Digital Tunnel Twin

Enriching the Maintenance & Operation of Dutch Tunnels

MSc. Thesis Kasper Tijs

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Enriching the Maintenance & Operation of Dutch Tunnels

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Preface

This document in front of you titled “Digital Tunnel Twin” is my thesis, describing the research process and research results over the last year. The project fulfils part of the requirements of the Master of Science degree in Construction Management and Engineering at the Delft University of Technology. The interest in the topic was a long time coming, I have been interested in digital modelling since I was a very young teenager; drawing, designing, and animating 3D objects for videos, games, and recently 3D printing. Unbeknownst to me at the time, this shaped my choice of study, the choice of this thesis topic, and probably a whole lot more.

During the entire process of the research, I have had a lot of support from people, who I would like to thank dearly. First of all, I would like to thank Paul Chan, Wout Broere, and Afshin Jalali Sohi for helping me steer my research, and teaching me countless lessons during the meetings and given feedback. Next, I want to thank Peter Schakel for his continuous involvement and full support throughout the process, easing the research process and improving the result. Further a thank you to Michel Dekker and the rest of Infranea, for providing a friendly and inspiring environment, motivating me throughout. Next, I want to thank the participants of the interviews, who were all very friendly, keen to help and share knowledge.

Finally, I would like to acknowledge and thank my family and friends, for supporting my choices and helping me with just about everything if i asked. Of course, just as important, I want to thank them for the distractions and fun experiences over the years. With this thesis I wanted to challenge myself, learn a lot, and produce something I am proud of, which I did, so I am proud to present this thesis which I hope you enjoy reading.

Kasper Tijs
Delft, November 2020

Summary

Introduction
The rapid growth of complex projects and increasing amounts of available data through emerging technologies are giving momentum to the digital twin as data management tool.

Digital twins started to emerge in 2012, and widely gained interest since 2017 (hundreds of papers in 2017, thousands today). With such an emerging and new technology, there is ambiguity in the definition and its characteristics, especially between industries. A definition commonly used for a digital twin is *a dynamic representation of an asset that mimics real-world behaviours in real time*. A digital twin is described to have a mirror-like characteristic, where the mirror (digital twin) visualises the same behaviours and reacts in the same way as the physical object. This is the key difference with other digital models, such as building information models (BIM), which only visualises static information.

A lot of research is done towards the software-architecture of digital twins, its integrative or modular nature, and applications in the manufacturing and healthcare sectors. Similarly, there is an increasing amount of research being done towards smart cities, construction, and architecture applications. However, what is still missing in literature, is research towards digital twin applications in (civil) infrastructure.

Objective
Hence, the objective of this research is to explore the possibilities in the use of digital twins towards the maintenance and operation of tunnels. This is explored by looking at the end users of the technology, to profile their needs and requirements and consider a digital twin design that focuses on this. This research is the start of a human centred design for a digital twin and provides the opportunity for further investigation of applications and discussion of their usefulness.

Context
Dutch traffic tunnels are the infrastructure system which are used for the context for the research. The Netherlands counts 72 tunnels with a length beyond 250 meters as per 2020. Each of these tunnels is unique in their own way, however significant efforts are being made to increase the uniformity between them, which includes the tunnel processes. The end users which are interviewed for the human centred design of this 'digital tunnel twin', are the facility managers of the tunnels.

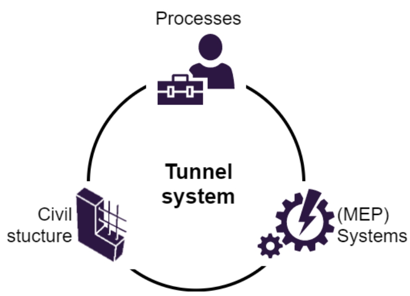

Figure 2: Tunnel system

Design
To map out the functional needs of facility managers within the Dutch tunnel sector, ten interviews were compiled. These interviews are based on digital twin literature in other sectors. The discovered needs within the interviews are analysed for patterns and compared to the characteristics of digital twins. This comparison is validated through a focus group with two digital twin experts and is done to consider if digital twins may offer opportunities for the needs mentioned.

Interview results
In these interviews, over 150 text fragments have been used which are relevant to the goal of the research, and they are given codes. The codes are assigned to interview transcript segments, which are combined into themes, based on their relation to each other. After a few iterations of considering similar relations between the codes, and their context, thirteen common themes are identified. These thirteen themes are visualised in figure 3, each with varying support and dependencies. The initial analysis of these themes and underlying codes conclude three things.

1. There is no uniformity in all the results of the interviews between participants.

   Results from the interviews indicate differences between facility managers in specific themes. Themes with dissimilar answers between participants are shown in the figure as having lines both towards both icons above and below the theme. Only three of the thirteen themes have uniform answers, these are dependent relations, stakeholder engagement and traffic information. This could be the result of personal biases, or a lack of experience in, awareness of and knowledge about digital twins. Traffic information, is found to be irrelevant for the tunnel facility managers, explained by the role definition of the tunnel facility managers, this is outside the scope of their work processes. The remaining two themes, dependent relations, and stakeholder engagement, are uniform, indicating their relevance. However, these themes were not included as specific interview questions during the interviews, meaning not all participants contributed to their formation. Because they were not specifically questioned, participants did not have the chance to argue against the theme, which contributed to their uniform answers.

2. Functional needs are not identical within the facility management of the building sector.

   There are differences between the results of similar research towards building facilities, and this research towards tunnels. Ten out of thirteen themes identified originated from related literature in the building industry. Half of these themes were found to be dissimilar to some degree, as statements given by tunnel facility managers contradicted the found functional needs in literature about the building industry. More specifically, themes that are not similar between the two sectors are: detecting faults, location, OTO control systems, OTO calamity, and traffic. These themes were dissimilar as current tunnel systems are considered sufficient, installations are relatively static, or were outside the scope of the facility manager processes.

3. Results are dependent on the characteristics of the tunnel facility managers.

   The participants of the research are grouped, and their answers are assessed based on specific characteristics. The characteristics which are considered are the organisation they work for, and the age of the tunnel they manage. Dependencies were found between the answers given by participants, and these characteristics. What is found is that the theme OTO maintenance is dependent on the organisation the facility manager works for. Educating, training, and practicing of (preventive, corrective, improvement) maintenance tasks were found more interesting by facility managers from an operational (contractor) perspective, and less from a strategic one (governmental). This could be the result of different responsibilities and direct involvement with maintenance tasks and therefore different perception of the complexity of these tasks. The second variable, tunnel age, had two dependent themes, the energy use and stakeholder engagement. Both themes were more interesting to the facility managers of newly built tunnels, in contrast to older tunnels. This difference could come from the contractual differences, where in newer tunnels there is more focus on these aspects.

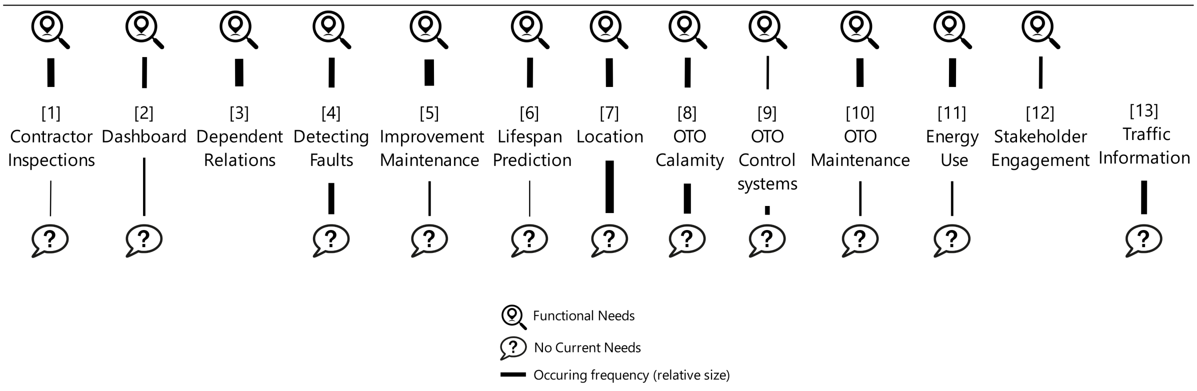

Figure 3: Themes and corresponding support

Research results

The interview results (codes that represent functional needs) are considered for a digital twin application. In other words, a synthesis is formed between digital twin characteristics and tunnel facility manager needs, to find in what capacity a digital twin should be considered for the maintenance and operation of a tunnel.

It is found that for a large majority of the identified functional needs of facility managers it requires the mirror like characteristic of a digital twin, when focusing on the needs related to tunnel behaviour. A digital twin that is designed for the identified needs, should focus primarily on decision supporting services for these facility managers, in other words, providing them with relevant data about the tunnel, at the right time and in a comprehensive manner.

An indication is given towards seven digital twin implementations that could benefit a tunnel facility manager, as visualised in figure 4. The first two are the monitoring of energy use, and monitoring the health of the tunnel system. It is concluded that energy use should be accounted for in a digital twin, and that the monitoring of system health is required for the quick understanding of problems in the tunnel and stakeholder management. The next three are predictive applications: predicting dependent relations between technical tunnel systems, maintenance scheduling, and operational simulations. These applications help anticipate risks during tunnel processes and provide opportunities for reaching better informed decisions regarding maintenance tasks, problem management and configuration management practices. One application, namely energy optimisation, can be considered fully autonomous, as such is not for decision support, but rather for tunnel optimisation, towards the control of energy use of tunnel technical installations.

The results of the interviews and research are based on ten interviews, they form indications of the potential of digital twins for tunnels. However, this exploratory research is only a start for a successful implementation and use of a digital twin. Further research should focus on increasing the reliability of the results and discovering alternative perspectives, application costs, quantifiable benefits.

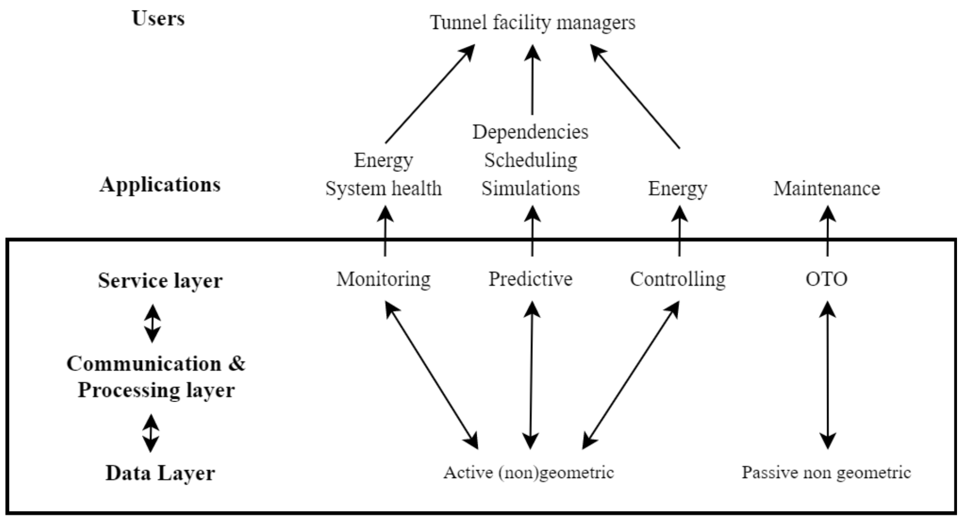

Figure 4: High level integrated digital twin for tunnel facility managers

Samenvatting [Dutch]

Introductie
De snelle groei van complexe projecten en de toenemende hoeveelheden beschikbare data afkomstig van onder andere opkomende technologieën, geven momentum aan de digitale tweeling als datamanagement tool.

Onderzoek naar digitale tweelingen begon in 2012 op te komen, en het onderwerp krijgt sinds 2017 steeds meer aandacht (honderden artikelen in 2017, vergeleken met duizenden vandaag). Met zo'n opkomende technologie, die snel verder wordt ontwikkeld, ontstaat er tegelijkertijd veel verwarring in de betekenis en karakteristieken ervan, vooral tussen verschillende sectoren. Een veelgebruikte definitie van een digitale tweeling is *een dynamische representatie van een fysiek object, dat simultaan het gedrag van het object real-time nabootst*. Er wordt vaak in literatuur beschreven dat een digitale tweeling een spiegelachtige eigenschap heeft, waarbij de spiegel (digitale tweeling) hetzelfde gedrag visualiseert en op dezelfde manier reageert als het fysieke object op bijvoorbeeld externe invloeden. Dit is het belangrijkste verschil met andere digitale modellen, zoals BIM (building information models), die alleen statische informatie visualiseert.

Er is veel onderzoek gedaan naar de software - architectuur van digitale tweelingen, het integrale of modulaire karakter ervan en de toepassingen in de verwerkende industrie en de gezondheidszorg. Verder wordt er steeds vaker onderzoek gedaan naar intelligente steden ('smart cities'), en bouw- en architectuurtoepassingen. Wat echter nog ontbreekt in de literatuur is onderzoek naar digitale tweeling-toepassingen in de (civiele) infrastructuur.

Doel
Daarom is het doel van dit onderzoek om de mogelijkheden in het gebruik van digitale tweelingen voor het onderhoud en de exploitatie van tunnels te verkennen. Dit wordt onderzocht door naar de eindgebruikers van de technologie te kijken, hun behoeften en vereisten te profileren en een digitale tweeling-ontwerp te overwegen dat zich hierop richt. Dit onderzoek is de start van een mensgericht ontwerp voor een digitale tweeling en biedt de mogelijkheid voor het verder onderzoeken van toepassingen en discussie over het nut ervan.

Context
Het infrastructuursysteem dat is gekozen voor dit onderzoek, zijn Nederlandse verkeerstunnels. Nederland telt 72 tunnels met een lengte van meer dan 250 meter (in 2020). Elk van deze tunnels is uniek op zijn eigen manier, maar er wordt flink gewerkt aan het vergroten van de uniformiteit tussen de tunnels, inclusief de tunnelprocessen. De eindgebruikers die worden geïnterviewd voor het mensgerichte ontwerp van deze 'digitale tunnel-tweeling', zijn de tunnel beheerders.

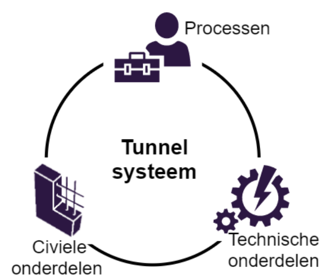

Figure 5: Tunnel systeem

Ontwerp
Om de functionele behoeften binnen de Nederlandse tunnelsector, van deze beheerders in kaart te brengen, zijn tien interviews samengesteld. Deze interviews zijn gebaseerd op recent onderzoek naar digitale tweelingen gebaseerd in andere sectoren. De ontdekte behoeften in de interviews worden geanalyseerd om patronen te vinden en worden vergeleken met de kenmerken van digitale tweelingen. Deze vergelijking wordt gevalideerd door een focusgroep met twee digital tweeling-experts en wordt gedaan om te overwegen of digitale tweelingen kansen bieden voor de specifieke behoeften die naar voren gekomen zijn.

Interviewresultaten
In deze interviews zijn ruim 150 tekstfragmenten gebruikt die relevant zijn voor het doel van het onderzoek, genaamd codes. De codes worden toegewezen aan transcriptiesegmenten, die op basis van hun onderlinge relatie tot thema's worden gecombineerd. Na een paar iteraties van het overwegen van vergelijkbare relaties tussen de codes en hun context, zijn dertien gemeenschappelijke thema's geïdentificeerd. Deze dertien thema's worden weergeven in figuur 6, elk met verschillende ondersteuning en afhankelijkheden. De eerste analyse van deze thema's en onderliggende functiebehoeften leidt tot drie zaken.

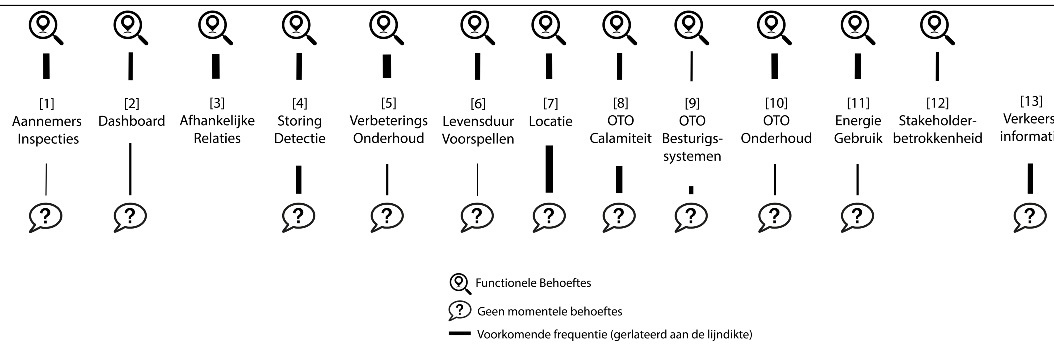

Figure 6: Themas en de vraag ernaar

1. Er is geen uniformiteit in de antwoorden van deelnemers aan de interviews.

   Resultaten uit de interviews geven verschillen aan tussen tunnel beheerders op specifieke thema's. Thema's met verschillende antwoorden tussen deelnemers worden in de afbeelding weergegeven met lijnen naar de pictogrammen boven en onder het thema. Drie van de dertien thema's hebben uniforme antwoorden. Dit zijn afhankelijke relaties, stakeholderbetrokkenheid en verkeersinformatie. Dit kan het gevolg zijn van persoonlijke vooringenomenheid, en een gebrek aan ervaring in, en bewustzijn en kennis over digitale tweelingen. Verkeersinformatie blijkt niet interessant voor de tunnel beheerders, wat verklaard kan worden door de roldefinitie van de beheerders, in principe valt verkeer namelijk buiten hun werkprocessen. De andere twee uniforme thema's, afhankelijke relaties en stakeholderbetrokkenheid, geven wel een indicatie dat ze relevant zijn. Ze werden echter niet specifiek bevraagd tijdens de interviews, waardoor niet alle deelnemers hieraan hebben bijgedragen. Het is voor te stellen dat er hierdoor minder tegen argumenten zijn genoemd.

2. Functionele behoeften zijn niet volledig vergelijkbaar met het facilitair management van de bouwsector.

   De resultaten van dit onderzoek, voor tunnels, komen niet precies overeen met resultaten van vergelijkbare onderzoeken in de bouwsector. Tien van de dertien geïdentificeerde thema's zijn afkomstig uit gerelateerde literatuur in de bouwsector. De helft van deze thema's bleken tot op zekere hoogte ongelijk te zijn, aangezien uitspraken van beheerders van tunnels in tegenspraak waren met de gevonden functionele behoeften in literatuur over de bouwsector. Thema's die niet vergelijkbaar zijn gebleken tussen de sectoren: het detecteren van storingen, locatie, OTO-controlesystemen, OTO-calamiteiten en verkeer. Deze thema's kunnen verschillend zijn omdat de huidige tunnelsystemen voldoende zijn, installaties relatief statisch zijn of buiten de scope van de beheer processen vallen.

3. Resultaten zijn afhankelijk van de kenmerken van de tunnelfaciliteitbeheerders.

   De deelnemers aan het onderzoek worden gegroepeerd op specifieke kenmerken en de antwoorden van deze groepen zijn vergeleken met elkaar. De kenmerken die zijn meegenomen, zijn het type organisaties waartoe de beheerders behoren en de leeftijd van de tunnel die ze beheren. Er werden afhankelijkheden gevonden tussen de antwoorden die gegeven weren en deze kenmerken. Wat werd gevonden is dat één thema afhankelijk is van de organisatie waarvoor de tunnel beheerder werkt. Het opleiden, trainen en oefenen van (preventieve, corrigerende, verbeter) onderhoudstaken werd door tunnel beheerders vanuit operationeel (aannemer) perspectief interessanter gevonden en minder vanuit de strategische groep (overheid). Dit kan het gevolg zijn van verschillende verantwoordelijkheden, directe betrokkenheid bij onderhoudstaken, en daardoor een andere perceptie van de complexiteit van deze taken. De tweede variabele, tunnelleeftijd, heeft twee afhankelijke thema's: energieverbruik en stakeholderbetrokkenheid. Beide thema's waren interessanter voor de beheerders van nieuw gebouwde tunnels, in tegenstelling tot oudere tunnels. Dit verschil zou kunnen komen door de contractuele verschillen, doordat er in nieuwere tunnels meer nadruk ligt op deze aspecten richten.

Onderzoeksresultaten

De interviewresultaten (codes die functionele behoeften vertegenwoordigen), worden vergeleken met digitale tweeling toepassingen. In andere woorden, de mogelijkheid om aan behoeftes van tunnel beheerders tegemoet te komen met een digital tweeling worden bekeken. Zo wordt bepaald in welke hoedanigheid een digitale tweeling moet worden overwogen voor het beheer en onderhoud van een tunnel. Het blijkt dat voor veel van de geïdentificeerde behoeften van tunnel beheerders de spiegelachtige kenmerken van een digitale tweeling nodig zijn, wanneer wordt gekeken naar de behoeftes die verband houden met tunnelgedrag. Een digital tweeling die wordt ontworpen voor de geïdentificeerde behoeften, moet zich primair richten op beslissingsondersteunende diensten voor deze tunnel beheerders. Met andere woorden, hen relevante gegevens over de tunnel, op het juiste moment en op een uitgebreide manier verstrekken.

Zeven digital tweeling toepassingen worden beschreven als mogelijkheden waar een tunnel beheerder baat bij zou kunnen hebben, gevisualiseerd in figuur 7. De eerste twee zijn het monitoren van het energieverbruik en het monitoren van de gezondheid van de tunnel systemen. Er wordt geconcludeerd dat het energieverbruik moet worden verantwoord in een digitale tweeling, en dat het monitoren van de gezondheid van het systeem vereist is voor begrip van problemen in de tunnel en het beheer van stakeholders. De volgende drie zijn voorspellende toepassingen: het voorspellen van afhankelijke relaties tussen tunnel systemen, onderhoudsplanningen en operationele simulaties. Deze toepassingen helpen bij het anticiperen op risico's tijdens tunnelprocessen en bieden de mogelijkheid om beter geïnformeerde beslissingen te nemen over onderhoudstaken, probleembeheer en configuratiebeheer. Één toepassing, namelijk energie-optimalisatie, kan volledig autonoom bekeken worden, en is niet van belang als beslissingsondersteuning voor beheerders, maar voor tunneloptimalisatie. Het is van belang voor de controle en optimalisatie van het energieverbruik van tunnelechnische installaties.

De resultaten van de interviews en het onderzoek zijn gebaseerd op tien interviews. Ze vormen een eerste indicatie van de potentie in het gebruik van digitale tweelingen voor tunnels. Dit verkennende onderzoek is echter pas het begin van een succesvolle toepassing en het gebruik van een digitale tweeling. Verder onderzoek moet zich richten op het vergroten van de betrouwbaarheid van de resultaten en het ontdekken van alternatieve inzichten, toepassingskosten en meetbare baten.

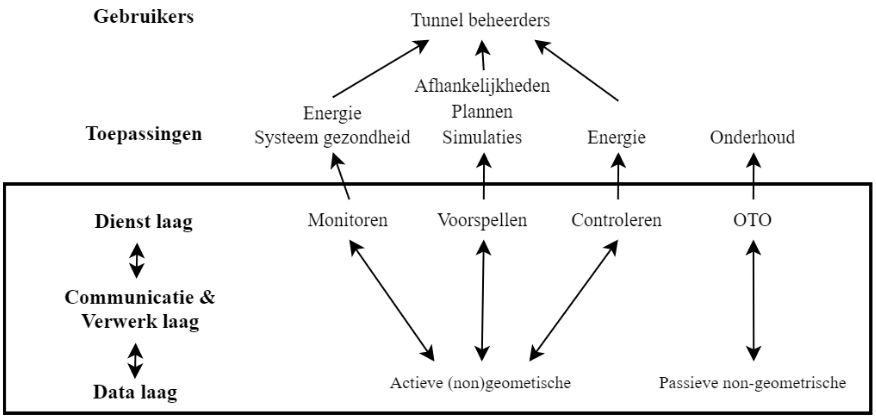

Figure 7: Geintegreerde digitale tweeling voor tunnel beheerders

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Acronyms

AEC Architecture, Engineering, Construction
BIM Building Information Model (or modelling or management)
CAD Computer Aided Design
DBFM Design Build Finance Maintain (contract type)
DT Digital Twin
IoT Internet of Things
LTS ’National’ Tunnel standard (Rijkswaterstaat)
M&O Maintenance and Operation
MEP Mechanical, Electrical, and Plumbing systems
OTO Educating, Training, Practicing
RWS Rijkswaterstaat
TTI Tunnel Technical Installation

1 Introduction

The rapid growth of complex projects and increasing amounts of available data through emerging technologies such as Internet of Things, wireless communication and cloud computing is giving momentum to the digital twin (Q. Lu, Xie, Parlikad, & Schooling, 2020). Digital twins are considered a key information management technology of this era (Gartner, 2019), they are a continuation of the digitisation of projects, where physical objects have a digital counterpart mirroring its properties and enabling the management of its information. This research aims to explore the possibilities of this emerging technology for the information management during the life cycle of construction assets.

To introduce the research, the chapter is separated in four sections. The relevance and transition of digital tools are explored in section 1.1. Section 1.2 contains the research objectives, and section 1.3 details the research design, to obtain the objectives.

1.1. Research context

Before discussing the practical and academic interest in digital twins for information management of the asset life cycle, the digital twin predecessors are discussed. The predecessors are mentioned, because often the development of a digital tool is related, for example as extension or expansion of the other.

Digital transitions

Over the years, many different IT-techniques have surfaced to support projects, and amongst those are programs supporting digital representations of the physical assets. The earliest digital representations are Computer-Aided Designs (CAD) which started in the early 1970s (Ghaffarianhoseini et al., 2017). CAD programs, such as AutoCAD are essentially digital drafting tools to represent a design with lines and arcs, which used to be done on paper (Autodesk, 2016).

However, CAD programs cannot be comprehensively understood by computers and they have limited information depth (Borrmann, König, Koch, & Beetz, 2018). To enhance construction-specific CAD, BIM was introduced in practice in the early 2000s (Volk, Stengel, & Schultmann, 2014). BIM is a term used especially in the construction sector, which stands for Building Information - Model, Modelling, or Management. The differences in the definitions relate to the emphasis of this building information: construction, processes, and use of information respectively (Bouwinformatieraad, 2020). The most obvious difference between BIM and previous CAD programs, is the three-dimensional geometry, which provides the basis for its integrative and predictive functionality (Borrmann et al., 2018; Ghaffarianhoseini et al., 2017).

BIM visualises and provides information about a 3D object in empty space and does so independently of time. BIM is the foundation of digital twins, as BIM provides the three-dimensional geometry and manages information which is unlikely to change. According to (Kahlen, Flumerfelt, & Alves, 2017) a digital twin is an addition to BIM and provide its dynamic nature (time-dependent), which is described as not just a three-dimensional drawing, but also the system behaviour. By representing the behaviour of systems, a more complete representation of a project can be achieved, improving its information management.

Relevance
Academically the interest in digital twins is increasing at a very fast pace. A Scopus[1] search for the term ”digital twin” gives a good indication of this. 2017 Accounted for one hundred papers, while 2019 counted nearly a thousand. The maturity in academic interest is different in various sectors, Love and Matthews (2019) found nearly 50% of digital twin articles stem from manufacturing industry, while only 6% from the Built environment. Nevertheless, research within the built environment is being actively promoted through, for example, national programs such as the national BIM program (Mcgraw, 2014), and The Gemini Principles (CDBB, 2020).

Similarly, the demand for the digitisation of the entire life cycle of assets is accelerating in practice (Wyman, 2018). This push is happening on different organisational levels, including European (EU BIM task Group) (Panteli et al., 2020), nationally through programs and policies (Rijkswaterstaat, 2014), and within companies. This research is conducted as part of the Master Construction Management and Engineering at the University of Delft, in collaboration with a company, Infranea[2]. Infranea has an interest in digital twins as it is a digital engineering company that was founded (2004) for the digitisation of infrastructure market. Infranea premiered digital twin services internally in 2018, as part of their offered services, and have an interest in expanding this service. Hence, Infranea is interested in discovering possibilities for expansion, by providing more services, or serving to a larger market. This research affiliation is a step towards that goal, as digital twin applications are reviewed, and functional problems in the infrastructure sector are researched, which are within the scope of digital twins.

1.2. Research objectives

This research aims to explore the possibilities of digital twins in the life cycle of a tunnel. The goal is to provide insight towards the use of digital twin services towards the improvement of information flow within the tunnel sector. This insight helps future research with focusing the design of a digital twins towards a fit for purpose tool for tunnels.

This goal is accomplished by researching the functional needs of the users of the technology, and aligning them with the possibilities of a digital twin. The functional needs not only refer to something that is missing, but also to the improvement of processes, i.e. desires of the user. The focus of the research is towards the relationships and the people and what they need, this is done because information systems that are designed based on an idea that does not have the end-user in mind, are set up to fail (*Project and People Mastering Success*, 2018). Problems originate from needs, as a problem is an unsatisfied need (Nicholas & Steyn, 2017), which means finding user needs will help address problems within the asset life cycle. Basing the adoption of digital twins on actual problems or business demands is required to secure its success (Love & Matthews, 2019). To meet the research goal and help materialise the results, a main research question (RQ) has been constructed. To help divide the research and answer this main question, four additional sub-questions (SQ) are formulated.

RQ *What functional problems of facility managers do you need to take into account when designing a digital twin for the maintenance and operation of tunnels?*

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[1]https://www.scopus.com/
[2]https://infranea.com/en/

SQ1 *How are digital twins designed and what applications do they provide?*

The first sub question identifies what a digital twin is, what it consists of, and what they are currently capable of in different contexts.

SQ2 *How are tunnel systems organised and how is information management incorporated in their maintenance and operation stage?*

The second sub question explores the context of tunnels, by looking at the decomposition of tunnel systems, including the tunnel processes and components. Additionally, the information management within this context is explored.

SQ3 *What functional problems do facility managers encounter during the maintenance and operation of tunnels?*

The third sub question builds upon the research for the first two sub questions, and identifies functional problems during the maintenance and operational phase of tunnels, by interviewing relevant stakeholders.

SQ4 *What functional needs in the tunnel sector can be supported with a digital twin?*

Lastly, sub question four considers the possible impact or influence digital twins can have on the identified functional problems, by looking at the services digital twins provide in other sectors.

1.3. Research design

Three stages are used to answer the main research question. The thesis is divided in three stages: Literature study, Empirical research, and Synthesis (as seen in figure 1.1). These three stages include three chapters each, as seen in figure 1.2.

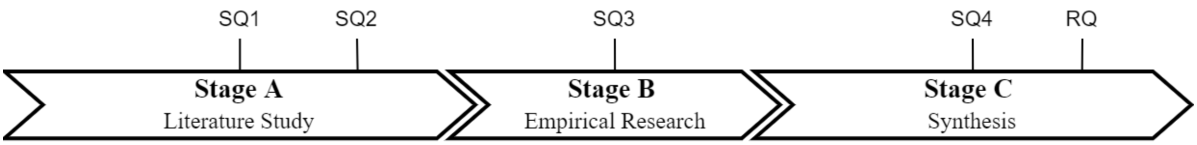


Figure 1.1: Research design schematic

Stage A. Literature Study
The literature study is the front-end of the report, which contains general information on digital twins and the context of the research. In chapter 2, the state-of-the-art research towards digital twins is summarised, to demarcate what is already known about the subject, and more importantly, what is still unknown. Following this, chapter 3 details the research gap by defining the context of the research. This stage answers the first two sub-questions, by describing the context of the tunnel sector, and identifying digital twin possibilities in other sectors.

Stage B. Empirical Research
The empirical research is the most specific stage of the report, detailing the interviews which are conducted. This qualitative method is used as it allows for the retrieval of the perceptions of participants (Saunders, Lewis, & Thornhill, 2016), which can be used in this exploratory study. Chapter 4 describes the methodology of conducting the empirical research to obtain the be able to obtain relevant data. Chapter 5 reveals the empirical research results and Chapter 6 analyses the interview results qualitatively. The interview results answer the third sub-question, which discovers functional needs of facility managers of tunnels, which are within the scope of digital twins.

Stage C. Synthesis
Lastly, the synthesis is the back-end of the report, and contains more general information. A synthesis is found between the results of the empirical research and literature study in chapter 7, and the research is

discussed and concluded in chapters 8 and 9. This stage highlights the potential of digital twin services to solve functional needs, answering sub-question 4.

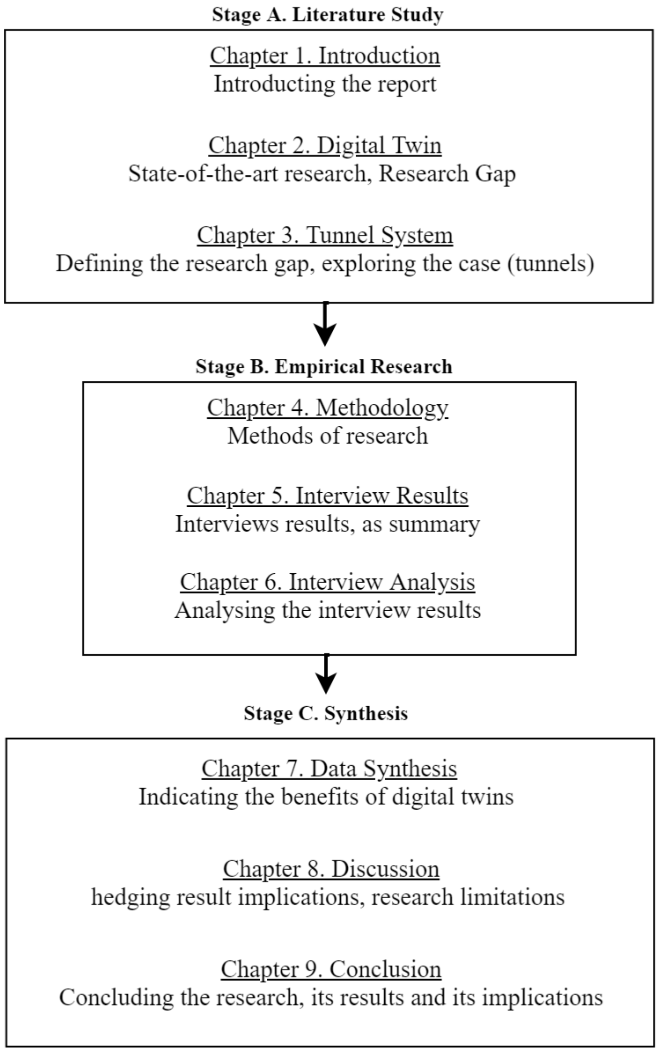


Figure 1.2: Outline thesis

2 Digital Twin

The purpose of this chapter is to gain an understanding of what we already know about digital twins, by looking at previous research papers. By doing this, this research can be positioned within the collective, and its contribution is described. Additionally, by discovering what a digital twin is, and what it can do, the first sub-question is answered:

SQ1 *How are digital twins designed and what applications do they provide?*

This chapter consists of four sections. 2.1 and 2.2 define digital twins on a high level, its definition and system architecture. 2.3 (Component level architecture) goes into more detail, discussing a digital twins unique characteristics. 2.4 (Applications) similarly goes into more detail, and describes the perspectives and context of digital twin research. Lastly, 2.5 (Sub conclusion) concludes the chapter by summarising the findings of the chapter, answering sub question 1, and details the research gap which is further discussed and demarcated in the following chapter.

2.1. Definition

Digital twins (DT) are the big new thing in tech, a buzzword, but what does it encompass. The concept of a digital twin was introduced in 2002 by Michael Grieves, to describe an ideal digital representation of an asset that is specifically designed to consider the asset life cycle (Kahlen et al., 2017). The concept digital twin references a likeness between a physical object and its digital representation which are linked by a data and information link. The term digital twin references this as ‘twin telepathy’ between the physical and digital twin.

Digital twins research started to emerge after 2012, after an article about a new “digital twin paradigm” within NASA was published, to accurately predict and control air- and spacecraft (Glaessgen & Stargel, 2012). Since 2012, the interest in the topic has expanded rapidly. Negri et al. (2017); Kritzinger et al. (2018) reviewed all digital twin papers available to them at the time, 26 and 43 digital twin articles respectively, to discover commonalities. Negri et al. (2017) found that certain characteristics of digital twins, such as the required amount of data, were not similar between all authors contributing to inconsistency on the topic, and ambiguity of the term. Kritzinger et al. (2018) similarly discovered that only recently appropriate concepts were being formed. The author described the main disagreement being the data/information flow between physical and digital twin.

More recently, articles have adopted more identical definitions and requirements of digital twins, often referencing the definition given by Glaessgen and Stargel (2012). Table 2.1 presents digital twin definitions in different sectors. Because of the similarities in digital twin technology between sectors, the next two sections (2.2 & 2.3 discussing digital twin architectures) will not distinguish between different industries. Definitions all reference three key aspects: a physical asset, a digital representation, and a mirror-like connection between the two, defined by Grieves and Vickers (2017) as the key feature of digital twins.

Table 2.1: Digital twin definitions

Sector, author (date)	Digital twin definition
Aerospace Glaessgen and Stargel (2012)	An integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.
AEC* Q. Lu, Xie, et al. (2019)	A digital model, which is a dynamic representation of an asset and mimics its real-world behaviours.
Architecture Farsi et al. (2020)	A concept that creates a model of a physical asset for predictive maintenance. This model will continually adapt to changes in the environment or operation using real-time sensory data and can forecast the future of the corresponding physical assets.
(Civil) Construction Bolton et al. (2018)	A realistic digital representation of assets, processes or systems in the built or natural environment
Manufacturing Lim et al. (2019)	A high-fidelity virtual replica of the physical asset with real-time two-way communication for simulation purposes and decision aiding features for product service enhancement

*AEC = Architecture, Engineering and Construction

2.2. System level architecture

Recent research has looked at the high-level architecture of digital twins. Integrated digital twins termed by some authors as 'full' or 'complete' digital twins, combining digital twin applications in a single architecture. Three papers have recently proposed such a system architecture where digital twin functions are integrated into a single model. Each paper focuses on a different aspect of the design of an integrated digital twin. Figure 2.1 visualises the proposed system architecture.

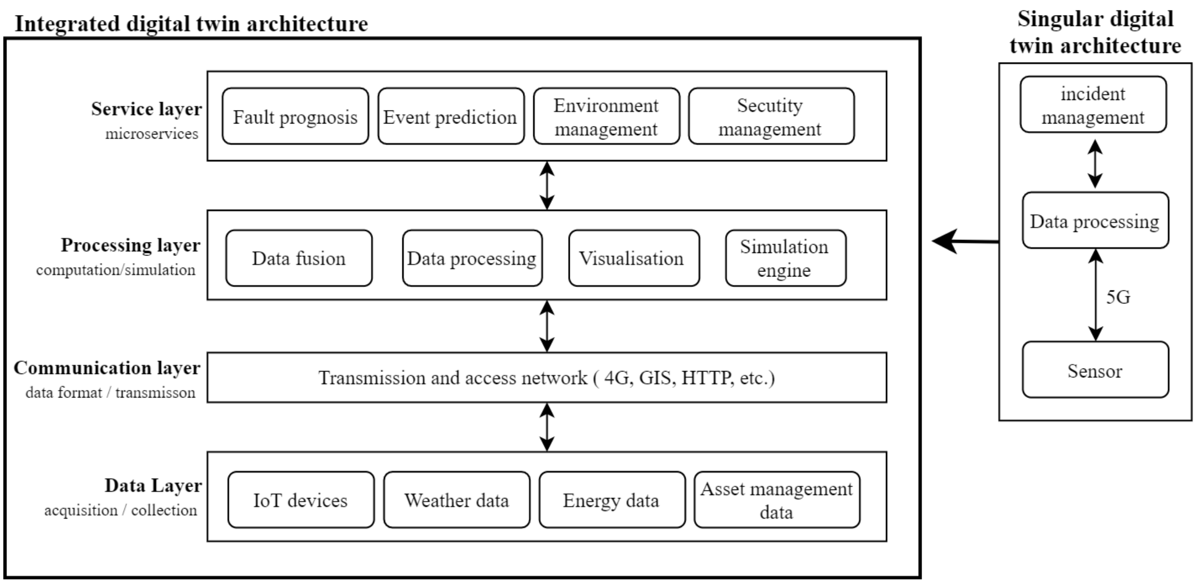


Figure 2.1: Integrated (full) digital twin architecture (adapted from Q. Lu, Parlikad, et al. (2019))

Lim et al. (2019) reviewed 123 digital twin papers, and analysed the tools and models used. The author then proposed a system architecture based on the individual architectures of the papers, to maximise the interoperability between sub-systems. The architecture consists of layers which are identical between single digital twin applications, forming a modular design.

Q. Lu, Parlikad, et al. (2019) designed an integrated digital twin architecture based on several articles specific to architecture (building engineering) applications. The research focused on finding the ideal manner of data transfer and management between different system layers.

Kazado, Kavgic, and Eskicioglu (2019) researched the technical implementation of an integrative system architecture, using various existing software packages. Kazado et al. (2019); Q. Lu, Parlikad, et al. (2019) tested their proposed architectures in pilot projects on campus buildings.

By combining digital twins' applications, the full digital twin is improved in several ways, including offering scalability due to the modular design and improved reliability though redundancy and checks (Shen, Hao, & Xue, 2012). Furthermore, these integrated digital twins provide additional insights in system behaviours because it accounts for the interconnectedness between subsystems and processes (Erkoyuncu, Butala, & Roy, 2018). Additionally, Whyte et al. (2019) researched the interdependence on a network level and found that digital twins can be used to generate new insights into network relationships between assets and projects.

Using an integrated architecture to connect and combine several digital tools in a modular fashion is not new, J.-R. Kim, Yoo, Kwon, and Cho (2008) researched and designed a very similar architecture for the data management of an integrated tunnel monitoring system. Shen et al. (2012) researched the customisability of such a system for specific purposes and end users. Beyond the integrated system architecture, an additional system layer is added, 'composite services', which combines specific services into applications for specific end-users. The composite services and end-users are shown visually in figure 2.2. The paper discovers benefits of applications through a case study, while maintaining benefits from a fully integrative system, the benefits of composite services include the support for automatic or semi-automatic deployment of user applications and creating systems that better fit the needs of a specific end user (Shen et al., 2012).

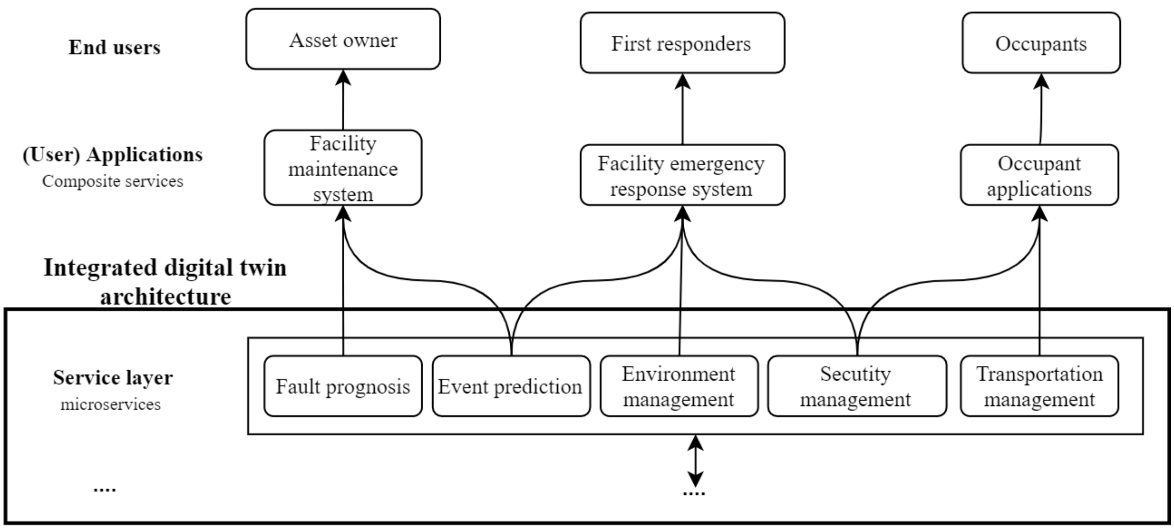


Figure 2.2: Integrated architecture showing combined services and users (adapted from Shen et al. (2012))

2.3. Component level architecture

In the following section, research towards the key characteristics of digital twins is shown. These characteristics are the flow of data and information, and digital twin services.

2.3.1. Data and information flow

Data is considered to be recorded symbols (including words, numbers and images) and quantifiable outcomes of observation (Liew, 2007). While information is processed data which is relevant and context-based, and knowledge is a subset of information which is useful and meaningful for a specific purpose (Parsanezhad, 2019). A digital twin obtains (raw) data from an asset through for instance: sensors, signals, and measurements. This data is then processed into information in the processing layer. This processed data or information subsequently flows back to the asset in various forms, such as through decisions made by stakeholders, or control signals which adjust systems.

There is discrepancy between authors on the required characteristics of the flow of data and information for a digital tool to be considered a digital twin. Kritzinger et al. (2018) reviewed 43 digital twin articles and sorted the papers according to their data flow characteristics. The author defined three different types of digital tools, according to the autonomous or manual flow, shown in figure 2.3. Kritzinger et al. found no uniformity between digital twin papers, 28 percent of the papers reference digital models, 35 percent digital shadows, and 18 percent digital twins. Since 2018, the exclusion of digital models from digital twin research is widely adopted, though the distinction between a digital shadow and a digital twin is still debated. Papers that do not distinguish between digital shadows and twins, frequently refer to digital shadows as less complex digital twins (Arup, 2019; Lamb, 2019; Y. Lu et al., 2020).

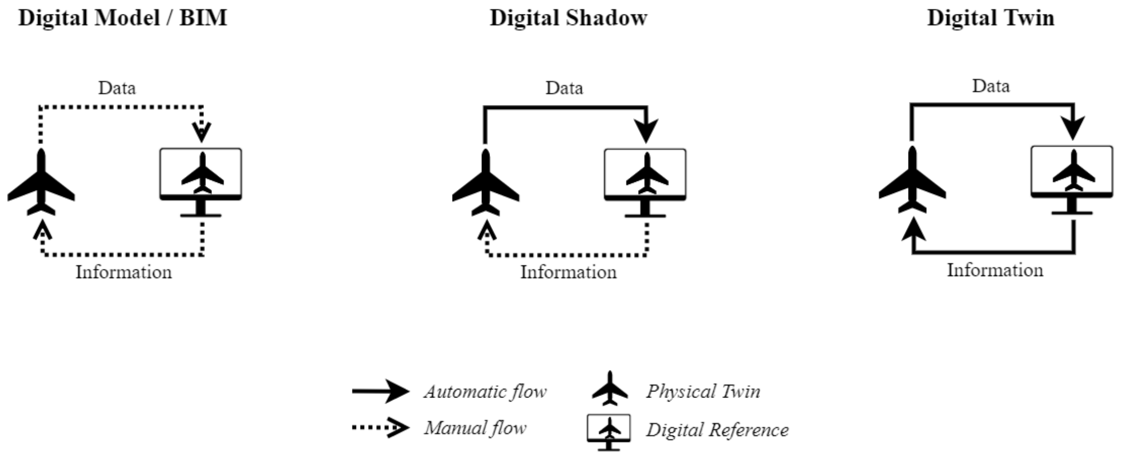


Figure 2.3: Flow of information and data (adapted from Kritzinger et al. (2018))

Specific to the construction industry, a Building Information Model (BIM) is currently considered a type of digital model. In part this results from the inability of widely used, underlying data formats (IFC[1]), to support the autonomous flow of data (Smarsly & Tauscher, 2015). Authors do often consider digital twins to be the continued development of BIM, using terms as “enriched BIM”, “IoT enabled BIM” or “Smart BIM” to describe digital twin technology (Andriamamonjy, Klein, & Saelens, 2015; Kang, Lin, & Zhang, 2018; Kazado et al., 2019). The continuation of the BIM term is explained in part by the use of BIM as essential building block of digital twins (Arup, 2019; Halmetoja, 2019), and the wide adoption and recognition of the term, BIM, in the construction sector.

[1] https://technical.buildingsmart.org/standards/ifc/

Data types
As seen in figure 2.3, the difference between a digital model (BIM) and a digital twin is the autonomous flow of data (and information). Halmetoja (2019) defines passive data as data that is not required to be autonomously collected. In other words, passive data is fixed data, that remains the same after it has been collected and active data continually changes to remain accurate.

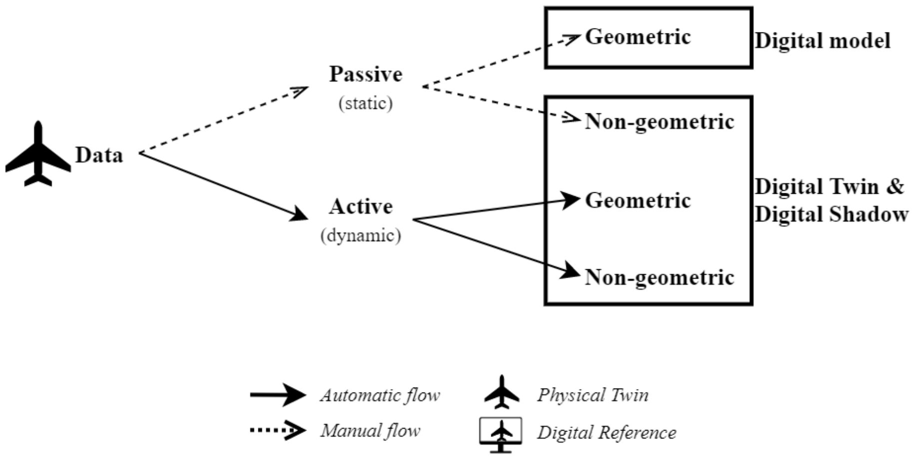


Figure 2.4: Data types and digital model association

Passive data is considered persistent and is mainly produced in the realisation phase (Halmetoja, 2019). The paper categorises passive data into permanent, long- and short- term, based on its persistence. Persistent passive data does not change throughout the lifetime of an asset, while short-term passive data changes rarely, due to renovation, repair, or replacement of equipment.

Active data requires an automatic flow of data, and is primarily generated by using and controlling an asset (Halmetoja, 2019; Q. Lu et al., 2020). Q. Lu et al. (2020) researched data anomaly detection in the maintenance and operation phase and found that asset data generation in this phase is active. The author discovered that active data is required in the maintenance and operation for effective decision making. Active data includes sensor data, interaction protocols (maintenance events), monitoring strategies, embedded algorithms, implicit dynamic relationships (Smarsly & Tauscher, 2015; Q. Lu et al., 2020).
Q. Lu et al. (2020) states BIM is in part ineffective for decision making in the maintenance and operation, as existing data formats (IFC) can only include basic geometry information. Love, Zhou, Matthews, and Luo (2016) researched the implementation of electrical signals and systems in BIM and Digital twins, and similarly proposed the use of digital twins due to the limitations of *non-geometric data* in BIM.

2.3.2. Service layer
The service layer is the top layer of an integrated digital twin. It refers to a software functionality such as the retrieval of specified information or the execution of operations. Services are not context based, ‘retrieval of specified information’ is a service that could be applied to many different actors and assets. Digital twin services are however the enabling feature for applications, which are context based (such as sector, actor, asset, and timing) (Lim et al., 2019; Shen et al., 2012). Multiple services can be combined for specific applications, and services can be reused for different applications, dependent on the relevant context and requirements (Shen et al., 2012).

Recently, several authors have reviewed digital twin application papers, and extracted the core services, to categorize them. Y. Lu et al. (2020) categorises applications as either monitoring, prediction, or control related services (figure 2.5). Boje, Guerriero, Kubicki, and Rezgui (2020) focused on construction papers, and found similar services: simulate, predict, optimise, and agency. Optimise and agency are defined as control type abilities to adjust the physical twin. Digital shadow applications are the most common in literature, and provide the basis for decision-making support for humans, which includes validation (Y. Lu et al., 2020).

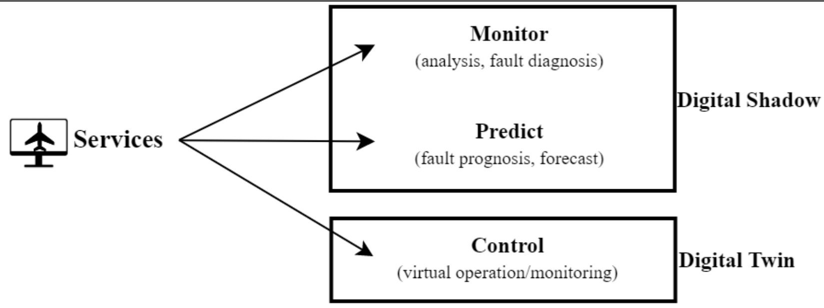


Figure 2.5: Digital twin services

2.4. Applications

Other than services, applications are context specific. Fuller, Fan, and Day (2019) reviewed digital twin articles to find applications in different sectors and found very different applications of digital twin services in different sectors. The author categorised three sectors and added their relative representation in literature: Healthcare (15%), Manufacturing (66%) and Smart cities (19%). This section describes the different contexts of applications, with a focus on construction (smart cities). The context is described here as the context influences, among other things, the stakeholder and application requirements (Chotipanich, 2004; Volk et al., 2014).

Of what

Digital twin services exist of people, assets and networks (Y. Lu et al., 2020). *Digital twins of people* are primarily found in the healthcare sector, examples are the monitoring of the body, prediction of drug effects through simulations and use of digital twins for planning and performing surgical procedures (Fuller et al., 2019). Digital twins of people in other sectors are focused on behaviour analysis and worker well being (Y. Lu et al., 2020; Tao et al., 2018).

Digital twins of assets are common in the manufacturing industry (Y. Lu et al., 2020) and construction sector (Kazado et al., 2019; Love & Matthews, 2019). Lastly, digital twins of networks are seen as a connection of human and asset digital twins (Y. Lu et al., 2020), or multiple asset digital twins and their interdependence (Whyte et al., 2019).

When

Digital twins are used throughout the lifecycle of an asset (Boje et al., 2020; Tao et al., 2018), the life cycle of an asset is divided in four phases, visualised in Figure 2.6. Q. Lu, Parlikad, et al. (2019) found that in construction projects, digital twins are required in the maintenance and operation, as digital models (BIM) are not sufficient due to the complex situations. Additionally, as discussed in (data types) most active data is produced in the maintenance and operation phase, emphasising its use in this phase (highlighted in Figure 2.6). Tang, Shelden, Eastman, Pishdad-Bozorgi, and Gao (2019) reviewed digital twin papers in the construction sector, and described limitations to the technology in the design and realisation phase. Problems encountered specifically in these project life cycle phases was requiring a full digital model (BIM) in these phases, and establishing a data flow that was automatic.

For whom

In the maintenance and operation phase, actors are categorised as (asset) user, (asset) owner, and service provider (Ihasalo, 2012). ISO 19650-1 (2018) sets standards for digital technology in the construction industry. This further divides service providers in facility managers and the information technology contractor (the appointed party). These actors have different application needs and perspectives. The owner has long term (strategic) interests, while facility managers has short term (operational) interests

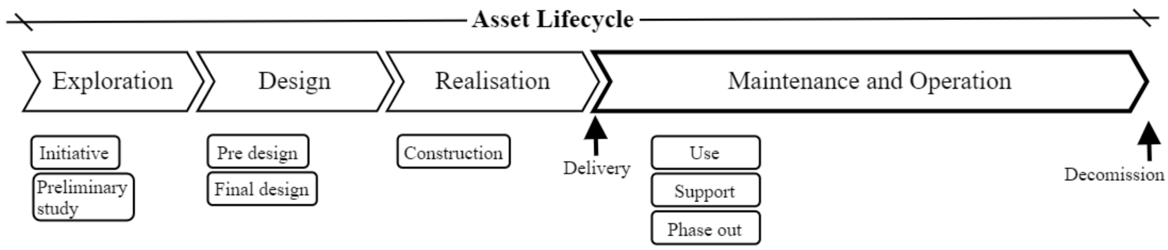


Figure 2.6: Project life cycle phases (adapted from (Rijkswaterstaat, 2005; Blanchard & Fabrycky, 2013))

(Hosseini, Roelvink, Papadonikolaki, Edwards, & Pärn, 2018; ISO 19650-1, 2018). Success of an information system is difficult to measure because of this. For a project manager a successful system is one that is completed in time and under budget, while the user defines a successful system as one that reduces the effort he spends to obtain information. Although the actors are no longer a part of a singular organisation (Ihasalo, 2012), the three actors are still interconnected. For example, service tasks are essential to the strategic needs of asset owners (Munir, Kiviniemi, Jones, & Finnegan, 2020), and users are central to facility manager operations (Chotipanich, 2004).

For what

Research towards digital twins for civil construction is limited. Of the identified 97 articles researching digital technology in maintenance and operation phase, Wong, Ge, and He (2018) discovered only 10 papers that research possible digital shadows and twins (BIM + IoT). (Tang et al., 2019) similarly reviewed possible digital shadows and twins (BIM + IoT), with more inclusive search terms, including smart buildings and smart cities, and found over 90 articles. This gives an indication towards the lower maturity of research in the civil construction sector compared to architecture (building engineering). Furthermore, the majority of the case studies in digital twin papers in the construction sector are for buildings. For this reason, this part is divided in two parts, building engineering (or architecture engineering) and civil infrastructure.

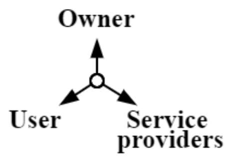


Figure 2.7: Actors in the M&O of building projects (Ihasalo, 2012)

Building engineering

Research has been done towards the implementation of composite digital twin services in buildings. In these papers, the end-user or building occupant is an especially important stakeholder for the design. Habibi (2017) researched a digital twin for building facilities, where the building climate (temperature, humidity) and the energy efficiency is based on user behaviours, to maximise their comfort. Q. Lu, Parlikad, et al. (2019) developed a digital twin for a campus facility by considering digital twin applications presented in other articles, and designed the integrative architecture and implementation of a digital twin using a composite service aimed at a facility manager. The composite service consists of 5 combined services: Anomaly detection in pumps, ambient environment monitoring, maintenance optimization, maintenance prioritisation, and environmentally friendly urban energy planning.

Infrastructure

10 identified papers discussing digital twin services for infrastructure are shown in appendix A. In general, the papers are very recent, and mostly in the form of conference papers (average publication year is 2019 and 7 of 10 are conference papers). The papers design digital twin applications by creating singular prototypes, meaning the research is not thoroughly tested and indicating the infancy of the research.

The services the applications provide can be categorised as monitoring (9 of 10), predicting (2 of 10), and controlling (1 of 10). Interestingly, four articles research digital twins during the design and realisation phase of tunnels (Deng, Chen, & Guo, 2016; Dohmen, 2019; Beaufils et al., 2011; Kang et al., 2018). The four articles research the monitoring of geotechnical conditions of tunnels, which allows an active data flow to be formed with the properties of surrounding ground conditions. The applications are designed to provide decision support regarding the subsidence of the ground in relation to the construction of the tunnel.

The remaining six papers research applications for the monitoring, prediction and control of infrastructure during the maintenance and operation phase. Three monitor and predict the service life of the civil construction (Ye et al., 2019; Kim & Kim, 2020; Panella et al., 2018), the civil construction is explored in more detail in section 3.1. However, it often encompasses the concrete parts of a construction (Rijkswaterstaat, 2020a), which have long life cycles. The remaining three papers research digital twins of people (users, including their vehicles), and of Mechanical, Electrical and Plumbing (MEP) systems. (Y.-D. Kim, Son, Kim, Song, & Lee, 2018) researched the identifying and locating of (vehicle) incidents in tunnels, and (Lin & Cheung, 2020) researched the monitoring and control of emissions of vehicles in parking garages. Lastly, (Pargmann, Euhausen, & Faber, 2018) researched the monitoring of wind farm systems.

How

Munir et al. (2020) researched the integration and implementation process of BIM with Asset management systems, on an organisational level, through a case studies. The research showed the importance of the ability to measure benefits when implementing digital technology, because this is where the organisation establishes project success (Munir et al., 2020). Traditionally the success of implementing an information system on an organisational level has been measured based on financial measures (return on investment, net present value, etc) (Ihasalo, 2012). Besides looking at just these tangible measures, more advanced methods have since surfaced. Love and Matthews (2019) researched the implementation benefits of digital twins by making implicit benefits, explicit, and assigning value them.

Other than measuring information system success on an organisational level through financial value, the success is measurable on an operational level, through user satisfaction (Gelderman, 1998). On such an operational level, Halmetoja (2019) proposed a digital twin based on the user perspectives in an building engineering context. The paper used 27 interviews, to question digital twin applications based on their perspectives. The result is a list of functions that are considered essential and its use cases for buildings.

2.4.1. Digital technology problems

Volk et al. (2014) researched the problems of digital technology, encountered during the life cycle stages of assets, and their relation to each other. The paper distinguishes four types of problems and describes the dependent relationships, as seen in figure 2.8. Functional problems are dependent on the life cycle stage of an asset, and influence the encountered informational, technical, and organisational problems.

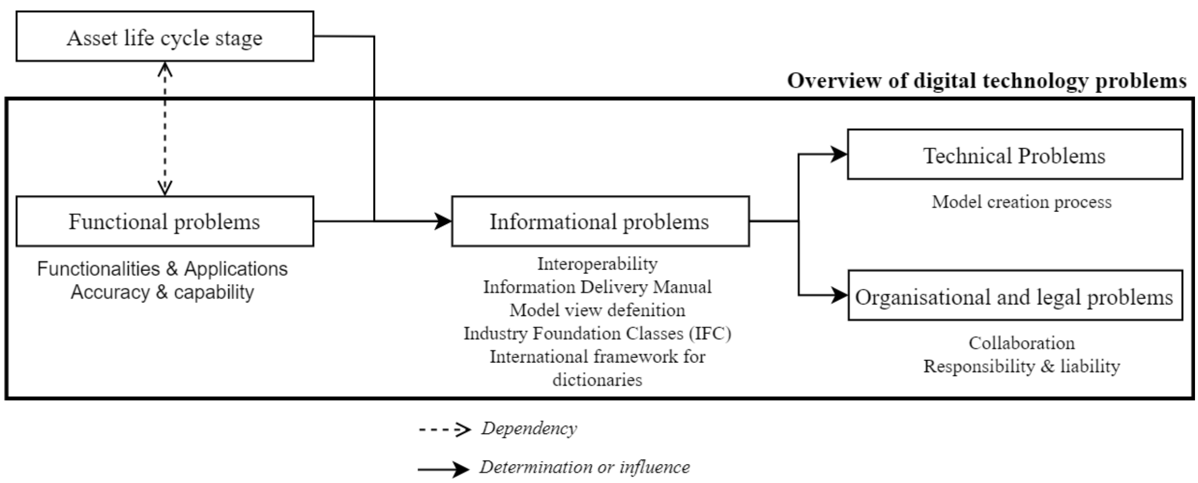


Figure 2.8: problems between life cycle stages and digital technology problems (adopted from Volk et al. (2014))

Functional needs arise from functional problems and originate in tasks, situations or assets (Volk et al., 2014). Fuller et al. (2019) notes that an important functional problem is the expectation that digital twins can solve all problems and are their benefit may be overestimated. Functional problems are dependent on the life cycle stage, and indirectly determine to a certain degree, all other problems. **Informational problems** require a suitable informational structure to be solved and require similar data exchange formats between digital models to guarantee interoperability. The interoperability is mentioned by Matarneh, Danso-Amoako, Al-Bizri, Gaterell, and Matarneh (2019) as one of the leading problems for the implementation of digital tools in the maintenance and operational phase. **Technical problems** encompass the problems during the model creation process, including the data capturing, processing, and interoperability problems between different digital tools. Fuller et al. (2019) details the main technical problem is creating the IT infrastructure and collecting high quality data which is accurate. **Organisational problems** determine the stakeholder roles, information rights, liabilities, and data output. These problems include lack of qualified personnel and contractual restrictions.

During the maintenance and operation, where digital twins provide the most potential due to the production of active data, not much empirical research has been conducted to find problems and needs (Munir et al., 2020). The reason why needs are not studied in detail can be attributed to the difficulty of finding them in practice (Ashworth, Tucker, Druhmann, & Kassem, 2016). This difficulty can be explained by the nature of stakeholder needs, as: they can change over time, they can be player specific (Frame, 2003) and people rarely focus on their needs because they are hard to articulate (Hoyer, MacInnis, & Pieters, 2013).

To find related articles, techniques discussed by (Saunders et al., 2016; Sayers, 2007) were used, which include scanning online databases and finding literature through snowballing and reverse snowballing. These techniques are used in particular as they offer a fast and comprehensive view of a topic that is not researched widely. Seven articles were identified that researched functional needs in an empirical manner shown in table 2.3. The articles all discover functional problems of digital technology, through interviews, surveys or focus groups with maintenance and operation stakeholders (facility managers). The sector of these stakeholders, and as such the research, are mainly the architecture sector. There is a gap in research regarding the problems of infrastructure projects, in the maintenance and operation phase. The discovered problems in the empirical research articles are combined in a single table, categorised by the type of problem (functional, informational, technical and organisational) and can be found in appendix B.

2.4.2. Functional problems

Functional problems are based on the applications of technology in a specific life cycle stage, and all other problems are dependent on them (Volk et al., 2014). For this reason, it is chosen to research specifically these problems in this report, for an application area where little related research has been conducted, infrastructure, and more specifically, tunnels. Literature empirically discovering application problems, shown in table 2.2 is used here to discover the functional problems in the building sector. The functional problems found in the articles are used in this research to discover their generalisability towards tunnels, and form interview topics.

All seven articles collected functional problems through interviews. The articles gathered the information for the consideration of digital models (BIM), which is in part explained by the age of the articles, and in part by not distinguishing between digital models and twins (figure 2.3). To account for this, functional problems requiring data associated with digital models (BIM) is excluded (passive, geometric information, as seen in figure 2.4). By doing this, a list of functional problems, primarily based in the building sector, is presented which apply within the scope of digital twins. This list is presented in table 2.3

problems were discovered relating to training, of both new and existing personnel. More specifically, the lack of training, assessing this lack, and the time it costs to train employees are mentioned [#1-6]. Closely related, a lack of comprehension was found of non-geometric information such as system operations, operation sequences, and movement of people and equipment [#7-13]. Next, problems

Table 2.2: Empirical research towards digital technology problems

Sector, authors (date)	Source	Method
Architecture Ashworth et al. (2016)	Proceedings of CIB World Building Congress	3 Focus groups with 20 FM professionals
AEC* Becerik-Gerber et al. (2012)	Journal of Construction Engineering and Management	Persona and expert Interviews
Architecture Cavka et al. (2017)	Journal of Automation in Construction 83	2 Case studies, a university building project and a building FM company.
Architecture Gnanarednam and Jayasena (2013)	Proceedings of The Second World Construction Symposium	Citing another source**
AEC* Liu and Issa (2016)	Journal of Performance of Constructed Facilities	Closed and open questionnaire with 63 respondents
Architecture Love et al. (2016)	Journal of Built Environment Project and Asset Management	Case study of a university complex
Civil engineering Johansson et al. (2019)	Journal of Sustainability 11.13	26 Interviews with maintenance development company

*AEC = Architecture, Engineering and Construction
**Original source can't be retrieved

with locating non visible components, and equipment [#14-15], and performance related problems, specifically regarding energy, water, waste and system performance [#15-18]. Lastly, problems related to maintenance and remodels, including predictive services for decision making (cost, planning and design, preventive maintenance) [#19-27] are found. The identified functional problems listed above are used to form more specific interview questions, to uncover their generalisability between the two sectors. Furthermore, the common topics as described above are the considered as themes for the organisation of the interview results in chapter 5.

Table 2.3: Functional problems found in literature

#	Author	problem
1	Becerik-Gerber et al. (2012)	Facility management personnel have to get familiar with processes, systems and facilities when newly hired or assigned.
2	Becerik-Gerber et al. (2012)	Assesing whether trainees are prepared for their tasks
3	Becerik-Gerber et al. (2012)	Training takes vast amounts of time
4	Becerik-Gerber et al. (2012)	Training relies heavily on abilities and experience of the trainers
5	Liu and Issa (2016)	Lack of trained personnel
6	Becerik-Gerber et al. (2012)	Evacuation plan training for building occupants
7	Ashworth et al. (2016)	Clear understanding of the design logistics planning, for movement of people/equipment, access routes, replacement space
8	Becerik-Gerber et al. (2012)	Information is not easily understandable for everyone, difficulty processing information into knowledge
9	Cavka et al. (2017)	System visualization
10	Cavka et al. (2017)	Sequence of operation (start-up/shut down information)
11	Cavka et al. (2017)	Installation manuals
12	Johansson et al. (2019)	Decision support by having the right information
13	Becerik-Gerber et al. (2012)	Emergency responders are required to make decisions without adequate information, there is a need for Organised data, displayed logically to take appropriate actions
14	Becerik-Gerber et al. (2012)	Locating MEP components which are not visible
15	Cavka et al. (2017)	Locations of equipment and system controlls
16	Cavka et al. (2017)	System performance information
17	Gnanarednam and Jayasena (2013)	Facilities produce a lot of waste during the building process
18	Gnanarednam and Jayasena (2013)	Facilities use a lot of energy and water
19	Cavka et al. (2017)	Cost information related to replacing and maintaining equipment and systems
20	Ashworth et al. (2016)	How easily spaces can be reconfigured to accommodate flexibility and change of use.
21	Becerik-Gerber et al. (2012)	Adding new building floor plans and monitored equipment, updating and maintaining graphical information
22	Becerik-Gerber et al. (2012)	Planning, designing analysing and simulating remodels, renovations or demolition work.
23	Love et al. (2016)	Option appraisal through visualisations for strategic decision making
24	Liu and Issa (2016)	Lack of preventive maintenance
25	Love et al. (2016)	Regular changes in building utilisation, requires a full time technician
26	Johansson et al. (2019)	Removing subjective assessments, to obtain better decision support
27	Ashworth et al. (2016)	Quick generation of tailored reports identifying facility space properties

2.5. Sub conclusion

This chapter set out to form the foundation of the research and answer the first sub-question:

SQ1 *How are digital twins designed and what applications do they provide?*

This was answered by firstly discovering the commonly agreed upon meaning of a digital twin in literature. The definition, as used for this research is as follows: *A digital model, which is a dynamic representation of an asset and mimics its real-world behaviours in real time.* A digital twin is described to have a mirror like characteristic, where the mirror (digital twin) visualises the same behaviours and reacts in the same way.

The design or architecture of a digital twin has different levels, at its highest level, a digital twin has a integrated nature, where singular digital twin services are combined in a modular fashion. Each of these singular digital twin services consist of four layers: data-, communication-, processing-, and service layer. The key characteristic of these layers, and a digital twin, is the autonomous flow of relevant data from the physical asset, to the digital reference. Relevant data for digital twins is defined as active data, predominantly found in the maintenance and operation phase of an asset, and includes: sensor data, interaction protocols, monitoring strategies, embedded algorithms and implicit dynamic relationships.

It was found that applications of a digital twin are context based services, and there is a clear separation found between construction articles of buildings, and infrastructure. Research has been conducted towards the implementation of digital twins (how), as well as empirical research towards the problems (application problems) for buildings.

However, what is missing is research towards the applications of digital twins in the infrastructure sector. The research conducted in this report will address part of this gap, namely, finding functional problems of tunnel stakeholders, relating to the applications of digital twins. The next chapter will describe this research gap in more detail, by looking at the specific context of tunnels as infrastructure system.

3 Tunnel System

The goal of the chapter is to position this research as part of the found research gap (digital twin applications in the infrastructure sector) formulated in the previous chapter. This is done by exploring the context of this research, a tunnel system, as part of the infrastructure sector.

This chapter details the tunnel system, the stakeholders within the system, their processes, and how these processes influence the design of a digital twin. By looking at this, the second second subquestion is answered:

SQ2 *How are tunnel systems organised and how is information management incorporated in the maintenance and operation stage?*

This chapter consists of five sections. 3.1 (Tunnel system) defines and describes *what* the tunnel system is comprised of. 3.2 (Tunnel stakeholders) looks at *who* the stakeholders are within the maintenance and operation of the tunnel system. 3.3 (Tunnel FM processes) describes current processes of tunnel facility managers such as the maintenance activities. 3.4 (Information management) looks at *how* facility manager processes influence the design of digital twins. Lastly, 3.5 concludes this chapter by summarising its findings, and answering sub question 2.

3.1. Tunnel system

A traffic tunnel is an enclosed road section, which are longer than 250m and part of an infrastructure network that is protected from the environment (Rijkswaterstaat, 2016). The Netherlands counts 72 tunnels as of June 2020 (COB, 2019), each with unique characteristics including ownership, contracts, age and purpose. Because of this, tunnels aren't uniform in scope, however significant efforts are made to standardise practices. In the Dutch tunnel sector this can be seen in the 'Landelijke Tunnel Standaard' (LTS), developed bij Rijkswaterstaat (RWS[1]) which is the executive arm of the Dutch Ministry of Infrastructure and Water Management. This standard is widely adopted or adapted by various tunnel owners throughout The Netherlands (Rijkswaterstaat, 2020b), hence, it is used to define standard tunnel systems for this research.

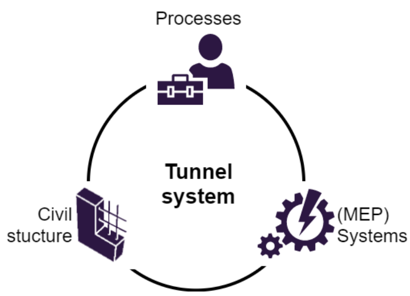


Figure 3.1: Tunnel system high level components (Rijkswaterstaat, 2016)

[1] www.rijkswaterstaat.nl/english

On its highest level a tunnel system consists of three domains: The civil structure, tunnel systems (MEP), and tunnel processes, as seen in figure 3.1. First the external but closely related influences are discussed, followed by the civil structures and MEP systems of tunnels. The third part of tunnel systems, processes is described in following sections (3.3).

Tunnel services

Tunnel services define the purpose of the tunnel system on its highest level, which interface with other networks such as nature habitats, cities, and transport routes. According to Rijkswaterstaat (2016) the primary services tunnels provide are the connection of two road or rail sections and its traffic management, and the security and safety of a tunnel.

What this implies is that the traffic passing through the tunnel, is not directly part of the tunnel system and its processes. The traffic has a lot of interfaces with the tunnel system, however, itself is part of the operational traffic management system (translated from the Dutch 'operationeel verkeersmanagement van het hoofdwegennet, OVM'). Processes within the tunnel system are, however, closely related to this system, namely incident management and maintenance processes related to tunnel technical systems.

Laws and Regulations

Next to the tunnel system itself, there are external factors that influence the maintenance and operation of tunnels. The European, national, and company requirements, are set in law and regulation (table 3.1), which are summarised next.

Table 3.1: Tunnel services, laws, and regulations (not exclusive)

Tunnel laws	**Regulations**
• Bouwbesluit	• ROK 'Richtlijn Ontwerp Kunstwerken'
• Warvw 'Wet aanvullende regels veiligheid wegtunnels'(Tunnel law)	• LTS 'Landelijke TunnelStandaard' (Tunnel standard)

Tunnel systems and services are governed by *laws* which set minimum requirements, in The Netherlands, there are two: the 'Bouwbesluit' and tunnel law. The 'Bouwbesluit' is oriented towards construction requirements and enforces the Eurocodes and national appendix. The tunnel law ('Tunnelwet') is an adaption of the European tunnel directive (2004/54/EC), and focuses on the safety requirements of tunnels.

In addition to these laws, it is possible tunnels have other requirements and standards, set and enforced in company *regulations*. Rijkswaterstaat is the largest owner of tunnels in the Netherlands (28 of 72 according to COB (2019)), and has created two of such regulations which relate to tunnels. The regulations are used by many other tunnel owners, either fully adopting the regulations or adapting them (Rijkswaterstaat, 2020b). The first regulation is the ROK ('Richtlijn ontwerp kunstwerken') which focuses on the design and realisation of civil structures, including tunnels. The second is the LTS, which focuses on the maintenance and operation of Dutch tunnels.

3.1.1. Tunnel civil structure and systems

The tunnel civil structure and (MEP) systems together form the majority of the visible aspects of tunnels (figure 3.2) and form the basis for the processes of the tunnel system, and the services it provides. These components are described next to define their relevance for the research, more specifically to discover *what* is within the scope of digital twins to mirror. This is done by considering the relevance of the automatic data collection characteristic of digital twins.

Tunnel civil structures

Components of tunnels which form the basis of the tunnel design and attached systems and processes. Civil structure components are the traffic tubes, emergency walkway, service building, water cellars and the concrete shell. The components are characterised by their high investment costs, low maintenance

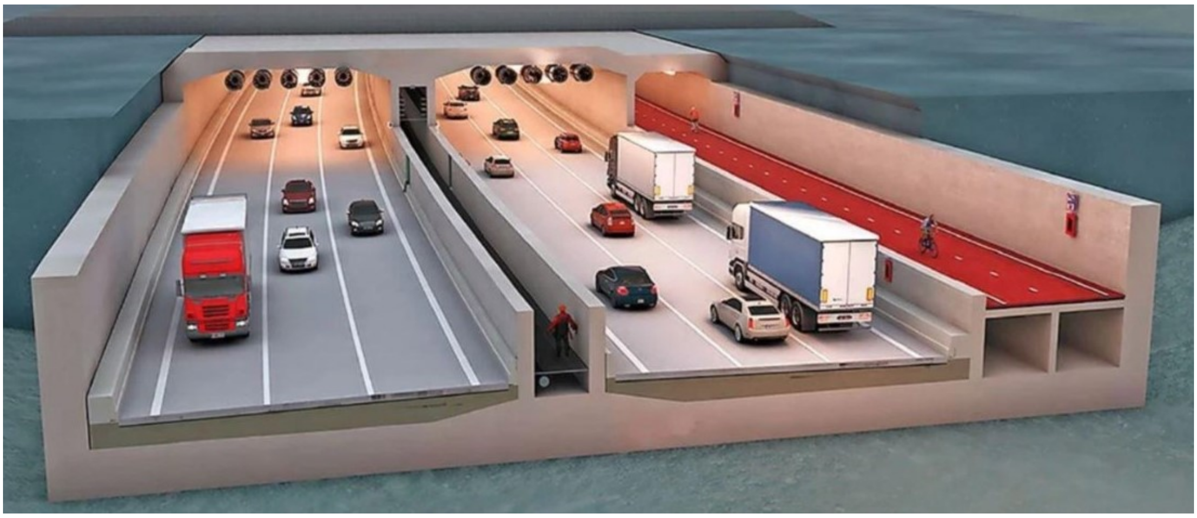


Figure 3.2: Visible tunnel elements (Lantis, 2020)

costs and long life cycles. The civil structure has a lifespan of at least 100 years, and removable components have a life cycle of 50 years (Rijkswaterstaat, 2020a). The civil structures produce little active data, as there are few interaction protocols (maintenance events, monitoring strategies, embedded algorithms, or dynamic relationships (as discussed in 2.3.1). Because of this characteristic and the scope of digital twins, less attention is given to these structures in this research.

Tunnel (MEP) Systems
Tunnel systems encompass the mechanical, electrical, and plumbing systems. Within the LTS, the mechanical and electrical systems are termed tunnel technical installations (TTI). Tunnel systems include: smoke exhaust systems and other ventilation (HVAC), electrical power supply (trains and systems), lighting systems, CCTV- and communication systems (stoplights, automatic gates and detection systems), emergency stations, pumping and drainage systems, control systems and other software.

Tunnel systems are characterised by short life cycles, and high maintenance costs. System hardware has a life cycle of 7 years, while software has a life cycle of 5 years (Rijkswaterstaat, 2016, 2020a). These systems are relevant to digital twins as the systems have non-geometric data (embedded algorithms), and most processes in the maintenance and operation relate to these objects (Rijkswaterstaat, 2016) resulting in active data. Hence, the research will primarily focus on discovering possibilities for digital twins relating to these assets. Additionally, to some degree, digital twin applications of people and vehicles are considered, to the extent that they are managed as part of the tunnel system processes.

3.2. Tunnel stakeholders

Tunnel roles are filled by various actors. The roles shown in the figure below are defined in the LTS as common roles which are filled by actors during the maintenance and operation of tunnels. The exact role definitions, their relationships, and actors who fulfil them are dependent on the context such as the location, the owner, and the type of contract. The roles described and used in this research will not go into the unique organisations of different projects and contracts, instead the general roles as described in the LTS are used. Nevertheless, a short introduction is given to Public-Private Partnerships (PPP) and Design Build Finance Maintain (DBFM) contracts, due to their wide use throughout the tunnel industry.

Compared to the general building actor diagram (figure 2.7) presented in the previous chapter, the roles are similar. Facility managers and safety officers can be categorised as service providers, resulting in a similar role distinction. However, unique to tunnels is the minor role of the tunnel user. As discussed in section 3.1 road and rail users are generally considered external roles, and are only tunnel users when there are interfaces with tunnels systems.

The empirical part of this research focuses on the facility managers of tunnels, and in specific the facility managers that are responsible for the operation of the tunnel system (Maintenance officers, Tunnel supervisors). These roles are considered because their work involves using tunnel information for the management of efficient operation and maintenance of the tunnel. These facility managers are present in different organisations, such as the contractor, municipal, provincial, national levels. The role descriptions vary based on variables such as the location, tunnel, and contract. The most common (new) type of organisational and contractual structure are the public-private partnerships, and DBFM contracts, which are introduced shortly.

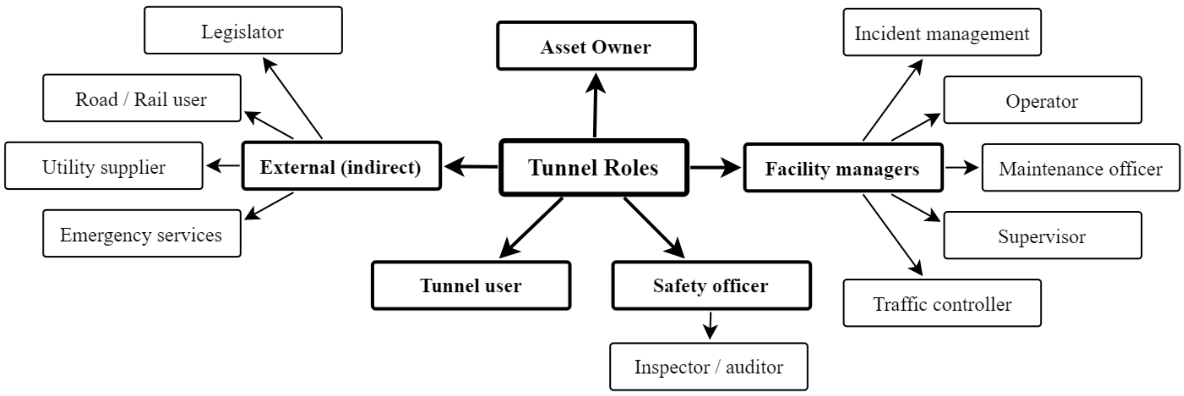


Figure 3.3: Tunnel roles as presented in (Rijkswaterstaat, 2016)

PPP and DBFM

A Public-Private Partnerships (PPPs) is an institutional form of cooperation of public and private actors, who work together towards a joint target (Hobma & Jong, 2016). These partnerships are very common in the Netherlands, particularly in the transportation infrastructure development because they are thought to have many benefits (Verweij, 2015). Furthermore, their use is increasing, as all new infrastructure projects above 60 million euros are required to be executed as PPP, by law (Rijksoverheid, 2020). This partnership approach is adherent to contracts including the operation phase and maintenance phases, including DBFM (*Project and People Mastering Success*, 2018).

Because of this relationship, DBFM contracts are increasingly being used in the Dutch tunnel sector. A DBFM in an integrated contract in which a consortium designs, builds finances and maintains a project. This contract does not account for the entire project life cycle however, as the contracts are often limited to a certain number of years of maintenance. For the purpose of this research, different contract types are not considered because the assumption is made that functional problems and possibilities are not specific to the type of organisation but rather the role of the stakeholder. More specifically, the operational processes and needs of specific roles are not dependent on who fulfills the role.

3.3. Tunnel FM processes

Tunnel facility managers have various tasks during the operation and maintenance of tunnels. The tasks are categorised, by Rijkswaterstaat (2016), according to a ”Plan, Do, Check, and Act” diagram, and distinguishes between management and maintenance processes. These processes are narrowly connected, management processes focus on the management of maintenance and other tunnel activities, while maintenance processes actually carry out the maintenance. These two types of processes are described in more detail next. Other than these two process types, the Plan, Do, Check, Act diagram describes different protocols including those used for teaching, training, practicing of tunnel personnel and evaluating the effectiveness of processes.

Management processes
The Tunnel Standard defines four management processes, which narrowly follow the maintenance processes.

- *Configuration Management*

  Registration and management of component information and the relation between them, of tunnel (MEP) systems. This encompasses the management of information in the asset information model, which form the basis for change management (termed CMDB ’Configuration Management Database’ in the tunnel standard).

- *Incident Management*

  Repair of function, with as little function loss of the traffic network, this encompasses corrective maintenance in figure 3.4. Incidents are registered for diagnosis in problem management. During the operation of a tunnel, the two most important types of incidents are traffic related and technical system related. Incident management processes include the support and enabling of related (external) processes to resolve the incidents.

- *Problem management*

  Detection of structural faults in tunnel system, diagnosis of the problem, and the origin of the problem. This management process is described as closely related to incident management, as incidents or problems that are encountered with high frequency are considered during problem management. A large part of this management form is ascribed to preventive maintenance and improvement maintenance, namely its detection and diagnosis. The information is used during change management.

- *Change Management*

  Problems from problem management are analysed and changes are considered with help of standard protocols with the goal to minimise impact on the tunnel services. Expected impact of changes are analysed with information from configuration management, and any applied changes are updated in the configuration systems.

Maintenance processes
These management processes can be visualised according to maintenance activities. The European standard EN 13306 separates maintenance activities based on type maintenance, improvement, preventive or corrective, as shown in the figure 3.4.

Corrective maintenance is the simplest form of maintenance (Horner, El-Haram, & Munns, 1997), where maintenance is done in a reactive manner. Faults are localised through reporting, breakdown, inspection, or condition monitoring and corrected immediately or with delay (deferred) (Hastings, 2015). This type of maintenance ensures the entire life cycle of assets are utilised, however, it has several disadvantages. Disadvantages include (Horner et al., 1997) the dependent failure of other assets, unplanned logistics (spare parts), and failures can occur at anytime leading to unplanned downtime of the asset. This last disadvantage is relevant for tunnels as it is a politically sensitive problem due to extensive media attention, the availability of the IJtunnel in Amsterdam, for example, was unavailable for around 10 minutes and resulted in a news article in a Dutch newspaper, titled “Chaos at IJtunnel” (Peijs, Schrijver, & Veldhuijzen van Zanten, 2014).

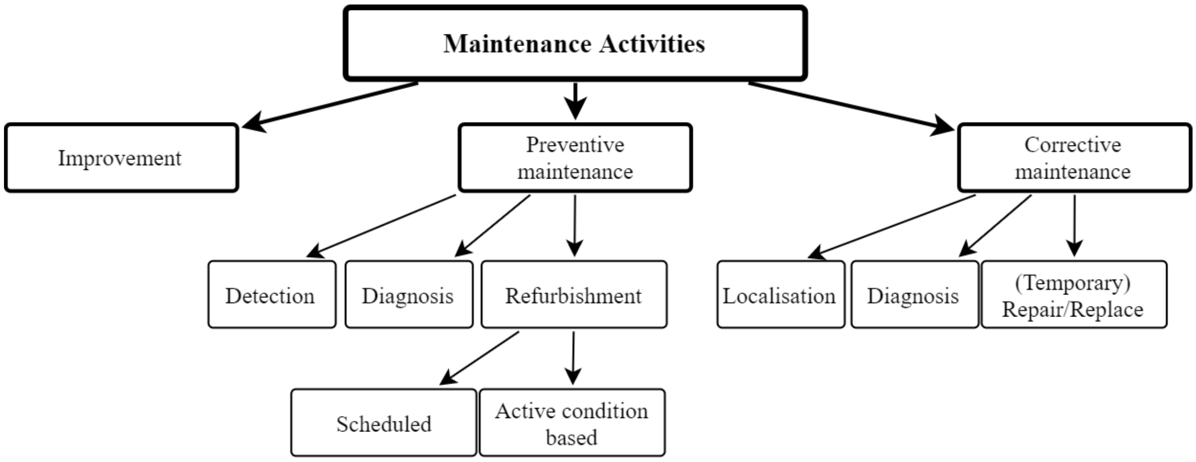


Figure 3.4: Maintenance services (adapted from (EN 13306, 2017))

Preventive maintenance is carried out before failure of an asset, and intends to assess and/or mitigate degradation and reduce the probability of failure (EN 13306, 2017). Preventive maintenance is divided in predetermined and condition-based. Predetermined is scheduled maintenance at determined intervals, and condition based maintenance is based on the analysis of the physical condition. To gain the full advantage from condition based maintenance, the condition of the asset should be monitored continuously and automatically (Ihasalo, 2012), which indicates the relevance of digital twin services (especially predictive services) for this maintenance activity. Notwithstanding, all maintenance activities are considered for the empirical part of this report.

3.4. Information management

This section describes how stakeholder requirements are introduced into digital tools, often referred to as information models. This is described by considering the NEN EN ISO 19650 (2018), which is a European and Dutch standard for the organization and digitization of information (including digital tools) about both building engineering and infrastructure works. The section is divided in two parts, the first describes the relation between different management levels within a project, and the second part focuses on the design of information models based on stakeholder requirements.

Management levels
Figure 3.5 visualises the hierarchical management relationships; information management is at the core of asset management, which in turn is central to organisational management (NEN EN ISO 19650, 2018).

An organisation is an organised body of people with a particular purpose (Oxford, 2020). *Organisational management* is the overarching management form, where organisational needs are identified, which give direction to the organisation's asset management strategy (NEN EN ISO 19650, 2018). The management of organisations has changed largely in Europe since the 1980s when asset management started to become an integral part of its structure (IAM, 2015). This change was triggered by the financial recession at the time which caused companies to consider the efficiency of their management, especially related to the management of assets (Parsanezhad, 2019).

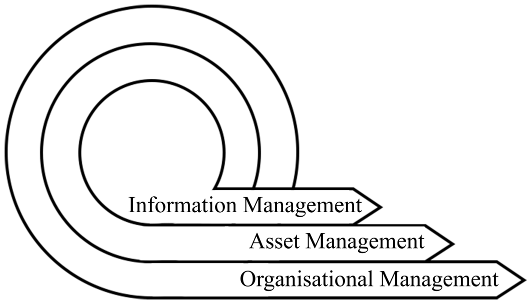
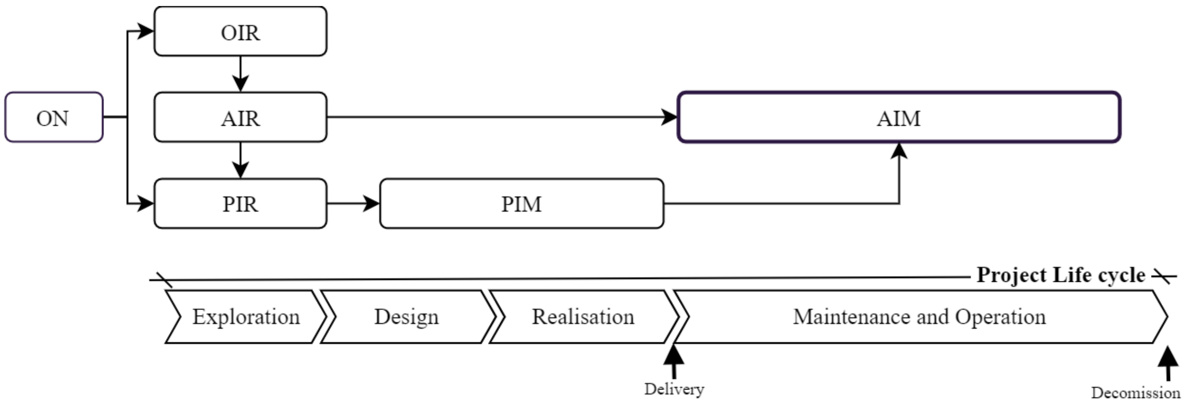


Figure 3.5: Management forms (adopted from NEN EN ISO 19650 (2018)

This brings us to the second level of management, *asset management*, which organisations are highly dependent on (Kenton, 2020). Asset management is about the optimisation and application of strategies towards an effective investments and work planning decisions of assets (Mohseni, 2003). Asset managers primarily depend on information to perform asset management tasks. Hence, information management is at the core of asset management (Figure 3.5).

Design of asset information models
Munir et al. (2020) has adapted the information management schematic found in the European standard (NEN EN ISO 19650, 2018), into one focusing on the maintenance and operation phase, which is visualised in Figure 3.6. The figure visualises how organisational requirements (OIR) influences the asset and project management requirements (AIR & PIR) early in the project life cycle and determine the design of the asset information model. As defined in figure 3.6, organisational needs and (information) requirements relate to the asset owner, while asset and project requirements stem from asset or facility managers. This distinction is also recognised in information technology (IT) research, as strategic, tactical and operational requirements described by (Brous, Janssen, Schraven, Spiegeler, & Duzgun, 2017).

Other than the dependent relation shown in figure 3.6, the reverse dependent relationship between operational requirements (AIR/PIR) and strategic impact (OIR/ON) has been highly acknowledged in literature. A highly cited (12000+ citations on google scholar) model by designed by Delone and McLean (2003) shows that the facility manager experience of the output of the information system, together with the impact on the facility managers work processes, directly impact the success on an organisational level. It is found that information requirements of facility managers, influence both the organisational needs, and the asset information model.



ON	Organisational needs are the high-level strategic and tactical objectives of the asset owner
OIR	Organisational Information Requirements explain the information needed to answer business needs on an organisational level.
PIR & AIR	Project- & Asset Information Requirements set out the explain the information needed to answer organisational information requirements on project and asset level.
PIM & AIM	Project- & Asset Information Models are structured repositories of information (NEN EN ISO 19650, 2018) for a specific project stage.

Figure 3.6: Information management along the project life cycle (adapted from Munir et al. (2020))

3.5. Sub conclusion

This chapter set out to specify the context of the research and answer the second sub-question:

SQ2 *How are tunnel systems organised and how is information management incorporated in the maintenance and operation stage?*

This was answered by defining a tunnel as an enclosed road section for traffic, with a length of at least 250 meters. It was concluded that tunnel systems in The Netherlands are not uniform but do frequently follow the ('National') Tunnel Standard (LTS), which is therefore used in this research to define the tunnel system. Tunnel technical installations are the most relevant physical parts of tunnels for the research, as they produce the most active data in the maintenance and operation phase. The LTS, describes a minor role of the 'tunnel user' (traffic), however, traffic is considered for the research.

The role within the tunnel system that is focused on in this research is the facility manager. Depending on the organisational structure of the tunnel, different tasks are fulfilled by roles, as such, facility managers from various organisational levels are considered for the interviews. Certain operational activities of facility managers, within the tunnel system, are more relevant for digital twins, however, none are excluded from the research.

Information management is formulated during the exploration and design phase of projects, by requirements dependent on the organisational needs. It is found that operational interests, of facility managers, in the maintenance and operation phase, directly influence strategic (organisational) goals. Hence, the requirements of facility managers of tunnels influence the design of information models and the management of information indirectly.

4 Methodology

The empirical data for this research, is obtained from ten interviews with professionals active in the facility management of tunnels to discover functional needs and problems. This is done through a semi-structured interview with questions originating from related literature from the building sector.

Section 4.1 describes the structure and characteristics of the interviews. Section 4.2 presents the individual participants of the interviews, and their (dis)similarities. Lastly, section 4.3 details the method of processing and using the interview results for the objective of the research.

4.1. Semi-structured interview

The goal of the interview is to discover functional problems and needs during the operation and maintenance phase of projects, within the scope of state-of-the-art digital twins and in the context of tunnels. To achieve the goal of discovering the monitoring, predicting, and controlling needs of maintenance and operation stakeholders, ten interviews are held. This format is chosen as needs are based on perceptions, memories and intentions which are unearthed during interviews (Verschuren & Doorewaard, 2007). Furthermore, interviews allow for follow-up questions and for the probing of answers (Saunders et al., 2016), which is required when finding needs, according to (Frame, 2003). It is required for two specific reasons:

1. *Solutions are often confused with needs.*

   When a stakeholder states “I need more cameras”, the actual need may be “I need to precisely locate incidents”. This actual underlying need could be solved by multiple solutions and defining the solution can result in a sub-optimal resolve. To find the actual need, a full set of questions are asked about the need, and the need is not accepted at face value. These follow-up questions include discussing whether it is the true need, or if there is an underlying, masked, need.

2. *Discussion is required* as unearthed needs should be relayed to the interviewee to not form researcher bias.

Semi-structured interviews

Semi-structured interviews are held, to be able to determine the structure of the interview, while leaving space for open discussion. This type of interview allows for the collection of a more rich and detailed set of data (Saunders et al., 2016). It is specifically useful for the purpose of this research, as the structure and question design allow the interviewee to consider many aspects, which may spark new needs and to surface.

The interview protocol

The Interview protocol consists of two parts containing questions, this protocol is found in Appendix C. The first part is sent to the participant before the interview starts, which is a short question form. These questions define the general information about the participants including: role, job description, and experience. This question form is sent to be able to refine the following interview based on the knowledge of the participant.

The second part, is the semi-structured interview itself, held in person (or electronic equivalent). Before questioning the interviewee, they are introduced to the subject of the research and the goal of the interview. Furthermore, practical matters are communicated, which include: The interviews are held in Dutch, they are recorded and transcribed anonymously, the transcriptions can be obtained on request, and the results of the interview are shared so the participant can object to them.

Generic to specific questions
The structure of the questions in the interview, is from general to specific. The interview will start with general questions, about activities of the interviewee, and general perceptions of these activities. Following this, the interview becomes more and more specific, by introducing digital twin services, and questioning the participants about possibilities of these services within their job activities. The last questions are the most specific, here examples are given from literature, where the participant is asked to consider in the context of tunnels.

Because needs are difficult to unearth, some questions are very specific towards tunnel processes and scenario's, so the participant can easily answer them, after which other examples may be presented by the participant. To ensure this does not restrict the the answers or form unwanted bias, initial questions about thoughts and ideas surrounding topics are asked first. Furthermore, some questions require yes/no answers, specifically those regarding the functional needs in other sectors, these questions are always followed by questions asking for examples or further explanations if these are not given initially. These validation questions are asked in the interview, to minimise response bias.

4.2. Participants

Ten interviews are held with a homogeneous group of experts, to acquire the required results, while obtaining data saturation (Saunders et al., 2016). The participants are facility managers of Dutch tunnels currently in the maintenance and operation phase. More specifically, participants have the role of tunnel maintenance officers or tunnel supervisors and have fulfilled this role within the last 3 years, for at least 2 years to obtain relevant and reliable perceptions.

During the selection process, attention is given to the composition of the group, to ensure the holistic representation of the data gathering, while keeping a homogeneous group, to ensure the data could be compared and analysed thoroughly. The differences between participants are mentioned next, which are based on the definitions given in chapter 3. The mentioned differences in table 4.1 are used as variables, to consider the results in respect to these variables. The group size is not large enough to conclusively tie results to particular variables. However, they may form indications towards interesting conclusions. This is done in the analysis of the interviews, in chapter 6.

Not project based but role based
The goal is to find functional needs in the Dutch tunnel sector, so the choice was made to research a variety of tunnel projects and contracts. The results are therefor not only analysed for a singular tunnel project and that tunnels perspective, but rather a wider range of tunnel projects in The Netherlands to form a more comprehensive view. The role of the participants is tunnel facility manager, i.e. they are in part responsible for the management of the operation and maintenance phase of tunnel projects. The exact role description differs per participant, influenced by the different contracts, organisational structure and the project phase of the tunnels. as shown in table 4.1.

Organisation, DB(F)M
Participants are distinguished based on the organisation they are apart of. Facility managers from both contractors and governmental organisations are interviewed to form a holistic representation of the role. Governmental organisations (participants 4-10) are further differentiated based on their operational level (municipality, provincial, national), because the distinction of contractor and government is not as categorical as it may seem. This can be indicated by two examples:

Table 4.1: Interview participant profiles

Participant number	Organisation	Experience (years)	Number of tunnels	Tunnel age (years)	DB(F)M	LTS
01	Contractor	10	1	0-7	no	yes
02	Contractor	12	2	49-56* & 0-7	yes	yes
03	Contractor	20	2	14-21 & 0-7	yes	yes
04	Province	10	1	0-7	yes	yes
05	RWS (Regional)	10	>3	Various	-	-
06	RWS (Regional)	4	>3	Various	-	-
07	RWS (National)	25	>3	Various	-	-
08	RWS (National)	12	>3	Various	-	-
09	Municipality	6	1	77-84*	no	yes
10	Municipality	12	1	77-84*	no	yes

* Renovated 0-7 years ago

1. Municipality participants 9 and 10, have similar job descriptions as the contractors, They are more operationally responsible for the tunnel. This is attributed to the less integrative nature of the contract type, and the focus on a singular tunnel (the municipality manages one tunnel).
2. Contractor participant three: this organisation used to be the tunnel owner, and according to the participant, the only reason they are not a part of the government is because The Westerschelde-tunnel is a toll tunnel.

Experience, number of tunnels, tunnel age
Further distinctions are made between participants based on the context of their role, this is done to possibly determine the relation between these variables and the answers given in the interviews.

'Landelijke Tunnel Standaard'
The tunnels follow, to a large degree, the LTS. This assures the tunnel processes and organisation are similar. Similar to the organisational distinctions, the LTS distinction can be nuanced, as the tunnels use different versions of the LTS (the version is set on the contract date), or varying implementations (adaptions can be made, and only nationally governed roads mandate its implementation).

4.3. Analysis

After the interviews are held, the interviews are reported and analysed. This is separated in three chapters, chapter 5 categorises and summarises the interviews, chapter 6 analyses the interview results, and chapter 7 provides synthesis between interview results and digital twin literature. The method and process of these three chapters is explored next.

4.3.1. Interview results (chapter 5)

The results of the interview are reported in a qualitative manner as the results of the interviews are unorganised answers and statements by participants. The purpose of the analysis is to structure this data to recognise underlying themes and patterns to fulfill the goal of the research. The processing of the data is done according to the qualitative analysis steps defined by (Baarda, De Goede, & Teunissen, 2000). The steps and final number of codes and themes are visualised in figure 4.1.

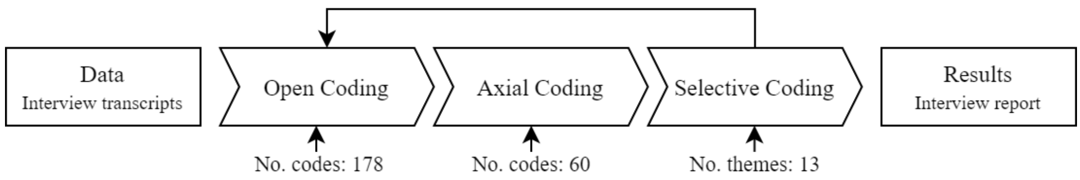


Figure 4.1: Qualitative coding steps

Transcribing interviews and data omission based on relevance.
The interviews are recorded and transcribed, word for word, to be able to analyse the data in a qualitative manner. Data that is collected, that is not part of the interview and is irrelevant to the research is omitted from the transcription. Once the analysis is complete, the omitted data is revisited to form a second judgement of its relevance. The omitted data is revisited as new insights after analysis may change the perceived relevance.

Open coding
The transcripts are added to a 'computer assisted qualitative data analysis software',specifically, MaxQDA[1] for organisational and clarity purposes. The interviews are split into sections, which are understandable on their own, and discuss a single subject. Next, codes are given to the data, these codes are labels or terms that characterise pieces of the interview fragments, relating to the research goal. Hence, the codes say something about functional needs or problems they face during their work. The names of the codes come from a combination of existing theory and keywords from the text fragments.

Axial coding
The codes are compared to each other, and the relation and overlap between codes are considered. Codes are merged based on overlap and similarity, this done by looking not only at the codes or text fragments, but rather the place within the transcript including the question asked and full response. This is done to ensure the similarity of the codes, by taking the context of a text fragment into account. The result of this step is a reduced list of relevant codes, with multiple underlying text fragments of transcripts.

Selective coding
The next step is to assign categories to the codes, called themes. These themes represent a relation between codes, which includes both confirming and contradicting fragments. The themes, similar to codes, are gathered from previous research, or from common topics of the text fragments. Open, axial and selective coding is an iterative process which is revisited until no significant changes are made to the coding of the transcripts. This iteration is done to assure the completeness of the analysis, and unambiguous results.

Reporting the results
The codes and themes assigned in the previous steps are translated and defined so it is clear what they entail. The origin of the themes is specified, and the codes contributing to each theme is detailed.

4.3.2. Interview analysis (chapter 6)
Using literature and the interview results (codes, themes, variables) the research objectives are answered. This is done in two separate chapters, chapter 6 (Interview Analysis) and 7 (Synthesis).

Chapter 6 draws conclusions from the themes and codes, primarily based on their occurrence and relationships. This chapter first looks at what themes are similar to those in the building industry, and which are not. This comparison is then used to assess the generalisability of the two sectors, and to highlight the differences which are not taken into account in digital twin literature. Furthermore, the further specification of the similarities and differences assesses which digital twin services and which research, applies to both sectors. Secondly, the participant (and tunnel) differences shown in table

[1] https://www.maxqda.com/

4.1 are considered in combination with the codes and themes they contributed to, to consider patterns within the results to indicate possible dependencies. This chapter considers all the identified functional needs in the interviews, irrespective of the literature study on digital twins, which is what the following chapter will focus on.

4.3.3. Interview synthesis (chapter 7)

Chapter 7 synthesises the literature study and interview results, This is done in two steps. First, the interview codes are assigned to digital twin characteristics. More specifically, the interview codes are categorised into data types, and data flow types, to consider what type of digital model is required. This is done to consider what discovered functional needs don't require a digital twin to be resolved.

Secondly, the chapter discusses the potential of digital twin applications for the management of tunnels, from the perspective of facility managers. Digital twin services and applications from previous research, discussed in chapter 2 are considered for the functional needs of tunnel facility managers. This is done by taking the assignment of types of digital model into account and the generalisability of building sector needs and related research, as discussed in chapter 6.

Focus group

To ensure the reliability of the research, the categorisation and findings of the chapter are validated with a focus group of digital twin experts. Two independent digital twin experts were asked to discuss the synthesis of the report, based on their knowledge and involvement with digital twins and tunnels. A summarised transcript of the results of this focus group are added as appendix E.

DT Expert (V1) has over ten years of experience within various construction contractors, fulfilling design and management roles closely related to digital twins, including virtual simulations of tunnel behaviour.

DT Expert (V2) has over 6 years of experience in the digital representation of construction projects, and is currently involved in the coordination and management of digital twin applications for construction and renovation projects of tunnels.

The experts are first introduced to the research, the research method, and digital twin classification. This is done as the interpretation of a digital twin varies between experts and by presenting the perspective of this research, this can be taken into consideration. The critiques and recommended adjustments of the experts are addressed in chapter 7. More specifically, the assignment of needs towards data types and data flows are focused on with the experts, to ensure the validity of the synthesis. Section 7.2 is discussed with the experts as well, however less attention was paid to this, as the chapter focuses on applications of previous research, and less on interpretations. Additionally the discussions of the focus group are used and reported in the following discussion and conclusion of the research.

5

Interview Results

This chapter is part of the Empirical Research, and presents a representation of the results of the interviews that are relevant to the objective of the research. The interviews are represented here as themes and codes, which are processed as described in section 4.3. These results will be used in chapter 6 for the analysis. Together with chapter 6, this chapter answers the third sub question of the research:

SQ3 *What functional problems do facility managers encounter during the maintenance and operation of tunnels?*

To represent the results of the interviews in a comprehensive manner, this chapter is divided in two sections. Section 5.1 discusses the themes formed by the interviews. Next, section 5.2 goes into more detail by discussing the underlying codes of the themes. The interview protocol is found in appendix C (Dutch), a table of interview results categorised in themes, codes, and occurrence frequencies is found in appendix D (English), the full interview transcripts (Dutch) are found in a separate document [1].

5.1. Themes

A theme is a broad category incorporating several codes that appear to be related to one another (Saunders et al., 2016). These codes and overarching themes are used to assess whether the participants have similar statements, and discover different perspectives on subjects. Figure 5.1 gives an indication of the relevance of the themes, as participants describing needs relating to the themes are shown as dots, where the size of the dot represents the number of times a code was assigned within an interview. The number of responses shown in the figure is strongly influenced by the questions, as some questions directly focused on certain themes. Hence, the formation of the themes is discussed here. The themes used and shown in figure 5.1 are formed based on various grounds. The specific reasons for themes are discussed next, followed by the identification number of the themes which are subject to that reason, in brackets (as shown in figure 5.1).

Related literature
Most themes originate from related literature, explored in section 2.4.2: contractor inspections, location, energy use, and traffic information (numbers [1,7,11,13] in figure 5.1). The identified research discusses the functional needs of facility managers in the building sector, these needs are questioned in this research to discover generalisability between sectors, as such the themes are used too. Theme, traffic information [13], similarly originated from the building sector (movement of people, users), which was adjusted towards tunnel users, namely the vehicles passing through it (detailed further in 3.1).

Common topics
Another source for the themes were the *answers of participants*, to the most generic questions, asked

[1] Thesis Digital Tunnel Twins_Full interview transcripts_Kasper Tijs.pdf (confidential, to ensure anonymity)

at the beginning of the interview. Participants responded with similar answers to these general questions, which then formed their own themes. These themes are: dashboard, dependent relations, and stakeholder engagement (corresponding with numbers [2,3,12]).

Separation of themes

The third, and last source is the separation of themes, two themes, maintenance and training, initially originating from literature are separated into three sub-themes based on the answers and decomposition in the LTS. The reason for there was a clear divide of answers within the existing theme, dependent on the tunnel system aspect. Technically these six themes originate in literature, however they were separated based on the answers and codes by the participants of this research, which is why they are mentioned separately here. The first theme was aimed at *maintenance activities*, this theme was separated into: Detecting Faults [4], which focuses on corrective maintenance activities, Improvement Maintenance [5], focusing on, as the name suggests, improvement maintenance. Lastly, Lifespan prediction [6], focuses on predictive maintenance activities. The second of separation of a theme, concerns *Educating, training, practicing* ([8,9,10]). The theme of educating, training and practicing was identified in literature, however, there was a large interest in the topic by the participants, and this interest was based on the type of personnel. As such three separate themes were created, one for each role. The Dutch abbreviation 'OTO' (Opleiden, Trainen, Oefenen) is used in this research, as it is a commonly used abbreviation in the Dutch tunnel sector, and LTS.

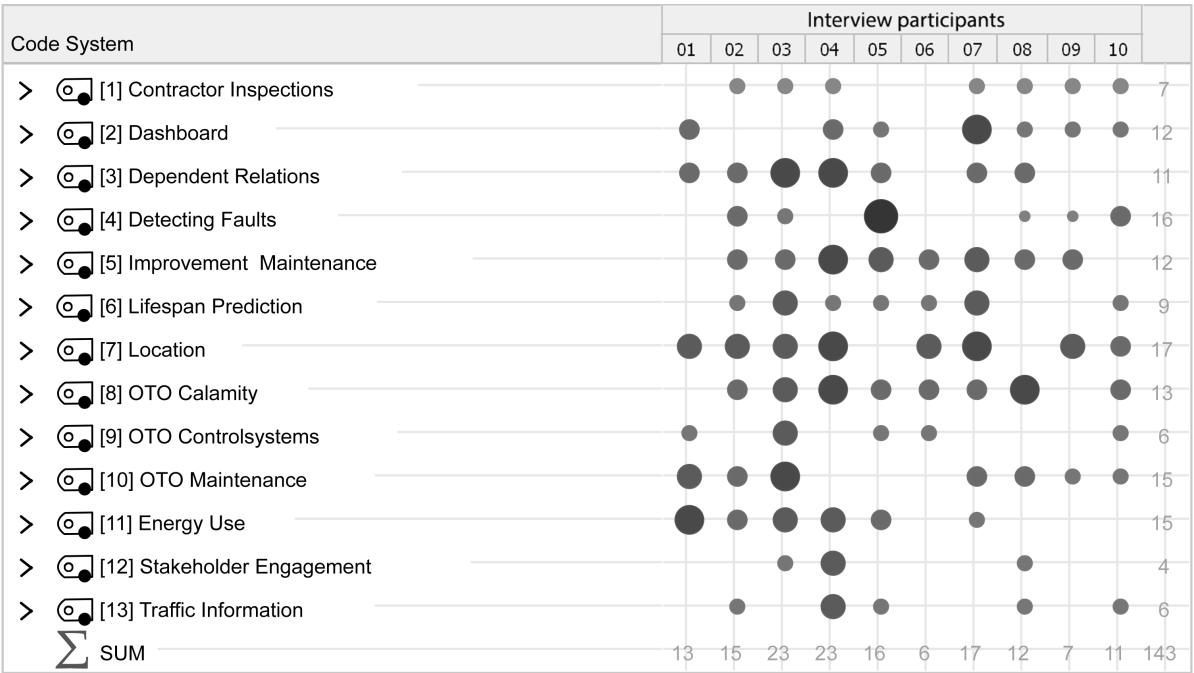


Figure 5.1: Themes and number of responses

5.2. Codes

The results of the interviews are discussed in more detail compared to the themes described in the previous section, by looking at the underlying codes. Codes are keywords, statements, or short sentences (Saunders et al., 2016). Codes have been given to the interview transcripts based on the research objective, which is to find functional needs. All the given codes are clarified (codes are made bold for clarity), and the number of participants are mentioned that have contributed to the generated code. A schematic quantitative table, listing all the themes and codes, including the number of occurrences and references to participants is found in appendix D.

5.2.1. Contractor inspections

Only visual

Three participants mention the current inspections are only visual, and lack a thorough inspection of electrical components. According to them, the actual components that determine the lifespan are not inspected (enough). An example is given by participant 7 (Interview, 2020): “To inspect the physical state of electrical components, they used the NEN2767, which judges the current state of installations on whether the casing is clean or not, this resulted in a ‘perfect verdict’. A week later the installation broke down because the batteries were end-of-life, which they didn’t have to inspect.”

Stakeholder bias

Three participants mention the biased nature of the (sub)contractor inspections, possible due to its subjectivity. The inspections benefit the inspector in question. Participant 3 (Interview, 2020) clarifies this with the following example: “ If you aren’t careful, a subcontractor will tell you the current state of the road is fine and doesn’t need repairs, until it is too late, and then they say it is too late for repairs, it instead requires a new top layer, and those costs, per contract, are for you instead of them.”

No current problems

One participant mentions there is no real problem with contractor inspections in general. They state that yes there is bias and subjectivity in inspections between companies, but this is known, so you can anticipate on it, which is fine too.

5.2.2. Dashboard

Current operational status tunnel

Three participants mentioned a need for more live information about the status of tunnel, such as the number of incidents, the current availability and accessibility numbers of the tunnel.

Predictive maintenance

wo participants describe the need of having trend analysis tools visible in a dashboard, which can examine the live information and provide information for the improvement of predictive maintenance.

Automation of work activities

One participant described a problem with having to manually enter the maintenance activities multiple times, and would want this to be in a centralised location, such as a dashboard.

GHS (chemical/danger symbols)Symbol recognition

One participant expressed a need for the automatic detection of GHS symbols on vehicles, and a warning based on that detection in a dashboard.

No current problems

Two participants describe that, when looking at the operational systems of tunnels, a lot of information is already being tracked, including the operational status of installations, and they don’t see the added benefit disclosing this in another way, or adding additional active information. Participant 7 (Interview, 2020) described this is the following manner: “There is a tunnel dashboard right now, which we made based on the log-fault, the operational status of installations is included, as well as the run-time of, for example, water pumps. Because the run-time of a pump in the Zeeburgertunnel was unusual, we manually considered and checked the reason for this, which resulted in us finding out a connection joint had been dislocated. The information is there, but the automatic link to consequences is not.”

5.2.3. Dependent relations

Interfaces

Four participants describe the need to understand the impact of design changes on other technical installations in the tunnel, in other words, what are the consequences of a certain action on the functioning of the tunnel. Participant 4 and 7 (Interview, 2020) said the following:“I’ve had land developers comes to me, asking whether he can freely drive piles near the tunnel, I would like to be able to determine the impact of the vibrations and possibly even the required safety measures that should be taken.” (Participant 4), and “When you replace the ventilation of a tunnel, or want to hang them lower, this is possible, as long as they don't go below the maximum height of vehicles. What is often forgotten however, that you should not only consider this, but also adjust the boundary settings of the height detection system of vehicles, which will otherwise constantly measure the height of the ventilators instead." (Participant 7)

Tunnel Interdependence
Two participants mentioned the relevance of tunnel installation behaviour information, in relation to other tunnel projects. They discuss the similarity of the behaviour between tunnels, and consider the benefits of knowing this information during the tender phase of a new tunnel.

Coherence
Two participants answered that they want to know how systems work together, how subsystems function together. Just looking at individual systems, and knowing whether they work or not is not enough. Participant 4 (Interview, 2020) stated: "On the one hand, I need to know the individual workings of an installation, but additionally, I need to know how the system works as a whole. That is important to me, that I can estimate what the systems as a whole mean towards the safety, availability or accessibility of the tunnel."

Operational Conditions
Two participants describe that they want to know how installations will function in different weather and operating conditions. Lights positioned near the opening of the tunnel requiring watertight armatures, for example (participant 1, Interview, 2020).

5.2.4. Detecting faults

No problems with fault detection
Five participants mentioned that fault detection was not something they currently had problems with. In part because of all the safety measures that are implemented in tunnels, such as hefty redundancy, cable monitoring and testing companies.

Speed of detection
Four participants explained that the key aspect when it comes to repairs, is the speed of repairs, which is contractually 24 or 48 hours depending on the type of installation, so finding ways to decrease the time it takes to repairing systems is very beneficial.

Unnoticed failures
Three participants mentioned that unnoticed failures do occur, and most often in dormant systems. They expressed the problem is that you don't know they are broken until you need them. Additionally, it sometimes happens that critical systems of the tunnel have failed without anyone knowing for awhile, as what happened in the Schipholtunnel. Participant 5 (Interview, 2020) said: "the installations we use for detecting the speed of vehicles, positioned under the road surface, turned out to be broken, and turned out to have been broken for awhile without us knowing. This should have been repaired and reported within 24hours, which had not happened, and that definitely created some panic within the organisation."

Complex failure definitions
One participant commented that the risk framework may be too complicated, or misunderstood too easily by (sub)contractors, leading to problems in the timely communication between stakeholders. To explain this, the example of detection of vehicle speed was provided (Example was noted in code 'unnoticed failures', of theme detecting faults). Related to this, they describe that there is too much leeway in the definitions, leading to ambiguous situations and sub optimal decisions.

Unknown size of the faults
One participant mentioned that installations malfunction or break one a time, leading to a kind of growing problem. This is a problem as this makes in unclear how big the actual problem is, and when exactly to intervene.

Missing Knowledge
One participant said that not all faults are traceable to them, the malfunctioning of systems is not always known, or resolved quickly.

5.2.5. Improvement maintenance

Digital validation
Four participants mention a need to understand and validate systems before implementing them into the tunnel. Having a digital test location is seen as a beneficial step to reduce problems during implementation and increase the operating time of the tunnel. Participant 3 (Interview, 2020) said the following about this: “The tunnel was renovated in part, and a traffic lights were implemented digitally, an endurance test was done on them. This resulted in finding bugs in the ’power over Ethernet’ component of the traffic lights, which was found because they could be tested a hundred times a day digitally, instead of once every two days physically.”

Discontinued installations
Two participants noted problems with installations that were discontinued, where the manufacturer stops supporting the software, or producing the same components. Currently they buy-in-bulk when they hear an installation they use is being discontinued, however often they do not know of the situation in time.

Problems originating in practice
Two participants said that digital testing of new installations has a drawback, namely that the problems would only be found when its implemented in practice. They note digital testing is helpful, but always in combination with physical testing.“The safety officer won’t give a positive recommendation based on our safety control plan, even though we used external physical test sites, simply because he hasn’t seen how it works in our tunnel. He wants to see the individual workings of systems, but also the integral workings of the systems together. (Participant 4)”

Increasingly complex systems
Two participants said that a digital test-ground was ideal for the current situation surrounding control systems, as over the years they are becoming increasingly complex, and it would be beneficial to test and adjust designs with a digital representation.

Credibility
One participant said that improvements to tunnels, especially innovations, are nice, but it would be better if it was ‘proven technology’. Participant 4 (Interview, 2020) gave the following example of why they think this is important: “in one of our tunnel entrances we installed fibre optic lighting, which directs sunlight into the tunnel. This entire project however does not replace lighting requirements from the LTS, but is extra. Because the LTS does not include these innovations, it can keep you grounded in your ambitions and halt developments.”

5.2.6. Lifespan prediction

Components with short lifespans
Two participants mentioned that they would like to predict the lifespan of components with short life spans. This includes two civil components, namely the asphalt and the expansion joints. Participant 3 (Interview, 2020) said the following about these two components: “ We are not completely in the dark about this, we don’t close the tunnel every time the asphalt begins to degrade, we know when it becomes bad. But what I need to know, and don’t, is whether we should repair the asphalt in 5 to 6 years, or in 2 years.”

Complex installations
Three participants talked about the prediction of lifespans of complex installations and systems. These include the ventilators and speed detection systems. They mention that because of the complex nature, and the added repairs over time, it is very difficult to say anything about these systems.

Known problem areas

One participant mentioned that they would want to monitor and predict parts of the tunnel, that they know are prone to problems. An example is given of monitoring a known crack in the wall to be able to predict when the crack will become an problem.

Standardisation of installations
One participant said that a problem they currently face is that no tunnels have the same installations, so its very difficult to draw relations between tunnels and installations.

Tunnel capacity
One participant mentioned a need of analysing capacity problems of the tunnel, in relation to the growing amount of vehicles over the years.

5.2.7. Location

The current location system is enough
Four participants mentioned that the current systems of locating objects was sufficient, and they did not have problems knowing where things were in a tunnel. More specifically they mentioned everything is well documented, and visualising the system would be unnecessary.

Location installations is unnecessary
Five participants noted that tunnel installations aren't replaced that often, maybe one or two components a year, and most of the installations of a tunnel are freely accessible in service tunnels.

Cables in the vicinity
Two participants mentioned the location of cables, in the vicinity of the tunnel, as these cables are not in dedicated service tunnels, the location is often unknown.

Non specialised stakeholder engagement
Two participants mentioned you had to be a specialist to be able to determine the location of tunnel technical installations, and it would be helpful if this was more intuitive and clear for everyone.

Manual update process
Three participants said that the disclosed location of components was occasionally wrong or missing altogether, which forms a problem especially if you do trust the information. An example is given of the required improvement of fire resistant panels, due to new European fire regulations. The problem that they had, was that was no information about the locations of cables and installations, or how installations they are attached to the tunnel. No information was gathered about these things, which 5 years later (time of the new regulations) would have proved to be very valuable.

Location of faults
One participant said that the location of faults can be important, as risk frameworks and failure definitions correspond to specific installations in specific areas.

5.2.8. OTO calamity

Slow OTO process
Three participants mentioned the need to increase the efficiency of the training process, to be able to train more employees, more often than once every few years. Participant 2 and 3 (Interview, 2020) had the following explanations: “We have 15 operators, and a calamity happens once every three to five years. We have employees who have worked for us for five years, and have never had to press the emergency button for real. It would be nice to digitally simulate similar situations, so the employees can practise 3,4,5 times a year how they need to react to the situation.” (Participant 3), and “An example is given of a car fire in the tunnel, where the barriers malfunctioned. The traffic control centre was unable to open the barriers for firefighters, because the button was installed in the wrong manner, after clicking the wrongly installed button three times, the remote system becomes ineffective, and the barriers have to be opened manually, which proved to be ineffective too, meaning the emergency services had to drive to the other end of the tunnel. The fact that the remote button was installed improperly could be traced by the contractor though the log-books, but the problem was there because testing the system

only happens once every few years as it requires the tunnel to be closed." (Participant 2)

Simulating stress and pressure
Four participants noted that practical tests were essential, because they believe you are unable to simulate the same level of stress and pressure as in real situation. Participant 4 (Interview, 2020) presented the following experience: "2 years ago I was present abroad, where the operators of the two Dutch tunnels, underwent a training in calamities. What caught my attention was that the person responsible with giving commands got the feedback to remain calm, because they were clearly full of adrenaline and was in a state of panic, which is why things went wrong in the exercise. This adrenaline and stress was there because of the physical - real nature of the exercise, and I don't believe you can recreate that same scenario fully with virtual reality services." (Participant 4)

Unique situation simulation
Two participants mentioned the need of being able to test more types of calamities, which you can't practice in a real situation, in a closed tunnel. They said that visualising real situations in a game like scenario might add realism.

Tunnel availability
One participant discussed the need to reduce the closures of the tunnel, and being able to train with calamities digitally, may be an option for this.

Frequency of training
Two participants said that trust is the key need here, as facility manager you need to trust that when a calamity does occur, you will handle efficiently. Being able to demonstrate and test this more often would be beneficial for the trust.

Standardisation
One participant said that there was a need towards more standardisation for calamity OTO, they had problems with this in the past.

5.2.9. OTO control systems

Visualisation of simulation
One participant said that there was a need towards the visualisation of actions done in the control system. They have training opportunities, but this is all textual, and not linked to the 3D model of the tunnel.

Increasing complexity
Two participants said there was a need towards the OTO of control systems, as over the years they will become more and more complicated, and being able to OTO before each new addition would be very useful.

No problems with current system
Four participants said that they did not experience problems with the training procedures of tunnel control operators. The reasons they gave was the standardised interfaces between tunnels, and the current testing possibilities virtual and physical. Participant 10 (Interview, 2020) said the following about this: " it was indicated that in the beginning of the project, there were problems with the OTO protocols, resulting in problems. However, after a collaboration effort with RWS, these protocols were adjusted and now the process does not give them any more problems."

5.2.10. OTO maintenance

Practicing Preventive Maintenance
Four participants said they saw benefits in practicing with a digital model, specifically for training and practicing preventive maintenance works nights. Participant 1 (Interview, 2020) said the following about practicing maintenance: "What we see now is when you have worked with the tunnel longer, and you've had multiple maintenance nights, you start to get a certain routine, and this experience means you require less time to actually do the activities.

Speed of repair
Four participants noted that they would like the speed of maintenance activities to be increased, as the payment scheme of their contracts are based on downtime of the tunnel, as such they indicate they would like to reduce this by practicing the required activities before closure.

Complex installations
Two participants would want their maintenance crew to be able to visualise and understand the complex systems of the tunnel before executing the actual activities in the tunnel.

No problems with current systems
One participant does not believe he has problems or needs concerning the OTO of maintenance activities."

Accessible installations
One participant mentioned that most installations are accessible while the tunnel is in operation, they are in a service tunnel beneath the road. However, they mentioned the need to understand the components that aren't.

Visualisation of installations
One participant thinks it would be beneficial if more people could form an idea of what the problem is, or what will be done, as now you need to be quite the specialist to understand it (participant 3, Interview, 2020).

Dependencies of installations
One participant would want to know what the dependencies are if a solution is chosen, 'what does the action mean for the rest of the installations?'

5.2.11. Energy use

Energy efficiency
Four participants discussed the need to monitor individual systems within the tunnel for their energy use. More specifically, heavy users were interesting to them, such as high voltage installations, ventilators, and lighting systems. the information would be used to optimise the use of energy where possible.

Efficiency based repair
Three participants found the idea of monitoring energy use very useful to determine whether systems were functioning properly, or to consider if action should be undertaken during the next maintenance round. Participant 3 (Interview, 2020) said the following about this: " Say a heating element of the camera is broken, meaning it requires a lot more energy to run, we would never notice that now. We would only find and fix that problem when we inspect the camera, which would only happen if say, the camera feed becomes blurry or stops working. The camera in this example is not critical enough for the monitoring, but ventilators, light concepts, high voltage installations and UPS units are."

Stakeholder engagement
Three participants noted they have problems communicating the use of energy towards authorities, for decision making, and understanding the impact of decisions such as extreme redundancy in ventilators. Additionally, the possibility to use the information for future bids for tunnel contracts was noted, as RWS is focusing more and more on sustainability. An example is given by participant 2 (Interview, 2020): "There are varying interests when it comes to energy use, RWS wants to become as energy efficient as possible, while local government falls behind in this regard. An example is given of a particulate matter vacuum system, required in the tunnel for its permit, and is responsible for 80% of the tunnels energy use. According to the interviewee, the system has been proven to be outdated and ineffective, but remains active for the local permit."

Break-even point
Three participants discussed the ability to be able to consider more closely, the point at which installations should be replaced when looking at energy efficiency of installations and their investment costs.

Additionally, they said the information could be used to discover how many 'green energy' solutions they would need to implement for the tunnel to become energy neutral.

Safety
Two participants discussed to probability of the reduction of energy, they stated that tunnels don't use much energy during operation, and only use significant amount during calamities, and this is not a situation where you would want to optimise in energy, as safety goes first.

5.2.12. Stakeholder engagement

Specialised information retrieval
Two participants described that they find tunnel information to be incomprehensible for non specialised stakeholders. The examples they chose were the financial reports of the tunnel, and the 2D drawings to understand the dimensions of tunnel objects.

Decision making
Two participants described a need to easily explain tunnel functions to external stakeholders, who are stakeholders in decisions, without much experience in the technical side of things. Related to this, participant 4 (Interview, 2020) gave this example: "Having a 3D model (3D printed) is a benefit, to show, engage , and comprehensively discuss with other stakeholders what makes the tunnel unique. Our tunnel is unique in certain aspects, which is where a simple 3D model can help especially. The vehicle barriers for example, our tunnel is required two sets of barriers at each end on the tunnel, which you can clearly illustrate when you look at a 3D model, because we have a semi-underground entrance to the tunnel, where you don't want vehicles to be when it closes as they can obstruct emergency services. Using the 3D model you can simply show what you mean, having this, is especially useful with these project-unique aspects."

5.2.13. Traffic information

Traffic information was another theme that all participants were on one line about. They either have very little to do with the traffic management in the tunnel, or have all the information they would need, if they want it. Participant 2 said the following. "We support, safety is a role of the client, Rijkswaterstaat. We have very little to do with that, we support, we offer services, we offer 24/7 emergency services, but the client is in charge."

6

Interview Analysis

This chapter analyses the interview data, this is done by comparing the themes and codes of chapter 5 with previous research (section 2.4.2) and with the participant variables (section 4.2). By doing the above, sub-question three is answered in this chapter:

SQ3 *What functional problems do facility managers encounter during the maintenance and operation of tunnels?*

The chapter is divided in three sections, section 6.1 analyses the generalisability of previously found functional needs for tunnels. 6.2 analyses the dependence of the interview results, based on the participant variables, and lastly, 6.3 concludes this chapter by summarising its findings, and answering sub question 3.

6.1. Generalisability

The interview protocol is partially based on the literature regarding functional needs in the building sector. Hence, this section discusses whether these functional needs can be applied in the context of tunnels. The data from the interviews in chapter 5 either confirms or contradicts with the functional needs as identified in the literature. The findings from literature and the interviews are compared to discover how the functional needs of facility managers in the tunnel sector differ from those in the building industry. This indicates the relevance and accuracy of the assumed distinction between the buildings and tunnels within the construction sector as research gap. Furthermore, this section can help define the required scope of digital twins, and the universality of digital twin services from the building sector, detailed further in chapter 7, 'Synthesis'. This section presents a more specific context (Digital twin - *of what*) compared to literature towards the building sector. In other words, an identified need (e.g. preventive maintenance) is coupled with tunnel system elements which are mentioned by participants as relevant (e.g. preventive maintenance *of* expansion joints). This is done because it allows the consideration of using a digital twin service for more specific purposes, required for the synthesis and research goal. Figure 6.1 shows the themes and the number of respondents specifying needs or an absence of needs, based on the width of the connecting line.

Similarities

Five out of ten themes discovered in the building sector are similarly relevant in the tunnel sector these themes are: contractor inspections, improvement maintenance, lifespan prediction, OTO maintenance, and energy use (shown in 6.1 with corresponding numbers [1,5,6,10,11]). These themes are identified by participants as having needs in the tunnel sector, while relatively few participants argue the theme.

Contractor Inspections [1]

Johansson et al. (2019) found the functional need of removing subjective assessments, to further improve decision support, in the civil engineering sector. 6 out of 10 facility managers in the tunnel sector mention closely related needs, supporting the statement. One participant however mentions the prob-

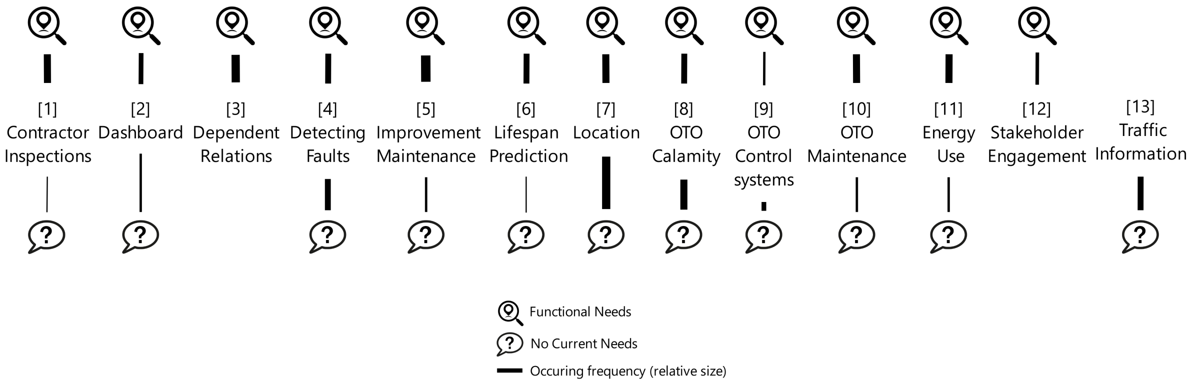


Figure 6.1: Themes and corresponding needs

lem is minimal, because you can anticipate this subjectivity. Underlying problems mentioned by the facility managers are: ineffective inspection standards, Inspector bias, and unclear failure definitions. The 6 tunnel facility managers that described needs were positive towards the possibilities that digital twins could bring for the objectification of inspections, to support their decisions regarding the required maintenance.

Improvement Maintenance [5]
Becerik-Gerber et al. (2012) described the functional need of planning, designing, analysing and simulating remodel, renovations or demolition work. Furthermore, (Love et al., 2016) found a need for option appraisal through visualisations for strategic decision making. Four tunnel facility managers mention related needs, they described a need to simulate and analyse improvement maintenance works, to detect failures and validate decisions before implementation. Two participants however said it would prove ineffective as problems originate in practice. In addition to this functional need, facility managers of tunnels specifically mention problems with discontinued installations.

Lifespan Prediction [6]
Liu and Issa (2016) found a lack of preventive maintenance in the Architecture, Engineering and Construction (AEC) sector, which is widely supported by the results of this research, for the tunnel sector. More specifically, tunnel system components are mentioned as subject for the need. Civil components are mentioned with short lifespans, namely asphalt and expansion joints, and complex installations are discussed, including ventilators and speed detection systems. As presented in figure 6.1, one participant described 'No Current Needs', as they mentioned the current (manual) trend analysis being necessary, as individual tunnel installations are not standardised between tunnels, meaning there is a lack of data to do this more effectively.

OTO Maintenance [10]
Becerik-Gerber et al. (2012) describes that facility managers need to get familiar with processes, systems and facilities, and this familiarity needs to be assessed. This need was nearly word for word repeated by tunnel facility managers, specifically when discussing the maintenance nights, when the tunnel closes during a part of the night for repairs. Familiarity and experience was a need, as it speeds up these shifts, minimising the risk of delays and associated penalties.

Energy Use [11]
Gnanarednam and Jayasena (2013) found a need of minimising, optimising and controlling how much energy and water is used in the building sector. This was confirmed by four participants sharing similar needs, specifically for the systems that use a lot of energy, including the ventilators, and lighting systems. Closely related to this was a need to consider climate friendly energy solutions for powering the tunnel. Two participants disagreed with the need however, noting that tunnels during normal operation hardly use energy, so its not as useful, and minimising energy during emergencies would reduce the safety of the tunnel. In addition to the need discovered in literature, three participants were interested

in using this energy data to assess the state of the installation. Interestingly, energy use was a theme that resulted in facility managers contradicting each other. Participants contradicted each other on the responsibility of energy costs in DBFM contracts, the energy efficiency of current tunnels, and the need for monitoring of energy. The contradictions indicate a lack of awareness and knowledge of the participants, which is explained by the indirect involvement of facility managers with tunnel energy use, and the recent contractual focus of clients on energy use.

Differences
Five themes contradict the themes discovered in the building sector [4,7,8,9,13]. This contradiction is based on whether a majority of the participants in this research argued against a need, or specifically noted an absence of needs.

Detecting Faults [4]
Detecting faults focuses on the corrective maintenance activities, and in particular whether there is a need to detect installation failures actively. Unlike the related themes [5,6] focusing on improvement and predictive maintenance, this theme was not as accepted by tunnel facility managers. The majority of the participants had no problems with the current detection system, as tunnel safety and detection system is very redundant to ensure the safety.

Location [7]
This theme was widely described as unnecessary in the tunnel sector, while it was described by (Becerik-Gerber et al., 2012) and (Cavka et al., 2017) as a functional problem in the building industry. Reasons why tunnel facility managers contradict this theme, is because installations are easily accessible (utility tunnels, or under the road), they are well documented (OMS systems, and physically labeled), and location data is not required often (estimated at once a year by participant 3) so an active stream of information is unnecessary.

OTO control systems [9]
This theme is part of the 'training' theme, found by (Becerik-Gerber et al., 2012) and (Liu & Issa, 2016), and this category was contradicted by participants. Reasons why participants noted a absence of needs was because of standardised procedures in the LTS, and existing training environments for the operators using the control systems. Participant 2 did however describe a need to visualise the training environment more, as it may help participants understand what their action actually encompass.

OTO Calamity& Traffic [8& 13]
The theme traffic (users) was described for the building sector by Ashworth et al. (2016) and Becerik-Gerber et al. (2012), and was contradicted completely by the facility managers of tunnels. This contradiction was expected, as traffic is seen as an external stakeholder in the tunnel system, defined in section 3.1. The specific reason why it was expected, and which was affirmed during the interviews, is because tunnel facility managers are not expected to deal with the end-users directly, contrary to the facility managers in the building industry. Becerik-Gerber et al. (2012) further finds that there is a need towards the evacuation plan training for building occupants, which isn't specifically mentioned by tunnel facility managers, however one participant does note something related. Participant 2 described an problem with the 'occupants' of the tunnel during emergencies, namely that they do not respond to, or simply ignore evacuation guidelines when they are presented to them. "(During a car fire) people in this large city, then think, good luck with that, we won't step out of our car and leave the tunnel"(Participant 2, Interview, 2020). The problem for tunnel facility managers is therefore not that occupants don't know what to do, but rather they don't do what they should do.

Additional themes
Three themes are excluded from this section, because they were formed inductively from common topics during interviews [2,3,12].

Dashboard [2] was a need mentioned by four participants, on multiple occasions, hence a separate theme was formed to indicate the relationship between the codes. Needs within this theme included a more centralised visual representation of live information about the tunnel, for their own knowledge about the tunnel. Two participants did however argue against such a dashboard, as something similar was present and the information was available.

Dependent Relations [3] was similarly a subject that was mentioned often during the interviews. More specifically, what this theme encapsulates is the the dependent relationship between the functioning of different tunnel technical installations. I.e. what is the influence of a planned change in the tunnel, on all other technical installations in the tunnel. This can be compared to current tunnel processes in the configuration management of the LTS. Configuration management provides the information required to assess the impact of a change. Participants noted they need a better understanding of what a taken action or choice has, as impact, on dependent installations and systems within the tunnel. For example, by changing the height one one installation, another installation might be obstructed.

Stakeholder Engagement [12] is a theme that was created, as the codes and needs within the theme did not belong to one theme, and are related to each other. Specific needs include the comprehensibility of tunnel information, which is often aimed towards specialists, while being beneficial to many other stakeholders.

6.2. Dependent participant variables

Visualising participant characteristics in relation to the provided needs, indicate possible dependencies between different facility managers. Participants with similar characteristics, as discussed in section 4.2 are grouped together, to assess the influence of the participant characteristics in their answers. Two characteristics are distinguished, their organisational position and the tunnel age. These dependent relations are important for the further specification of digital twin applications for specific tunnel roles.

Organisation

Participants are categorised as contractor or governmental based on the organisation they are apart of, and contract type the tunnel uses. Participants 1,2,3,9,10 are categorised as contractor, because of their similar job descriptions. Participants 9 and 10 work for a local municipality, however because the municipality has a singular tunnel, and the contract for this tunnel is not integrative, their daily activities are very similar to those of the contractors 1,2,3. Participants 4,5,6,7,8 are labeled as Governmental, as they work for regional or national governmental organisations, and have similar, more strategic responsibilities. A complete visual representation of this variable with all themes and codes is added as appendix D, in figure D.2. Due to the limited size of the variable groups, results aren't conclusive but rather indicative.

Comparing the contractor with governmental facility managers, there are differences between responses of the themes. Themes that have a difference in the response rate of 50% are considered to be significant, and are detailed further. The group includes 5 participants, so if there is a difference of more than two, they are detailed. Interestingly, OTO maintenance was the only theme that indicated a dependence of the organisational variable, all other themes had a response difference of 2 or fewer.

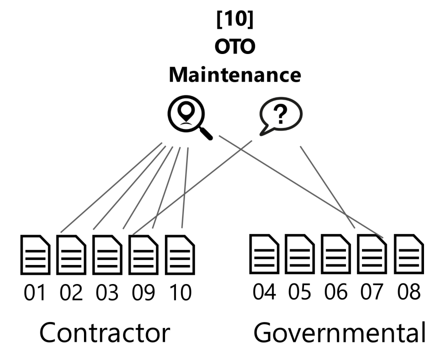


Figure 6.2: Organisational dependence of theme ten

A significant dependence is found for the theme *OTO maintenance [10]*. All five contractors identified needs, while only one governmental participant mentioned one. The needs of all five contractors can be summarised as needing to know exactly what they have to do and how long doing that will take. Additional benefits they mention is finding the most optimal solution to a problem, and being able to quickly involve newly hired employees in the routine and understanding of the tunnel maintenance slots. The functional need by governmental facility manager was about the indirect benefit of a speedy and comprehensive maintenance action, as a type of verification. Participants also mentioned a lack of problems, contractor participant 3 said most installations are accessible during the day so OTO digitally would be unnecessary, and governmental participant 7 said tunnel systems aren't that complicated, there aren't any specialised components.

Tunnel age
The interest of specific themes, based on the tunnels age is considered. The tunnels are categorised as either newly built or newly renovated, as all tunnels fall under either one of these categories. Because four of the participants manage multiple tunnels (more than 2), they are excluded from this comparison. Participants managing two tunnels, both a newly built tunnel, and a newly renovated tunnel (participant 2,3) are categorised based context given during the explanation of the need. Similar the previous participant variable, response differences of more than 50% of the group size are detailed, meaning for this variable, a difference of more than one. A complete visual representation of this variable with all themes and codes is added as appendix D, in figure D.3.

The strongest dependencies between these categories, are themes [11,12], which are mentioned more often by participants managing newly built tunnels. Participants 1 and 3 explain *Energy Use [11]*, by the increased contractual focus on energy usage in tunnels nowadays, which falls under the responsibility and expenditures of the contractor. Participant 4 adds to this, by doubting the effectiveness, as replacing installations based on energy use would bring huge sunken costs.

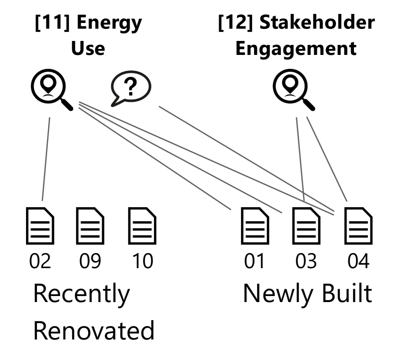


Figure 6.3: Age dependence of theme 11 & 12

Stakeholder Engagement [12] is the second theme highlighted due to its dependency to age. Managers of newly built tunnel indicated that there is a need to visualise or make designs more accessible for (external)stakeholders, as they can not fully comprehend information, as it is designed for specialists (participants 3,4,8, Interviews, 2020). According to these participants, there is a huge benefit in stakeholders understanding the tunnel system, beyond their individual scope.

6.3. Sub conclusion

This chapter set out to answer the third sub question of this research:

SQ3 *What functional problems do facility managers encounter during the maintenance and operation of tunnels?*

This sub questioned was answered by discussing functional problems that were found in related sectors, with the facility managers of tunnels to consider the generalisability and discover other problems. This results in a list of problems which are considered to be relevant to tunnel facility managers, by the tunnel facility managers.

The functional problems encountered by tunnel facility managers, independent of their characteristics, are apart of the themes: contractor inspections, dashboard, dependent relations, improvement maintenance, and lifespan prediction. Two of these themes, dashboard and dependent relations, were not questioned specifically during the interviews, hence, further research may indicate their actual importance (discussed further in section 8.2, limitations).

Similarly independent of tunnel facility manager characteristics, however, supported only in part by the tunnel facility managers, are: OTO calamity, and OTO control systems. These themes are only supported in part, as tunnel facility managers indicated that the current training environments are sufficient or because they have the belief that there are limitations to the possibilities of digital training. However, these beliefs are opinions based on current practices, hence, the importance of these themes can be underestimated (discussed further in section 8.1).

Three themes are found to be dependent on specific characteristics of the tunnel facility managers: OTO maintenance, energy use, and stakeholder engagement. Facility managers of newly built tunnels showed more interest in the energy use and stakeholder engagement of tunnels. This indicates a growing interest in the energy use of tunnels, and the communication between stakeholders of the projects. Facility managers in contractor organisations, which have more operational responsibilities showed more interest in the training, practicing and educating of maintenance activities (OTO maintenance). This is expected and explained by their processes, as they are directly responsible for the maintenance operations in the tunnel.

Largely unsupported by tunnel facility managers, and thus the biggest differences between the building and tunnel sector, are seen in the themes: location of components [7], detection of faults [4], and traffic [13]. The detection of faults of tunnel technical installations was not interesting, because tunnels are built with excessive safety precautions (redundancy), and current detection systems of faults work well. The location of tunnel components can be considered mostly static, the location of components of tunnels are generally fixed, and changes are infrequent. The last theme, traffic [13], was unsupported, as expected. This is due to the traffic being largely outside the scope of tunnel facility manager processes.

7 Data Synthesis

In this chapter, a synthesis is formed between the literature study and empirical research. More specifically, functional needs of tunnel facility managers are matched with digital twin characteristics. Furthermore, Digital twin services that can benefit the maintenance and operation are highlighted, by doing this, the fourth and last sub-question is answered in this chapter:

SQ4 *What functional needs in the tunnel sector can be supported with a digital twin?*

To synthesise between the research results and digital twin literature, this chapter consists of three sections. Figure 7.1 reintroduces and combines figures from chapter 2 to visualise the process of this chapter. Section 7.1 aligns the functional needs of tunnel facility managers with the data type and data flow characteristics of digital references. In the figure, this is represented by the first three sets of arrows. Section 7.2 describes the related digital twin services and applications for tunnels, including their potential benefit, shown at the right side of the figure. 7.3 summarises the results from the focus group, to validate the results of this chapter, as discussed in section 4.3.

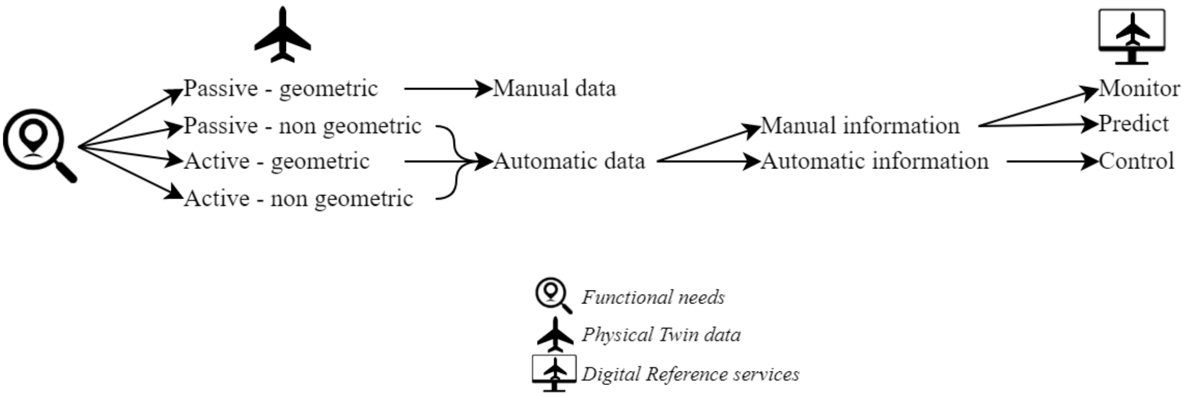


Figure 7.1: Combined digital reference characteristics

7.1. Digital tunnel twin characteristics

To effectively categorise the needs, the three types of digital references are used for this section (Digital Model, Digital Shadow, Digital Twin). More specifically, this is done to consider the type of services found in literature which are assigned to the type of digital reference. Beyond this section however, once again, a digital shadow is considered a less complex form of a digital twin and the two are not differentiated.

Type of data

The functional needs are categorised into data types in table 7.1. This shows the relevance of different digital references for the needs of facility managers. This table does not provide a black-and-white representation of how beneficial digital twins are compared to other types of digital models in the maintenance and operation phase of tunnels. The empirical data gathered is based on digital twin literature, meaning the data is biased towards digital twins. Hence, the table is used primarily to exclude needs of facility managers that do not fit the scope of a digital twin.

The data that is required to fulfill the functional needs of the tunnel facility managers is categorised based on the context of the functional need. For example: the code Digital Validation of theme Improvement Maintenance [5], requires active - non geometric data, as when a traffic light is digitally validated, the software is tested (which is non geometric), and this software is active because is comprised of embedded algorithms and implicit dynamic relationships (Smarsly & Tauscher, 2015; Q. Lu et al., 2020). The categorisation of the data types is synonymous with the type of digital reference which is required by the functional need. Active data, and passive-non geometric data is attributed to digital twins and shadows, while passive geometric data is associated with digital models (often referred to as BIM).

Four codes are assigned to have passive geometric data requirements, meaning they could be assigned to a digital model (BIM) instead of requiring a digital shadow or twin. Functional needs that require both geometric and non-geometric data, are not included in the geometric column, because doing so misrepresents the fulfilment of the requirement. For example, simulating the [3] interfaces between two tunnel technical installations, to predict maintenance complications, requires both geometric (size and location) and non geometric (software) data. The functional need can potentially be fully alleviated by a digital twin, but not by a digital model. *location [7]* codes are assigned to passive geometric, due to the infrequent change in location of the components. This is applicable for tunnel installations as well as cables (in or near the tunnel). Lastly, a problem was presented for stakeholder engagement, where there is a need to visualise the tunnel structure (civil part), with stakeholders, to comprehend the size and geometry of the tunnel. This need similarly does not need to actively be updated, and moreover, in the context of the need, a 3D printed model was considered, which is incapable of changing and thus does not require a digital twin to be printed.

The table indicates a significant number of identified needs of tunnel facility managers that require data that is infeasible for digital models. The reason why digital models are ineffective for these types of data is because of their design, as found by Q. Lu et al. (2020); Love et al. (2016). A visual representation of this decomposition is shown in figure 7.1.

Table 7.1: Functional needs categorised into data types

Active		Passive	
Geometric	Non-Geometric	Geometric	Non-Geometric
[1] Stakeholder bias [2] GHS symbols [5] Discontinued installations [6] Short lifespans [6] Known problem areas [6] Complex installations [11] Efficiency based repair [11] Stakeholder engagement [11] Break even point	[1] Only visual [2] Current operational status [2] Automation of work activities [2] Predictive maintenance [3] Tunnel interdependence [3] Coherence [4] Unnoticed failures [4] Complex failure definitions [4] Unknown size of the faults [4] Missing knowledge [4] Speed of detection [5] Digital validation [5] Discontinued installations [5] Credibility [5] Increasingly complex systems [6] Tunnel capacity [6] Complex installations [7] Manual update process [11] Energy efficiency	[7] Location of faults [7] Stakeholder engagement [7] Cables in vicinity [12] Decision making	[3] Interfaces [3] Operational conditions [8] Standardisation [8] Unique situation simulation [8] Frequency of training [8] Slow OTO process [8] Tunnel availability [9] Visualisation of simulation [9] Increasing complexity [10] Speed of repair [10] Practicing preventive maintenance [10] Accessible installations [10] Visualisation of installations [10] Dependence of installations [10] Complex installations

Table 7.2: Functional needs categorised into digital model types

Digital Model	**Digital Shadow**	**Digital Twin**
[3] Interfaces, [7] Location of faults, [7] Stakeholder engagement, [7] Cables in vicinity, [12] Decision making	[1] Only visual, [1] Stakeholder bias, [2] Current operational status, [2] Predictive maintenance, [2] Automation of work activities, [2] GHS symbols, [2] GHS symbols, [3] Coherence, [4] Unnoticed failures , [4] Unknown size of the faults , [4] Missing knowledge , [4] Speed of detection, [4] Complex failure definitions, [5] Digital validation , [5] Discontinued installations, [5] Increasingly complex systems, [5] Credibility, [6] Short lifespans, [6] Tunnel capacity, [6] Short lifespans , [6] Known problem areas, [6] Complex installations, [6] Tunnel capacity, [6] Short lifespans , [6] Known problem areas , [6] Complex installations, [7] Manual update process, [11] Efficiency based repair, [11] Stakeholder engagement, [11] Break even point, [12] Information retrieval	[11] Energy efficiency
Digital Model or Digital Shadow		
[3] Operational conditions, [3] Tunnel interdependence, [8] Tunnel availability, [8] Unique situation simulation, [8] Frequency of training, [8] Slow OTO process, [8] Standardisation, [13] Energy efficiency, [9] Visualisation of simulation, [9] Increasing complexity, [10] Speed of repair, [10] Practicing preventive maintenance, [10] Accessible installations, [10] Visualisation of installations, [10] Dependence of installations, [10] Complex installations		

Type of flow
To further specify the type of digital reference that is required for the needs of facility managers, the empirical data is categorized based on the required data and information flow between physical and digital asset. Table 7.2 distinguishes between digital models, shadows, and twins. The table has two remarkable aspects, which are discussed next.

Firstly, comparing these two tables, in combination with the empirical data brings an interesting topic to the surface, regarding the OTO themes [8,9,10], and [3] Dependent relations. The functional needs within these themes require non-geometric data as interaction protocols are required, and implicit dynamic relationships are used. As such, a digital model is not sufficient due to its existing data formats limitations to basic geometric information (Q. Lu et al., 2020; Love et al., 2016). However, this data does not require an active flow of data, from the physical object to the digital reference, because the data can form its own instance (independent of each other, removing the need for the mirror-like characteristic of digital- shadows & twins). Hence the themes only fit the characteristics of a digital model according to (amongst others) Kritzinger et al. (2018), while being excluded from digital models on the grounds of the required data types(Q. Lu et al., 2020; Love et al., 2016). Because of these two contradicting statements of digital twins in literature and used in this research to define a digital twin, themes [8,9,10] are positioned separately from the other needs, in table 7.2. What this essentially means, is that OTO related services are formed in a digital twin environment, while not requiring the communication layer of a digital twins architecture (as visualised in figure 2.1).

Secondly, there are a large number of digital shadow codes, and a singular digital twin one. The difference between a digital shadow and a digital twin, is the required automatic flow of information from the digital reference to the physical object. In other words, the digital reference obtains data from the tunnel autonomously, processes it autonomously, and decides to adjust the tunnel autonomously based on this processed data. A reason for the lack of identified digital twin needs is discussed by three participants (8,9,10) during the interviews.

> “It really depends how you look at it, no I don’t miss anything, and yes I miss a lot ... you arrive at questions that you don’t know you should ask. I would already be very happy if sensor data was available with which I could do the maintenance of TTI differently.” (participant 8, Interview, 2020)

The participants describe that they can’t describe needs for autonomous changing or controlling attributes of the physical object, because ‘their organisation is not that far yet’ (participant 10, interview, 2020). Additionally this may be explained by the perspective of the tunnel facility managers, which require specific services of a digital reference, namely decision aiding services, which will be described further in the next section.

7.2. Digital tunnel twin applications

In order to fulfil the current functional needs in the maintenance and operation of tunnels, a digital model is not enough. A digital twin is required as the functional needs are based on the active and non-geometric data requirements, as was discovered previously (Q. Lu, Parlikad, et al., 2019). The digital tunnel twin should be an integrated system of compiled digital twin services, composited as applications for specific end users. A high level visualisation of this shown in figure 7.2, which shows applications being digital twin services with context, for the end user. The figure is based on integrated ‘full’ digital twin architecture as discussed in chapter 2.

To describe the possible benefits of a digital twin application for facility managers, this section defines the digital twin services for the maintenance and operation of tunnels. The section details the relation between digital twin services (chapter 2), and the context of functional needs of tunnels detailed in chapter 3 and 5. In other words, digital twin services, relevant to tunnel facility managers are described here, these digital twin services are based on literature, and supported by the data found in this research. These digital twin services are not equal to the themes or codes, as codes are needs, and themes function as umbrella topics of closely related codes.

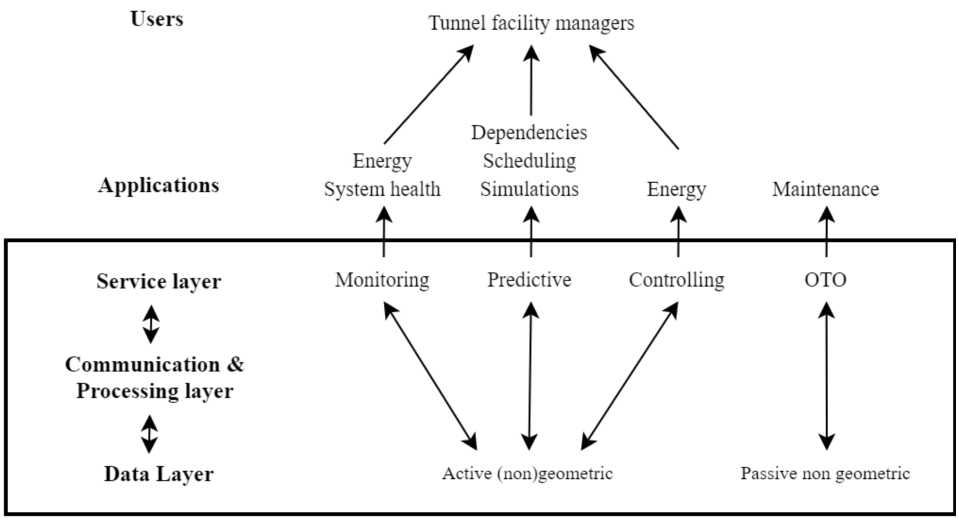


Figure 7.2: High level integrated digital twin for tunnel facility managers

Monitoring
Monitoring services are considered less interesting compared to predictive services for the facility managers, as extensive safety procedures exist in the LTS (installation redundancy, cable guards), and active location services are widely deemed as unnecessary. Nonetheless, predictive services depend on data, gathered through the active monitoring of components, hence monitoring services are included in predictive applications. Two digital twin monitoring services that are beneficial for tunnel facility are discussed here first.

Firstly, the energy use of installations can be actively monitored by a digital twin (researched by, amongst others, Q. Lu, Parlikad, et al. (2019); Kaewunruen, Rungskunroch, and Welsh (2019); Love et al. (2016)). Tunnel facility managers mentioned that energy use is becoming increasingly important in tunnel contracts, and the it is not yet monitored on an individual installation level. The use of this service is towards future tunnel bids, stakeholder engagement, and to consider optimisations.

Secondly, system health monitoring is a digital twin monitoring service that benefits the tunnel management (researched by, amongst others, Kim and Kim (2020); Ye et al. (2019)). Benefits of this service for facility managers include the monitoring of dormant systems, and the electrical components of systems that are excluded from current inspection standards. Furthermore the service benefits tunnel management by visualising information for (non-specialised) stakeholder management and engagement, and lastly for the comprehension of operational figures including status, availability, accessibility numbers. The benefits do however exclude fault detection, this was not supported.

Predicting
The active collection of tunnel data provide the basis for increasingly accurate prediction services of digital twins. Together with the results of the interviews, a clearer picture can be formed towards its benefits in the research context. Three main areas are described here to highlight the potential benefit of digital twins for a tunnel.

Firstly, predicting dependent reactions, through dependent relations (researched by among others, Whyte et al. (2019); Erkoyuncu et al. (2018)). By providing such a digital twin service, problems during maintenance activities are minimised, by considering the effects of changes, and operating conditions of components. This leads to fault predictions and validation possibilities in predictive and improvement maintenance. The beneficial services specifically target dependent technical installations (including height detection systems) and software. This service is not only beneficial towards components within the tunnel system, but also beyond, for example neighbouring works, and similar tunnels elsewhere.

Secondly, maintenance scheduling is a beneficial service for tunnel facility managers (researched by, amongst others, (Panella et al., 2018; Luo, Hu, Ye, Zhang, & Wei, 2020)). The predictive functionality of digital twins can provide benefits towards more accurate and inclusive estimates of component life spans. This is especially interesting for tunnel facility managers as schedules and maintenance tasks are often restrictive in time, per contract. Contractors are essentially penalised for every 15 minutes the tunnel is closed to traffic, hence maintenance scheduling is highly demanded. The service is beneficial towards: complex installations (including ventilators, and speed detection systems), and technical installations with with short lifespans, including the civil components: asphalt layers, and expansion joints. Additionally, a beneficial application is that towards the prediction and planning of discontinued installations, so buy-in-bulk scenarios can be minimised.

Thirdly, a predictive service in the form of operational simulations (researched by, amongst others,(Q. Lu, Parlikad, et al., 2019; Glaessgen & Stargel, 2012)) are beneficial towards the needs of tunnel facility managers. The service assists in the validation of improvement and preventive maintenance. These maintenance activities are scheduled in advance, to be executed in specific time slots, hence they include preparation time. Facility managers indicated a need towards the verification and validation of these activities prior to their realisation. They wish to understand installations that are implemented, to help communicate choices between stakeholders. Specifically, this includes the break-even points of electrical components, both towards 'efficiency versus investment' and 'energy use versus green-energy' analysis. Additionally, the benefit of this digital twin service is targeted towards credibility of innovative solutions and new technical installations.

Controlling
One service is identified where a digital twin automatically controls the physical twin (through the autonomous information flow from digital to physical twin). Digital twin controlling services encompass the identified needs towards energy optimisations in the tunnel, which could automatically be implemented in the tunnel installations.

Very few controlling services are described here, due to the limited number of identified needs requiring autonomous data and information flows in the previous section. This can be attributed to the perspective of the empirical data. Tunnel facility managers are responsible for choices made within the maintenance and operation of tunnels. Section 3.3 detailed the processes as configuration-, incident-, problem-, and change management. As expected, the functional needs of the facility managers are inline with these processes, as they focus on the provision of relevant (timely) information towards decisions they face. In other words, what tunnel facility managers need is a tool that helps them make decisions, instead of a tool that makes and executes the decisions itself. Hence, the services of a digital reference that best befit them are those of decision making support. As noted in section 2.3, digital twins with manual information flow applications provide the basis for this decision making support for humans (Y. Lu et al., 2020). This is reflected in the need distribution between the digital references in table 7.2.

Practicing, Training, Educating (OTO)
As mentioned in the previous section, OTO needs have an exceptional status regarding the allocation towards digital twins or digital models. They are positioned somewhere between the two. Hence, they are mentioned separately, here. A large number of needs were identified towards OTO, signaling its importance, and potential benefit. This includes being able to offer more OTO possibilities, towards additional stakeholders being trained, a faster process, and more experienced personnel. Furthermore, there are needs towards immersion filled experiences, and unique scenarios which can not be tested physically.

7.3. Expert Validation

The results of this chapter are discussed with two digital twin experts. The experts provided additional perspectives and insights that adjusted or added to the presented results. Their key observations and remarks are summarised here, and a more extensive version is provided in appendix E.

Geometric data
The data input of a digital twin is the data that comes from the asset itself, not the resulting processes. This means stakeholder bias [1], in the given context of asphalt repairs, is geometric information. The data you gather is about the condition of the pavement, and not the bias of the stakeholder.

Geometric data cannot be time dependent, digital model programs do not support this type of data. Operational data that is required for the dashboard is therefore not geometric. For example, the car geometry, their location and the number of cars can be considered geometric, but the number of cars going through a tunnel at a specific time is not geometric. This remark resulted in the adjustment of operational conditions [3] towards non-geometric data.

Functional needs can require both geometric and non-geometric data, dependent on the exact context. Sometimes issues have a geometric nature, and a digital model would have prevented it, however, if both data types are probable, a digital twin is the model you need. The reason for this is because digital twins are a continuation of digital models, we start every digital twin with a BIM model, but not the other way around. Therefore, codes in both columns for digital models and digital twins give the wrong representation of facts. This effected the codes [5] credibility and [3] interfaces, which have both been adjusted accordingly.

Active data
The key aspect for the active data requirement, is where the line is drawn between passive and active requirements. Tunnel components such as cables, that move maybe once every few years, should not qualify as active data. This insight resulted in the positioning of location [7] and dependent relations [8] codes as a passive data requirement.

Another interesting point is when data is available on day one. Tunnel capacity [6] uses predicted future traffic values, which can be set in stone (passive data) from day one, or it can be adjusted continuously according to the most relevant data (active). The same is true for the operational conditions [3] and energy use [13], for example the amount of ice days per year or the energy efficiency requirement of the tunnel. Similarly, the code discontinued installations, requires active data until the date at which the installation is discontinued is known, after which the data becomes passive. These points effected the data requirement table, the codes were assigned to the data type that follows from the exact context in which they were given by the facility manager.

Constrained to facility manager knowledge
The context given by the facility managers is passive, non-geometric data, but this restricts the results to the limits of their imagination. The experts are of the opinion that having a 3D printed model is old fashioned. More advanced methods are in the experts opinion, a lot more effective towards decision making [12], and do require active data.

Improving current methods instead of replacing them
The experts reiterate the result that a digital twin can be used, at least in part, for the problem of biased inspections. However, it is discussed that other than the provided digital twin services for a need, other solutions should be considered. A better solution to the code of biased inspections, might be the reformulation of fault definitions, or an improved inspection norm. A digital twin service is not always the cheapest or most effective solution, so it should not be the only option. This point of concern is taken into account, however not in the synthesis of the report, because the cost benefit of digital twin services are not a part of the scope of the research and they cannot be compared to alternative solutions. However, when considering implementing digital twin services, considering alternatives, and comparing solutions is an important aspect, this is highlighted in the discussion of the report. Additionally, it forms a recommendation for further research.

Educating, Training, Practicing

OTO control systems [8], OTO calamity [9], and OTO maintenance [10] are actually similar to the discussion about active data. The experts agree with the statements that these OTO needs are neither strictly a digital model or digital twin. They mention that a changing training protocol once every five years should not be considered active data or require an active stream of data. Additionally, they similarly found digital models to be insufficient for this, they themselves currently use additional programs to establish the training environments. Control system training environments may however be an exception because they primarily depend on software systems, and an autonomous flow of data is established relatively easily.

8 Discussion

Section 8.1 further hedges possible implications of the research results, in a more general manner. In other words this section, contrary to the previous chapter, discusses possible implications beyond the specific scope of the research. Also, the limitations of the research are discussed in section 8.2.

8.1. Digital tunnel twin

Definition

A Digital Twin is a broad concept, leading to disparity in research and understanding by those working with it. A common discussion in the interviews was around the meaning of a digital twin, and whether current tunnel systems qualify to be considered as such a twin. Tunnel facility managers with knowledge of digital twins, classified a digital representation to be a digital twin if the representation of the asset is more than just the geometric information. The difference between the common understanding in literature (including the definition for research) and practice is therefore the required active link or data stream between the physical and digital twin. In other words, updates in 'real-time' are not necessary, as described in the definitions of among others (Farsi et al., 2020; Lim et al., 2019; Glaessgen & Stargel, 2012). This difference may be attributed to two different factors. Firstly, the relevance of continuous updating of civil assets is less pertinent because the technical installations are currently less complex, hence less often producing active data. Secondly, the current application of digital twins is heavily focused on the realisation phase of tunnels, namely the validation of 'to be built' assets, hence no active data stream can be realised with an object that does not exist yet.

Sector wide digital twins

Despite digital twin successes in the maintenance and operation of the building industry in the form of research and pilots, it is still largely absent in the tunnel sector. Although the two sectors are often positioned under the umbrella term 'smart city' or 'construction', the functional needs and therefore the use of digital twin applications are not equal. By considering the similarities and differences in the needs of the two sectors, the reason for this becomes clear.

Tunnel facility managers are less interested in the active tracking of component location and outages of tunnel installations. This was not initially expected. Three aspects may be of influence here, compared to the building industry: tunnel components can be considered more static, tunnel components can be considered less complex, and current tunnel systems more fit for purpose. The third topic which are less interesting to tunnel facility managers is traffic, of the end-user of the asset. This was however expected, as the role description does not include these users in its scope. These topics were often disputed by tunnel facility managers, so we can not conclude that there are no useful digital twin services for these areas, but rather there are none from the perspective of a tunnel facility manager.

Tunnel facility managers are more interested in the availability of their asset compared to the research towards the building industry. There was a lot of interest in increasing and securing the availability of the tunnel. This was seen throughout the codes, including: preparing maintenance tasks through

OTO, verifying and validating improvement maintenance before installation, assessing the lifespan of tunnel components for timely maintenance, and visualising the availability through a dashboard. An explanation for this focus, is the structure of tunnel contracts, where penalties are given for downtime, measured in minutes.

The differences between the building and tunnel sectors show that universal digital twins, with the same applications for different assets would result in sub optimal solutions. Research should be done towards discovering the generalisability between tunnels, and other infrastructure assets including bridges. By doing this, conclusions can be drawn towards infrastructure sector as a whole, instead of specifically tunnels. Infrastructure assets such as bridges and tunnels may prove to be similar enough because of contract types, functions, and lifespans to consider standardised digital twin practices.

Digital Twin problems
Apart from identifying functional needs, more hurdles need to be addressed before digital twins can be implemented. These problems (Informational, organisational and technical, according to Volk et al. (2014)) are not part of the scope this research, hence they were not topics in the semi structured interviews. However, they were often brought up as topics by the participants. Because the perception of digital twin users influences the adoption of the tool, they are discussed here to indicate the perception of facility managers about digital twins and provide topics for future research. The main concerns of the tunnel facility managers towards digital twins were trust, upkeep, and ownership.

DT trust
there is a lack of trust in the technology. This is indicated by needs towards knowing exactly what the digital twin is doing and why, and by opinions of participants stating that the technology will never replace on site validation. Moreover, a digital twin is compared to the black-box concept of artificial intelligence and participants described that current digital twins are not, and never will give enough validation to the tunnel safety officer, to give approval. This lack in trust, combined with a lack of knowledge can limit the future implementation of a digital twin.

Furthermore, what is seen in other studies, is that when participants are not well informed about subjects like AI, machine learning, digital twins, they wrongfully assume it can solve all problems and do everything (Fuller et al., 2019). This assumption can give facility managers a false sense of trust, or set their expectations too high.

Tunnel facility managers are not computer scientists and may reject technology based on false perceptions. This problem is overcome by educating the users, so they understand what is, and is not, possible. The importance of educating user was echoed during an exploratory conversation with COB[1] who mentioned there should be acceptance created first, which is done by raising awareness, because 'unknown makes unloved' (Janssen, 2020). Similarly, in a closely related thesis, Kharoubi (2019) quoted an anonymous Professor stating "We don't have to make a transition plan (for implementing 5D BIM), we need to find a way to educate the people".

DT upkeep and ownership
Tunnel facility managers said that they foresee problems in the upkeep of such a digital twin. Two interviewed specifically mentioned the number of software licences and knowledge requirements of those packages, that are required to use the digital twin. Two others mentioned the difficulty in keeping the digital twin up to date, relating to all the changes in the tunnel, and the aging of the software over time.

the ownership and organisational structure of the digital tunnel twin is still a question mark. More specifically, if constructing and designing a digital twin should be the responsibility of a private company, a governmental company as RWS, or a combination of the two. RWS is the largest owner of tunnels in The Netherlands and they are working towards standardisation of their tunnels. Hence the potential benefit of using digital twins is the biggest for RWS. Facility managers of both contractor and governmental organisations argued against RWS being the designer and owner, because of lack of software expertise and recent missteps with AIRBIM (Mackor, 2020). AIRBIM was a development for

[1]Centrum voor Ondergronds Bouwen: https://www.cob.nl/

the connection of a digital model (BIM) models with other data applications currently in use ‘connection through the air’. On the other hand, contractors are hesitant towards investing in digital twin services, because they fear their investment will be sunken- & lost costs, when RWS catches up and pushes an alternative format and demands standardisation. Instead, they proposed a combination of the market and clients as owner and developers, where both share responsibility and benefit.

Organisational complexity
Next to the design of a digital twin and acceptance of change, another important factor is the organisational complexity of tunnels. Meaningful change through innovation needs to go hand in hand with organisational change (Peppard & Ward, 2016). Organisations should invest to accommodate change, otherwise a digital twin, still does not lead to any actions or meaningful improvements to the tunnel system. Tunnel facility managers described they had been offered a digital twin at the start of the maintenance and operation, but had declined the offer, in part because they do not have the capability to maintain it. Contractors capable of designing, adjusting and maintaining digital twins are removed from the project after delivery of the tunnel. Moreover, there is currently a lack of expertise and structure within the asset management organisations of tunnels of both clients and contractors, to use and maintain digital twins. One possibility of utilising digital twins for the maintenance and operation of tunnels without changing the organisational structure is through servitization[2], where a company specialises, designs, and maintains a digital twin while offering services for the maintenance of the tunnel. This business model can bring advantages for the digital tunnel twin, such as improved product innovation, centralised knowledge, higher efficiency, and customer loyalty as discussed by Baines et al. (2017) for the manufacturing industry. A related case is one from the company Caterpillar (Emerald, 2020), who sells products (including excavators), and additionally offers a service towards monitoring of equipment for preventive maintenance to reduce downtime (remotely monitoring active data sent from the vehicles).

8.2. Limitations of the research

This section describes the limitations of this research, regarding both the empirical data gathering and the analysis of this data. The section is divided in three parts: data saturation, data bias, and data results, to comprehensively describe these limitations.

Data Saturation
Data saturation is a limitation of the research. Results of the data analysis show a possible lack of saturation. Towards the end of the process participants were found to contribute additional unique needs, meaning more needs could still surface through additional interviews. To account for this, needs were not omitted based on the number of occurrences in the transcripts, as all needs mentioned may prove to be of similar importance. More research may provide additional insights into the relevance of themes and their relations. This is especially the case for the themes which were not questioned during the interviews specifically, namely dashboard, dependent relations, and stakeholder engagement. Not all participants had the chance to consider needs or the lack of them, for these specific themes, hence their importance is not as clear.

The empirical research does not focus on project specific characteristics, in an attempt to be able to generalise nationally. To do this, participants from many different tunnels in The Netherlands were approached, while maintaining comparability of the results by narrowing the selection to facility managers. This method does however limit the number of participants with similar tunnel characteristics such as tunnel age, tunnel length, and toll tunnels. Additionally, the limited number of participants excludes other tunnel variables altogether, such as privately owned tunnels. Concluding , it can be stated the research provides a good first look towards the generalisability between sectors, and functional of needs of tunnel facility managers in The Netherlands. However additional interviews could be held to further ensure the reliability of the results and conclusions of the interviews.

[2] A process of building revenue streams for manufacturers from services (Baines et al., 2017)

Data bias

The participant knowledge of tunnels influenced the interviews. Between interviews, contradicting statements were found about tunnels. These contradictions included perceptions or opinions about whether the energy use of lighting systems was significant or not, if energy costs are the responsibility of the contractor or client, and whether tunnel systems are considered complex or not. These perceptions influenced whether a participant stated a need for the monitoring or optimisation of energy use, or the necessity of monitoring specific tunnel installations. To account for this, every statement was considered for the results of the research. Specifically regarding the energy cost of tunnel lighting systems, this could be considered quantitatively, however this is not apart of the scope of this research, and instead forms a recommendation of further research.

In general, participants do not have knowledge about digital twins, which is good because it allows them to think outside the box and simply consider needs within their current working process. However it also brings limitations to the research. Preconceived notions of digital technology can create unwanted skepticism, limiting the number of responses. This was seen in the interviews, as participants would back-track on ideas, because they would consider, with their experience and knowledge, if it was actually possible to achieve something. Additionally, discussing digital twins without participants having experience or concrete references with it in other sectors, makes it difficult to visualise its effects and possibilities. This results in participants not knowing what they are missing, by not being able to relate their processes to others.

Other than bias of the data by the participant, the subjective view or disposition of the researcher can influence the interpretation of participant responses (Saunders et al., 2016), and the results of the research. To limit this, explanations during the interviews were formed before the interview, and the interviews were structured so the questions, and the given explanations would be the same between interviews. Furthermore the synthesis of the research was validated by external digital twin experts. This led to new insights and adjustments to the results, as other perspectives were considered.

Data Results

The research captures the perceptions, memories and intentions and ideas (Verschuren & Doorewaard, 2007) of the group of interviewees at a certain point in time. This list of needs is not complete or exhaustive. Over time more needs may surface, based on new insights or beliefs. Additionally, this research finds, compares, and concludes on functional problems, but does not include other identified problems such as informational, organisational and technical problems (Volk et al., 2014). These problems should be included and analysed to fully comprehend the implications and benefits of digital twins in practice. In the analysis of the empirical data, benefits of digital twins are highlighted, however, due to the two limitations mentioned, this is an incomplete consideration. For this reason, the benefit – cost relation of the digital twin services is not included. The results of the research are on the prospects of needs being completely resolved. In other words, additional research is required to understand to what degree digital twins benefit the facility management of tunnels.

9 Conclusion

This chapter concludes the research, by considering the research objectives and questions, and relating them to the discovered results. Section 9.1 summarises the research design and concludes the sub-questions one to four. Section 9.2 concludes the answer to the main research question. Lastly, section 9.3 presents the recommendations for further research and practice.

9.1. Sub questions

The aim of this research was to discover the possibilities of digital twins in the life cycle of an asset, which was accomplished in three stages. *Stage A* consisted of a literature study, where current research towards digital twins is explored and literature towards Dutch tunnel systems is explored, to understand what is already known and what is not. *Stage B* contains the empirical part research, specifically the reporting and analysis of the interviews. *Stage C* consists of the synthesis between the first two stages, including this conclusion. Within these three stages, four sub questions (SQ) are answered which contribute to the main research question (RQ) discussed in 9.2:

SQ1 *How are digital twins designed and what applications do they provide?*

A digital twin is a digital reference of a physical object, characterised by an autonomous stream of data from the physical object to the digital twin. A digital twin consists of four layers, which can work together in an integrative manner: data collection, communication, processing, and service. The data that is most relevant to digital twins is *active data*, this is data that continuously requires updates to stay relevant, consequently benefiting from the autonomous stream of data provided by a digital twin. Active data includes sensor data, interaction protocols, maintenance strategies, software, and implicit dynamic relationships. *Digital twin services* can be divided into monitoring, predictive and control services, for specific purposes. These digital twin services are combined in applications, for a specific context (*of what, for what, when*) and for a specific user.

SQ2 *How are tunnel systems organised and how is information management incorporated in the maintenance and operation stage?*

A tunnel system consists of three parts, the tunnel structure (civil works), MEP systems (technical installations), and processes. *The organisation* of tunnel systems in The Netherlands are not uniform, however a large majority are organised based on the LTS, a standardisation document constructed by Rijkswaterstaat in conjunction with professional market parties. *Tunnel processes* are managed by facility managers, who are responsible for the functioning of tunnel services. These facility managers primarily depend on information to perform their tasks, hence the management of information is at the core of their job description. Information management is incorporated in the maintenance and operation through organisational, asset and project information requirements, which are translated into an asset information model. The information requirements are influenced by both the organisational needs and facility manager needs.

SQ3 *What functional problems do facility managers encounter during the maintenance and operation of tunnels?*

The functional problems of facility managers are very wide, encompassing most of their work processes, including configuration management, incident management, problem management, change management and maintenance processes. 178 codes are assigned to ten interview transcripts, which are fragments of text describing functional needs or the absence of them, which were subsequently categorised into themes based on their relation to each other. The themes of these needs that were supported by participant responses are summarised next.

Needs exist relating to improvement and preventive maintenance, contractor inspections, energy use, dependent relations of installations, and stakeholder engagement. Within these themes, problems existed which result in better informed decisions, the validation of these decisions, and minimising the operational downtime of the tunnel.

Next, needs exist within the education, training and practicing (OTO) of personnel, these problems indirectly benefit facility managers by minimising mistakes and improving tunnel processes. Identified OTO problems were primarily towards maintenance works, and less so towards calamities and control systems. These problems included the education of new employees, training to improve the experience of tunnel personnel, and practicing with a more comprehensive representation of the tunnel and scenarios.

SQ4 *What functional needs in the tunnel sector can be supported with a digital twin?*

The functional problems identified during sub question three, in the empirical research, have data and information requirements. The facility managers require relevant data at the right time, in the right format. To assess whether a digital twin is capable of providing this data and information, the functional needs are categorised and compared to digital twin traits. The problems are effectively filtered by properties of digital twins and digital models (BIM), to visualise which can be supported by digital twins. What is found is that digital twins are required for the majority of needs mentioned above, except for those requiring passive geometric data, and those requiring passive non geometric data are seen as ambiguous.

Functional needs that can be realised by digital models, hence not requiring digital twins, include geometric interfaces between objects (clash detection), the location of objects, and specific stakeholder engagement needs. More specifically, assessing a digital model based on location, appearance, position, and size, can be considered static because of infrequent changes in tunnel components.

The ambiguous needs include the OTO needs, and individual stakeholder engagement needs. These needs are not assigned as they have properties that do not fit either definition perfectly. They are not digital twin needs because they do not require an automatic connection between the physical and digital twin, and they are not digital model needs because they are not geometric properties.

9.2. Research question

RQ *What functional problems of facility managers do you need to take into account when designing a digital twin for the maintenance and operation of tunnels?*

For what

Based on 10 interviews with tunnel facility managers, preliminary conclusions are drawn on what a digital twin design should include. Three main services exist for digital twins: monitoring, predicting, and controlling. The majority of services that should be considered in relation to the functional problems of tunnel facility managers are towards the decision aiding of the facility managers. The three types of digital twin services, in the context of tunnels, provide possible applications which are beneficial. *Two monitoring applications* are considered, the monitoring of energy use, and system health. It is concluded that energy use should be included in a digital twin, and that the monitoring of system health is required for comprehensibility of problems and stakeholder management. *Three predictive applications* are considered: dependent relations, maintenance scheduling, and simulations. These applications help facility managers anticipate risks during tunnel processes, and provide opportunity for reaching better informed decisions regarding maintenance tasks, problem management and configuration management practices. *One controlling application* is discussed, the automatic control and optimisation of energy use in the tunnel.

When

Currently digital twin applications are only considered during tunnel tendering, due to the investment and design costs. This means a digital twin is currently considered during the construction (new) or renovation (old) of the tunnel, for the following maintenance and operation phase of the tunnel. Other than the limited implementation time frame, it was concluded that the digital tunnel twin is dependent on the age of the tunnel. What is found in the research is that facility managers of newly built tunnels are more interested in both the energy use of the tunnel and stakeholder engagement of tunnel decisions compared to managers of older tunnels.

For who

The research is aimed at a specific role of the tunnel industry, hence the perspective is singular. However, one distinction is made based on the dependence of the organisational position of the facility manager. The OTO of maintenance tasks should specifically be taken into account for digital twins for tunnel facility managers that are operationally responsible for the tunnel, so contractors in DBFM contracts or governmental participants in non-integrative contracts.

Of what

The research found that digital twins for asset management only make sense towards specific tunnel components, specifically tunnel technical installations, and civil structures with very short lifespans (asphalt layers and expansion joints). This is supported by current tunnel standards, the LTS only defines maintenance and management processes for these components, due to their high maintenance costs and short lifespans. Lastly, it is supported by research, Q. Lu, Parlikad, et al. (2019) describes the large amount of active data for the technical installations, and Aono, Lajnef, Faridazar, and Chakrabartty (2016) according to who IoT is only practical if the IoT infrastructure matches the useful life of the physical asset.

Scientific relevance

An absence of research was discovered towards the design of a digital twin for the maintenance and operation of the infrastructure sector. This research contributes to literature by looking at part of the infrastructure sector, namely tunnels. The functional needs of tunnel facility managers are researched to explore digital twin applications during the maintenance and operation phase. By doing this, the research emphasizes possibilities to improve the information flow, and provides the first foundation for the design and implementation of a digital tunnel twin. The research discusses the differences between the building and tunnel sector, and emphasizes their distinction from each other. This emphasizes the necessity to distinguish digital twin applications between assets and sectors within the smart city or construction domain, often used in current digital twin research.

9.3. Recommendations

Research recommendations

- This research found the functional needs of tunnel facility managers, further research could discover the functional needs of other roles within the tunnel sector, including the tunnel user (traffic), safety officers, owner, and emergency services.
- This research indicated possible beneficial applications for digital tunnel twins, further research should be done to discover the related costs of such applications.
- This research found functional needs of tunnel facility managers, further research should determine associated informational, technical and organisational problems.
- This research discovered three additional themes: dashboard, dependent relations, and stakeholder engagement. These themes should be researched and defined further as they were not specifically questioned during the interviews, but initial results indicate their importance.
- This research found dependencies between the age of a tunnel and the organisation of the M&O, further research should be done to further strengthen and visualise these dependencies.

Beyond this research

- Research the similarities between other infrastructure assets, such as bridges, viaducts, highways, and locks to discover the similarities between a beneficial digital twins between these assets.
- Researching implementation strategies of a digital twin for a tunnel in the maintenance and operation.
- Researching the correlation between functional failures of similar tunnel technical installations between different tunnels.
- Researching possible interrelation between increasing energy use and the degradation of a tunnel technical installation

9.3.1. Practical recommendations

Infranea

Focus on universally supported needs for tunnel applications

- The inspections of tunnel technical installations are found to be lacking behavioural considerations, discovered as part of the theme contractor inspections. A digital twin can improve the reliability and analysis of these components by looking at their performance, more than current visual inspections.
- There is a need towards impact analysis of an adjustment in software or technical installation on the functioning of other technical installations (dependent relations). Current configuration management of the dependent relations of different tunnel technical installations are shown to be insufficient, as problems occur frequently.
- Focus on creating immersive calamity scenarios. There is a need towards stimulating stress and adrenaline during calamity scenarios, virtualisation of scenarios is needed in scenarios which can't be recreated practically, or don't evoke the same responses when they are practiced physically.
- A demand for the training and preparing for maintenance activities is found in the research. The results indicate especially contractors are very interested in increasing the knowledge and expertise of maintenance personnel regarding preventive and improvement tasks, before the scheduled maintenance slot. The training should focus on reducing the risk of faults and the time that is required for the slot. This is interesting for newly built tunnels, or newly employed employees, which don't yet have the experience of repetition.
- Needs are discovered for improvement maintenance, and stakeholder engagement. There is a potential benefit towards verifying and validating of new additions to the software or technical installations, through virtual testing.

Consider current perceptions of digital twin problems

- Problems are discussed regarding the upkeep, ownership and complexity of a digital tunnel twins. Consider simplifying the digital tunnel twin. Requiring software licences, especially from multiple vendors, should be avoided. These licences not only have related costs, but licenses add to the complexity and maintenance of the tool (updates, versions, fault diagnostics, vendor dependency, discontinued software). Further simplification can be considered by integrating digital twin services into a singular system, as reviewed in the research (integrated 'full' digital twin). Having singular, separated, models or applications for each task, adds to the fragmentation of information and the complexity of the tool.
- Consider servicizing maintenance scheduling services. Predictive maintenance is something uniformly supported by the needs of facility managers, and something currently lacking in the construction world. Infranea is in an unique situation where is has both knowledge of digital infrastructure and civil constructions, where a large part of the construction world is conservative. Prediction maintenance based on data and data processing capabilities is something that will be continuously improved over time, and benefits from a centralised provider.

Tunnel industry

- Invest in process improvements during the maintenance and operation of assets. Research indicates at least two thirds of asset costs are attributed to the maintenance and operation phase, while innovations in this phase is often unsupported financially. Facility managers from both client and contractor indicated the limited funds beyond delivery of the project, and the difficulty of asset management involvement before delivery.
- Actively seek cooperation for tunnel process innovations. By forming alliances and cooperatively looking towards (digital) innovations, which benefit all involved stakeholders, hurdles are overcome, and more meaningful solutions may be formed.
- Standardise tunnel installations. By further standardising tunnel components, meaningful comparisons become apparent between tunnels, and a greater understanding of tunnel systems can be reached. This is important to say something meaningful about the end of life of tunnel systems, and increasing meaningful preventive maintenance practices.
- Increase digital awareness. Increase the awareness of digital tools within the tunnel organisation. There are huge potential benefits of existing and new digital tools, for all types of tunnels. By educating tunnel facility managers within the tunnel organisation, the success of these ventures is increased.

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A

DT Application research in infrastructure

Table A.1: Infrastructure applications digital twins

Author (date)	Source	Research	Application	Method, sector
(Y.-D. Kim et al., 2018)	Sustainability 2018, 10, 2509	How can tunnel incidents be tracked and identified automatically	Incident tracking and identification	Prototype, M&O of tunnel
Deng et al. (2016)	ISRM 2nd International Conference on Rock Dynamics	How can large amounts of tunnel location data be processed into information for management purposes	Automatic warnings for surface subsidence	Prototype, realisation of tunnel
Panella et al. (2018)	ACUUS-Associated Research Centers for the Urban Underground Space	How can tunnel cracks be identified autonomously, for inspection purposes	Tunnel shell crack detection	Prototype, M&O of tunnel
Dohmen (2019)	Conference exhibition Near surface geoscience	How can digital twin be designed to support tunnel boring machines, what are the advantages to using a digital twin	Ground condition monitoring	Prototype, realisation of tunnel
Beaufils et al. (2011)	Springer Series in Geomechanics and Geoengineering	Can a reusable BIM and geotechnics be created to form a long-term sustainable solution	Reusable geotechnical data management	1 Case study, design of tunnel
Kim and Kim (2020)	Sustainability	Can digital twins be used to more accurately predict the lifespan of a noise barrier tunnel	Service life prediction	Prototype, M&O of tunnel
Kang et al. (2018)	17th International Conference on Computing in Civil and Building Engineering	How a digital twin can be used to predict challenges and risks during drilling operations	Performance monitoring	Prototype, M&O of utility tunnel
Ye et al. (2019)	Proceedings of the 12th International Workshop on Structural Health Monitoring	Can a digital twin be designed to monitor the structural health of bridges	Structural health monitoring	1 Case study, M) of bridge
Lin and Cheung (2020)	Journal of Management in Engineering	How can emissions be controlled in parking garages	Emission monitoring	Prototype and 1 case study, M&O of garage
Pargmann et al. (2018)	International Conference on Cloud Computing and Big Data Analysis	How can windfarms be monitored externally, with use of IoT and augmented reality	Performance monitoring	Prototype, M&O of wind farm

B

Digital tool challenges during the maintenance and operation

Functional

Author	Issue
Cavka et al. (2017)	Cost information related to replacing and maintaining equipment and systems
Gnanarednam and Jayasena (2013)	Facilities are costly to operate
Liu and Issa (2016)	Budget/cost
Ashworth et al. (2016)	Quick generation of tailored reports identifying facility space properties
Ashworth et al. (2016)	Asset information including maintenance history and responsible party
Becerik-Gerber et al. (2012)	planning, designing analysing and simulating remodels, renovations or demolition work.
Gnanarednam and Jayasena (2013)	Too many change orders
Johansson et al. (2019)	Decision support by having the right information
Johansson et al. (2019)	Removing subjective assessments, to obtain better decision support
Liu and Issa (2016)	Accessibility/clearance issues (of spaces)
Love et al. (2016)	option appraisal through visualisations for strategic decision making
Cavka et al. (2017)	system performance information
Gnanarednam and Jayasena (2013)	FM cannot control costs very well
Gnanarednam and Jayasena (2013)	Facilities produce a lot of waste during the building process
Gnanarednam and Jayasena (2013)	Facilities use a lot of energy and water
Liu and Issa (2016)	lack of preventive maintenance
Love et al. (2016)	Regular changes in building utilisation, requires a full time technician
Ashworth et al. (2016)	Availability of information well ahead of delivery
Becerik-Gerber et al. (2012)	Emergency responders are required to make decisions without adequate information, there is a need for Organised data, displayed logically to take appropriate actions
Ashworth et al. (2016)	Clear understanding of the design logistics planning, for movement of people/equipment, access routes, replacement space

Ashworth et al. (2016)	Visualization of spaces for identification and comprehension of problems
Becerik-Gerber et al. (2012)	Information is not easily understandable for everyone, difficulty processing information into knowledge
Cavka et al. (2017)	System visualization
Cavka et al. (2017)	Sequence of operation (start-up/shut down information)
Cavka et al. (2017)	Installation manuals
Liu and Issa (2016)	Lack of space designed in the ceiling to contain MEP systems
Liu and Issa (2016)	Limited space for air handler unit filter access
Liu and Issa (2016)	Lack of adequate space for mechnical room
Liu and Issa (2016)	Lack of equipment accessibility
Ashworth et al. (2016)	how easily spaces can be reconfigured to accommodate flexibility and change of use.
Liu and Issa (2016)	Poor design of equipment layout
Becerik-Gerber et al. (2012)	Adding new building floor plans and monitored equipment, updating and maintaining graphical information
Becerik-Gerber et al. (2012)	Locating MEP components which are not visible
Becerik-Gerber et al. (2012)	Locating building components (equipment, materials, finishes)
Cavka et al. (2017)	locations of equipment and system controlls
Becerik-Gerber et al. (2012)	Evacuation plan training for building occupants
Becerik-Gerber et al. (2012)	Facility management personnel have to get familiar with processes, systems and facilities when newly hired or assigned.
Becerik-Gerber et al. (2012)	Assesing whether trainees are prepared for their tasks
Becerik-Gerber et al. (2012)	training takes vast amounts of time
Becerik-Gerber et al. (2012)	Training relies heavily on abilities and experience of the trainers
Liu and Issa (2016)	Lack of trained personnel

Informational

Author	**Issue**
Becerik-Gerber et al. (2012)	Information and knowledge retrieval is fragmented
Gnanaredṇam and Jayasena (2013)	Timely information is rare
Gnanarednam and Jayasena (2013)	duplicates in data collection
Johansson et al. (2019)	easily receive information via computers
Johansson et al. (2019)	machine-readable information, so authorized parties can have easy access.
Liu and Issa (2016)	Manufacturers and supliers do not provide adequate information
Johansson et al. (2019)	the right information needs to be delivered to the right person at the right time
Johansson et al. (2019)	Using standardized platforms
Liu and Issa (2016)	Information accessibility
Liu and Issa (2016)	Software interoperability
Becerik-Gerber et al. (2012)	Inconsistent naming conventions
Gnanarednam and Jayasena (2013)	Inaccurate drawings
Gnanarednam and Jayasena (2013)	increasing poor quality
Liu and Issa (2016)	Poor as-built document
Liu and Issa (2016)	Information accuracy

Love et al. (2016)	The same data is recorded twice, manually
Johansson et al. (2019)	Information should be organized and simple to understand.

Technical

Author	Issue
Becerik-Gerber et al. (2012)	Creating assets and associating them with correct data from various databases
Becerik-Gerber et al. (2012)	laborious attribute updates
Becerik-Gerber et al. (2012)	Lack of experience and example projects
Liu and Issa (2016)	Software interoperability
Love et al. (2016)	Software interoperability
Love et al. (2016)	Difference in software and asset lifecycles (BIM 1-2years, FM systems much longer, and buildings 50+ years)

Organisational

Author	Issue
Liu and Issa (2016)	Cooperation and trust between parties
Gnanarednam and Jayasena (2013)	Lack of legal framework for early participation of AM organisations
Gnanarednam and Jayasena (2013)	Facilities are costly to operate
Gnanarednam and Jayasena (2013)	Facilities use a lot of energy and water, product waste during the building process
Becerik-Gerber et al. (2012)	FM requirements are not taken into account during design
Liu and Issa (2016)	Lack of trained personnel
Liu and Issa (2016)	Cooperation and trust between parties
Becerik-Gerber et al. (2012)	Model ownership, level of development, liabilities and fees are not stipulated or standardised
Gnanarednam and Jayasena (2013)	building often end up in litigation and duplicates in data collection
Becerik-Gerber et al. (2012)	Individual cultural issues with adopting a new technology
Becerik-Gerber et al. (2012)	Organizational resistance of investments in infrastructure, training and tools
Gnanarednam and Jayasena (2013)	Too many change orders

C

Interview Protocol

The interview protocol consists of two parts, these two parts are added below. The first part, an introduction PDF-form (voorbereiding interview - Introductie vragen), is sent to participants before the actual interview takes place. This form has the purpose of defining participant characteristics, to form control variables for analysis and to personalise the second part of the protocol.

The second part of the interview protocol, is a list of questions, forming the structure of the interview. This interview guideline was used during the interview, and was personalised slightly based on the participants background as indicated above. For the purpose of clarification, the guideline version presented in this appendix has additional information regarding the purpose and relevance of the questions.

Voorbereiding interview

Introductie vragen

TU Delft

Bedankt dat u wilt meewerken aan het interview!

Dit formulier bevat enkele vragen vooraf, zodat de interview vlot en effectief kan verlopen.
Na het invullen van de lege velden, zou ik u graag vragen het formulier terug te sturen.

Algemene Informatie

Voor- en achternaam

(Werkzaam) Bedrijf

Tunnels in beheer

Werkzaamheden

Wat is uw rol of functie binnen uw bedrijf?

Hoeveel jaar heeft u ervaring in de beheer en onderhoud

En hoeveel jaar ervaring in de beheer en onderhoud van tunnels?

Voorkennis

In hoeverre bent u bekent met de volgende digitale gereedschappen?

	Nog nooit van gehoord	Wel eens van gehoord	Ik ken het, maar geen ervaring	Ik ken het, en heb ervaring
BIM (Building Information Modelling)				
Digital Twin (of: digitale tunnel tweeling)				

Gebruik je BIM of Digital twins tijdens je werkzaamheden?

- Ja, Digital Twins
- Ja, BIM
- Weet ik niet
- Nee

Interview Guideline

Introductie praatje

Ik studeer aan de TU Delft, in de richting van civiele techniek en ben nu bezig met mijn afstudeeronderzoek.

Het onderwerp van mijn onderzoek is digitale gereedschappen in de beheer en onderhoud van tunnels. Het doel van dit interview is om een beeld te krijgen van de behoeftes en meningen van tunnelbeheerders en asset managers. Voor de duidelijkheid, wat ik verwacht uit dit interview, zijn jou meningen over wat er wellicht beter kan, of waar je tegenaanloopt tijdens jou werkzaamheden.

Voordat we kunnen beginnen, nog even wat praktische zaken:

- Alles is in het Nederlands
- Alles wordt annoniem verwerkt
- Het wordt opgenomen, zodat het achteraf beter verwerkt kan worden
- De resultaten zijn openbaar, dus als je wilt kan ik je het verslag toesturen.

Vragen	**Relevantie**
Zou je jezelf kunnen voorstellen? Kunt u in het kort uitleggen wat uw functie is, en wat uw hoofdwerkzaamheden zijn?	Inleiding interview, en een beeld creëren van de werkzaamheden, waar de volgende vragen op gefocussed kunnen worden.
Weet u of de landelijke tunnel standaard van toepassing was? Is het onderhoudscontract deel van een DBFM? In hoeverre worden digitale management systemen toegepast? Wordt er al gebruik gemaakt van BIM?	Eigenschappen tunnel achterhalen, als mogelijke variablen in de analyse

Uitleg

Digitale tweelingen zijn meer dan een 3D tekening, ze verzamelen automatisch informatie over objecten en kunnen zo de toestand van een object monitoren. U kan hierbij denken aan een smartwatch, die elk minuut uw temperatuur, hartslag, ademritme meet, en vervolgens de ambulance kan inschakelen als er iets mis is.

Vragen	**Relevantie**
Kunt u mogelijkheden bedenken waar een monitorende functie van een computerprogramma u kan helpen bij uw werkzaamheden?	In de breedste zin kijken of er al functionele behoeftes naar voren komen gezien monitorende functie digital twins
Tijdens uw werkzaamheden, mist u 'actieve data' of mist informatie over de tunnel, of tunnel onderdelen?	In een iets specifiekere zin kijken of er functionele behoeftes naar voren komen die in de scope van digital twins vallen
Wordt verkeer in een tunnel gemonitord? Zo ja, op welke manier wordt dit gedaan, en waarvoor wordt dit gedaan? Zo nee, denkt u dat het beheer of onderhoud te verbeteren is, als dit wel gedaan zou worden?	Identificeren of er mogelijkheden zijn met een digitale tweeling voor verkeer, zelfs al is die buiten de scope van een facility manager
Komt het voor dat de foutieve werking van een tunnel installatie te laat kenbaar wordt? Zo ja, zou u een voorbeeld kunnen geven, en zou het monitoren van deze systemen helpen met het kenbaar maken? (Ervaart u dit als een groot probleem?)	Specifiek bepalen of het monitoren van de tunnel positief zou kunnen helpen tijdens werkzaamheden en de snelheid van fout detectie
Komt het voor dat bij onderhouds-werkzaamheden het niet duidelijk is wat er foutief werkt?	Specifiek bepalen of het monitoren van de tunnel positief zou kunnen helpen tijdens werkzaamheden en fout detectie
Is de locatie van reserve onderdelen van tunnels goed te achterhalen? (En dat van ander tunnel materiaal?) De locatie kenbaar maken van bijvoorbeeld kabels en leidingen in de muren die niet zichtbaar zijn Zie jij hier toepassingen voor, voor tunnels?	Identificeren of het live monitoren van tunnel elementen nuttig is, en of er specifieke elementen zijn die relevant zijn (actieve locatie data)
Er wordt in gerelateerd onderzoek gesteld dat inspecties van tunnel onderdelen te subjectief is waardoor verkeerde beslissingen genomen worden. Hoe denk jij hierover? Bent u het hiermee eens? (Is dit een groot probleem?)	Bepalen of het er een vraag is naar een meer objectieve kijk naar inspecties, zoals in de literatuur wordt aangegeven voor de bouw sector

Uitleg

Naast het monitoren van tunnel objecten, kan een digitale tweeling, met al de informatie van het monitoren, voorspellingen maken.

Vragen	**Relevantie**
Kunt u mogelijkheden bedenken waar een voorspellende functie van een computerprogramma u kan helpen bij uw werkzaamheden?	In de breedste zin kijken of er al functionele behoeftes naar voren komen gezien voorspellende functie digital twins
Zijn er onderhoudswerkzaamheden in tunnels waar tunnelsystemen worden verbeterd of vervangen door andere? Zo ja, is er onzekerheid over de werking ervan? Zou het digitaal testen van nieuwe systemen voor verificatie en validatie hierbij van dienst kunnen zijn?	Specifiek bepalen of er behoeftes zijn voor het voorspellen van tunnelgedrag in combinatie met risicos tijdens het vervangen van tunnel technische installaties
Komt het voor dat er in de tunnel nieuwe besturingssystemen worden geïmplementeerd, zonder dat u er ervaring mee hebt? Zo ja, zou het handig zijn om met de systemen te oefenen voor ze worden geïmplementeerd?	Specifiek bepalen of er behoeftes zijn voor het voorspellen van tunnelgedrag in combinatie met het oefenen met te vervangen tunnel technische installaties
Worden nutsvoorzieningen gemonitord in de tunnel? Zou het nuttig zijn om mogelijkheden te zoeken om het elektriciteitsgebruik te optimaliseren?	Identificeren of nutsvoorzieningen worden gemonitord, en of de optimalisatie ervan praktisch is voor tunnels, zoals in de literatuur wordt aangegeven voor de bouw sector
In literatuur over kantoren wordt vaak gesteld dat een goeie toepassing van digitale tweelingen het monitoren en kunnen optimaliseren van elektriciteit en water is. Zie jij hier toepassingen voor, voor tunnels?	
In gerelateerde literatuur wordt gesteld dat het opleiden van nieuwe werknemers te veel tijd kost, en te afhankelijk is van de ervaring en kunde van medewerkers. Zou u zeggen dat u het hiermee eens bent? Zo ja, denkt u dat virtueel oefenen hierbij kunnen helpen? En geldt dit ook voor het oefenen en trainen van ervaren werknemers? (Met enige regelmaat)	Identificeren of digitale tweelingen een nuttige bijdrage kunnen leveren aan OTO, en wat de perceptie is van participanten over de actuele training van medewerkers.
Zijn er protocollen of processen als evacuaties die u niet kunt oefenen omdat de tunnel dicht moet om het te oefenen?	
Is het tijdens ongeplande onderhouds-werkzaamheden aan technische tunnel-elementen, duidelijk wat er gedaan moet worden, en op welke manier?	

Afsluiting interview

Nogmaals ontzettend bedankt dat je wou meewerken aan het interview, dit helpt mij weer vooruit met mijn onderzoek. Het duurt nog even voordat ik klaar ben met het onderzoek, maar wil je het onderzoek ontvangen van mij?

Het zou kunnen dat ik een vraag ben vergeten te vragen, of dat ik toch wat meer uitleg zou willen ergens over, vind je het goed als ik je daarvoor bel of email?

D

Interview Results and Analysis

D.0.1. Interview codes
D.0.2. Interview themes and variables


Interview participants
Code System
01 02 03 04 05 06 07 08 09 10 SUM
[1] Contractor Inspections 0
Only visual 4
Stakeholder bias 3
No current issues 1
[2] Dashboard 0
Current operational status tunnel 3
No current issues 2
Predictive maintenance 2
Automation of work acivities 1
GHS symbol recognition 1
[3] Dependent Relations 0
Interfaces 7
Coherence 4
Tunnel interdependence 3
Operational conditions 2
[4] Detecting Faults 0
No issues with fault detection 6
Speed of detection 4
Unnoticed failures 4
Complex failure definitions (+) 1
Unknown size of the faults 1
Missing Knowledge 1
[5] Improvement Maintenance 0
Digital validation 6
Discontinued installations 3
Problems originating in practice 3
Optimizing design 2
Increasingly complex systems 2
Credibility 1
[6] Lifespan Prediction 0
components with short lifespans 4
Complex installations 3
Known problem areas 2
Standardisation of installations 1
Tunnel capacity 1

Figure D.1: Interview codes and occurrences

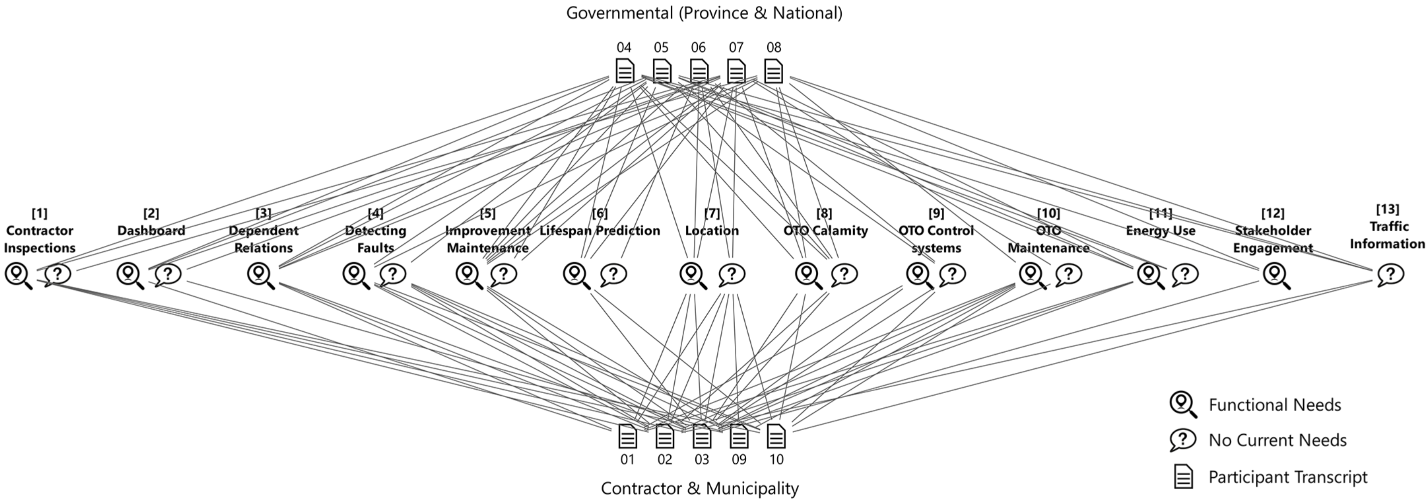

Figure D.2: Interview themes relation with participant organisation

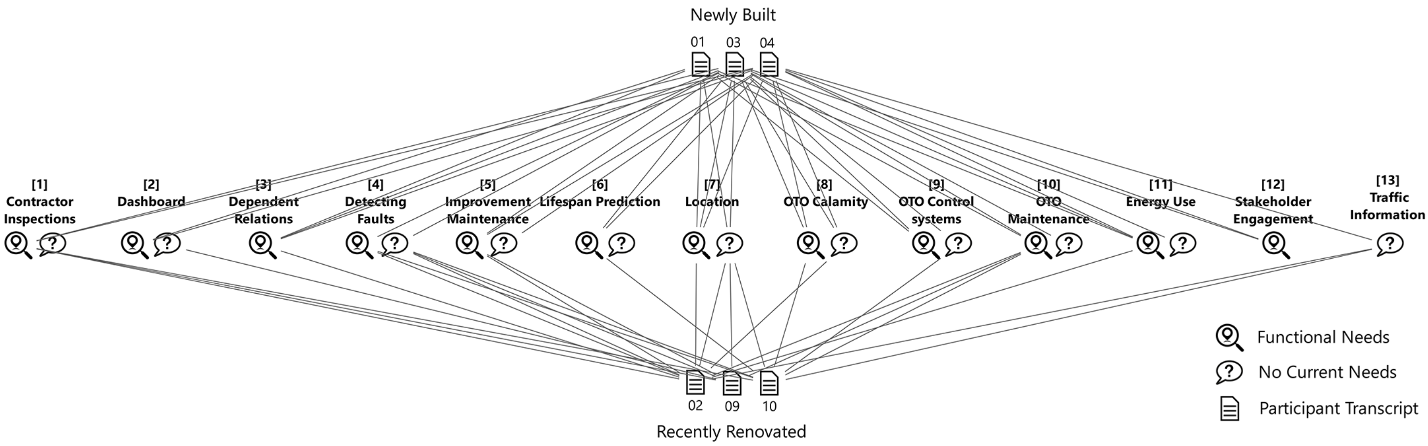

Figure D.3: Interview themes relation with tunnel age

E
Synthesis Validation

This appendix is a summary of the focus group, where discussions and conclusions are mentioned which contributed or adjusted the results of the report. Because of the similar profile of the validation experts, and the discussion format of the validation round, they are not differentiated throughout the text.

[1] Contractor Inspections

Only visual

I agree this is non-geometric, you consider the sensor data and other electrical components so there's nothing geometric about this context.

Stakeholder bias

I worked at a large contractor before this job, and they used camera's to detect surface damages, so you drive over the road, and the computer processes the data to highlight worry some positions in the asphalt. The data should be geometric instead of non-geometric because the data you gather is geometric. The processing and requirements make it active.

[2] Dashboard

Current operational status tunnel

This data is non-geometric, instead of geometric. This is because it is time-dependent but also dependant of so much more than just geometric data, for example the number of cars passing through.

GHS

When its applicable, its located somewhere. So only when there is an emergency, the symbols are relevant and localised, so its geometric only when there's an emergency.

[3] Dependent Relations

Interface

The ventilator is moved once or twice, so its rather passive. I would however suggest moving it to geometric, instead of non-geometric, as its more often than not, geometric information that you need. A type of BIM clash detection. I guess it may be both, depending on the context.

Tunnel Interdependence

It depends whether your talking about the first of second tunnel, for the first tunnel its active data. Because you want to actively collect the data. If you discuss the second tunnel, its passive information, because the information wont change, it is the start point. So active and non-geometric because it will mostly be from visual inspections and sensors. The information of the tunnel that you want to use for other tunnels, is the behaviour of tunnels, so for example, if i use this installation, how long can I expect it to work, will I have to repair it often? So this is generally very active data.

Operational conditions
Its more about the functional descriptions of the installations, its about what the lamp can handle. I think however that its passive information because they are specifications of installations, and therefore don't need to be updated. This is all done on day one.

[4] Detecting Faults
I agree that detecting faults is non-geometrics. Except when you consider concrete and asphalt aspects, but that's not apart of the context.

[5] Improvements Maintenance
Digital validation
This is very similar to what we do in our digital twin projects. And I agree its non-geometric.

Discontinued installations
Its not geometric, I agree, however something is deliverable or it not, and that date will not change over time. However, you do need to actively monitor when it is known when an installation will be discontinued.

Increasingly complex systems
Yes I agree, its active and non-geometric, because its increasingly more complex, its about a type of acceleration.

Credibility
Location of the light would be geometric, but the amount of light is not geometric.

[6] Lifespan prediction
Complex installations
I would instead put it as non geometric, because the things you want to know are not geometric. Its actually comparable with the first functional need we discussed, you don't just look at something, you want to measure it.

Known problem areas
Its about whether you want to keep monitoring the active situation, and I think in this context it is active and geometric.

Tunnel Capacity
I agree its non-geometric, but I'm not sure about geometric, are you measuring it before you start the tunnel construction, then its passive, it's a requirement. If its something continuously monitored or simulated, then its active.

[7] Location
I think most tunnel installations are relatively static, so its rather passive.

Cables in the vicinity
The cables outside, don't really move, and when they are moved, you only need the location data at that second. You move the cable, and then you record the new location, and you have a static cable. And I agree there is no need for this in the tunnel, the utility tunnels are available. And its geometric because its about the cable, and not whats going through the cable.

[8] OTO Calamity
This is an interesting one, I don't think its active data, you will eventually have to adjust the training with new data, but that data does not need to be active changed. You adjust it once, not many times. I don't think its geometric, because your testing procedures, and not say the collapse of the tunnel. Its about the process of learning about it, so non geometric. [9] OTO control systems and [10] OTO

maintenance are actually the same. I don't think adjusting the training protocol once every five years can be considered active. You do however need both geometric and non geometric data to construct the OTO system.

[11] Energy Use

Energy efficiency

active data, I agree, but I think its non-geometric instead. The only thing I can think of is that you have a set number for the electricity that your allowed to use, which is known at the start of the tunnel construction, then it may be passive data that you require. If you buy a house you get a certificate for energy efficiency, and something similar is available for tunnels, so before construction. You measure it constantly, actively, but you also have passive data.

[12] Stakeholder Engagement

Decision making

I do think its rather old fashioned to use a 3D model, why not put it in a HoloLens, and include active information. But in this context, a 3D model, I agree its passive information. I think both are very possible.

Automatic flow of information or manual

I like and agree with your conclusion that OTO is somewhere in between digital models and twins, because its impossible for me to create these OTO environments within a BIM model software, we use additional software for this, to add all the dynamics and behaviours, in Unity. But the input of geometric information does come from the BIM model.

Going into the example you're giving about biased inspections, I think parties may want an improved norm for this, or an independent party that does the inspections. A need may lend itself more towards those solutions, than trying to measure it with a digital twin. I do think a digital twin may be used for this though, for example the unbiased advisor may use the model to inspect the object. Is the key of the problem not somewhere else, in a good contract for example.

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