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Developing a functional design of digital twin use cases in bridge management

Master Thesis
Civil Engineering and Management

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Samenvatting

Veel bruggen in Nederland laten in het komende decennium een forse vervangingspiek zien. Veranderingen zoals de toenemende en veranderende mobiliteit en klimaatverandering vragen om een slimme en efficiënte aanpak met betrekking tot het beheer en onderhoud van bruggen. In het brugbeheer zijn de huidige onderhoudsstrategieën voornamelijk gebaseerd op visuele inspecties. Deze inspecties vinden plaats met lange tussenpozen, zijn arbeidsintensief en duur. Daarnaast zijn met visuele inspecties niet alle schades goed vast te stellen en is met name de oorzaak van de schade moeilijk te achterhalen. Om storingen in de toekomst te voorkomen, is het van belang dat bruggen efficiënter worden geïnspecteerd en onderhouden dan nu het geval is.

Tegelijkertijd zijn er veel ontwikkelingen in het brugbeheer op het gebied van technologie. Werkwijzen worden steeds meer gedigitaliseerd en geautomatiseerd. Op dit moment zijn er verschillende projecten in Nederland waar geëxperimenteerd wordt met het gebruik van een Digital Twin (DT). Echter is er nog geen duidelijk beeld welke uitdagingen in de huidige praktijk van het brugbeheer met DT's kunnen worden ondersteund en hoe DT's in die specifieke gevallen kunnen bijdragen in de huidige praktijk, wat de aanleiding vormde voor dit onderzoek.

De doelstelling van dit onderzoek was het ontwikkelen van een functioneel ontwerp voor de meest relevante DT-use cases voor ingenieursbureaus in het brugbeheer. In dit onderzoek werd de design cycle methode van Wieringa gebruikt, deze methode bestaat uit kennisvragen en een design problem. Het doel van de kennisvragen was enerzijds om de uitdagingen in de huidige praktijk van het brugbeheer in kaart te brengen en anderzijds om de use cases van DT's in het brugbeheer te identificeren. Het doel van het design probleem was het koppelen van bestaande kennis over het gebruik van DT's aan de praktijk van brugbeheer door een functioneel ontwerp te ontwikkelen voor de meest relevante use cases.

Om de kenmerken van DT's in het brugbeheer te identificeren werd een literatuurstudie uitgevoerd waaruit blijkt dat DT's in het brugbeheer zich met de volgende vier aspecten kenmerken: connectiviteit tussen de fysieke wereld en de virtuele wereld, gemeenschappelijke data-omgeving, visualisatie van data en informatie en simulatie van 'wat-als'-scenario's. Aangezien de definitie van een DT contextafhankelijk is en daarom meerdere definities kent werd in de literatuurstudie een DT-referentie raamwerk gekozen dat aansluit op het brugbeheer. Het gekozen DT-raamwerk bestaat uit zes DT-bouwstenen die semantisch met elkaar zijn gekoppeld. Semantisch betekent betekenis geven aan de modellen, informatie en gegevens zodat ze door mensen en computers kunnen worden geïnterpreteerd. De zes DT-bouwstenen zijn: de fysieke laag, de model laag, de data laag, connectie laag, de service laag en de enterprise laag.

Aan de hand van de DT gerelateerde uitdagingen van een ingenieursbureau in de huidige praktijk van het brugbeheer werden acht DT use cases geïdentificeerd. Om de toepasbaarheid in de praktijk van DT's te beoordelen en de bijdrage van DT's in het brugbeheer in kaart te brengen werden de meest relevante DT use cases uitwerkt tot een functioneel design. Het DT-raamwerk vormt de basis voor het ontwikkelen van het functioneel ontwerp. De volgende twee use cases werden uit de lijst met acht DT use cases gekozen op basis van de expertise van een expertpanel van een ingenieursbureau in Nederland:

- Digitale toegang tot inspectie informatie en invoer van inspectiegegevens tijdens een visuele inspectie.
- Het voorspellen van de prestaties van de brug.

Het functionele ontwerp van beide use cases laat zien dat het huidige werkproces en de besluitvorming in brugbeheer verbeterd kunnen worden door gebruik te maken van DT's.

De eerste use case biedt een praktisch voorbeeld hoe een DT kan bijdragen in de huidige praktijk van het brugbeheer, door de inspecteur digitaal toegang te geven tot inspectie informatie en de mogelijkheid te bieden om digitaal inspectiedata in te voeren tijdens een visuele inspectie. Het functionele ontwerp bestaat uit een dataschema voor een 3D-informatiemodel. Door het koppelen van het 3D-informatiemodel met een inspectieapplicatie heeft de inspecteur tijdens een inspectie digitaal toegang tot het 3D-informatiemodel. Validatie toonde aan verwacht wordt dat de use case bijdraagt aan het

automatiseren van meerdere stappen in het huidige werkproces, waardoor de frequente overdrachtsmomenten van gegevens en informatie wordt gereduceerd en de kans op inspectiefouten afneemt. Bovendien wordt een digitale inspectieapplicatie door het panel van experts beschouwd als een geschikt communicatiemiddel voor de inspecteur tijdens een inspectie.

Het voorspellen van de prestaties van de brug is een praktisch voorbeeld hoe een DT kan bijdragen in het voorzien van de informatiebehoefte van de klant. Sensoren genereren gegevens die in een 3D-omgeving worden opgeslagen. Met behulp van rekenmodellen wordt de sensordata vertaald naar informatie. De asset manager heeft toegang tot een dashboard waar belangrijke parameters uit de rekenmodellen visueel worden weergegeven. Validatie toonde aan dat de visuele weergave van de parameters met behulp van een dashboard de informatiepresentatie richting de klant verbeterd.

De conclusie van dit onderzoek is dat de implementatie van DT's in de huidige praktijk van brugbeheer voor ingenieursbureaus zal leiden tot een efficiëntere en effectievere benadering van inspectie, vervaging en verlenging van de levensduur van bruggen. DT's bieden meerdere toepassingen die bijdragen aan de uitdagingen van het hedendaagse brugbeheer. De belangrijke bijdrage omvat het digitaliseren van meerder stappen het huidige werkproces, waardoor het aantal overdrachtsmomenten van data en informatie wordt gereduceerd en de kans op inspectiefouten afneemt.

Aanbevelingen voor toekomstig onderzoek betreffen het vergroten van de populatie voor wat betreft het afnemen van interviews met betrokkenen en deskundigen in het brugbeheer. Interviews met meer engineers en experts van andere ingenieursbureaus zullen mogelijk leiden tot andere inzichten en de generaliseerbaarheid van het onderzoek vergroten. Verder wordt aanbevolen om voor beide use cases een pilot te starten waarbij een Proof of Concept (POC) wordt uitgevoerd om te valideren of de use cases ook daadwerkelijk uitvoerbaar zijn in de huidige praktijk van het brugbeheer. Als de POC haalbaar wordt bevonden, kan in verschillende projecten gestart worden met de implementatie van de use cases.

Summary

Many bridges in the Netherlands will show a significant replacement peak in the coming decade. Changes such as increasing and changing mobility and climate change require a smart and efficient approach to bridge management and maintenance. In bridge management, current maintenance strategies are mainly based on visual inspections. These inspections take place at long intervals, are labor intensive and expensive. Besides, not all damage can be properly determined with visual inspections, and it is particularly difficult to determine the cause of the damage. To prevent failures in the future, it is important that bridges are inspected and maintained more efficiently than is currently the case.

At the same time, there are many developments in bridge management in technology. Working methods are increasingly digitized and automated. At the moment there are several projects in the Netherlands where experiments are being done with the use of a Digital Twin (DT). However, it is not yet clear which challenges can be supported in the current practice of bridge management with DTs and how DTs can contribute to those specific cases, which prompted this research.

The aim of this research is to develop a functional design for the most relevant DT use cases for engineering firms in bridge management. Wieringa's design cycle method was used in this research, which consists of knowledge questions and a design problem. In this research, the aim of the knowledge questions is on the one hand to map out the challenges in the current practice and on the other hand to identify the use cases of DTs in bridge management. The aim of the design problem in this research is to link existing knowledge about the use of DTs to bridge management practice by developing a functional design for the most relevant use cases.

To identify the features of DTs in bridge management, a literature study was carried out showing that DTs in bridge management are characterized by the following four aspects: connectivity between the physical world and the virtual world, common data environment, visualization of data and information and simulation of 'what-if' scenarios. Since the definition of a DT is context dependent and therefore has multiple definitions, a DT reference framework was chosen in the literature review that is in line with bridge management. The chosen DT framework consists of six DT building blocks that are semantically linked to each other. Semantic means giving meaning to the models, information, and data so that they can be interpreted by humans and computers. The six DT building blocks are: the physical layer, the model layer, the data layer, connection layer, the service layer, and the enterprise layer.

Based on the DT related challenges of an engineering firm in current bridge management practice, eight DT use cases have been identified. To assess the applicability of DTs in practice and to map the contribution of DTs in bridge management, the most relevant DT use cases have been developed into a functional design. The DT framework forms the basis for developing the functional design. The following two use cases have been chosen from the list of eight DT use cases based on the expertise of an expert panel from an engineering firm in the Netherlands:

- Digital access to inspection information and input of inspection data during a visual inspection.
- Predicting the performance of the bridge.

The functional design of both use cases shows that the current work process and decision making in bridge management can be improved by using DTs.

The first use case provides a practical example of how a DT can contribute to current bridge management practices by giving the inspector digital access to inspection information and the ability to digitally enter inspection data during a visual inspection. The functional design consists of a data scheme for a 3D information model. By linking the 3D information model with an inspection application, the inspector has digital access to the 3D information model during an inspection. Validation showed that the use case is expected to help automate multiple steps in the current workflow, reducing the frequent transfers of

data and information and reducing the probability of inspection errors. In addition, a digital inspection application is considered by the panel of experts as a suitable means of communication for the inspector during an inspection.

Predicting bridge performance is a practical example of how a DT can contribute to meeting the customer's information needs. Sensors generate data that is stored in a 3D environment. Using calculation models, the sensor data is translated into information. The asset manager has access to a dashboard where important parameters from the calculation models are visually displayed. Validation showed that the visual representation of the parameters using a dashboard improves the information presentation to the customer.

The conclusion of this study is that the implementation of DTs in current bridge management practice for engineering firms will lead to a more efficient and effective approach to inspection, fading and extension of bridge life. DTs offer multiple applications that contribute to the challenges of today's bridge management. The important contribution includes the digitization of several steps in the current work process, reducing the number of transfers of data and information and the probability of inspection errors.

Recommendations for future research concern increasing the population with regard to conducting interviews with stakeholders and experts in bridge management. Interviews with more engineers and experts from other engineering firms may lead to different insights and increase the generalizability of the research. Furthermore, it is recommended to start a pilot for both use cases in which a Proof of Concept (POC) is performed to validate whether the use cases are actually feasible in the current practice of bridge management. If the POC is found feasible, the implementation of the use cases can be started in various projects.

Preface

Before you lies the report '*Developing a functional design of digital twin use cases in bridge management*'. This report is the result of research into the use of Digital Twins for engineering firms in bridge management. The research is the end product of the master Civil Engineering and Management with the specialization Markets and Organization in Construction at the University of Twente. The research was carried out on behalf of Antea Group's Asset Management department.

The exceptional situation caused by Covid-19 made the graduation process extra challenging. Unfortunately, it was less possible to meet and get to know with colleagues physically in the office. Nevertheless, during the graduation period I felt full commitment to the colleagues of Antea Group.
The research has given me more insight into current practice and developments in bridge management and maintenance. With the results of this research, I was able to contribute to new knowledge about digitization in bridge management. During the research I was able to deploy and develop my specialism and expertise, so that I am prepared for the work field in civil engineering.

First of all, I would like to thank the graduation committee of the university for the great guidance and support during the graduation process. In addition, I would especially like to thank my internship supervisor from Antea Group Giel Klanker, with whom I had weekly contact, for his feedback and guidance.

I would also like to thank my colleagues at Antea Group for the great cooperation. I sparred and discussed the research with several colleagues from different departments within the organization. In addition, I would like to thank the respondents who participated in this research.

Finally, I would like to thank my family and girlfriend. They helped and supported me during the graduation process.

I wish you a lot of reading pleasure.

Sjoerd Wientjes
Apeldoorn, November 2021

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Glossary and abbreviations

API	Application Programming Interface
AR	Augmented reality
BOL	Beginning of Life
CAD	Computer-aided design
CBM	Condition-based management
Civil 3D	Civil engineering design software
CUR	Document with technical building rules in the Netherlands
DT	Digital Twin
EOL	End of Life
GBI	Data management system of Antea Group
IoT	Internet of Things
IRIS	Integral Result Oriented Information System
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LAN	Local area network
LoRa	Low power wide area network modulation technique
LTE-M	Low power wide area network radio technology
MATLAB	Programming and numeric computing platform
MOL	Middle of Life
NEN	Dutch standard
POC	Proof of Concept
VR	Virtual reality

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1 Introduction

This chapter is concerned with the introduction of the research where the background information and the relevance of the research are described. Moreover, the problem of the initiator of the research, the research goal and the research questions are presented.

1.1 Background

Bridge management has become a major challenge. The aging of bridges and the increasing performance requirements lead to a great maintenance task. Many bridges in the Netherlands built in the 1960s and 1970s are approaching the end of their design lifespan. In addition, traffic weights have increased in recent decades. The combination of the aging of bridges, the increasing performance requirements and increasing traffic weights can lead to, for example, fatigue symptoms for bridges. These are small cracks in the structural elements of the bridge that can continue to grow over time. The cracking reduces the load-bearing capacity of the bridge, which can lead to restrictions on freight traffic. Furthermore, cracks in concrete bridges can lead to corrosion of the reinforcement, which affects the concrete.

Moreover, the effects of climate change, limited funding, inaccessibility of data and vague decision-making practices further complicate the challenge (Allah Bukhsh, 2019). The effects of climate change are a major challenge for low-lying areas such as the Netherlands. Climate change can lead to extreme weather conditions, rising sea levels and a rise in temperature (Kim & Lim, 2016). This can lead to serious long-term consequences, especially for critical infrastructures such as bridges, according to research by Markolf, Hoehne, Fraser et al. (2019). For example, steel decks of moveable bridges can get stuck because the steel deck expands at extremely high temperatures. Another factor is the limited funding for infrastructure maintenance. The condition of transport infrastructure is rapidly deteriorating due to the significant lack of investment and maintenance funding since 2008 (European Commission, 2018). The accessibility of data ensures that a lot of data is collected by, for instance, transport companies or bridge management agencies to register assets. However, this data is not centrally stored and used for analyses. Gualtieri (2016) reports that 70% of all collected data within an enterprise is never used for analysis and decision-making. The last factor is the vague decision-making practices. The decision-making process depends on implicit reasoning based on previous experience and expert knowledge. The importance of infrastructure maintenance is increasingly recognized because of these factors (Gleave, 2014). An efficient and effective approach to inspecting, replacing, and extending the (technical) lifespan of the infrastructural objects is necessary. This brings us to the concept of bridge management.

The essence of bridge management is the ability to provide services of bridges over a period through activities and decisions, based on a maintenance policy. Condition-based maintenance (CBM) is one of the most used maintenance policies in bridge management decision-making (Allah Bukhsh, 2019). CBM is based on the regular assessment of the physical condition of the bridge, using the assessment information to decide on maintenance actions and to predict remaining service life.

By deploying and developing digital technologies, bridge management can be performed more efficiently and effectively. One of those technologies is a Digital Twin (DT). The DT can be seen as a virtual representation of the properties, state, and behaviour of the physical system (e.g., a bridge). Since a DT is a broad concept in the literature, a definition was drawn up as first step in the research. In this research a DT is defined according to the framework of Hokkeling (2020), in which a DT is regarded as: *a semantically linked collection of models, information and data that describes the physical system*. Semantic means, giving meaning to the models, information, and data so that they can be interpreted by humans and computers. A DT is not regarded as a large database that contains all information about a physical system. Instead, a DT integrates these models, information, and data using semantic technologies. This collection of models, information and data is regarded as DT building blocks. The framework of Hokkeling (2020) consists of six building blocks: physical layer, model layer, data layer, connection layer, service layer, enterprise layer. The building blocks can display all information about the physical system (in this research the bridge). The physical layer, for instance, reflects all construction purposes in the physical system divided into three categories: observable entities (e.g., the bridge, the tools, materials), observers (e.g., inspectors, sensors, scanners, and cameras), and data transmission components (e.g., network equipment). Because each stakeholder is interested in different information, there are multiple perspectives for presenting relevant information to certain stakeholders. These perspectives are called DT lenses. Each DT lens contains a set of information about a process that is relevant to a specific (set) of stakeholder(s) or application(s). By semantically linking different building blocks, a DT integrates unified view (a DT lens) of the information that is relevant to a stakeholder.

The DT can be used to monitor, analyse, simulate, and predict the life cycle performance of the physical system (Qi, Tao, Hu et al., 2019). The information from the DT can lead to actions on the physical system. However, little is known about the role of a DT in bridge management. A clear picture of which functional needs can be supported by a DT and how a DT can contribute to bridge management is lacking.

1.2 Antea Group

This research is carried out within the asset management department of the consultancy and engineering firm Antea Group. The asset management department advises customers (often asset owners) on the management and maintenance of various types of assets, including bridges. The main customers are Rijkswaterstaat, provinces and municipalities in the Netherlands. Antea Group carries out (technical) inspections to determine the condition of the bridge. The information from these inspections is used by various stakeholders, such as structural engineers, data analysts, asset managers, to ultimately draw up an advice and present it to the customer.

Antea Group is working to make inspections more efficient and accurate by investing in technologies such as sensors, drones, and DTs. Antea Group is working on various pilots with these technologies. For example, the Stephenson Viaduct in Leeuwarden, also known as the 'Smart Bridge', where Antea Group installed dozens of weigh-in-motion sensors to measure the traffic weight. The data from the sensors is then compared with the theoretical models to determine the exact lifespan of the bridge (Antea Group Nederland, 2020).

1.3 Problem description

Although Antea Group is increasingly involved in pilot projects, there is still no clear picture of which challenges can be supported in current practice with DTs and how DTs can function in those specific cases. Antea Group expects that the use of DTs can contribute to the current work process of bridge management and ultimately improve decision-making.

The problem statement of this research is:
In current bridge management practice, there is no clear picture of what challenges can be supported with DTs and how DTs can function in those specific cases.

1.4 Research goal

This research focuses on the implementation of DTs in the current work process of engineering firms in bridge management. This research aims to provide a functional design for the most relevant DT use cases for engineering firms in bridge management. A use case describes the specific circumstances in which an artifact is used. A use case in this study is a description of the specific circumstances in which a DT is used for bridge management. The functional design is structured on the basis of six DT building blocks, as mentioned in the introduction.

The aim of the study is formulated as follows:
This research was aimed at identifying DT use cases and providing insight into how these use cases can contribute to the current work process of engineering firms in bridge management.

1.5 Research questions

To achieve the aim of this research, the following three research questions must be answered:

1. What DT related challenges in current work process do engineering firms encounter in bridge management decision making?
2. How can a DT support the challenges in the current work process of engineering firms in bridge management decision-making?
3. What does the functional design look like for a specifically chosen use case?

1.6 Research scope

This research focuses on the use of DTs in the current practice of engineering firms in bridge management. It is investigated how DTs can contribute to the activities in the current practice of bridge management. The research is conducted on the basis of input from Antea Group, the initiator of the research. The scope of the research is limited to the management and maintenance phase in the life cycle of a bridge, as the asset management department of Antea Group is involved in the management and maintenance of infrastructural assets.

1.7 Reading guide

The research is structured as follows: in chapter 2 the theoretical framework is presented in which background information is described and the DT reference framework is introduced. In chapter 3 the methodology of this research is presented. Chapter 4 focuses on identifying the challenges in current bridge management practice. In addition, the chapter provides an overview of use cases that can contribute to the current practice of bridge management. Chapter 4 concludes with the selection of the most relevant use cases. In chapters 5 and 6 the most relevant use cases are developed into a functional design based on the DT framework. In chapter 7 the results of this study are discussed, and the limitations of the study are presented. Finally, this report concludes with chapter 8 of the conclusions of the study, recommendations for future research and recommendations for Antea Group.

2 Theoretical framework

This chapter is concerned with the theoretical framework in which background information about the concept of bridge management is described. The concept of DT and the DT reference framework are also introduced. Finally, the literature gap is described.

2.1 Definition of bridge management

The concept of asset management has emerged as an approach in the public infrastructure sector that aims to achieve more value with fewer resources (Moon, Aktan, Furuta et al., 2009). Bridge management can be defined as the optimal management of bridges that are of value to an organization. The interpretation of "optimal" is prompted by the goals that the organization strives for and the balance between performance, risks, and costs.

In recent decades, national budgets for infrastructure maintenance within the EU have shifted from capital investment to management and maintenance of existing infrastructure (Gleave, 2014). The reason for this is that, among other things, the capital goods are approaching the end of their technical lifespan, the raw materials are becoming more expensive, and the available financial resources are limited (Allah Bukhsh, 2019). Asset managers are faced with a major challenge. To get the maximum performance out of an infrastructure object and to guarantee safety, making optimal decisions with as much available data as possible is central.

2.2 Bridge management decision-making

Decision making in bridge management can be described in three asset control levels and vary at different levels of the infrastructure system (Pintelon & Gelders, 1992). The three asset control levels are visualized in Figure 1 and described in detail in below.

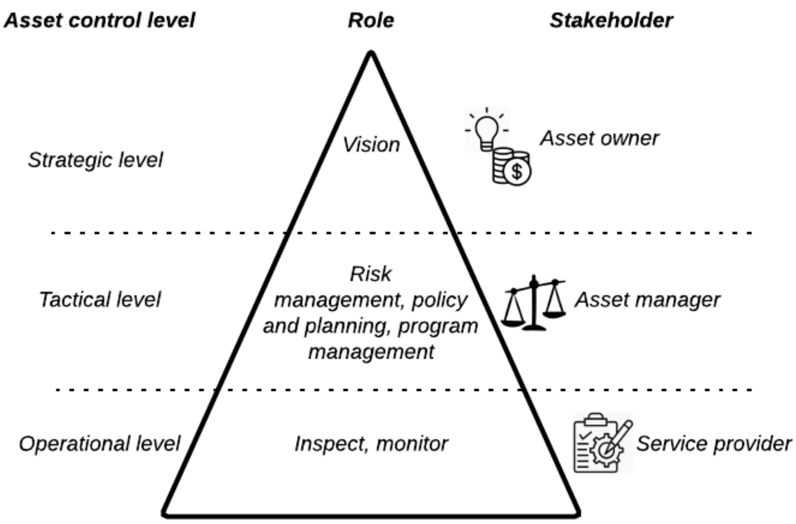

Figure 1.; *Three asset control levels in bridge management decision-making*

Long-term objectives are formulated at a strategic level that are managed by the asset owner (in the Netherlands often Rijkswaterstaat, province or municipalities). Strategic decisions have a long-term horizon and are mainly made at the level of the infrastructure network. An example of a decision at a strategic level is how to invest in a network of bridges.

Tactical decisions are made by the asset manager for the medium term and relate to infrastructure assets or parts of the infrastructure. The asset manager bases his decisions on the data generated from the operational phase. The asset manager must ensure the optimal balance between costs, risks, and the performance of the bridge. The asset manager supervises the quality that the service provider delivers in the operational phase. An example of a decision on a tactical level is to take certain maintenance measures.

Operational decisions have a short time horizon. These decisions are taken by the service provider within the parameters set by the asset manager. The service provider's work focuses on specific work on parts of a bridge. An example of an operational level decision is the allocation of people and resources to perform a maintenance measure.

Additionally, in the context of bridge management, a distinction can be made between three life cycle stages, respectively: Beginning of Life (BOL), Middle of Life (MOL) and End of Life (EOL). The BOL phase is the first and most complex phase of the bridge and includes the conception, design, testing, development, and construction of the bridge. The BOL phase ends with the commissioning of the bridge. The MOL phase is the longest phase in the life cycle of the bridge. This phase includes the commissioning, maintenance, and renovation of the bridge. The end of the life cycle phase is the EOL phase. In this research, it is assumed the EOL phase begins when the bridge is taken out of service. The EOL phase includes decommissioning, removal, and recycling of the bridge. This research focuses only on the MOL phase.

2.3 Maintenance strategies in bridge management

As mentioned in the introduction of this research, there are various forms of maintenance within the MOL phase of bridge management. Condition-based management (CBM) is emerging and is being applied more widely, partly because of the decreasing costs and improved reliability of instrumentation (e.g., sensors) and information systems (e.g., DTs) (Niu, Yang & Pecht, 2010). Before CBM is explained in more detail, the various maintenance forms within bridge management are first explained. Dhillon (2002) distinguishes three typical maintenance policy types:

1. **Corrective maintenance** includes unplanned maintenance when a failure occurs that prevents the asset from achieving its intended purpose, also known as the run-to-failure approach.
2. **Preventive maintenance** is an approach in which assets are maintained at predefined intervals or based on specific criteria.
3. **Condition-based maintenance** is a performance-based approach in which the physical asset is assessed based on inspection or monitoring results to predict or diagnose maintenance.

According to Allah Bukhsh (2019), the traditional maintenance programs, the first two types of maintenance policies, result in higher maintenance or replacement costs. Corrective policy contributes to higher failure costs because maintenance actions take place unexpectedly and unplanned. And preventive maintenance leads to unnecessary maintenance because in some cases unnecessary maintenance is carried out. Partly because of this, CBM is one of the most appreciated maintenance policies. As well as referred to as predictive maintenance, CBM aims to prevent sudden system failures and loss of life. The CBM policy is based on the physical condition of the system (bridge), using the diagnosis of the current situation to decide maintenance actions, and forecast the remaining life. The CBM policy can be described in four main steps (Jardine, Lin & Banjevic, 2006) as shown in Figure 2.

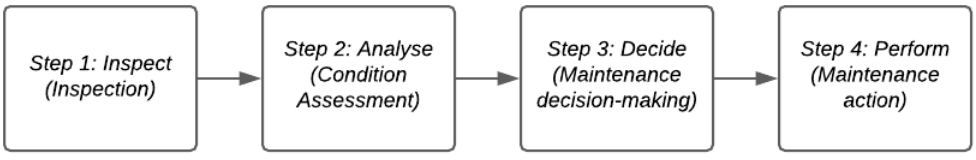

Figure 2.; *Key steps of condition-based maintenance (Jardine et al., 2006)*

Inspection involves conducting a condition assessment or technical investigation to collect data about the condition of a bridge. During the analysis, an assessment is made based on the collected data. The decision step includes all decision-making activities in each of the three different time horizons (strategic, tactical, and operational). Finally, the perform phase includes construction supervision of the maintenance actions. This research focuses on the first two steps within the CBM policy, steps three and four are outside the scope. The CBM policy requires good data and information management, which is linked to the life cycle management of the bridge. According to Qi et al. (2019), the DT technology can support the activities of the CBM policy by analysing, simulating, and predicting the life cycle performance of a bridge. The DT concept is discussed further in the next paragraph.

2.4 The rise of Digital Twin

There are several explanations and definitions of a DT from the literature as it is linked to multiple sectors (Tao, Cheng, Qi et al., 2018). The concept of a DT was first proposed in 2002 by Dr. Grieves in a presentation on Product Lifecycle Management (PLM). At the time, a DT was formulated as a virtual, digital equivalent of a physical product (Grieves, 2014). Later in 2010, the concept of DT was used for the first time in a scientific publication by the US space agency NASA in their technology roadmaps (Grieves & Vickers, 2017). Until 2015, there was limited exploration of the DT concept. As of 2015, the rise of machine learning, wireless communications and cloud computing has made the concept of DT a hot topic in the research world (Lu, Liu, Kevin et al., 2020).

2.5 Digital Twin in the construction industry

In the construction sector, the concept of DT is often compared to the Building Information Modelling (BIM). According to Succar, Sher and Wiliams (2012), BIM is an integrated set of policies, processes and technologies that generate a methodology whereby project designs and project data can be managed digitally throughout the life cycle. Although there are different views in the literature, in this research DT is considered part of BIM. The BIM technologies emphasize the virtual world, while DT is used for the relationship between the physical and the virtual world (Tao et al., 2018). A DT provides insight into the events in a physical world which can be analysed in a virtual world and then presented to users (Tao, Sui, Liu et al., 2019; Tao, Zhang, Liu et al., 2019; Boschert, Heinrich & Rosen, 2018). By monitoring, analysing, simulating, and predicting the behaviour of the physical asset in the virtual world, DT ensures better data exchange with the aim of optimizing business processes (Qi et al., 2019). As mentioned in the introduction to this research, a DT is defined in this research as: *a semantically linked collection of models, information and data that fully describes the physical system.*

In the context of bridge management, the following key features of DT can be defined (Qi et al., 2019; Ye, Butler, Calka, et al., 2019):

- The bridge is **connected** to the DT. By collecting data from the bridge in the physical world and displaying it in the virtual world.
- Sharing data in a **common data environment**. The DT includes one model in which all data is stored and accessible and modified by various bridge management stakeholders.
- **Visualizing data and information**. The DT can be used as a **visualization tool** that can be used to retrieve data from information in context, stimulate communication and collaboration.
- **Simulating 'what-if' scenarios**. The DT can be used to run what-if scenarios to, for example, assess risks and make predictions about future performance of the bridge. What-if scenarios can mimic the behaviour of the different bridge and display scenarios.

2.6 Digital Twin building blocks

Hokkeling (2020) developed a reference framework for DT in construction as described in the introduction of this research. The framework consists of six building blocks: physical layer; model layer; data layer; connection layer; service layer; enterprise layer. The framework is generic for the DT in construction, the contents of the building blocks are context dependent. The building blocks are explained in more detail in the sections below. Figure 3 represents the DT building blocks in bridge management.

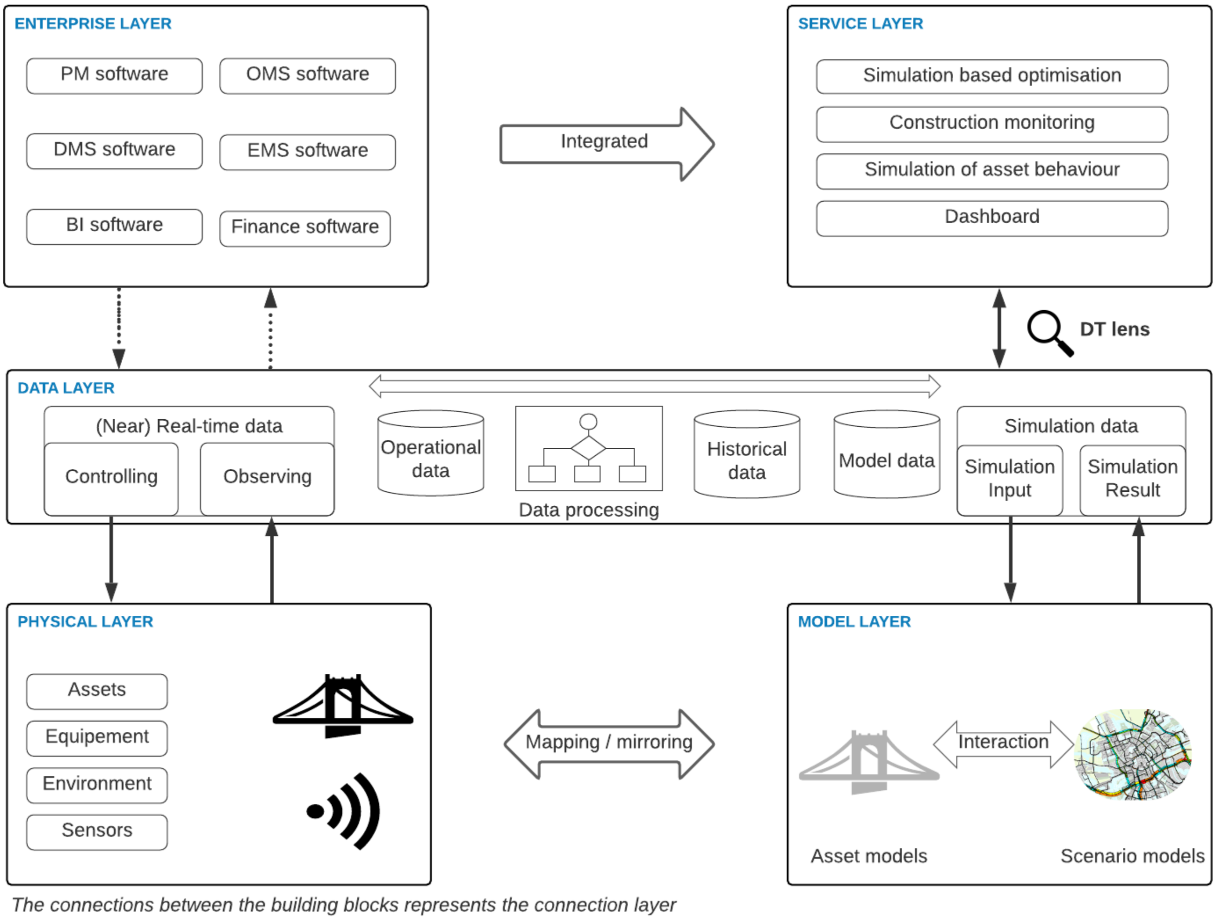

Figure 3.; *DT building blocks in bridge management. Adapted from Hokkeling (2020)*

Physical layer
The physical layer is the first building block and refers to the physical system reflected by the DT. The physical layer concerns all building resources in the physical system that are necessary for execution, observation, data transmission and the final product (built construction). In this research, the physical system is a bridge. The physical layer consists of three categories: Observable entities (1) refer to things from the real world that can be observed but cannot themselves communicate with the virtual world. Observable entities include in bridge management: the bridge, tools, materials, processes, and the environment. Observers (2) are entities that could observe the observable entity and record data. Observers in bridge management include the following elements: the inspectors, sensors, scanners, and cameras. Data transmission components (3) include network equipment that act as transmission components. The network equipment can transfer the data collected by the observers to the virtual world.

Model layer
The model layer is the second building block consisting of multiple models that together fully represent the physical system in virtual space. The physical system in the virtual space consists of two categories: asset models and scenario models. The asset model consists of a collection of models that reflect the physical asset in the virtual space. The different models are: 1) geometric model; 2) physical model; 3) behavioural model. In bridge management, the geometric model contains geometric information of the bridge. A geometric model can be, for example, a CAD model in the form of Revit or Civil3D model. In addition to the geometric model that describes all the geometric information of the bridge, a physical model can be used. In contrast to a geometric model, a physical model contains information about the characteristics of materials, such as performance. The behavioural model registers the behavioural logic of the bridge or its structural elements. Behavioural Modelling in bridge management can display dynamic behaviour of an element or elements.

Scenario models in DT reflect the physical processes of the bridge in the virtual space. The scenario model consists of four different models: 1) environmental model; 2) equipment model; 3) process model; 4) numerical optimization model. An environmental model reflects the bridge's surroundings. In bridge management this can be done, for example, in the form of a traffic model in which the traffic intensity can be included. Equipment model reflects the resources in the virtual space, these models can relate to auxiliary machines (e.g., drones) or auxiliary structures (e.g., scaffolding). A process model represents the process steps required in the physical process in the virtual space. Finally, with a numerical optimization model, different scenario results can be evaluated to arrive at the optimal scenario. In bridge management, for example, various scenarios could be considered for maintenance measures to be taken.

Data layer

The data layer is the third building block of the DT, which consists of the elements responsible for acquiring, processing, storing, and integrating data. The data layer is considered the central element that connects all building blocks. The data layer has the following five functionalities: 1) data collection; 2) data transfer and data storage; 3) data processing; 4) data integration; 5) data visualization.

In bridge management, the data for a DT can be collected from various sources: hardware, software, and network sources. Hardware resources can be divided into static and dynamic data. Static data includes information characteristics about the physical bridge, such as the structural elements and sensors. Dynamic data includes all data collected by observers in the physical layer. Data in the form of sensor data, point clouds, images and so on. Software data contains data from information systems. In bridge management these are data management systems. Network data includes data from the internet that can be collected by search engines. Data transfer and data storage are two functionalities that go together. Data transmission techniques can be divided into wired and wireless technologies. The Internet of Thing (IoT) is now widely used for the transmission of sensor signals to a data storage. All data generated by sensors, cameras and scanners is collected and sent to a data store via Wi-Fi or LAN. Data processing involves extracting relevant information from a large database that is collected by observers from the physical layer. The following type data are used for bridge management: signals, images, and point clouds. Signals from sensor data can be processed using algorithms or statistical methods. Visual material and point clouds both clearly show the as-is situation of the physical entity. Image recognition can be used to process data from images into useful information. Based on a large number of classified damage images, the image recognition algorithm is trained to detect damage from images (Gao & Mosalam, 2018). Using photogrammetry software, image material can be converted into a point cloud containing 3D information. Data integration is the process of presenting data from different sources in a single view. Data integration combines data from the physical layer, model layer and enterprise layer. Ultimately, the data integration is used to present the data to the end user.

Service layer

The service layer is the fourth building block of the DT that presents the specific services that a DT can offer to the end user. The service layer reflects the data in a user interface for the DT applications. The service layer consists of three elements: 1) interactive digital model/dashboards; 2) applications/web portal; 3) devices. The interactive digital model or dashboard are interfaces to present relevant information to the end users. Applications or a web portal makes the digital model or dashboard accessible to the end users. Devices, such as a telephone, tablet, PC or VR/AR glasses display the digital model or the dashboard to the end users.

Connection layer

The connection layer is the fifth building block of the DT, which connects the other building blocks. The connection layer semantically connects the different models, information constructions and databases. Semantic means that data is made meaningful and computer interpretable. By making data meaningful and computer interpretable with data structures, a network of linked data structures can be created. One of the most important data structures mentioned by Hokkeling (2020) is the ontologies. An ontology contains knowledge about the physical object as well as a non-physical object, such as processes, activities, and relationships. The ontology tool is increasingly appreciated in the construction sector. Example of a technique used in the construction industry is Semantic Web technology. The semantic web is based on an open web-based environment where product models and other relevant information are exchanged.

Enterprise layer
The enterprise layer is the last building block, this building block contains external software systems that can control the physical entity and are therefore relevant to integrate into the DT services offered by the service layer. The layer consists of various software systems that are used within that organization and software that contains information about the asset or the associated process. DT facilitates the data exchange with the software applications between the Data layer and the Enterprise layer by means of a bidirectional connection. The bidirectional connection ensures that changes to the software application (the enterprise layer) are updated throughout the asset lifecycle for the DT services.

The DT building blocks will serve as a framework for developing the functional design of the use cases in chapter 5 and 6 of this research. Each building blocks will be specified based on the content of the use cases.

2.7 Literature gap

It is assumed that DTs support the activities of the first two key steps of CBM policy (inspect and analyse). The functionalities of a DT meet the needs of the bridge management. Namely, providing insight into the physical world in a virtual world, by monitoring, analysing, simulating, and predicting the behaviour of the bridge. However, there is no clear picture of how DTs can support the challenges of bridge management engineering firms. To meet the research objective, this research first identifies in chapter 4 the challenges of engineering firms in the current practice of bridge management. Subsequently, in chapter 4, the use cases are identified on the basis of, among other things, the identified DT related challenges. Finally, in chapters 5 and 6, a functional design of the most relevant use cases is developed to demonstrate how DT can contribute to bridge management decision-making.

3 Methodology

This research is carried out using design scientific methodology of Wieringa (2004). In design science methodology, there are two types of research questions: knowledge questions and a design problem. Phase 1 (the current practices) and phase 2 (identify the DT use cases) are knowledge questions. The purpose of knowledge questions is on the one hand to map out the challenges in the current work process and on the other hand to identify the use cases of DT in bridge management. Phase 3 is concerned with the design problem. The aim of phase 3 is to link existing knowledge on the use of DT with bridge management practice by developing a functional design for the most relevant use cases. Figure 4 shows a visualization of the research approach. The research approach per phase is described in more detail below.

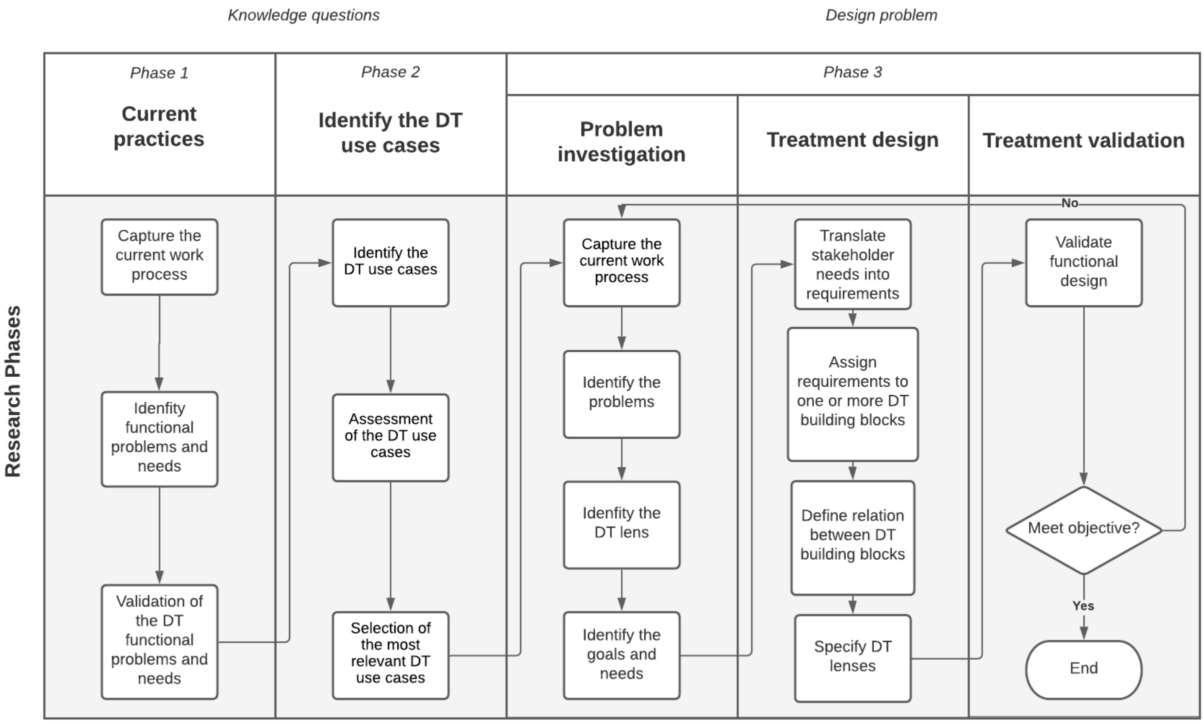

Figure 4.; *Visualisation of the research approach*

3.1 Phase 1 – current practices

In the first phase of this research, the objective was to map the challenges in the current work process of bridge management. To achieve this, interviews were held with people involved in bridge management who are employed by the initiator of this study, Antea Group. The interviews were conducted virtually as semi-structured interviews. The concept of DT was introduced and discussed in the introduction of the interview. During the interviews it was specifically asked which DT related challenges there are in the current work process. In addition, it was discussed whether the interviewees could come up with suggestions and solutions for the challenges discussed. The identified challenges were validated as DT related challenges based on the four main DT features as discussed in section 2.5. In conclusion, the first phase ended with a list of identified DT related challenges in current practice. In this way, the first research question: *what DT related challenges in current work process do engineering firms encounter in bridge management decision-making?*

3.2 Phase 2 – identify the DT use cases

In the second phase, the aim was to identify DT use cases for bridge management decision-making. The identified DT related challenges from the previous phase served as input. In addition, semi structured interviews were held with experts from other departments within Antea Group who are involved in various projects involving innovations, automation, sensors, and DTs. These interviews were conducted to collect data from other disciplines. Furthermore, literature and internet publications were searched for

DT technologies. The identified use cases were assigned to the four features of DTs in bridge management (connectivity between the physical world and the virtual world, common data environment, visualization of data and information and simulation of 'what-if' scenarios) discussed in chapter 2.5. The result of this phase is a list of use cases for DTs in bridge management decision-making which covered the second research question: *how can a DT support the challenges in the current work process of engineering firms in bridge management decision-making?*

From the list of identified use cases for DTs in bridge management, the most relevant use cases were selected to be developed into functional design in the next phase of the research. The selection of these use cases was made through an expert session with four experts from Antea Group. The criterion used in the selection is:

- To what extent does the use case relate to developments within Antea Group (pilot projects)?

Based on the expertise of the four experts, two use cases were chosen to further develop into a functional design.

3.3 Phase 3 – develop a functional design

Phase 3 is a design problem; the purpose of this phase was to make a functional design of the selected use cases from the previous phase. The functional design is developed using the design cycle method of Wieringa (2014) (see Figure 5).

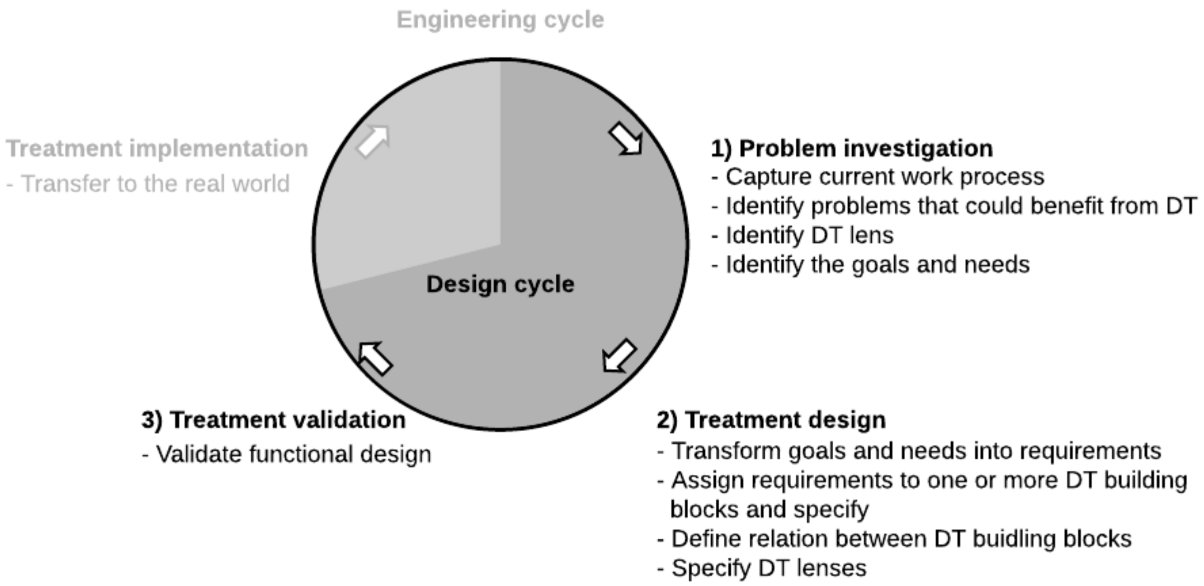

Figure 5.; *Design cycle. Adapted from Wieringa (2014)*

The first step (1) of the design cycle is the problem investigation. Based on the interviews from phase 1 and four additional semi-structured interviews, the problem research for the two use cases was elaborated. First, the problem investigation examined the current process, the stakeholders, and the areas for improvement. Both use cases contain multiple stakeholders and thus DT lenses. The most relevant stakeholder was selected in consultation with the initiator of the research, Antea Group. Finally, the goals and needs of this relevant stakeholder have been determined.

In the second step (2) of the design cycle, the stakeholder goals and needs from both use cases are translated into requirements based on the perception of the researcher. The MoSCoW method (Van Vliet, 2008) was used for this. Subsequently, a design solution was developed by assigning the requirements to the DT building blocks and specifying them based on literature and existing solutions mentioned during the interviews. Using a DT lens, various building blocks are linked together, and DT integrates an unambiguous picture of the information relevant to the relevant stakeholder. Finally, the information is presented in a functional design.

In the third step (3) of the design cycle, the functional design was validated in the form of an expert session with four experts. The expert session focused on the following two aspects that were discussed:

- Completeness and prioritization of the functional requirements.
- Validate the functional design.

The result of this phase is a functional design for two use cases for DT in bridge management decision making, which answers the final research question: *what does the functional design look like for a specific chosen use case?*

4 Use cases for DT in bridge management

This chapter deals with identifying the DT related use cases in bridge management and developing a functional design for the most relevant use cases for Antea Group. First of all, the challenges in the current work process of bridge management within Antea Group are mapped out. Subsequently, based on the identified DT related challenges, DT use cases are presented from which the most relevant alternatives for Antea Group's business operations are selected for further elaboration.

4.1 Current work process

To gain insight into the current work process of bridge management within Antea Group, semi-structured interviews have been conducted with a selection of stakeholders. This selection was made based on function. For the asset management department, all project leaders, project managers and senior advisors within the asset management department were interviewed, a total of seven people. During the interview, several questions were asked about the current work process.

The current work process focuses on the first two steps within the CBM policy, as described in chapter 2.3. Figure 6 shows an overview of all steps in the current work process. The first key step in the CBM policy is the inspection and in the current work process consists of 4 steps (step one to step four in Figure 6). Steps five, six and seven in the current work process belong to the second key step in the CBM policy.

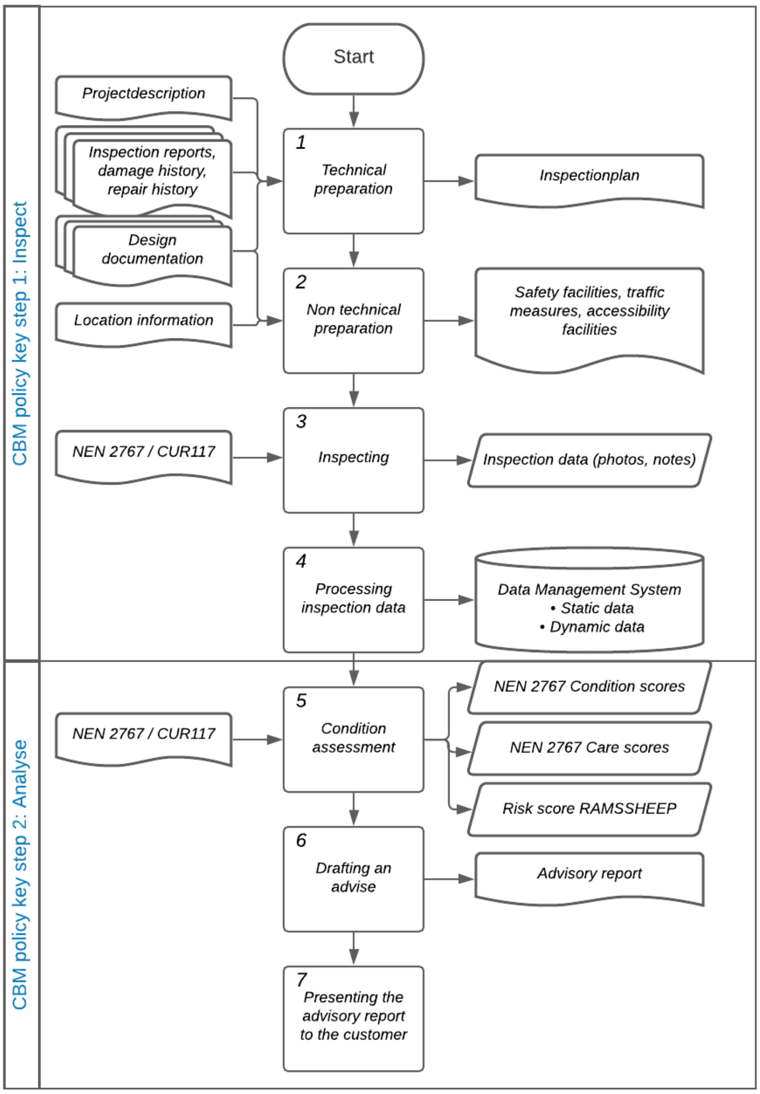

Figure 6.; *Process steps of the current work process*

4.1.1 Identify the challenges in the current work process

During the semi-structured interviews, the interviewees were asked what challenges are experienced in the current work process. The interviews showed that the current work process is characterized by seven DT related challenges. The seven DT related challenges are described in Table 1.

Table 1.; *Challenges in the current work process*

Nr.	Description
1.	**Frequent transfers of data and information** There are many transfer moments of data or information in the current work process, which means that the probability that information will be lost is high. The loss of information takes a lot of time and (negative) energy to recover. In addition, too many transfer moments of data or information result in the probability that incorrect data will be collected, analysed, or presented. As a result, later in the process, the information does not meet the needs of the end user.
2.	**Deluge of data** Those involved in the work process experience difficulties in filtering the relevant data from the large amount of data available. As a result, filtering information takes a lot of time or information is not even found.
3.	**Data from previous inspections is often inaccessible** In the current work process, it is not possible to view previous inspection results in digital during an inspection. As a result, the preparation for an inspection takes a lot of time. In addition, the inspector does not have access to information that is sometimes essential, which is at the expense of the quality of the inspection.
4.	**Preparations for visual inspections are seldom thorough** There is insufficient preparation before a visual inspection due to insufficient time and/or budget. In complex or dangerous inspections, this can lead to dangerous or unforeseen situations. This may endanger the inspector's safety. Furthermore, insufficient preparation leads to an increased risk of inefficiency with the result that the inspection quality decreases.
5.	**The efficiency of visual inspections is not optimal** The inspector records his findings in writing and on photos and draws up an inspection report. These are largely manual actions. This method can lead to errors. Automation of (part of) these actions prevent these errors and is faster.
6.	**Visual inspections are subjective to an inspector's interpretation** Visual inspections are subjective, which means that there is a chance that the quality will not always be achieved by the inspector. This aspect is reinforced if the inspector is still inexperienced.
7.	**The presented information may mismatch the expected (or needed) information to the customer** Because information is often presented in text, it is difficult for the customer to analyse. Analysing the information is time consuming and potentially inefficient. The customer often has a need for insight instead of information. The customer is more interested in the consequences than the technical condition of the bridge.

4.1.2 DT related challenges

To demonstrate that the identified challenges were related to DT, the challenges in this section were linked to at least one of the four features of DTs, as described in chapter 2. Arguments have been added for each challenge to justify that the challenge is related to at least one of the features of the DT concept. see Table 2.

Table 2.; *Arguments why the identified challenges are DT related*

Nr.	Description
1.	**Frequent transfers of data and information**
	Using a DT, it is possible to store and modify data and information during the inspection process in a **common data environment**, reducing the number of transfers of information and data.
2.	**Deluge of data**
	The DT has a **common data environment** where all data is stored in one model, accessible and can be changed by different stakeholders in the work process. This makes it easier to find and filter information.
3.	**Data from previous inspections is often inaccessible**
	The DT is connected to the physical bridge because all previous inspection results are stored in a **common data environment**. Using a DT, his previous inspection results are digitally accessible to the inspector during an inspection. This increases the validity of the inspection results.
4.	**Preparations for visual inspections are seldom thorough**
	With the help of a DT, it is possible during the inspection to have digital access to a **common data environment** in which all inspection documents that are usually only available in the current process during the preparation of a visual inspection.
5.	**The efficiency of visual inspections is not optimal**
	The DT is **connected** to the physical bridge because during the visual inspection inspectors can digitally collect, store and process data and information in the **common data environment**. This reduces manual actions and the probability of errors.
6.	**Visual inspections are subjective to an inspector's interpretation**
	The DT is **connected** to the physical bridge because different data sources (e.g., visual inspections, sensors, cameras) are integrated into one **common data environment**. This makes more objective and more complete information available.
7.	**The presented information may mismatch the expected (or needed) information to the customer**
	The DT can be used as a **visualization tool** to retrieve information in context and communicate it to the customer. In addition, DT can be used as a **simulation tool** to perform what-if scenarios and present them to the customer. This way of presenting information is in line with the needs of the customer and provides more insight into the (future) behaviour of the citizen.

4.1.3 Validation

The DT related challenges were validated with the interviewees through a questionnaire. The respondents were asked whether they recognize the identified challenges. The questionnaire showed that six of the seven challenges were recognized by the respondents. Half of the respondents did not recognize themselves in the following challenge 'Visual inspections are experienced as labour-intensive, because it is mainly done visually'. Respondents' explanations showed that the labor intensity of visual inspections was not perceived as a problem. However, the respondents did indicate that visual inspections can be organized more efficiently. The formulation of the challenge has therefore been adapted to: 'The efficiency of visual inspections is not optimal'.

4.2 Identify the DT use cases

The use cases have been identified based on the DT related challenges, the interviews from the previous paragraph and literature on DT applications. In addition, five interviews were conducted with experts from other departments within Antea Group. The selection of experts was made based on an affinity with innovation, automation, sensors, and DTs. During the interviews, suggestions were made for DT applications that can be applied in bridge management.

A total of eight use cases have been identified. Each use case is linked to one or more challenges from chapter 4.1. Table 3 shows an overview of all use cases. Table 3 is followed by a description per use case, including a substantiation to which problem or problems the use case contributes and a description of what the use case looks like.

Table 3.; *Overview of the identified use cases with a link to the problems of the previous paragraph*

Nr.	Use case	Challenge						
		1	2	3	4	5	6	7
1.	Digital access to inspection information and input of inspection data during a visual inspection	X		X		X		
2.	Visualization tool to retrieve data from the context		X					
3.	Damage detection						X	
4.	Simulation of complex or dangerous inspections				X			
5.	Inspector is navigated during the visual inspection					X		
6.	Simulation of what-if scenarios							X
7.	Prediction of the development of a damage pattern					X		
8.	Prediction of the performance of the bridge							X

1. Digital access to inspection information and input of inspection data during a visual inspection
In the current process, an inspector has no direct access to information about the bridge during a visual inspection. As a result, it is possible that risks are not properly estimated, for example because the inspector has no information about previous inspection results (challenge 3). In addition, in the current process, the inspection data is manually recorded on location and processed in a data management model at the office (challenge 5). Which creates many moments of transfer of data and information (challenge 1), increasing miscommunication. Interviews with Antea Group engineers have shown that they expect that a digital inspection tool could contribute to solving the above-mentioned problems.

In this use case, the DT is connected to the physical bridge because inspectors can retrieve, store and update information about the bridge during a visual inspection (Rasheed, San & Kvamsdal, 2020). The DT is used to give inspectors digital access during a visual inspection to information needed while inspecting the bridge such as design documentation, maintenance history and previous inspection results. This gives inspectors more insight and allows the inspector to assess elements better, so that risks can be better estimated. Furthermore, it is possible for the inspector to change or enter inspection data in the DT during the visual inspection. This allows inspectors to record the inspection data on location, making the processing of the inspection data more efficient and less error-prone due to fewer transfer moments.

2. Visualization tool to retrieve data from context
In the current process, filtering relevant data from a large amount of data is experienced as a challenge by the interviewees (challenge 2). It is expected that visualizing information will make information more understandable and provide more insight for those involved in the project. During the interviews, the interviewees mentioned data visualization techniques such as a dashboard or a heat map (a graphical representation of data that uses a color-coding system to represent different values).

In this use case, a DT is used to make more complex information easier to understand by applying visualization techniques. By using the DT as a visualization tool, data or information can be retrieved in context. This will promote communication and collaboration between project stakeholders (Ye et al., 2019).

3. Damage detection
In the current process, visual inspections can be incomplete or subjective (challenge 6). When damage is found, important details are often unknown, such as: how did the damage develop over the past period? For example, because the interval of the periodic visual inspection is too long, so that damage is discovered too late. Or because damage is not detected by the inspector. Another question could be: how is the bridge used (for example in terms of traffic weight)? How is the damage linked to environmental variables (e.g., temperature)? It is expected that sensors can contribute to the inspection process.

In this use case, the DT is used to integrate data from different sensors so that damage to the bridge can be analysed. Sensors can be used to detect damage in hard-to-reach places. For example, sensors can monitor hidden defects (e.g., incipient corrosion) in hard-to-reach places (Dohrmann, Gesing & Ward, 2019). Sensors can collect data about, for example, the dimensions of a crack, traffic weight, vibrations, deflection, and outside temperature. By relating and analysing different types of sensor data using data analysis methods, underlying trends, patterns, and correlations can be identified. This makes objective and more complete information available about the damage, so that better decisions can be made.

4. Simulation of complex or dangerous inspections
In the current process there is little time and budget to prepare visual inspections (challenge 4). This may pose a risk for the safety of inspectors, especially in complex or dangerous inspections. Insufficient preparation can also lead to inefficiencies that have a negative impact on the quality of the inspection.

In this use case, DT is used to run simulations of a complex or dangerous inspection. The inspector can simulate a complex or dangerous inspection in the virtual world before performing it in the physical world. By simulating complex or dangerous inspections, the inspector is trained to carry out the inspection. This increases the efficiency of the inspection. In addition, the risk of complications or accidents is reduced.

5. Inspector is navigated during the visual inspection
In the current process, the inspector has a list of elements to be inspected and the inspector follows a certain route on his own intuition. The interviews with Antea Group engineers led to a suggestion for navigation for the inspector during an inspection. This directs the inspector to the correct location. This allows the inspector to inspect faster and more efficiently (challenge 5).

In this use case, a DT is used to navigate the inspector during an inspection. The inspector is sent directly to the correct location with the help of the DT (Ma, Cai, Mao et al., 2018. This allows the inspector to carry out the inspection faster. The probability of errors is also reduced, the inspector does not forget any elements or does not inspect elements twice.

6. Simulation of what-if scenarios
Chapter 4 shows that the customer needs insight instead of information (problem 7): the customer is more interested in the consequences of a certain scenario than in the technical condition of the bridge. A simulation of what-if scenarios can provide insight into different scenarios.

In this use case, a DT is used to simulate what-if scenarios. Simulating what-if scenarios provides insight into the consequences of, for example, certain maintenance measures, repair interventions or investments. This gives the customer insight in advance into what effects the above measures will have on the bridge and the surrounding environment. The simulations can be weighed up against each other, assessed and presented to the customer.

7. Prediction of the development of a damage pattern

In the current process, visual inspections can be organized more efficiently (challenge 5). Visual inspections are performed periodically, which means that limited information is available about the historical development of a damage mechanism. The historical development of a damage mechanism on a bridge is an important aspect for the further development of a damage mechanism.

In this use case, a DT is used to make predictions about the occurrence of damage to a bridge. In addition to detecting damage (use case 4) a DT can predict the course of damage. Sensors are placed on or near an incipient or existing damage. Sensors can collect data about, for example, the dimensions of a crack, traffic weight, vibrations, deflection, and outside temperature. This dataset can be used to predict the development of the deterioration and deterioration of material properties. The development of the damage can be determined using calculation techniques. An example of a calculation technique is the prognosis of fatigue damage mentioned in the study of Saad, Fu, Zhao et al. (2018). With this method the fatigue damage is assessed and to predict the growth behaviour of the cracks. When the development of the damage is predictable, an inspector needs to inspect less often. As a result, visual inspections can be organized more efficiently.

8. Prediction of the performance of the bridge

In the current process there is a mismatch between the way information is presented to the customer and the customer's needs (challenge 7). The customer has a need for technical residual life, the risk of failure and the development of damage mechanisms of the bridge.

In this use case, a DT is used to predict the performance of the bridge. The DT is used to display multiple information sources (including static and dynamic data) of the bridge in an expected model. The developing model consists of, are physical and probabilistic models with the technical, occurrence of failures and development of the game. The predictive model provides in the technical implementation, the risk of failure and the development of insight into the system of the bridge, resulting in the information being more in line with the customer's wishes.

4.2.1 Selection of the DT use cases

In this section, the most relevant use cases have been selected for further elaboration in the next phase of the research. The selection of the use cases is based on an expert session with four experts from Antea Group. There is one criterion that determines the selection of the most relevant use cases, and that is: the use case must be in line with developments and innovations (pilot projects) within Antea Group. The four experts of Antea Group assessed the use cases using the five-scale method (1 = insufficient, 5 = very good). The average scores of all experts are shown per criteria in Table 4.

Table 4.; *Overview of the use cases*

Nr.	Use case	Score
1.	**Digital access to inspection information and input of inspection data during a visual inspection**	**4,5**
2.	Visualization tool to retrieve data from context	3
3.	Damage detection	3,5
4.	Simulation of complex or dangerous inspections	3
5.	Inspector is navigated during the visual inspection	3,5
6.	Simulation of what-if scenarios	3
7.	Prediction of the development of a damage pattern	2,5
8.	**Prediction of the performance of the bridge**	**4,5**

Based on the assessment of the four experts, the following two use cases have been chosen to further develop into a functional design in the next phase:

- Digital access to inspection information and input of inspection data during a visual inspection.
- Prediction of the performance of the bridge.

To further explain the choice of use cases, an explanation has been formulated for each use case:

Use case 1: 'Digital access to inspection information and input of inspection data during a visual inspection' is in line with the developments of the GBI data management system within Antea Group:

GBI management system. Antea Group uses the GBI management system. GBI is a management system for infrastructural assets in public space. Users can view and update information about infrastructure assets and objects. In the current process, the inspection data is processed in GBI after the inspection at the office. Antea Group is investigating how GBI is digitally available to the inspector on location. This allows the inspector to enter inspection data in GBI on location, making the process faster and more efficient.

Use case 2: 'Prediction of the performance of the bridge' is in line with two pilot projects within Antea Group where multiple sensors have been placed to predict the bridge's performance:

Smart Bridge Leeuwarden. In the Smart Bridge Leeuwarden pilot, Antea Group uses sensors to predict the remaining lifespan of a fixed construction. The 1963 viaduct is monitored in the smallest detail by a total of 30 sensors. The main type of sensor used is the Weigh in Motion system. This makes it possible to determine exactly how much (freight) traffic is driving over the bridge. The data from the sensors is used to measure the deflection. Calculation models can then be used to determine which minimum standards the viaduct must meet. Subsequently, the actual traffic weight is tested against the standards to be able to make statements about the remaining lifespan of the bridge.

Prinsenbrug Haarlem. The second pilot project is the 'Data driven predictive maintenance Prinsenbrug in Haarlem'. A movable concrete bridge where the Machine Condition Monitoring system of Antea Group is being tested. The malfunction analysis of the Prinsenbrug shows that 26% of the malfunctions can be traced back to the mechanical and hydraulic movement works. And 30% of the malfunctions can be traced back to the barrier boxes. These disruptions result in high maintenance costs and unavailability of the bridge for road and/or water users. The maintenance of the bridge drive is monitored using sensors. Antea Group wants to use the data to predict failures so that failures can be reduced in the future. By constantly monitoring critical parts of the bridge, material degradation can be made transparent. This means that measures can be taken in good time to prevent malfunctions in the future.

5 Use case 1: Digital access to inspection information and input of inspection data during a visual inspection

This chapter is concerned with the development of the functional design of the first use case using the design cycle method of Wieringa (2014). The chapter is structured in the following three tasks: problem investigation, treatment design, and treatment validation.

5.1 The problem investigation

This section is concerned with the problem investigation, the first task in the design cycle. The problem investigation consists of the following parts: capturing the current process, identification of the problems in the current process, selection of the DT lens and the identification of the stakeholder goals and needs.

Bridges are characterized by their longevity and slow developing damage mechanisms. Periodic visual inspections are performed by inspectors to monitor the condition of the bridge. Inspectors report the inspection data per bridge section or damage mechanism, there are various methods for this. The most common method is to record the findings in writing and by photo during the inspection. All findings are subsequently processed in the data management system at the office. Based on the inspection data and the damage records, the inspectors and structural engineers assess the bridge and determine any maintenance measures necessary to guarantee the performance of the bridge and manage the risks. Finally, in consultation with the asset manager of the engineering firm, an advice is drawn up in an inspection report.

The results of chapter 4 and additional interviews with two inspectors show that current practice is characterized by the following problems:

1. Many moments of data or information transfer. During the inspection process, data and information are exchanged at many different moments. The current process leads to a high risk of miscommunication.
2. Insufficient validation with previous inspection results. In the current work process, it is not possible to view previous inspection results in digital during an inspection. As a result, an inspector may end up in an unforeseen situation and the inspection may have to be carried out again, with high costs as a result.
3. Manual operations. The inspector records his findings in writing and on photos and draws up an inspection report. These are largely manual actions. This method can lead to errors. Automation of (part of) these actions prevent these errors and is faster.

As mentioned above, there are several stakeholders involved in the inspection process of a bridge. Each of these stakeholders has their own interests and therefore their own DT lens. Due to the limited time for this research, the development of the functional design focuses on one DT lens. The most important stakeholder when inspecting a bridge is the inspector. This use case therefore focuses on the inspector's DT lens.

In order to develop the functional design of this use case, the goals and needs of the inspector have been worked out. Two inspectors were interviewed for this. The interviews with two inspectors show that a DT:

1. Provides information about the static asset information about the structural elements of the bridge.
2. Provides information about the damage history and repair history of the damage mechanisms.
3. Provides information about the inspection dates of previous inspections.
4. Must be able to store digital the inspection data.
5. Must be able to share asset information with other stakeholders (e.g., the structural engineer and the asset manager).

5.2 Treatment design

This section is concerned with the treatment design, the second step of the design cycle the treatment design. The treatment design consists of the following parts: translating the stakeholder goals and needs into requirements, specifying the DT building blocks and specifying the DT lens.

5.2.1 Requirements

In this section, the inspector's goals and needs are broken down into functional requirements. The requirements are defined based on four different types of requirements according to the MoSCoW method, which is used in the definition and prioritization of requirements (Van Vliet, 2008):

- Must haves: requirements that are essential)
- Should haves: requirements that are important, but not necessary)
- Could haves: less important, but interesting in the future)
- Won't haves: requirements that may be relevant that are not included)

The number(s) after each requirement refers to the goals and needs of step 1 (1 = goal or need number 1). See Table 5 for an overview of all functional requirements.

Table 5.; *Functional requirements use-case 1*

Must haves	Should haves	Could haves	Won't haves
Digital data display: DT must be able to digitally show asset information, damage history, repair history and previous inspection results to the inspector during the visual inspection (1, 2, 3).	**Visual representation in 3D**: DT should be able to display asset information**,** damage history, repair history and previous inspection results to the inspector (in 3D) during the inspection (1, 2, 3).	**Recognizing speech and gestures:** DT could recognize speech and gestures during the inspection (4).	**Prescriptive**: DT does not have the ability to automatically propose interventions (4).
Store and process data: DT must be able to collect, capture, organize, structure and store data (4).	**Recognize GPS location**: DT should be able to determine and log the inspector's real-time GPS location (x, y, z) during the inspection (1, 2, 3, 4).	**Damage image recognition**: DT could recognize damage from images and videos (4).	
Store and process photos: DT must be able to collect, organize, structure and store photos (4).	**Store and process videos**: DT should be able to collect, organize, structure and store 360-degree photos and videos during the inspection (4).	**Prescribed (suggestive):** DT could make suggestions for measures to be taken or condition scores to be given. (4).	
Sharing data: DT must be able to digitally share data and information with stakeholders during the inspection (5).	**Data model recognition**: DT should be able to easily suggest and open the correct data model prior to an inspection (5).		

Contribution arguments were added for each requirement to justify the requirements, see Table 6. In addition, each requirement was assigned to one or more DT building blocks (P = physical layer, M = model layer, D = data layer, S = service layer, E = enterprise layer). The connection layer represents the connection between the other building blocks, so this layer is not shown. The DT building blocks, as described in chapter 2.6 of this study, form the frame of reference.

Table 6.; *Contribution arguments functional requirements use case 1*

Requirement	Goal	Contribution argument	P	M	D	S	E
Digital data display	1,2,3	To provide the inspector with information, the design documentation, maintenance history and previous inspections must be digitally available to the inspector.		X	X	X	X
Store and process data	4	To speed up the processing of the inspection data, the inspector must be able to digitally store inspection data in the correct location in the DT during the inspection.			X		X
Store and process photos	4	To speed up the processing of the inspection photos, the inspector must be able to digitally store the photos in the correct location in the DT during the inspection.			X		X
Sharing data	5	Those involved in bridge management (for example the structural engineer or the asset manager) must have access to the DT during the inspection so that the inspection data is immediately available.		X	X	X	
Visual representation in 3D	1,2,3	The inspector must have digital access to a visualization of the bridge during the inspection, so that the design documentation, maintenance history and previous inspection results can be easily found.		X	X	X	X
Recognize GPS location	1,2,3,4	The inspector's GPS location must be recognized in real-time, so that the GPS location can be linked to the inspection data.			X		
Store and process videos	4	To speed up the processing of the inspection photos, the inspector must be able to digitally store the 360-degree photos and videos in the correct location in the DT during the inspection.			X		X
Data Model Recognition	5	To organize inspections more efficiently, it must be possible to simply open the data model of the DT at the start of an inspection.		X			X
Recognizing speech and gestures	4	During the inspection, the inspector must be able to digitally enter inspection data into the DT with speech or gestures, so that the inspector must perform fewer manual actions.			X		
Damage Image Recognition	4	The DT must recognize damage images from photos and/or videos, so that part of the visual inspection can be automated.			X		X
Prescribed (suggestive)	4	To automate part of the analysis, the DT must be able to make suggestions for repair			X		X

		or rehabilitation work based on image recognition.					

The next section describes the DT building blocks and the relationship between the DT building blocks.

5.2.2 DT building blocks

This section describes what each building block in this use case looks like and what its functionalities are. The connection layer represents the connection between the other building blocks, this layer is not further elaborated. Figure 7 visualizes the framework and the relationship between the building blocks for this use case.

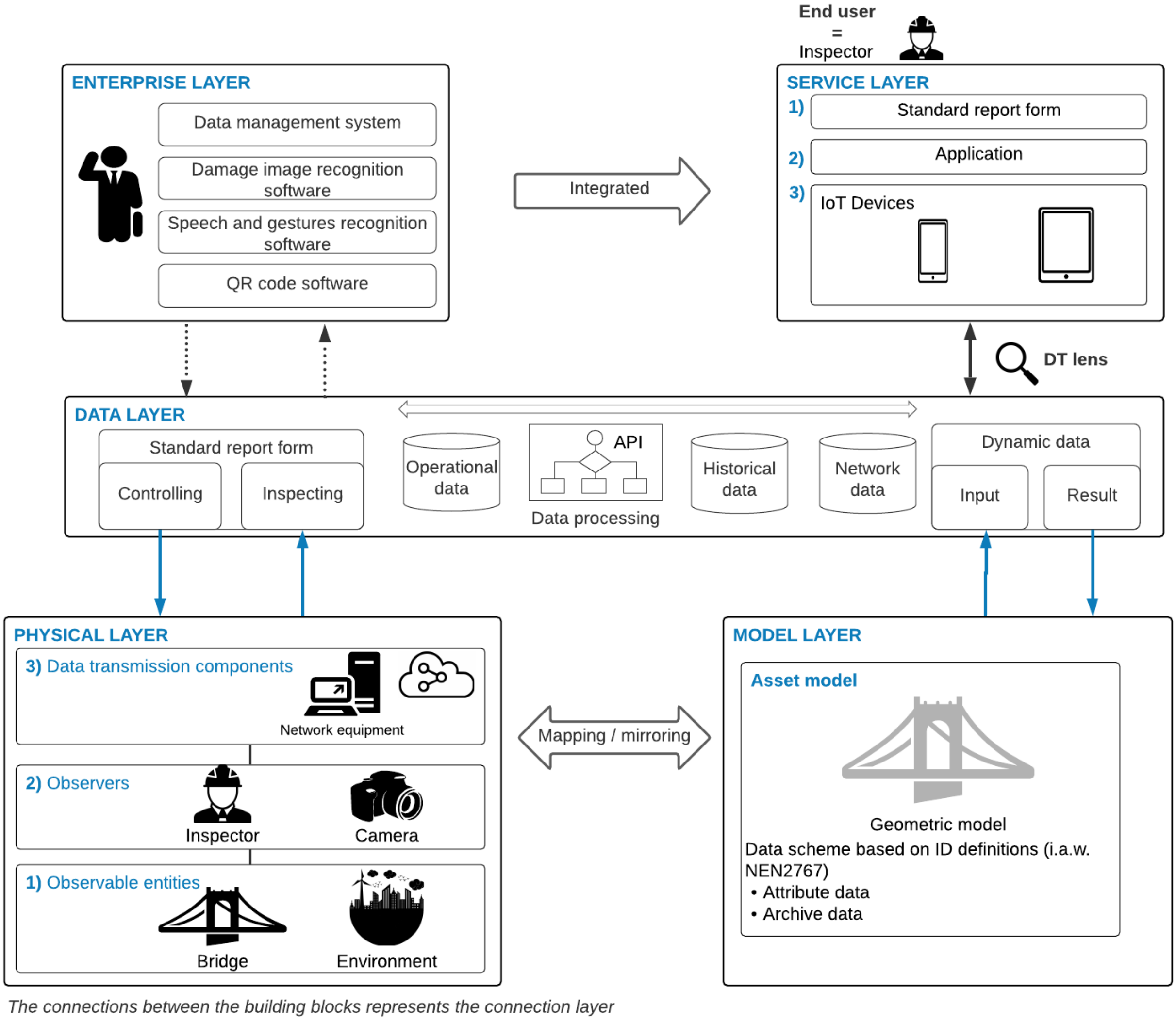

Figure 7.; *Relation between DT building blocks use case 1*

Physical layer

As described in chapter 2.6, the physical layer consists of three categories: 1) observable entities, 2) observers, 3) data transmission components. The physical system in this use case is the bridge. *Observable entities*. This use case involves inspecting the structural elements of the bridge and the environment that may affect the condition of the bridge. The observable entities for this use case are the bridge and the nearby environment. *Observers*. Since the inspection is performed by the inspector using tools such as a camera, the observers for this use case are the inspectors and the camera. *Data transmission components*. The data obtained by the observers is transferred to the virtual space in the data layer using network equipment.

Model layer

In this use case, the main observable entity in the physical layer includes the bridge in the MOL phase. The model layer can be divided into two categories, as described in chapter 2.6: asset models and scenario models. Only the asset models are relevant for this use case. The scenario models are not included because the use case does not focus on scenarios.

For this use case, the asset model consists of the geometric model. The geometric model contains information about the dimensions of all structural elements of the bridge, the type of material, material thickness and other material properties of these elements needed when inspecting a bridge. To be able to show this geometric information to the inspector, the information from the bridge must be available in a digital environment. For inspection work, the traditional 2D CAD model is limited in terms of linking data such as attributes and archives. The research of Shim et al. (2019) shows how such a 3D environment can be constructed. All structural elements of the bridge must be identified with their own ID. In the Netherlands this is done with a decomposition in accordance with NEN2767. Based on the role or service in the bridge system, the structural elements are classified in an inventory system. The inventory system consists of superstructures (e.g., road surface, cable, handrail) and substructures (e.g., abutment, bridge pier). Based on the geometric data, the inventory system, and the ID definition of the structural elements of the bridge, a 3D model will be generated. Figure 8 shows what a data scheme looks like. The ID of the structural elements contains two main characteristics: 'attribute' and 'archive'. The attribute function contains geometric information and information about the role of the element in relation to the bridge system. The archive function contains, among other things, the inspection data, the damage history, and the repair history.

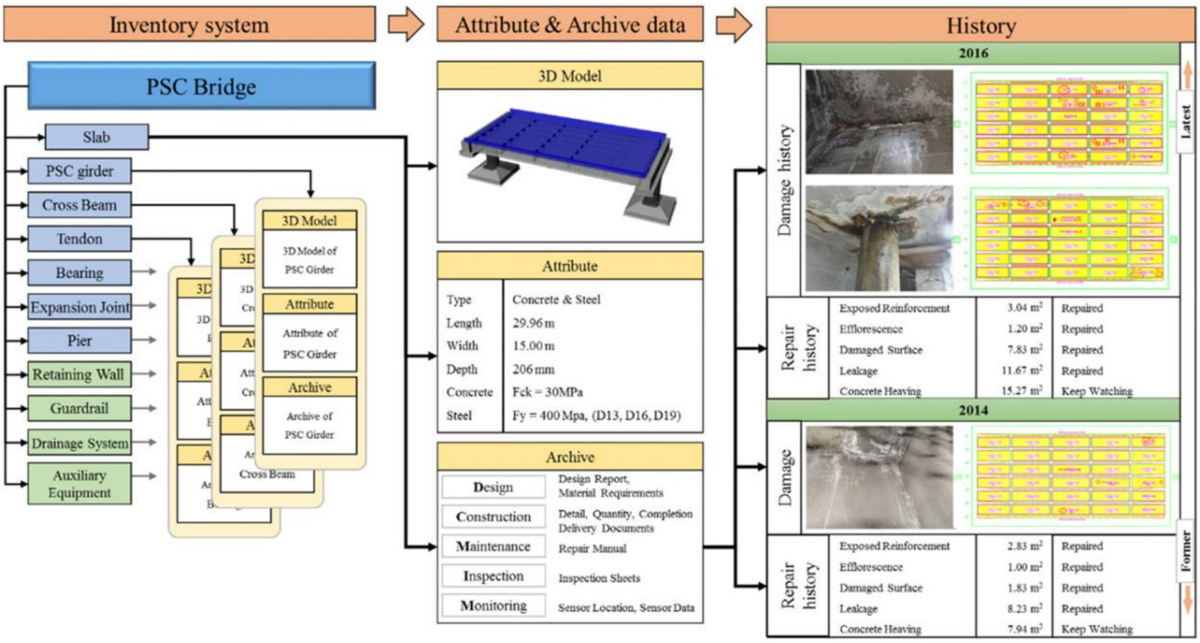

Figure 8.; *A data scheme of the 3D model of a bridge (Shim et al., 2019)*

Data layer

The data layer is the core element within the DT and is responsible for the following five functionalities: *Data collection.* In this use case, static data describes the geometric information of the bridge, as discussed in the previous section, these data falls under the main characteristic 'attribute' of the model layer. This data is retrieved from the data management system of the bridge. The dynamic data in this use case consists of the inspection data, inspection (360-degree) photos and videos, the damage history, repair history and the condition score. This data falls under the main feature 'archive' of the model layer. A standard report form is used to create the archive function. To create a standard report form, the inspection data must be stored in primitive file formats (.pdf for documents, .jpg for photos, .avi for videos) (Shim et al., 2019). The inspector has access to readable information from the archive function with a standard report form. Furthermore, new inspection data are entered in the standard report form.

The standard report forms are linked to the ID of the structural elements, so that the inspection data is automatically stored in the correct location. During the visual inspection, the inspector describes the damage to the bridge based on his observations by manually completing (or based on speech and gesture recognition) a standard report form. With the help of GPS, the location of the inspector is followed, so that inspection data contains GPS coordinates and is stored at your correct location. Image recognition ensures that parts of the visual inspection are automated. In addition to static- and dynamic data, this use case also includes network data, also known as open data. Network data includes weather data and temperature measurements (from KNMI, Royal Netherlands Meteorological Institute). Network data is linked to the 'archive' attribute of the model layer. This data is relevant to determine the cause of damage mechanisms.

Data transfer and data storage. The inspection data generated by the inspector is sent via IoT devices to the data management system of the DT through the connection layer using a connectivity network. Examples of a connectivity network are existing mobile networks (2G, 3G, 4G), the new 5G or special IoT networks such as LoRa or LTE-M (Ding, Nemati, Ranaweera et al., 2020). Which type of connection is best depends on the amount of data, the energy consumption and the frequency with which data is collected. It follows from the requirements that it must be possible to easily retrieve the correct data model from the DT at the start of the inspection. Logging in with a QR code is a solution for this. The inspector scans the QR code with the IoT device, which immediately opens the data model of the bridge (Shim et al., 2019). The QR code is a physical QR plate attached to the bridge.

Data processing. When processing data, useful information is filtered from a large database that is collected by the observers from the physical layer. The technology used to extract useful information depends on the type of data. In this use case, two types of data are collected: inspection reports and visual material (photos and videos). Inspection reports are filled in digitally in the inspection application using a standard report form, which data is automatically linked to the data model based on predefined rules. The image material is processed into relevant information in the business layer using external software systems (damage image recognition software, speech, and gesture recognition software and QR code software).

Data integration and data visualization. Integration of data ensures that data from different data sources are combined into new information in one overview (the DT) (Qi et al., 2019). In this use case, data integration ensures that the data that the inspector enters in the standard report form is combined with the data from the data management system of the engineering firm. Application Programming Interface (API) is used to provide the interface between the models and the data layer and filter the relevant information. Data visualization ensures that the inspection data is digitally presented in a clear manner to the end user (in this case the inspector during the visual inspection).

Service layer

The fourth DT building block is the service layer, which in this use case focuses on the presentation of information provided by the DT to the inspector. In this case, the service tier mirrors the user interface of the standard report form. As described in chapter 2.6, the service layer consists of the following elements:

1. Interactive digital model/ dashboards
2. Applications/web portal
3. Devices

In this use case, the information from the DT is presented to the inspector via the standard reporting forms and the 3D model of the bridge. This information is digitally accessible to the inspector via IoT devices such as a smartphone or a tablet. To increase the accessibility of the DT, a (cloud-based) web portal is used, so that the inspector has access to the DT from anywhere.

Enterprise layer

The enterprise layer contains external software systems that are used to inspect the physical bridge. In this use case, these are the following systems: *Data management system.* In the data management system with information about the bridge that is relevant when inspecting the bridge. The information in this data management system includes design documentation, inspection reports, damage history, repair history, guidelines, and recommendations. Antea Group uses a data collection platform called 'Golden Eye' to store data. The data is processed and read by Antea Group's portal called 'Antea World'. The data management systems used are GBI and IRIS (Integral Result Oriented Information System) of Rijkswaterstaat. *Damage Image Recognition Software.* This software is used to recognize damage from (360-degree) photos and videos generated by the inspector during the inspection. *Speech and gesture recognition software* is used to replace manual actions during the inspection. *QR code software* is used to log into the appropriate bridge data management system at the start of the inspection.

5.2.3 DT design alternative and additional functionalities

To complete the functional design, this section presents the basic alternative and the various additional functionalities of the functional design. The basic alternative and functionalities are based on the first three types of requirements (must haves, should haves, could haves) according to the MoSCoW method used in section 5.2.1 to define and prioritize the requirements. First, the basic alternative is provided and described. This is followed by additional 'should have' and 'could have' functionalities that function (separately) from each other.

Must have functionalities (basic alternative)

The 'must have' functionalities are based on the requirements of the 'must haves' from chapter 5.2.1 and form the basic alternative for the functional design of this use case. The functional design based on the 'must have' functionalities is shown in Figure 9. First, a 3D model of the physical bridge is generated based on the as-built documents (location, geometry, materials). The data scheme for a 3D information model (Figure 8) is used to structure inspection data making it organized and accessible to those involved in bridge management. In the data scheme it is shown that all structural elements of the bridge are identified with their own ID. The elements contain in the data scheme two main characteristics 'attribute' and 'archive', as described in the model layer of the previous section.

Via standard reporting forms the inspector has access to the inspection data, damage history, repair history and the condition score from the 3D model. This improves the validation accuracy of the current inspection data with the historical inspection data because the inspector can consult historical inspection data while inspecting. The inspector uses the standard reporting forms to change or add inspection data and photos, reducing the number of data and information transfers. By implementing the above-mentioned functionalities, steps one to four of the current work process (1. technical preparation, 2. non-technical preparation, 3. inspection, 4. the processing of inspection data) are optimized. More efficient data exchange reduces the risk of inspection errors and miscommunication. In addition, all project stakeholders (e.g., structural engineer, asset manager) have digital access to information from the DT, which promotes communication and collaboration.

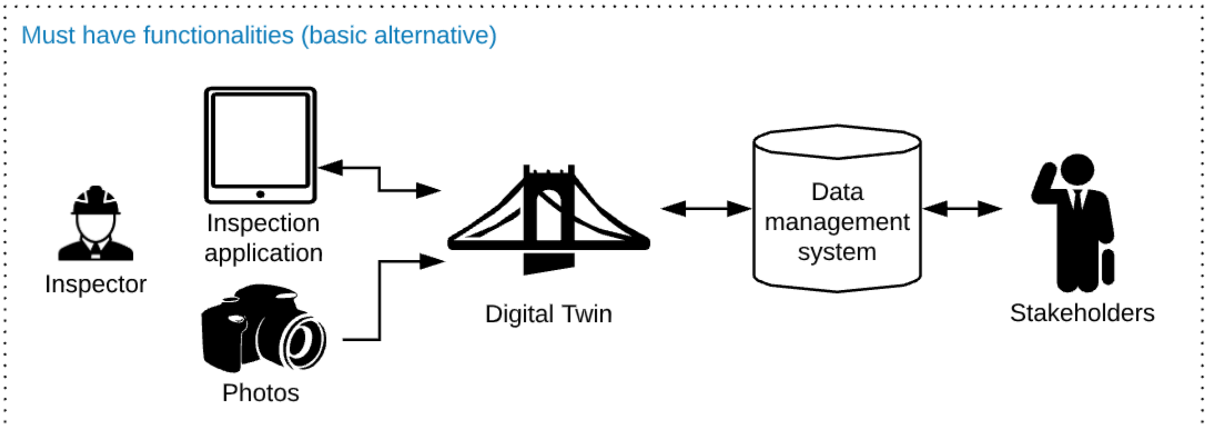

Figure 9.; *Functional design based on the 'must have' functionalities*

Should have functionalities

The ‘should have’ functionalities are based on the requirements of the 'should haves' from chapter 5.2.1. The 'should have' functionalities are shown in Figure 10. In addition to the functions related to the 'must haves', the inspection application shows a visual representation of the bridge to the inspector. The inspector has a visual overview of the elements of the bridge. This gives the inspector even more insight into the structure of the elements of the bridge, so that the inspector can interpret information better. This functionality optimizes the preparation of the inspection (steps one and two in the current work process, see figure 6), the inspection (step three) and the processing of the data (step four). However, the development of a detailed 3D model is more complex and expensive compared to the data model in the alternative 'must have', making this alternative only profitable for inspections of larger bridges or complex structures.

Another should have functionality is to include a GPS location when completing the standard reporting forms to accurately store the data in the 3D model. Because in this alternative all inspection data contains a location component, the inspection data is stored more accurately in the DT. The third should have functionality is to store and link 360-degree photos and videos to the 3D model. This makes the inspection data more complete, improving the quality of the data model. As a result, people involved in the project gain even more visual insight into the current state of the bridge. The last should have functionality is scanning a QR code at the start of the inspection to immediately open the correct data model of the bridge. This gives the inspector direct access to all available information from the data model for inspecting a bridge, increasing the efficiency of the visual inspection.

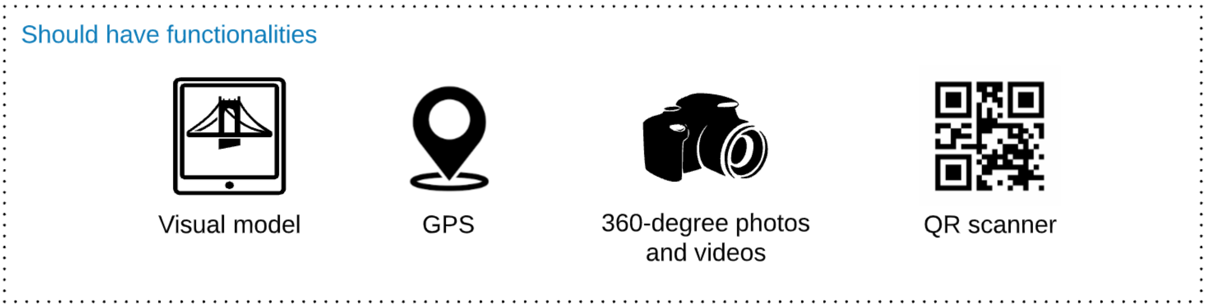

Figure 10.; *The 'should have' functionalities, additional for the functional design of the 'must have' functionalities*

Could have functionalities

The could have functionalities are based on the requirements of the 'could haves' from chapter 5.2.1 and are shown in Figure 11. In addition to the 'must' and 'could have' functionalities, the inspection application recognizes the inspector's speech and gestures and stores the data in the data model. This automates the manual actions of the inspector when filling out the standard report form, making the inspection more efficient. In addition to automating manual operations, this functionality is also useful for inspections where the inspector is unable to operate an IoT device, for example in hazardous inspections where the inspector needs both hands to hold on. An IoT device is attached to the helmet and recognizes the inspector's gestures and speech. A second could have functionality is image recognition, in which damage is traced from a large number of damage images. This analysis is performed by software systems from the enterprise layer and used by the inspector and the asset manager when preparing the advisory report. The last could have functionality is to propose repair or rehabilitation work based on the damage recognition. This analysis is also performed by enterprise layer software systems and partly replaces the analysis performed in the past by the inspector and the asset manager. Compared to other functionalities, these functionalities are technically complicated and can therefore only be used for inspections with often the same type of damage. With the help of these two functionalities, the damage analysis can be automated, increasing efficiency.

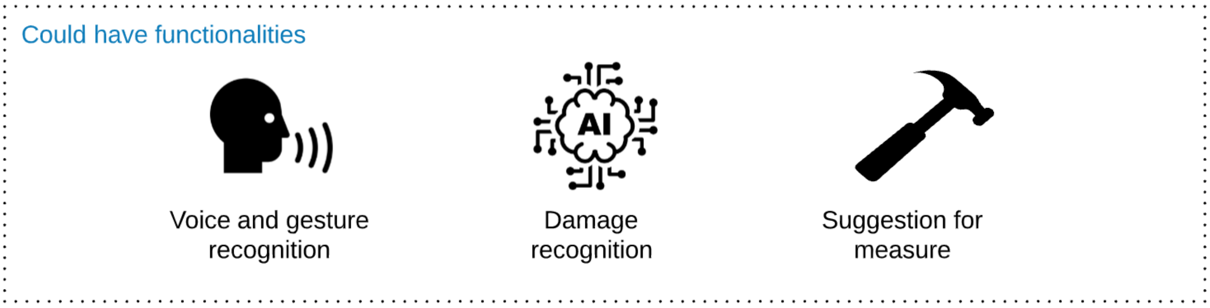

Figure 11.; *The 'could have' functionalities, additional for the functional design of the 'must have' and the 'should have' functionalities*

5.3 Validation

The last step of the design cycle is the validation where it is validated whether the design, if implemented in the work process, contributes to the goals, and needs of the stakeholder (Wieringa, 2014). The design was validated based on the expertise of four experts from Antea Group, where the design solution was presented to the experts. The expert session was conducted with two project leaders, a project manager, and a senior advisor from the bridge management department. The purpose of the expert session was twofold, first validating the requirements for completeness and prioritization. Second, the functional design was validated. The experts indicated that the set of requirements was complete, no additional requirements could be formulated.

Regarding the functional design, the session mainly focused on whether the design would be valuable in the implementation of the use case. Experts indicated that the functional design would be valuable if the inspection application were implemented in current practice. The validation showed that the basic alternative with the 'must have' functionalities has the most potential to be implemented in current practice in the short term. The standard reporting forms provide an easy way to show the inspection data to the inspector during the inspection, to store inspection data and to process inspection data. This automates a large part of the current process of collecting, storing, and processing data. As a result, fewer transfers of data and information take place. In addition, the inspector can easily share the findings on location with those involved (e.g., the structural engineer and the asset manager), which improves cooperation. The experts concluded that this functional design optimizes steps one to four of the current work process, resulting in a better quality of inspection data.

With regard to the 'should have' and 'could have' functionalities, the experts indicated that the biggest challenge lies in developing a 3D model of the bridge based on the associated data scheme. Design documentation is usually only available as physical design documentation or available digitally in 2D from the customer. Moreover, the experts indicated that there is currently a broad discussion in the sector about the ownership rights of the data and data models. Developing a 3D data model costs a lot of time and money, the question is who will pay for it. For the inspections of larger bridges (3D) data models are available from the asset owner himself. The asset owner owns the data model in which Antea Group supplies inspection data. This way of processing inspection data is in line with the way this functional design was developed. The experts expect that larger asset owners (such as Rijkswaterstaat and provinces) will invest in developing data models for their assets. When asset owners stimulate the development of DT by investing in 3D data models, the step for engineering firms such as Antea Group to implement DT in current practice becomes smaller.

Implementation of additional applications discussed in section of the 'could have' functionalities such as speech and gesture recognition or damage pattern recognition are expected to be valuable. Experts indicated that these applications are emerging in the sector and are also very interesting to investigate further.

6 Use case 2: Prediction of the performance of the bridge

This chapter is concerned with the development of the functional design of the second use case using the design cycle method of Wieringa (2014). The chapter is structured in the following three tasks: problem investigation, treatment design, and treatment validation.

6.1 The problem investigation

This section is concerned with the problem investigation, the first task in the design cycle. The problem investigation consists of the following parts: capturing the current process, identification of the problems in the current process, selection of the DT lens and the identification of the stakeholder goals and needs.

In the current process, in addition to visual inspections, sensors are used to monitor the condition of the bridge. Sensors can monitor continuously over a longer period. Besides, observations can be made that the human eye cannot. Furthermore, monitoring sensor data can be used to predict the state of the bridge in the future. Antea Group is investigating how the theoretical lifespan can be extended with the Smart Bridge Leeuwarden pilot project. With the data, Antea Group also wants to be able to predict failures, so that failures can be reduced in the future. By continuously monitoring critical parts of the bridge, patterns in the data can be recognized. Deviations from these patterns can indicate component failure and preventive maintenance measures can be taken to avoid failures.

The results of chapter 4.2 and interviews with two asset managers show that current practice is characterized by the following problems:

1. There is insufficient insight into the technical residual life of the bridge.
2. There is insufficient insight when the malfunctions occur.
3. There is insufficient insight into the development of damage mechanisms.

When predicting the performance of the bridge, several stakeholders are involved in inspecting a bridge, such as: the inspector, the data specialist, the asset manager, and the asset owner. Each of these stakeholders has its own interests and therefore its own DT lens. Given the limited time for the research, one DT lens is being developed. The most important stakeholder when predicting the performance of the bridge is the asset manager who manages the bridge from a technical point of view. To that end, the DT lens in this use case focuses on the asset manager.

Since this use case focuses on the DT lens of the asset manager are two asset managers consulted for their goals and needs. The interviews with the two asset managers show that, according to the asset manager, a DT:

1. Provides information about the static data of the physical bridge, including all structural elements of the bridge such as material type, material thickness and other material properties.
2. Provides information about the dynamic data of the physical bridge, such as: traffic weight, fatigue phenomena, joint transition leaks, drive of the bridge, weather-dependent parameters (temperature, wind force, air humidity).
3. Provides information about the contextual data of the bridge, such as: damage history, repair history, incident history, contract details, reports, drawings, future vision of use.
4. Provides information about future failures.
5. Provides information about the development of damage.

6.2 Treatment design

This section is concerned with the treatment design, the second step of the design cycle the treatment design. The treatment design consists of the following parts: translating the stakeholder goals and needs into requirements, specifying the DT building blocks and specifying the DT lens.

6.2.1 Requirements

In this section, the goals and needs of asset managers are translated into functional requirements. The requirements are defined based on four different types of requirements according to the MoSCoW method. The number(s) after each requirement refers to the goals and needs of Step 1 (1 = goal or need number 1). See Table 7 for an overview of all functional requirements.

Table 7.; *Functional requirements use-case 2*

Must haves	Should haves	Could haves	Won't haves
Visual representation: DT must be able to visualize the information to the asset manager (1, 2, 3, 4, 5).	**Recognizing patterns**: DT must be able to identify underlying trends, patterns, and correlations within the data set (4, 5).	**Diagnosis**: DT could determine the underlying reason for the deviation or damage (4, 5).	**Prescriptive**: DT does not have the option to automatically suggest interventions (4, 5).
Providing static data: DT must be able to store and present the static data of the bridge (1).	**Recognize aberrations**: DT must be able to recognize deviations in the data (classification algorithm error detection) (4, 5).	**Predictive**: DT could predict failures or damage (degradation models) in the future (4, 5).	**Prescribing:** DT does not have the ability to automatically schedule interventions (4, 5).
Providing and progressing of dynamic data: DT must be able to collect, record, organize, structure, store and present the dynamic data (2).	**Signal**: DT must be able to signal that an intervention is needed somewhere (4, 5).	**Suggest interventions**: DT could make suggestions for interventions (4, 5).	
Providing contextual data: DT must be able to store and present the contextual data (3).			

Contribution arguments were added for each requirement to justify the requirements, see Table 8. In addition, each requirement was assigned to one or more DT building blocks (P = physical layer, M = model layer, D = data layer, S = service layer, E = enterprise layer). The connection layer represents the connection between the other building blocks, so this layer is not shown. The DT building blocks, as described in chapter 2 of this study, form the frame of reference.

Table 8.; *Contribution arguments functional requirements use case 2*

Requirement	Goal	Contribution argument	P	M	D	S	E
Visual representation	1	To gain insight into the development of the bridge, the asset manager must have access to a visual representation of the available information.		X		X	
Static data progress	1	To gain insight into the static data (material type, material thickness and other static material properties) of the bridge, it must be possible to store the static data in the DT.			X		X
Dynamic data progress	2	To gain insight into the dynamic data (e.g., sensor data), it must be possible to collect, record, order, structure and store the dynamic data.	X		X		X
Contextual data progress	3	To gain insight into the contextual data (for example damage history, repair history and incident history) of the bridge, it must be possible to store the contextual data in the DT.			X		X
Recognize patterns	4, 5	To be able to analyse the data, the DT must be able to recognize patterns in the data.			X		
Recognize aberrations	4, 5	To apply error detection, the DT must be able to recognize anomalies in the data.			X		
Signal values	4, 5	To signal error detection in the data, it should be possible for DT to signal deviations through signal values.			X		
Diagnose	4, 5	It might be possible to trace the underlying reason for the deviation or damage in the data model.			X		
Predictive	4, 5	It could be possible to predict deviations or damage based on calculation models. As a result, part of the process is automated.			X		
Suggest interventions	4, 5	To automate part of the process, it may be possible for the DT to make suggestions for repair or rehabilitation work to be undertaken.			X		

The next section describes the DT building blocks and the relationship between the DT building blocks.

6.2.2 DT building blocks

The DT building blocks, as described in chapter 2.6 of this research, form the frame of reference. This section describes what each building blocks looks like and what its functionalities are. The connection layer represents the connection between the other building blocks. Figure 12 visualizes the framework and the relationship between the building blocks for this use case.

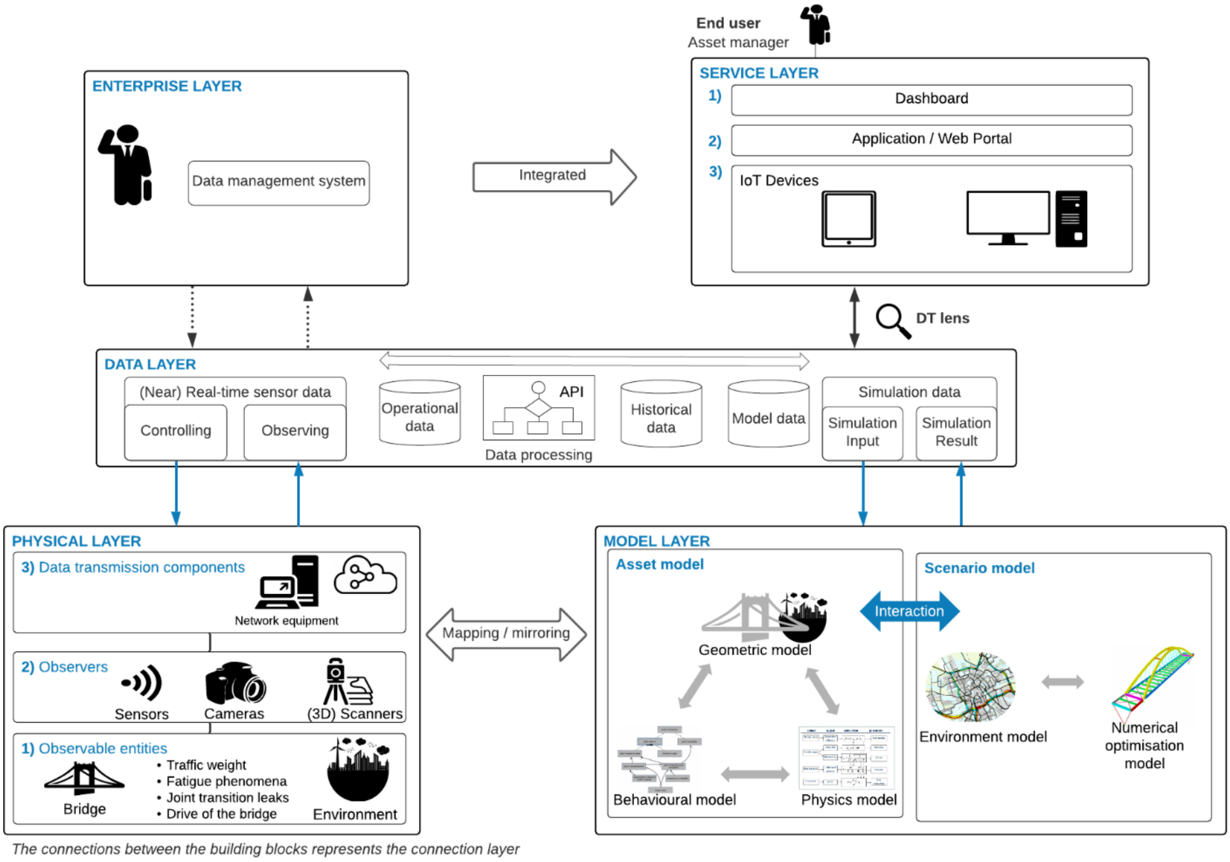

Figure 12.; *Relation between DT building blocks use case 2*

Physical layer

As described in chapter 2.6, the physical layer consists of three categories: 1) observable entities, 2) observers, 3) data transmission components. The physical system in this use case is the bridge. *Observable entities*. This use case involves predicting the performance of the bridge based on data from the past. This data includes traffic intensity, traffic weight, fatigue phenomena, joint transition leaks and the drive of the bridge. In this use case, the observable entities are the bridge and the environment of the bridge. The environment of the bridge includes the traffic intensity and the traffic weight. *Observers*. Observers in this use case generate the data needed to predict the performance of the bridge. It follows from the requirements that it must be possible to store data from sensors, scanners, and cameras. Which observer is used depends on the type of dynamic data to be collected. The observers in this use case are sensors, scanners, and cameras. *Data transfer components.* The data collected by the observers must be transferred through the connection layer to the virtual space where the data is processed. In this case, the mobile network will be used for data transfer.

Model layer

The model layer is the second building block that consists of several models that together fully represent the physical system in the virtual space. The physical system in the virtual space consists of two categories: asset models and scenario models.

Asset models. In this use case, the observable entity in the physical layer is the bridge and the environment of the bridge. Therefore, the asset model represents the virtual representation of the bridge and its environment. As described in chapter 2.6, the asset model consists of three models: 1) geometric model, 2) physical model and 3) behavioural model. All three models are relevant in this use case.

The geometric model contains geometric information about the bridge. As mentioned before, geometric information in the current process is often recorded in the design documentation, including 2D drawings, and the project description. The geometric model contains information about the dimensions of all structural elements of the bridge, type of material, material thickness and other material properties relevant for predicting the bridge's performance. As described in the functional design of use case 1, the geometric information can be represented digitally by modelling the information in a 3D environment (Shim et al., 2019). All structural elements of the bridge are integrated in the 3D environment and are identified with their own ID. Based on the role or service in the bridge system, the structural element is classified in an inventory system. The inventory system consists of the superstructure (e.g., road surface, cable, railing) and maintenance (e.g., abutment, bridge pier). A 3D model is generated based on the inventory system and the ID definition of the structural elements of the bridge. Figure 8 shows what an example data scheme might look like. The ID of the structural elements contains two main attributes: 'attribute' and 'archive'. The attribute function contains geometric information and information about the role of the element in relation to the bridge system. The archive function contains, among other things, the inspection data, the damage history, and the repair history.

In addition to the geometric model, the physical bridge is represented in virtual space with a physics model. The physical model contains information about the materials used and their performance. In the current process, this information is often recorded in inspection reports by inspectors. In this use case, the information from the sensor data is generated.

The behavioural model establishes the behavioural logic of the (parts) of the physical bridge. This allows dynamic behaviour of the structural elements of the bridge to be displayed. By defining the interaction between system components, state transitions and performance degradation over time.

Scenario model. As described in chapter 2.6, the scenario model permanently reflects the physical processes of the bridge in the virtual space. The scenario model consists of four models: 1) the environment model, 2) the equipment model, 3) the process model and 4) the numerical optimization model. The environmental model focuses on the reflection of the environment. The environmental model is relevant for this use case because predictions are made based on the actual traffic intensity. In this use case, the environmental model contains traffic intensity models with which traffic over the bridge is analysed and simulated. Since the observable entities do not focus on resources or the process, the equipment model and the process model are not included. Numerical optimization models make it possible to weigh up different scenarios. The numerical optimization model is relevant for this use case because predictions must be made about the state of the bridge. An example of a numerical optimization model system is MATLAB.

Data layer
The data layer is the core element within the DT and is responsible for the following five functionalities:

Data collection: In this use case this is data about the bridge, namely: traffic weight, fatigue phenomena (both for steel and concrete), joint transition leaks, drive of the bridge. And data about the environment of the bridge, namely: weather conditions (e.g., wind force, temperature). All this data is generated by different types of sensors, scanners, or cameras:

- *Traffic weight: weigh in motion system.*
  One of the sensors that is used is the Weigh in Motion system. This makes it possible to determine exactly how much (freight) traffic crosses the bridge. The data from the sensors is used to measure the deflection. Calculation models are used to determine which minimum standards the viaduct must meet. The actual traffic weight is then tested against the standards to make statements regarding the remaining life of the bridge (Antea Group, 2019).

- *Fatigue symptoms: crack sensors*
  As a result of aging and the increasing traffic weight, fatigue can occur. Fatigue cracks occur in both steel and concrete bridges. Crack formation is difficult to inspect, so crack width sensors are used to gain insight into the development of the cracks. The sensor registers deviations in the length or width of the crack.

- *Leaking joint transitions: leak detection sensor*

A common defect in bridges is the leakage of joint transitions. To allow for thermal expansion/contraction, a joint is designed for bridges. This joint has a long rubber profile to make the joint watertight. In practice it is difficult to determine the watertightness of the joints with inspections. This watertightness is necessary to protect the concrete under the bridge from saltwater that is created because of the road's icing. This salt water has a corrosive effect on, among other things, the reinforcement of the concrete. Failure to detect these leaks can result in very high costs. A joint leak sensor has been developed to make it easier to detect these leaks.

- *Drive of a (movable) bridge*
  Sensors can be used to monitor the drive of the (movable) bridge. In movable bridges, the hydraulic bridge drive and road barriers are a significantly source of malfunctions. These disruptions result in high maintenance costs and unavailability of the bridge for road and water users. The different sensors monitor, among other things: the power supply, the power consumption, the voltage, the vibrations, the oil pressure, the oil temperature, and the wind force.

Data transfer and data storage. The sensor data is sent to a data collection platform by the connection layer using a connectivity network. Examples are existing mobile networks (2G, 3G, 4G), the new 5G or special IoT networks such as LoRa or LTE-M (Ding et al., 2020). An engineering firm's data collection platform is a data management system in which all information is stored. Examples of a data management system are GBI and IRIS. Network data includes open data, for example from the KNMI (Royal Netherlands Meteorological Institute). This data about weather conditions can be used to determine the cause of damage mechanisms.

Data processing. Data processing extracts useful information from a collection of data. This step is relevant for processing the data collected by sensors, scanners, and cameras. By relating the data, underlying trends, patterns, and correlations can be identified. API is used to provide the interface between the models and the data layer and filter the relevant information.

Data integration and data visualization. Integrating data ensures that data from different sources can be seen immediately. The data is integrated from the engineering firm's data management system to the service layer in which the data is accessible to the end user (the asset manager). The basis of the DT is the 3D model of the bridge. For linking data such as attributes and archives, the traditional 2D CAD model is limited. The main task is to develop a 3D bridge model. As in the functional design of the previous use case, parametric modelling can be used to develop the 3D bridge model. Examples of parametric modelling systems are Autodesk Civil 3D or Autodesk Revit.

Service layer
The service layer presents the information to the end user, in this case the asset manager. It follows from the requirements that the end user must have access to a visual form of information presentation. The service offered in this use case is an interactive dashboard that must be accessible to the end user. Using the dashboard, the asset manager has insight and control over the bridge via various parameters. Because the dashboard must be accessible to the asset manager, a web-based portal is used, which is available everywhere via the internet. IoT devices, such as a laptop or a tablet, are used to display the dashboard to the asset manager.

Enterprise layer
The enterprise layer contains information (e.g., geometric information, damage history, repair history, previous inspection results) from various external software systems about the physical bridge that are relevant to predict the performance of the bridge. Examples of external software systems are GBI, ‘Antea Word’ (Antea Group's software program to translate data into information), ‘Golden eye’ (Antea Group's data collection platform) and IRIS (from Rijkswaterstaat).

6.2.3 DT design alternative and additional functionalities

To complete the functional design, this section presents the basic alternative and the various additional functionalities of the functional design. The basic alternative and functionalities are based on the first three types of requirements (must haves, should haves, could haves) according to the MoSCoW method used in section 6.2.1 to define and prioritize the requirements. The basic alternative is given and described first. This is followed by additional 'should have' and 'could have' functionalities that can function independently of each other.

Must have functionalities (basic alternative)
The 'must have' functionalities are based on the requirements of the 'must haves' from chapter 6.2.1 and form the basic alternative for the functional design of this use case. The functional design based on the 'must have' functionalities is shown in Figure 13.

Static data (for example information about material properties from the data management system), dynamic data (for example sensor data) and contextual data (for example information about the maintenance history of a bridge) are integrated in a 3D data model. In the 3D data model, all elements of the bridge are integrated and contain their own ID. Based on a proposed data scheme (Figure 8), the ID of the structural elements contain two main features 'attribute' and 'archive' to which all available information about the structural elements is associated. Sensors generate data that is stored in the 3D data model. Using calculation models, the data is translated into information. Contrary to current practice, the asset manager has direct access to the most relevant information from the data model. By implementing this presentation method, step seven in the current work process (Figure 6) is optimized by giving the asset manager visual insight into the performance of the bridge.

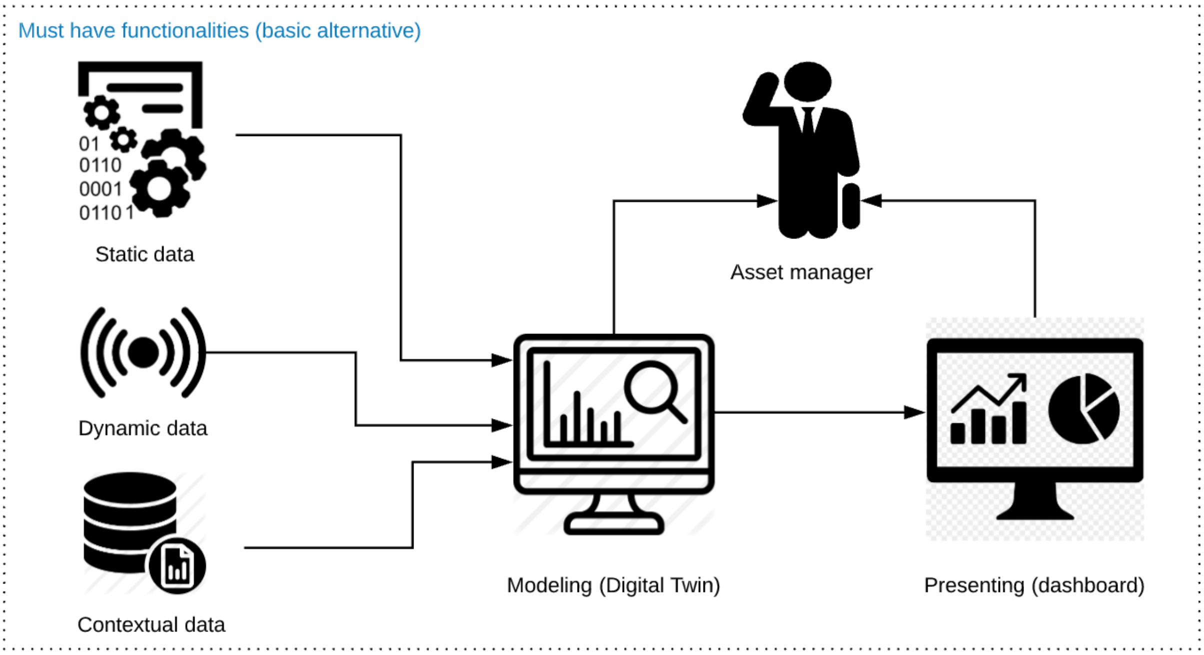

Figure 13.; *Functional design based on the 'must have' functionalities*

Should have functionalities
The ‘should have’ functionalities are based on the requirements of the 'should haves' from chapter 6.2.1. The 'should have' functionalities are shown in Figure 14. The 'should have' functionalities make it possible to recognize patterns in the data with the DT and to classify patterns in data. Pattern recognition consists of data analysis methods that use machine learning algorithms. This automates the analysis of data. Compared to the current work process, this application increases the speed and reliability of the analysis. However, these functionalities are technically complicated and expensive compared to current data analysis methods. Specifically for analysing larger data sets, these functionalities are useful.

The other functionality is that the system gives a signal to the asset manager if an error is detected, or a limit value is exceeded. As a result, the asset manager does not have to periodically monitor the dashboard, which reduces the risk of incorrect observations by the asset manager and greater efficiency.

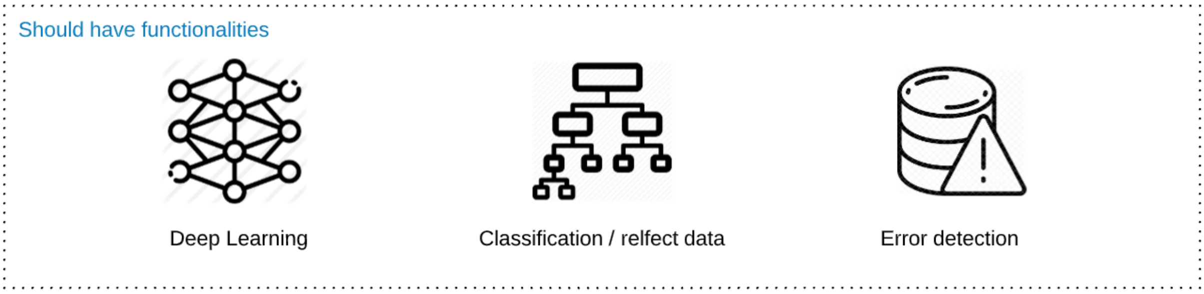

Figure 14.; *The 'should have' functionalities, additional for the functional design of the 'must have' functionalities*

Could have functionalities
The could have functionalities are based on the requirements of the 'could haves' from chapter 5.2.1. The 'could have' functionalities are shown in Figure 15. The 'could have' functionalities make it possible to find out where the error in the data comes from. In addition, the functionalities can predict data patterns in the future and propose (maintenance) intervention. These functionalities combine historical data with calculation models, making these functionalities technically very complicated compared to current data analysis methods. As a result, these functionalities only offer an alternative for larger data sets.

Figure 15.; *The 'could have' functionalities, additional for the functional design of the 'must have' and the 'should have' functionalities*

6.3 Validation

The last step of the design cycle is the validation where it is validated whether the design, if implemented in the work process, contributes to the goals, and needs of the stakeholder (Wieringa, 2014). The design was validated based on the expertise of four experts from Antea Group, where the design solution was presented to the experts. The expert session was conducted with two project leaders, a project manager, and a senior advisor from the bridge management department. The purpose of the expert session was twofold, first validating the requirements for completeness and prioritization. Second, the functional design was validated.

About the requirements, the experts indicated that the package of requirements was complete. The prioritization of the requirements was drawn up in agreement with two asset managers during the interviews. The experts agreed with the prioritization of the requirements.

Regarding the functional design, the session mainly focused on whether the design met the requirements and the validity of the research results. The experts indicated that the functional design has been fully worked out to a certain level of abstraction. In current practice, the performance of the bridge is still predicted for few bridges. An exception is the Stephenson Bridge in Leeuwarden, also known as the Smart Bridge, where Antea Group has been collecting sensor data since 2019. The first results of that project show that the lifespan is at least ten years longer than anticipated (Antea Group, 2021). The experts expect that the functional design will not be widely implemented in the short term. The experts emphasized that the elaboration of this design contributes to the knowledge needed for the development of more smart bridges in the future.

About diagnosing the cause of an anomaly in the data, the experts indicate that this will not be implemented in the short term. Identifying the underlying reason for a discrepancy in the data is very complex and depends on many factors, not all of which are measurable. It is expected that this will remain a human work for the time being.

7 Discussion

This chapter discusses DTs contribution to bridge management for engineering firms. Furthermore, the limitations that may affect the results of the study are presented and described.

7.1 Discussion of the results

This research explored how DTs can contribute to the current practice of engineering firms in bridge management by developing a functional design for two use cases. Validation of the functional design for both use cases shows that DTs have potential to be implemented in practice. The results of this study are therefore in line with the findings of existing studies on DT in the literature.

Although it has been shown that DTs can contribute to bridge management for engineering firms, implementation of DTs in current practice faces several challenges. A point of discussion is the extent to which the developed designs comply with the term functional design. The elaboration of the functional design is limited. The development of the functional design also relates to designs outside the researcher's field of research, such as ICT. These subjects have been developed to a limited extent due to insufficient expertise. For example, possible ICT solutions are mentioned in the description of the DT building blocks, but no choice has been made. Given the level of abstraction of the functional designs of the two use cases, they cannot be directly implemented in current practice.

To implement DTs in current practice, it is first necessary to develop a 3D data model. However, developing a 3D data model is technically complicated and financially expensive. Moreover, the construction and infrastructure sector are highly fragmented (Dubois & Gadde, 2002), and many different parties are involved during the lifespan of a bridge, ranging from asset owners, engineering firms, construction companies to subcontractors. With regard to DTs, each party operates from different interests and has different needs and working methods. Aspects such as property rights of data (who owns the data) are still major issues in the sector. In short, good agreements between all parties involved are crucial to promote the implementation of DTs in practice.

It is also questionable whether engineering firms are the most important party in stimulating the implementation of DTs in bridge management. As suggested in the validation session with experts (Chapter 6.3), asset owners (e.g., Rijkswaterstaat) are seen as the most important party when it comes to financing the DTs. It is expected that when asset owners start to stimulate the development of DT by investing in 3D data models, the step to implement DT in current practice will become smaller.

7.2 Research limitations

This study has several limitations that may affect the results. Limitations of this study are aimed at the completeness and representativeness of the study results, which may limit the validity of the study. The following paragraphs outline the limitations regarding the data collection method, the use cases, and the functional design.

Data collection method. Based on twelve interviews with Antea Group employees, the current work process of bridge management within Antea Group was mapped out. This resulted in a list of DT related issues. However, the list is based on the business process of Antea Group and is therefore not exhaustive and can be generalized to a lesser extent to other engineering firms. More interviews with inspectors or engineering firms could have led to new insights.

Use cases. The DT related challenges were used as input in identifying the DT use cases for engineering firms in bridge management. This resulted in a list of eight DT use cases. However, this list should be considered non-exhaustive as it was impossible to translate a complete overview of DT applications from the literature into DT use cases. The input from the literature is too broad to provide a complete overview of all possible DT use cases**.** In addition, the choice of the most relevant use case may be less valid as it has been chosen by a panel of experts from Antea Group and is based on current developments and innovations within Antea Group. The developments and innovations within Antea Group are only moderately representative of other engineering firms in bridge management.

Functional design. The functional design for both use cases was developed with input from multiple engineers from the bridge management practice. For developing the functional design for both use cases, only a limited number of stakeholders within Antea Group were consulted to formulate the goals and needs of the functional design. This makes the findings less representative and generalizable for other engineering firms. Consulting more stakeholders from other companies ensures more generalizability of the final research results. Moreover, these functional designs were then validated for completeness and practical needs in bridge management by a panel of experts from an engineering firm. It is questionable whether experts from the bridge management sector have sufficient knowledge of DTs to validate the results. Experts from other engineering firms can assess and validate the DT use cases and validation differently. Based on this, it can be stated that the results of research are of limited validity, a repetition of this research could possibly lead to different results.

8 Conclusions & recommendations

This chapter summarizes the main findings per research question. Next, directions for future research are described. Finally, a number of recommendations are made for Antea Group.

8.1 Conclusions

The problem statement of this research was that in current bridge management practice, there is no clear picture of what challenges can be supported with DTs and how DTs can function in those specific cases. This study aims to create a functional design for the most relevant DT use cases for engineering firms in bridge management. To achieve this, the research was divided into three phases, in which first the DT related challenges in the current work process of engineering firms in bridge management were mapped. Second, based on these challenges, DT use cases were identified. Finally, a functional design was developed for the most relevant use cases to demonstrate how DT could contribute to the current work process.

The current practice in bridge management is characterized by at the following DT related challenges: 1) frequent transfers of data, 2) deluge of data, 3) data from previous inspections is often inaccessible, 4) preparations for visual inspections are seldom thorough, 5) the efficiency of visual inspections is not optimal, 6) visual inspections are subjective to an inspector's interpretation, 7) the presented information may mismatch the expected (or needed) information to the customer.

DTs in bridge management are characterized by the following four aspects: connectivity between the physical world and the virtual world, common data environment, visualization of data and information and simulation of 'what-if' scenarios. Because the definition of DT has several definitions, the DT was defined in this study as: *a semantically linked collection of models, information and data that describes the physical system*. In addition, this research follows Hokkeling's framework. This framework consists of six building blocks that are semantically linked. The six building blocks are: the physical layer, the model layer, the data layer, the connection layer, the service layer, and the enterprise layer. The framework forms the basis for developing the functional design.

The applicability of DT in current bridge management practice is demonstrated by developing the following use cases into a functional design:

- Digital access to inspection information and input of inspection data during a visual inspection.
- Prediction of the bridge performance.

The functional design of both use cases shows that DTs can contribute to the current practice of bridge management for engineering firms.

Digital access to inspection information and input of inspection data during a visual inspection reflects an application for inspectors while inspecting structural elements of the bridge. The use case contributes to digitizing and automating steps one to four of the current work process (Figure 6) by using a digital inspection tool. The functional design uses a 3D scheme (Figure 8) whereby all elements of the bridge are stored in a structured manner in the 3D information model and are available to all parties involved in the project. Inspectors have digital access to inspection data, damage history, repair history and the condition score from the 3D model via an inspection application. The inspector can change or add inspection data using standard reporting forms. The functional design also contains additional functionalities that can be implemented separately from each other in practice, these functionalities are shown in Figures 10 and 11.

The validation of the first use case shows that Antea Group experts expect that digitizing the processing of the inspection data contributes to automating steps one to four of the current work process (Figure 6). This reduces the frequent transfer time of data and information and reduces the chance of inspection errors. In addition, a digital inspection request is seen as a suitable means of communication for an inspector during an inspection. Experts believe that the applicability of the use case is great and can be implemented in the current work process. Further development of data management systems is necessary to realize the use case. Customers play an important role in this because they often own the data models and decide to invest in them.

Prediction of the bridge performance reflects an application for asset managers while advising the client on the performance of the bridge. This use case contributes to meeting the customer's information needs, step seven in the current work process (Figure 6). DT is used by integrating multiple data sources into one 3D data model. In the 3D data model, all elements of the bridge contain their own ID and are stored structured according to the proposed data scheme (Figure 8).

By translating all available data into information and visualizing it using forecast models, asset managers gain more insight into the development of the bridge's performance. By using a dashboard, the asset manager has access to parameters that are relevant for the prediction of the lifespan of the bridge. It is expected that the visual representation of the parameters using a dashboard will improve the information presentation to the customer.

8.2 Directions for future research

This research shows how a DT can be applied in two use cases in current practice in bridge management by developing a functional design for these two use cases. Based on these study results and the limitations of this study, the following recommendations are made for future research:

Increasing the population (number of interviewees). This research was carried out with the help of input from engineers and experts from Antea Group. A recommendation for future research is to involve experts and engineers from other engineering firms. Interviews with experts and engineers from other engineering firms can lead to different insights and increase the generalizability of the research.

Research from the customer's perspective. This research focuses on the practical applicability of DT in bridge management and is conducted in collaboration with an engineering firm. To broaden research on DTs in bridge management, future research could be done from the perspective of the asset owner, for instance Rijkswaterstaat.

Elaboration of multiple DT use cases. This research has shown based on two use cases that a DT can be of added value in the current practice of bridge management. To get a complete picture of the added value of DTs in bridge management, future research should focus on developing a functional design for multiple use cases.

8.3 Recommendations for Antea Group

The replacement and renovation task in bridge management requires a smart and efficient approach with regard to the management and maintenance of bridges. Based on the results of this study, the following recommendations are made:

- Validate the added value of the two use cases by performing a Proof of Concept.
- Start developing a data scheme.
- Focus on the development of the standard report form for the inspection application.
- Work with asset owners on pilot projects to drive the implementation of DTs.

The two use cases show how DT can contribute in practice to improve the work process. The validation of both use cases showed that the experts involved find the implementation of DTs an added value for current practice in bridge management. However, the implementation of the DTs has yet to be validated in current practice. The recommendation is to start a pilot for both use cases in which a Proof of Concept (POC) is performed to validate whether the use case is actually feasible to implement in current bridge management practice. If the POC is found feasible, the implementation of the use case can be started in various projects.

To develop a POC, not all functionalities of the functional design need to be included. The real added value can be validated by starting to realize the basic alternative of the use cases. Both use cases use a data scheme (Figure 8). The proposed data scheme should be used as a starting point in the development of the final data scheme. The data scheme is the structure for building the DT and the data management system.

Another recommendation is to start with the realization of the standard report form that is used in the inspection application in the first use case. The added value of a standard report form is that the inspector has digital access to inspection information and can change or add inspection data. This will reduce manual handling and the frequency of data transfer and increase the efficiency of inspection. Ultimately, the inspection application can be extended with the various functionalities that are described in the functional design as 'should' and 'could' have functionalities.

Asset owners (such as Rijkswaterstaat) are seen as the most important party in financing DTs, according to the validation session with experts from Antea Group. In the Smart Bridge Leeuwarden pilot project, Antea Group is working together with the municipality of Leeuwarden to predict the residual lifespan using sensors. The final recommendation is to establish more partnerships with asset owners to stimulate the development of DTs in the sector.

In conclusion, the implementation of DTs in current bridge management practice will lead to a more efficient and effective approach to inspecting bridges, replacing bridges, and extending bridge life for engineering firms. DTs offer multiple applications that contribute to the challenges of today's bridge management. Collaboration between all parties involved in bridge management is crucial to advance the development of the concept of DT. Ultimately, financial investments are needed, which at the same time is perhaps the biggest bottleneck in scaling up the DT concept.

References

Allah Bukhsh, Z. (2019). Providing decision support for transport infrastructure maintenance planning: Through application of multi-criteria and machine learning methods. University of Twente. https://doi.org/10.3990/1.9789036548229

Antea Group. (2019, July). Smart Bridge voorspelt zelf z'n eigen levensduur. Retrieved from https://bit.ly/3iFEe4s

Antea Group. (2021, July). "Er mag best wat meer vaart worden gemaakt met smart bridges". Retrieved from https://bit.ly/36WPS48

Boschert, S., Heinrich, C., & Rosen, R. (2018, May). Next generation digital twin. In *Proc. tmce* (pp. 209-218). Las Palmas de Gran Canaria, Spain., Spain.

Dhillon, B. S. (2002). Engineering maintenance: a modern approach. cRc press.

Ding, J., Nemati, M., Ranaweera, C., & Choi, J. (2020). IoT connectivity technologies and applications: A survey. arXiv preprint arXiv:2002.12646.

Dohrmann, K., Gesing, B., & Ward, J. (2019). Digital Twins in Logistics. Retrieved from https://bit.ly/3bFpWga

Dubois, A., & Gadde, L. E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. Construction management & economics, 20(7), 621-631.

European Commission. (2018). Transport in the European union, current trends, and issues. 'Mobility and Transport'. Available on: https://bit.ly/3w0APS1.

Gao, Y., & Mosalam, K. M. (2018). Deep transfer learning for image-based structural damage recognition. Computer-Aided Civil and Infrastructure Engineering, 33(9), 748-768.

Gleave, S. D. (2014). Eu road surfaces: Economic and safety impact of the lack of regular road maintenance, study. Policy Department Structural and Cohesion Policies.

Grieves, M. (2014). Digital twin: manufacturing excellence through virtual factory replication. White paper, 1, 1-7.

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In Transdisciplinary perspectives on complex systems (pp. 85-113). Springer, Cham.

Gualtieri, M. (2016). Hadoop is data's darling for a reason. Available: https://bit.ly/3w3jk3K.

Hokkeling, J. (2020). Towards construction 4.0: An assessment on the potential of Digital Twins in the infrastructure sector.

Jardine, A. K., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical systems and signal processing, 20(7), 1483–1510.

Kim, D., & Lim, U. (2016). Urban resilience in climate change adaptation: A conceptual framework. *Sustainability*, 8(4), 405.

Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., & Xu, X. (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications, and research issues. Robotics and Computer-Integrated Manufacturing, 61, 101837.

Ma, Z., Cai, S., Mao, N., Yang, Q., Feng, J., & Wang, P. (2018). Construction quality management based on a collaborative system using BIM and indoor positioning. Automation in Construction, 92, 35-45.

Markolf, S. A., Hoehne, C., Fraser, A., Chester, M. V., & Underwood, B. S. (2019). Transportation resilience to climate change and extreme weather events–Beyond risk and robustness. Transport policy, 74, 174-186.

Moon, F. L., Aktan, A. E., Furuta, H., & Dogaki, M. (2009). Governing issues and alternate resolutions for a highway transportation agency's transition to asset management. Structures & Infrastructure Engineering, 5(1), 25-39.

Niu, G., Yang, B. S., & Pecht, M. (2010). Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance. *Reliability Engineering & System Safety, 95*(7), 786-796.

Pintelon, L. M., & Gelders, L. F. (1992). Maintenance management decision making. European journal of operational research, 58(3), 301-317.

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., ... & Nee, A. Y. C. (2019). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems.Journal of Manufacturing Systems.*

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges, and enablers from a modeling perspective. IEEE Access, 8, 21980-22012.

Saad, T., Fu, C. C., Zhao, G., & Xu, C. (2018). Development of a Fatigue Life Assessment Model for Pairing Fatigue Damage Prognoses with Bridge Management Systems. In Bridge Optimization-Inspection and Condition Monitoring. IntechOpen.

Shim, C. S., Dang, N. S., Lon, S., & Jeon, C. H. (2019). Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. Structure and Infrastructure Engineering, 15(10), 1319-1332.

Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management*, 8(2), 120-142.

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. (2018). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, *15*(4), 2405-2415.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing, and service with big data. *The International Journal of Advanced Manufacturing Technology*, *94*(9), 3563-3576.

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., ... & Nee, A. Y. C. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935-3953.

Wieringa, R. J. (2014). Design science methodology for information systems and software engineering. Springer.