridges are safe wit calculations and he explains that it is not possible to do this, because there are so many bridges. When a risk is identified, a damage is detected or the design of the road changed, then a recalculation can be executed.

- Structural engineer 2 states that structural engineers are responsible for the safety calculations. They should prove that bridges are safe, when they were asked to by the asset manager. There is different level of details for these calculations. They start with a very easy and short calculation. When this shows that the bridge does not meet the standard, it is always possible to do a more comprehensive calculation. The structural engineer should balance level of detail of the calculations and costs.

- Structural engineer 2 agrees that shear strength is the most important risk for old concrete bridges. He also mentions ASR as a possible risk for a concrete bridge. Furthermore, the growing traffic loads in combination with the changed load policy (like described by Structural engineer 1) can cause that bridges do not meet the safety standard anymore.

- Structural engineer 2 states that it is beneficial for an asset manager to identify the loads of the bridge. In this way, the asset manager can see what the actual loads of the bridge are instead of using a pre-determined load class. This can also be used for the long run to make a more probabilistic load model instead of making use of deterministic calculation model.

- Structural engineer 2 states that the safety of concrete bridges can be improved by measuring if too heavy traffic is crossing the bridge. Furthermore, a SHM system can detect damage in an early stage. SHM can measure continuous, while visual inspections are less frequent. Damage can be detected, before they worsen.

- Structural engineer 2 agrees with the other experts that costs can be cut by preventive maintenance or by postponing maintenance, strengthening or replacement activities.

- Structural engineer 2 also agrees that SHM can improve the planning of maintenance activities, which can reduce the hindrance to the bridge user.

- Structural engineer 2 does not think that SHM system can replace visual inspections. Since you have several limitations. However, SHM systems can be used for aspect that require attention based on visual inspections, like crack growing or soil settlement.

- Proof loading can be used to determine the capacity of your bridge.

- Subsidence measurements with SHM systems can be used when some settlement is identified during visual inspections. It is not the most critical failure mode. You do not have a problem when the bridge settles a few centimetres. But it can cause higher loads on specific components. Especially when a bridge has more than two bearing points.

- Structural engineer 2 explains that cracking is a problem when reinforcement bars or pre-stress corrodes. Then the structure can lose its tension strength. Corrosion has a bigger volume than steel. Therefore, the reinforcement bars will expand and pushes the concrete cover from the bars. This leads to even faster corrosion. You can measure the width of the crack. When you see strange cracks, you want to monitor it to find the cause of the crack. Therefore, sensors can be very beneficial. You should measure several months. You want to see the growth (length and width). The structural engineer should analyse the data together with an advisor asset management.

- Structural engineer 2 explains that the deflection should be measured in combination with the loads, to validate the structural model. First, a pre-determined load should be placed on the bridge. When this is done, you can also say something about others loads. The deflection alone does not say something useful about the strength of the bridge.

Expert 9: SHM / data specialist 3

SHM / data specialist 3 is an assistant professor at the University of Twente. He focussed on long term performance of structures using thermal responses. He looked at anomalies in the structure. He helped asset manager in SHM projects with analysing data from SHM systems. Later, he started working as a lecturer and started his own research group focussing on vision based SHM. The group especially focussed on performance assessment. He is not familiar with the maintenance policy in the Netherlands.

Findings:

- SHM / data specialist 3 explains that SHM can have value for an asset manager by optimizing maintenance activities. Costs can be saved. Because you have a better insight in the condition of components, it is possible to make a planning optimization. Furthermore, it is possible to expand the lifespan of the bridge.

- SHM / data specialist 3 states that many bridges do not reach the end of life. They are most of the time designed for 100 years. But not all bridges reach this, because they are replaced before, because does not meet the functional requirements. It is hard to predict for over 100 years.

- SHM / data specialist 3 gives several criteria that can be used to distinguish different SHM systems: applicability in the environment, suitable for required duration of measurements, reliability, resolution, experiences in other projects and costs.

- SHM / data specialist 3 explains that the supplier should calibrate the sensors before they are used in the project.

- SHM / data specialist 3 explains that there should be thought about several things during the installation of the SHM system: power supply, long life of the sensor, hide or protect the wires, access issues of the bridge, health and safety issues, working on heights, traffic disruptions, installation difficulties like (wind, dirt etc.)

- Weather conditions, people influence, and drift can influence the reliability of the measurements over time. However, the amount of drift of sensors is known.

- SHM / data specialist 3 explains that the reliability of the sensors during the measurements can be checked by doing the right data analysis. If you have multiple sensors and only one sensor gives another value. You can see that the sensor is not measuring correctly. If there is something wrong with the bridge, then the total structure works different and all sensors give different values.

- SHM / data specialist 3 advises that the data should be stored by a service provider. He is than responsible for the security of the data. There should be a back-up of the data.

- SHM / data specialist 3 states that you should look at conditions and patterns of one bridge. You might can improve the design, by looking at what are the weak points of a design. Every bridge is unique, because of geometry, different loads. You cannot use data from bridge A to do the analysis for other bridges.

- The costs of SHM systems consists of maintaining the system, installing the system, purchasing the system, data storage and data interpretation.

- SHM / data specialist 3 states that hindrance to bridge users can be reduced by the correct planning of the installation. You should know that the SHM system can break. Access to the SHM system is important for the location placement.

- SHM / data specialist 3 explains that an asset manager should demand for the service of a SHM system. So, it should work for a period. The contractor is then responsible that the system works.

- SHM / data specialist 3 explains that you can measure the deflection of the structure and the loads to get an idea of the performance of the bridge.

- SHM / data specialist 3 is convinced that it is possible to measure the amount of chloride intrusion in the concrete.

- SHM / data specialist 3 explains that measuring the length and width of a crack can be used to identify the cause of the crack. Furthermore, it can be used to check if the crack is not big enough, such that water and chemicals can penetrate to the reinforcement bars.

Expert 10: Structural engineer 3

Structural engineer 3 is a senior structural engineer at a Dutch engineering firm.

Findings:

- Structural engineer 3 explains that the safety of bridges is assessed by calculations and visual inspections. Structural engineers especially focus to the loads related to the strength of the structure. For new structures, it is easy, because you know the material properties of the structure. But for old structure, several aspects can be unknown.

- Structural engineer 3 explains that you can prove that a bridge is safe, by schematizing how forces are working in a structure. You can have global failure and local failures. Local failure is not always bad. The Eurocode 91.2 and the NEN 8700 series are used for calculations. Rijkswaterstaat uses the Richtlijn Beoordeling Kunstwerken (RBK). The RBK can be a little bit overdone for small agricultural bridges.

- In the past, you had three load classes: 30-ton, 45 ton and 60 ton. Nowadays, all bridges should meet the 60-ton standard. (60 ton with two axles). The loads by traffic is increasing, so it understandable that the standards are changed. However, nowadays it can be a problem for smaller bridges.

- Fatigue is hard to identify for concrete bridges. Fatigue can also influence the rest life. Fatigue can be a problem.

- Possible risks of concrete bridges are:

    - Failure of the supportive construction. This is hard to detect. Only when deformations occur.
    - Rebars can be exposed. When rebars are exposed, you must remove the concrete, clean the rebars, add primer and recover the concrete. This can be caused by carbonatation.
    - Moment can also cause failures. Low quality steel will flow first. This will result in evenly crack pattern.
    - Another risk is shear force. Shear force does not ‘warn’. Shear force problems can only be detected by doing calculations. It is not possible to see it from the outside. The shear force capacity based on your steel and concrete. When it is bigger than this capacity you have a shear force problem.
    - ASR is another risk. It is easy to detect with white tarnish and craquelure
    - When the joint is leaking, you can get chloride intrusion. Chloride intrusion can be measured with samples. Chloride can decompose the steel. Then you can get put corrosion.

- The remaining life span is hard to identify. You should look at the risks. The remaining life span is often determined based on the carbonatation depth of the structure.

- The Dutch standards includes stochastic values, which are based on a bridge near Rotterdam (Brieneroordbrug).

- A bridge is often stiffer, than the value that the structural engineer uses in his calculations. You can prove this, by measuring the stiffness related to the loads that are over the bridge.

- If a SHM system give the correct input for his calculations, Structural engineer 3 does not mind how the system works. Costs are of course important for the asset manager. Furthermore, he states that it might be interesting to look at the duration of installation, and the frequency that you need to go to the SHM system.

- Measuring the chloride intrusion and the amount of carbonatation can be used to prevent worse damage. The amount of chloride intrusion is currently determined with samples. Carbonatation is now identified with phenolphthalein. Structural engineer 3 thinks that this can also be measured with sensors.

- Structural engineer 3 thinks that visual inspections can be partly replaced by SHM systems. Drones with cameras can be used for hard accessible spots. You can use SHM to replace visual inspection, especially for hard accessible spots. Use drones to check critical spots. These can be inspected later, visually, when needed. He should use a drone, but it is also possible to scan the complete bridge with 3D visualisation. At the office should be decide what spots should be paid attention to. The result of the inspection will be the general condition of the bridge. The results will be photos or videos. The requirement is that the system is close enough to every component, there is paid attention to dark and light and everything should be visible. Furthermore, it should be possible to zoom in. The visual inspections can be extended by checking the deformation. The results should be analysed by inspector or structural engineer. Structural engineer should not look an hour to one bridge. Only when it is critical or only critical parts. For the structural engineer, it is only interesting to store the critical parts.

- When cracks are measured, the difference between with or without variable loading may not be too big. The crack width should be measured. The result should be the crack width per interval. The interval depends. Preferred is continuous measurement. Most cracks are added in realisation phase. You can determine if the bridge flowed and have been overloaded. Requirements are range, resolution. The crack should first be calibrated. Maybe there should be checked if the measurements are still correct after a year. However, this is not the responsibility of the structural engineer. The structural engineer should work with the results, whereby he assumes that the measurement data is correct. You want to check the minimal and maximum crack width over time. IF you want to identify the crack cause. Other cracks might be interesting.

- There are a lot of bridge that does not meet the standards, but on the outside you do not see any signs. First, you should exclude brittle collapses. Then you can look at the deformation. You should doubt the input parameters of the calculation. You can do proof loading to prove that the bridge is still safe, or load restriction. You can overrule the Eurocode and RBK with prove of measurements. However, what if heavy load does happen. You should look at the risk of collapse. Keep track of the “spannings-rek”diagram. When you want to look at the deformation related to the loads. Ideally you place the loads like it is noticed in the Eurocode, 60-ton, 1.20 width. Deflection in the middle. You want to measure at the maximum deflection, because it is already a small value. However, it is also to measure it somewhere else. The structural engineer is responsible for the validation. You have a calculation model. A lot of assumptions are done.

- Structural engineer 3 does not mind about the specific format of the results. However, he should be able to open the file.

- Structural engineer 3 thinks that that it is beneficial to store as much as possible. Data is power. Ownership of data is important.

Expert 11: Visual inspector 2

Visual inspector 2 is a visual inspector and senior advisor at an engineering firm in the Netherlands.

Findings:

- Visual inspector 2 explains that visual inspections are used to get an indication about the safety of the bridge. Based on damages inspectors try to identify if there is any structural risk. Sometimes, visual inspections are not enough to say something about what is going on. Then further research is required.

- Visual inspector 2 states that condition inspections of concrete bridges should be executed approximately once every 5 years. However, there is no law who oblige the asset manager to do this. You should have a maintenance and control plan.

- Visual inspector gave a brief explanation how condition inspections are conducted. They do several bridges per day. We execute the condition inspections with two persons. The bridges should be assessed in a structured way. Every component should be assessed from one-meter distance, but this is not always possible. There should be paid attention to specific risks. Think about deformation / settlement, cracks, barriers, loose tiles, concrete damages. Cracks are the most important, especially at the deck. Concrete is always cracking, but you should pay attention how the crack is caused. The size of the cracks should be compared with the results of the previous condition inspection. These are not always available. The result of the inspection is a report. For every component of the bridge, the failures are described. This can be followed by a recovery advise. The asset manager is responsible for the storage of the reports. An experienced inspector should look at the cause.

- The strength of the bridge can be detected but measuring the deflection, related to the loads.

- Visual inspector 2 states that the CUR 117 gives a complete overview of the possible analyses and inspections

- SHM systems can be used to make a 3D model from the bridge and identify the dimension of the bridge. This can be helpful. However, Visual inspector thinks that SHM is not the best solution. This is too expensive, and you do not need this much information.

- Visual inspector 2 thinks that it is interesting to measure the loads on a bridge. You can see which bridges are loaded the most.

- Visual inspector 2 explains that a risk analysis is very broad concept. You can do it per object. Then are you really focussing on failure modes. How big is the chance that this occurs? But it is also to do this for an entire areal. Then it is based on the type of bridge, its year of construction etc.

- Recovery advise can be executed after the condition inspection. It presents what measures needs to be done to recover the damage. For concrete damage it is not always possible to directly come up with a recover measure. First, they need to identify the cause of the damage.

- The input of the multiple year planning are the condition inspections. It gives an indication which measures should be executed and what budget is required. It can be done for one object or the entire areal.

- Visual inspector 1 states that there can be serious differences between the strength in theory and practice. He often sees that the bridge has 'failed' according to the calculations, but nothing can be detected outside.

- Several aspects are sometimes monitored visually: concrete damages, corroding rebars, width and length of cracks, number of cracks, but also tilt. It is possible to replace this visual monitoring with SHM systems. You get objective and continuous information. Furthermore, it can reduce costs, because you do not need to go to the bridge.

- Visual inspector 2 believes that it can be beneficial to use SHM system for monitoring a crack. It can be used to identify the cause of the crack. The crack width should be monitored over time. Location of the crack. Crack width over time. Also, other cracks might be interesting to assess. Requirements should be set to the accuracy of the data. There should be a verification step in the measurements. It is interesting to see the results live in an online application. The location of the crack and the temperature should also be presented.

- Visual inspector 2 states that it is important that the SHM system has a verification step in the measurements. So, that you can verify if your measurements are reliable.

- Visual inspector 2 explains that SHM systems can help with condition inspections by looking at hard accessible spots. When safety measures are required, it can be beneficial to do it with drones. This saves costs and reduces the duration of one inspection. The result should be video. The systems should scan the complete concrete surface. An advisor should analyse the result. For concrete you should be able to detect cracks, which can start from 0.1 mm. The asset manager should store the data and make a history for every bridge. To be able to compare results over time. Results should be checked by an experienced advisor. The results should present the specific location of damage, weather conditions and temperature. Furthermore, it is interesting that the files are compatible with other software. Finally, visual inspector 2 explains that the results should be presented in an advice report to the asset manager.

- Visual inspector 2 states that SHM can be expensive and that the asset manager should always consider different solutions. For example: Is it not better to repair the concrete, instead of monitoring the quality of the concrete?

Expert 12: Asset manager 3

Asset manager 3 is a senior advisor Asset management at a Dutch engineering firm. He has a good overview of the policies of different asset managers.

Findings:

- Asset manager 3 explained that in the Netherlands a lot of assets are deteriorated and should be replaced in the coming decades. A lot of asset were built in the same period. So, the bridges should theoretically be replaced in the same period, as well. The challenge can differ per asset manager. According to Asset manager 3, Rijkswaterstaat must deal with big infrastructure projects that have big influence on the environment. The challenge for municipalities is the number of small projects. Municipalities do not have the resources to replace or renovate all bridges / assets, directly.

- Asset manager 3 explained that the safety of bridges is assessed with visual inspections and calculations by structural engineers. According to the civil code, the asset manager is liable that the asset can be used safely.

- Asset manager 3 stated that asset managers have paid more attention to risks. Risks are increasing, while budgets decline. There is a realization that governments should spent their budget more efficiently. RWS focus especially on the risks and an analysis of the risks. Municipalities focus less on risks and have a reactive approach.

- Asset manager 3 explains that you can do several things, when the bridge does not do meet the standard. First tried to improve the calculations. Change the use (limit restriction), strengthening, or monitoring / risk control.

- Asset manager 3 explains that the remaining life span of a bridge is estimated during the visual inspection, is it possible to make an indication how long the bridge can be used. Now a lot of structure are reaching their statistical end of life. This make the life prediction a little bit harder. There are bridges that reach their end of life according to calculations, but you do not see anything outside. Asset manager 3 states that it is important that the life span estimation should be well underpinned.

- Asset manager 3 stated the following risks for concrete bridges:

    - Carrying capacity is not enough anymore. This can be caused by shear strength or the moment. Shear strength can cause a brittle collapse.
    - Higher loads on the bridge;
    - Degradation of material. This can lead to corrosion of the reinforcement bars

- Asset manager 3 stated the following damages for concrete bridges:
    - <u>Carbonatation</u>; all bridges in the Netherlands
    - <u>Chloride intrusion</u>; especially on bridges near the coast and spots where salts meet the construction.
    - <u>Alkali Silica Reaction</u>; this reaction occurs on bridges with aggregates from certain sources. This is often known by the asset manager

- Asset manager 3 should monitor a crack when there might be a structural cause for the crack or when the cracks are large. The cracks should not be bigger than 0.2mm. This can fasten corrosion of the reinforcement bars.

- Asset manager 3 should use SHM to postpone renovation or replacement of the bridge. This can save much money for the asset manager. This can be done by measuring the deflection related to the loads. Furthermore, the bridge can be used longer, when a specific risk is controlled by monitoring the risk.

- Asset manager 3 states that it can be beneficial if the carbonation or the chloride intrusion is detected in an early state. However, he states several issues: how do you know that you measure on the right location. Furthermore, he states that you should pay attention on the performance of the SHM system over time.

- Asset manager 3 states that SHM can be used to speed up the visual inspections. This can reduce the costs of visual inspections. It is useful to use SHM systems for hard accessible spots. Asset manager 3 thinks that the role of the visual inspector will change in the coming decade. Automatic detection can be used, but this should be developed.

- Asset manager 3 has doubts about the benefits of proof loading. Proof loading can be used to know what the bridge could have had. When the bridge is loaded to heavily, he loses its bearing capacity. Asset manager 3 sees more potential value by measuring the difference in behaviour. When thousand trucks are driving over the bridge and the deflection is increasing, you know that the strength of the bridge is decreasing.

- Asset manager 3 should measure the loads over the bridge to check whether the loads are in line with the loads that you assumed in the standard.

- Asset manager 3 states that SHM system can be used for the input of new regulations.

- Asset manager 3 explains that asset managers want to invest in improving new SHM techniques. He explains that most asset managers have budget for innovation projects. It is an opportunity to improve your maintenance policy in the long run.

- Asset manager 3 states that agreements about the ownership of data should be made. Data is valuable and everyone wants to have the data. The asset manager should be the owner, according to Asset manager 3. He explains that raw data should be stored. This can be used to trace back if the analysis is executed correctly. Asset manager 3 states that data should be stored in basic format, such that it can be opened with different software.

Appendix D: Case description

The framework is applied in two cases. In this appendix, the cases will be described, and the case specific key driver diagram will be presented per case. The case specific key drier diagram is developed by executing the steps that are presented in Chapter 5.

Case 1

This bridge is in the centre of a Dutch city and is located over the train track and a city road. In recent years, much research has been done into the (concrete) construction of the superstructure of the Stephenson Viaduct. This research of the concrete construction tried to get a better insight in the chloride and carbonation-initiated reinforcement corrosion, structural components and the reinforcement fatigue. A recalculation of the construction has also been carried out. Based on the research results and the recalculation, it has been determined that the bridge still has a remaining service life of 30 years (from 2013). This is based on the fatigue, that is normative for the life span prediction (according to the analysis that were executed). In 2043 the viaduct will thus reach its (theoretical) end of life. Given the high replacement value of this bridge (> 10 million euros), a year-on-year delay is a significant saving in time for the municipality. For a bridge of this age, it is of great importance to have an insight into the current condition and thus to guarantee safety. The case specific key driver diagram for this case is presented on the next page.

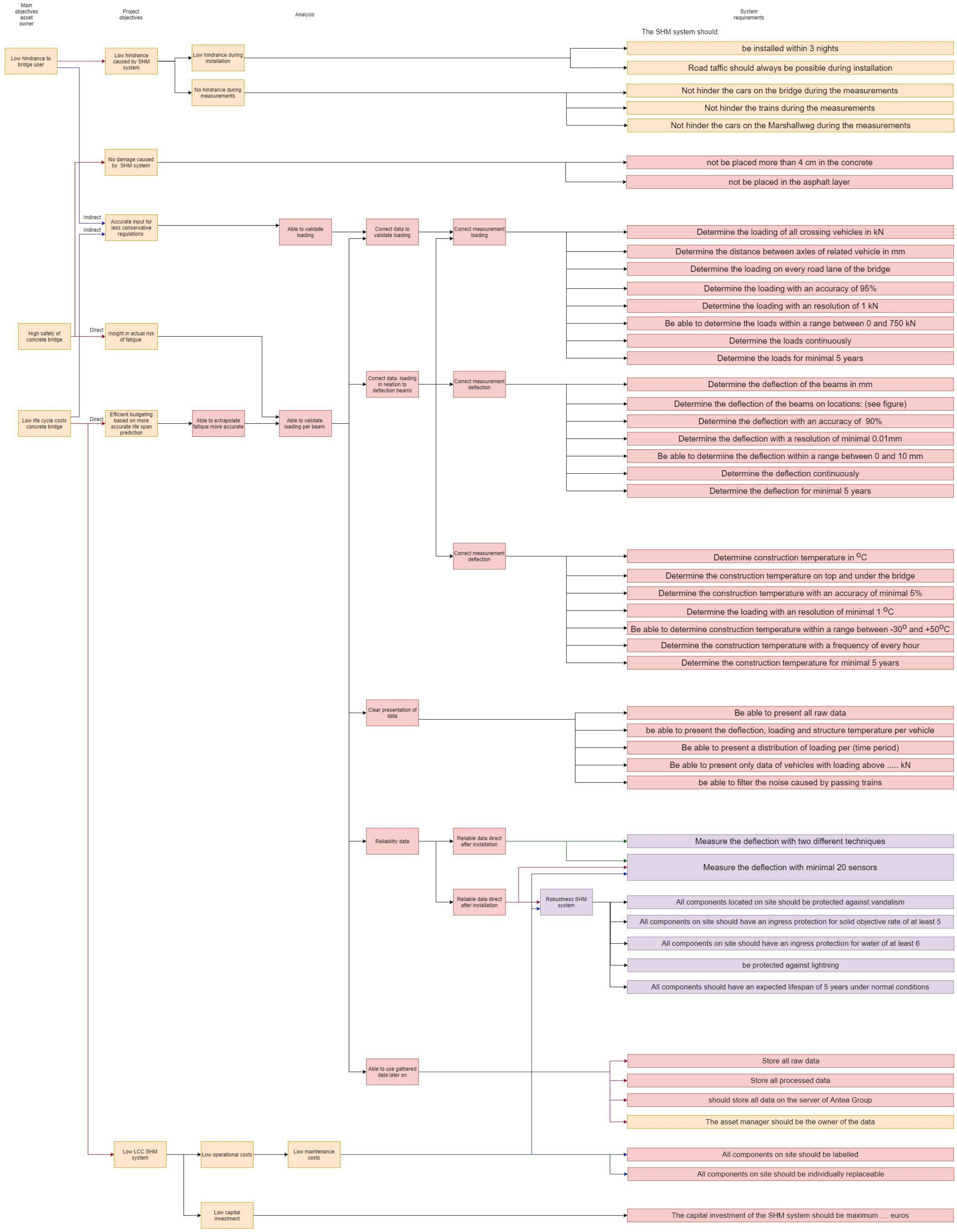


Figure 27 Case specific key driver diagram Case 1

Case 2

This bridge is a concrete 2-cell tube girder bridge of approximately 1 km. Based on a calculation, the bridge does not meet the standard anymore and should be strengthened. This is planned for 2022. Furthermore, a crack is identified in the tube of the bridge. The crack is located on a location where also cracks for shear forces can be located. Therefore, it is possible that the crack is an indication that the bridge faces the risk of shear force. This can be dangerous, because this can lead to a brittle collapse of the bridge. The asset manager wants to make sure that the bridge is still safe, by monitoring the bridge. At first, this is done visually. Later, there is decided to use SHM systems for this. The crack should be continuously monitored with sensors for three years (until 2022). This should reduce the costs of visual monitoring and should give a continuous insight in the risk of shear force. The case specific key driver diagram for this case is presented on the next page.

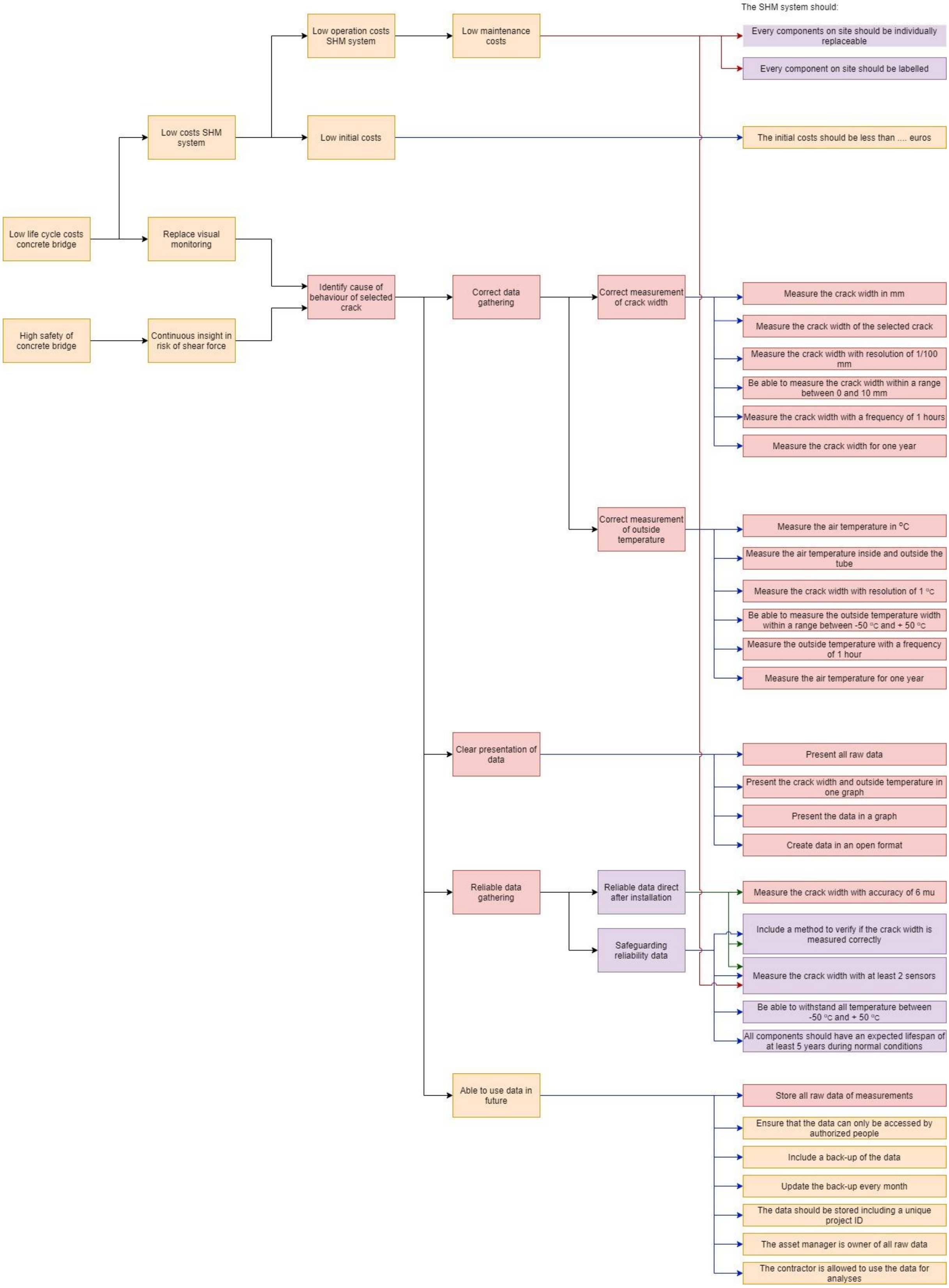


Figure 28 Case specific key driver diagram Case 2

Appendix E: Validation questions with project leader of case

The validation will be executed by evaluating the results of the framework, based on the criteria that are set in the objective of this research. The following questions should give an indication about the correctness of the outcome of the framework. he questions are answered by the project leader of the project. The results are later on discussed via skype.

Soundness

1. Are the correct main goals derived? (why/ why not?)
2. Are logical sub-goals derived, based on the main goals? (why/ why not?)
3. Do the system requirements that are set, benefit to the main objective of the asset owner? (why/ why not?)
4. Are the values of the system requirements correct? (why/ why not?)
5. Does the key driver diagram present how a SHM system can contribute to the objectives of the asset managers? (why/ why not?)

Completeness

1. Does every solution that meets these requirements benefit to the main objectives? (why/ why not?)
2. Is the set of system requirement complete? What system requirements are missing?
3. If incomplete, what is the consequence of this incompleteness?
4. Are the system requirements detailed enough? (why/ why not?)

Understandable

1. Can you understand how the case specific key driver diagram works? (why/ why not?)
2. Is every link between goals, sub-goals and system requirements clear? (why/ why not?)
3. Are you able to adapt the system requirements yourself? (why/ why not?)

Ease to use

1. Was it hard to understand how the case specific key driver diagram is structured?
2. Can the key driver diagram be used to check whether a SHM system is suitable or not? (why/ why not?)
3. Can the key driver diagram be used for comparing different solutions? (why/ why not?)
4. Can the key driver diagram be used for the procurement of SHM techniques? (why/ why not?)

Verifiable

1. Are you able to verify if the system requirements contribute to the main objectives of the asset owner? (why/ why not?)

Right tailored for the concrete bridge

1. Is the specification correct tailored for this case? (why/ why not?)

Appendix F Questionnaire expert validation session

After the framework was presented to the experts, this questionnaire was sent to them. This questionnaire helps the expert evaluating the framework concerning the criteria: soundness, completeness, ability to tailor for every concrete bridge, verifiability, ease to use and understandability. The answers were later on discussed in a personal interview.

Generic key driver diagram

1. Diagram 1: Are this indeed the correct main objectives of the asset manager or can there be more objectives?
2. Diagram 1: Are the derived sub-goals derived from the main goals? (correct linkages, complete?)
3. Diagram 2: Are the analyses correct linked to the project objectives? (correct linkages, complete?)
4. Diagram 3: Are the right sub-goals derived for the execution of the analysis? (correct linkages, complete?)Are these sub-goals applicable for every analysis?
5. Diagram 4: Does these system requirements lead to a system that gathers the correct data for the analysis? (correct linkages, complete?)
6. Diagram 5: Does these system requirements lead to a system that presents the data in correct way, such that the analysis can be executed? (correct linkages, complete?)
7. Diagram 6: Does these system requirements lead to a system that gathers reliable data? (clear linkages, complete?)
8. Diagram 7: Do these system requirements lead to a system that makes sure that the data can be used in the future? (correct linkages, complete?)
9. Diagram 8: Doe these system requirements that:
    a. The total costs of the SHM system are limited? (correct linkages, complete?)
    b. The hindrance by the SHM system are limited? (correct linkages, complete?)
    c. Unsafe situations caused by the SHM system are limited? (correct linkages, complete?)
10. Can the generic key driver diagram be used to verify why a specific system requirements is set? (Motivate your answer)
11. Can the diagram be understood easily? (Motivate your answer)
12. Were the linkages and the formulation of the goals, sub-goals and system requirements always clear? (Motivate your answer)
13. Do you have more remarks on the diagram?

Framework

1. Do you think the right activities needs to be executed in the framework? (Motivate your answer)
2. Is the sequence of the activities correct? (Motivate your answer)
3. Do you think that the right conditions are set? (correct linkages, complete?)
4. Do you expect that the framework will result in a correct list of system requirements for every concrete bridge? (correct specification, complete specification)
5. Is the framework applicable for every concrete bridge in the Netherlands?
6. Is it clear how the framework works:
    a. Is it clear how the generic key driver diagram needs to be used? (Motivate your answer)
    b. Is it clear how the diagram can be expanded? (Motivate your answer)

c. Is it clear how the diagram should be built up? (Motivate your answer)

7. Is the framework easy to use? (Motivate your answer)
8. Is it clear what the result of the framework will be? Is it clear what you can do with the result? (Motivate your answer)
9. Do you expect that the asset manager can evaluate if a SHM system is suitable for his project or not? (Motivate your answer)
10. Do you expect that asset manager can compare different SHM systems for his project? (Motivate your answer)

Appendix G: Overview derived system requirements and considerations during specification process

In this appendix, the system requirements, that are also presented in the generic key driver diagram, are presented in a table. Furthermore, the considerations during the specification process are presented. Hereby should be mentioned that the list of system requirements and considerations are not complete.

Contribute to sub-goal	System requirement
Correct data gathering (main principle and environmental condition)	The SHM system should measure the ………… (principle) in …………(unit)
Correct data gathering (main principle and environmental condition	The SHM system should measure the ………… (principle) on location(s) …………………
Correct data gathering (main principle and environmental condition)	The SHM should measure the ……………. (principle) with a resolution of ……….. (unit)
Correct data gathering (main principle and environmental condition)	The SHM system should be able to measure the ……………. (principle) within a range between ……………. (unit) and ……………. (unit)
Correct data gathering (main principle and environmental condition)	The SHM system should measure the ……………. (principle) between date ……………. and date …………….
Correct data gathering (main principle and environmental condition)	The SHM system should measure the ……………. (principle) with a frequency of every ……………. (unit)
Correct presentation of data	The SHM system should present the raw data per ……………. (time unit)
Correct presentation of data	The SHM system should present average value per ……………. (time unit)
Correct presentation of data	The SHM system should present maximum value per ……………. (time unit)
Correct presentation of data	The SHM system should present minimum value per ……………. (time unit)
Correct presentation of data	The SHM system should present conditions during the measurements
Correct presentation of data	The SHM system should present the data in a graph
Correct presentation of data	The SHM system should present the data in a table
Correct presentation of data	The SHM system should present the data in format …………….

Reliability data direct after installation	The ……………. (principle) should be measured with a accuracy of ……………. (unit)
Reliability data direct after installation	All components of the SHM system have a quality assurance certificate of the supplier
Reliability data direct after installation	The SHM system should be used …………….times before in the Netherlands
Reliability data direct after installation	The SHM system should consists of at least ……………. sensors
Reliability data direct after installation	The ……………. (principle) is measured with ……………. (amount) different methods
Protection against environmental threats	The SHM system should be able to withstand a humidity of minimum ……………. % and maximum ……………. %
Protection against environmental threats	The SHM system should be protected against vandalism
Protection against environmental threats	The SHM system should be able to withstand temperatures of minimum ……………. degrees and maximum ……………. degrees
Protection against environmental threats	The SHM system should be protected against mechanical damage
Protection against environmental threats	The SHM system should be protected against dust
Robustness	All components should have an estimated life span of approximately ……………. years
Able to use the data in the future	The SHM system should store all raw data
Able to use the data in the future	The SHM system should store all processed results
Able to use the data in the future	The SHM system should ensure that only authorized people can have access to the data
Able to use the data in the future	The SHM system should store the data on server …………….
Able to use the data in the future	The SHM system should store a back-up of the data on server …………….
Able to use the data in the future	The SHM system should store the data ……………. (time unit)

Able to use the data in the future	The SHM system should store the data for at least ……………. (time unit)
Able to use the data in the future	The SHM system should store the data including an identical project number
Able to use the data in the future	The SHM system should store the data including date and time
Low hindrance caused by SHM system	The SHM system should not hinder the bridge users during the measurements
Low hindrance caused by SHM system	The SHM system should be installed date ……………. and date …………….
Low hindrance caused by SHM system	The SHM system should be installed within ……………. (time interval)
Low maintenance costs SHM system	System requirements that contribute to sub-goal protection again environment
Low maintenance costs SHM system	System requirements that contribute to sub-goal robustness
Low maintenance costs SHM system	All components of the SHM system should be easily accessible
Low maintenance costs SHM system	All components of the SHM system should be individually replaceable
Low data management costs	The data should be stored including identical project number
Low data management costs	The measurement of the SHM system should be stored including the corresponding sensor
Low data management costs	The SHM system should only store ………………. (content storage)
Low capital investment SHM system	The capital investment of the SHM system should be maximum € ……………….
No unsafe situation caused by SHM system	The SHM system should not be attached to the concrete bridge
No unsafe situations caused by SHM system	The SHM system should be covered to protect bridge users

Answering the following questions can result in more system requirements:

- What data is required for the analysis and how can the SHM system gather the data that is needed for the analysis?
- What conditions can influence the measurements of the pre-defined parameter and how can the SHM system measure the condition?
- How should the data be presented?
  - What content should be presented?
  - What method of presentation should be used?
  - In what format should the data be presented?
- How reliable should the data be, to be able to execute the analysis?
- How can be assured that the SHM system delivers reliable data directly after installation?
- How can the reliability of the SHM system be affected over time and how do you make sure the SHM system can cope with this threats. Examples of external threats are:
  - Weather conditions
  - Human influences
  - Technical disruptions
- Why should the gathered data be used in the future and how do you make sure that the SHM system makes it possible that people in the future are able to use the data?
  - What data should be stored?
  - How do you make sure that the data stays available?
  - How do you make sure that future users are able to interpret the stored data?
- How can costs for installation be limited?
- How can the costs of hardware be limited?
- How can the costs of maintenance be limited?
  - How can the amount of maintenance to the SHM system be limited?
    - How do you make sure that the SHM system is robust?
    - How do you make sure that the SHM system is able to withstand threats from the environment?
  - How can the maintenance be executed more easily?
- How can the costs for interpreting the data be limited?
- How can the hindrance for bridge users during the installation of the SHM system be limited?
- How can the hindrance for bridge users during the measurements of the SHM system be prevented?
- How can be prevented that the SHM system cause unsafe situations during installation?
- How can be prevented that the SHM system cause unsafe situations during measurements?