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An Exploration of BIM Uses for Asset Management in the Dutch Construction Industry

Master Thesis by:

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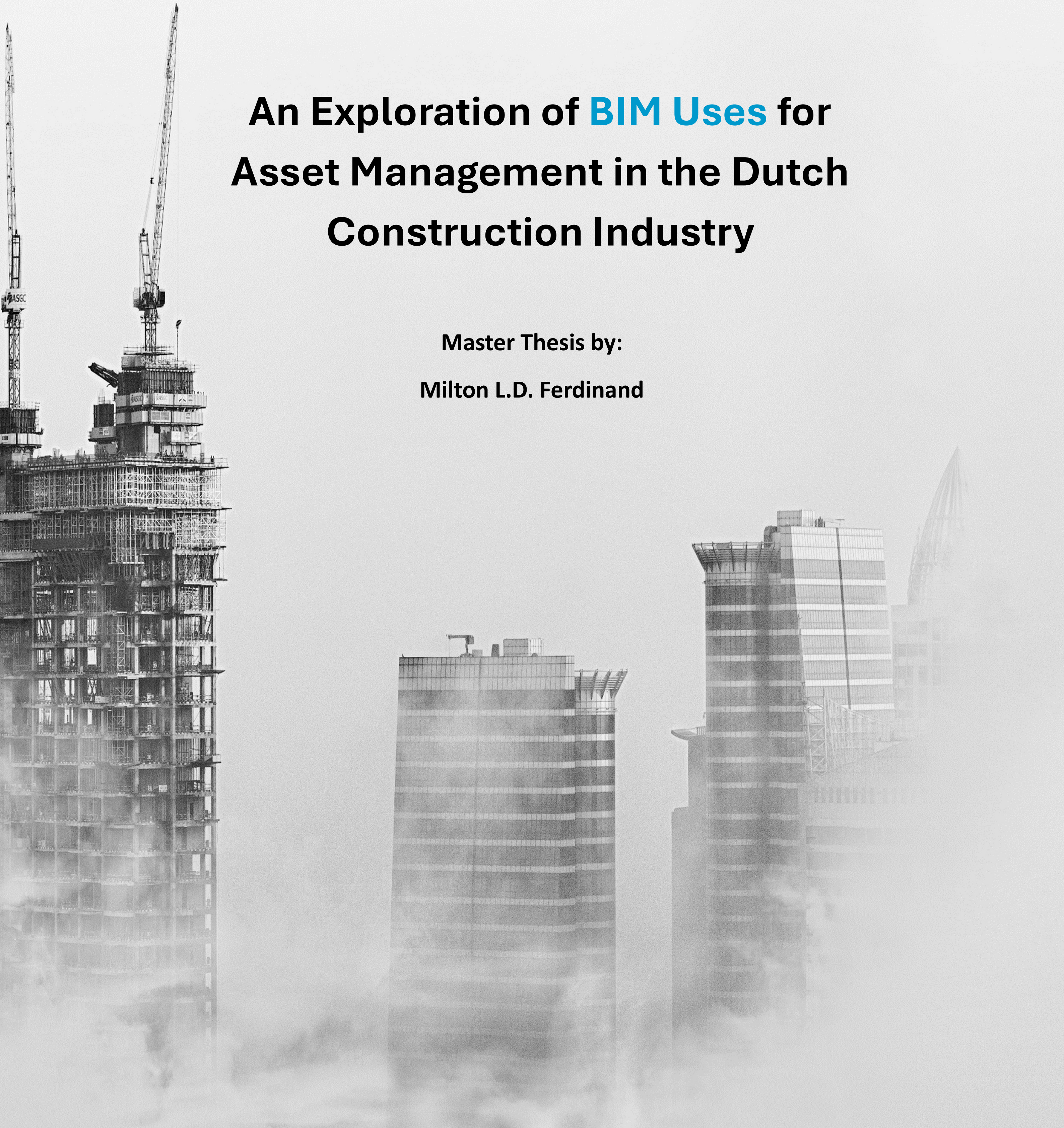

An Exploration of BIM Uses for Asset Management in the Dutch Construction Industry

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- Witteveen+Bos
  PMC Lifecycle Management

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Preface

The construction industry is renowned for its ability to shape the world around us, but it's oftentimes also criticized for its unsustainable and wasteful practices. Building Information Modeling (BIM) is theorized to help the construction industry achieve the much-needed sustainability and efficiency gains, especially in combination with asset management (AM). This thesis explores BIM uses for asset management in the operations and maintenance (O&M) phase of assets. It reveals how currently barriers exist that impede the adoption of these BIM uses. It was inspiring to uncover however, that despite these barriers, people persist, and strive to innovate in the Dutch construction industry! Through this research I hope to have shed a light on the work of these individuals and raise awareness on the BIM uses for AM in the O&M phase.

Inside each of us resides the desire for growth, exploration, and innovation. It was this combination of factors that drove me to board a one-way flight in the midst of a pandemic and start my journey at the University of Twente. Throughout this journey I have been helped by many people and I would like to take this opportunity to extend my appreciation to them.

I would first like to thank my supervisors Arjen, Hans, Justin, and Gert. They have guided me throughout this research project with great expertise and I have truly learned a lot from them. I would also like to thank the interviewees and my colleagues at Witteveen+Bos for their contribution to this research project. I would especially like to thank Jan Verbrugge for showing me around on the REHT project and sharing his knowledge with me.

I would hereafter like to thank my parents, my brothers John and Lynden, and my sister Janice. They have supported me wholeheartedly throughout my studies and words can't express how grateful I am for their support. Next, I would like to thank my friends. They have been there with me on this journey at the university of Twente and made it all the better. A special thanks to my friend Ryan Harnandan, who introduced me to Witteveen+Bos and who's guidance throughout this project has been invaluable.

Finally, I would like to thank the University of Twente for granting me the opportunity to expand my knowledge. I will forever cherish the memories of my time here!

Abstract

Building Information Modeling (BIM) has become an important part of the construction process in the Netherlands. A study by BIMloket (2021) had shown significant differences however between the usage of BIM in different phases of the project's lifecycle. As such, BIM usage in the design and construct (D&C) phase was found to be around 5 times higher than that in the operations and maintenance (O&M) phase. This significant lower usage of BIM in the O&M phase is surprising, as BIM in combination with asset management (AM), had been theorized to deliver great efficiency gains in the O&M phase. A gap in the scientific literature existed in our understating of the BIM uses for AM and the factors which work as barriers and drivers to their adoption in the context of the Dutch construction industry. This study set out to address this gap in the scientific literature.

This study used a qualitative research methodology. The research was guided by a main research question (MRQ) and 4 sub research questions (SRQ's). The research employed a literature review, systematic literature review, and case study research to find the answers to the research questions. The SLR was conducted on the SCOPUS platform. Two case studies were selected in the Netherlands and data collection occurred via document analysis and 7 semi-structured interviews with key stakeholders of the two cases.

The study first set out to develop a theoretical framework to study the BIM uses for AM. The theoretical framework was grounded in Rogers (2003) Diffusion of Innovations theory and consisted of 8 variables pertaining to the perceived attributes of the innovation and nature of the social system. The choice for the DOI theory was based on two major arguments. First, the DOI theory was deemed suitable for this research as it is backed by sufficient empirical evidence which demonstrates its suitability for studying BIM adoption in the construction industry. Second, BIM adoption involves the individual as well as organizational structures, organizational norms, and social factors. The DOI theory offers a balance between the social system dynamics, organizational factors, and the individual. The chosen variables for the framework were: the relative advantage (V1), compatibility (V2), Complexity (V3), trial-ability (V4), Observability (V5), The role of opinion leaders (V6), Norms and cultures of the system (V7) and the structure of the system (V8). Applying the theoretical framework to two case studies in the Dutch construction industry resulted in its validation as 7 out of the 8 variables were found to influence adoption. The variables relative advantage, compatibility, complexity, observability and trial-ability, norms of the social system and role of opinion leaders were found to influence adoption of the BIM uses. There was however no influence found between the structure of the social system adoption. Additionally, the non-variable related "perceived time pressure" and "procedural agreements i.e. lack asset information requirements" were also found to influence adoption.

The study further set out to identify the BIM uses for AM in the O&M phase, which was done via a systematic literature review (SLR). The platform SCOPUS was used for this research activity and after scoping 27 research papers were chosen for full text analysis. This resulted in the identification of 7 BIM uses for AM. These BIM uses were the BIM use for RAM analysis (BU1), Asset Condition Monitoring & Health Assessment (BU2), Asset Commissioning (BU3), Asset Performance Analysis (BU4), Asset information management (BU5), BIM based FM (BU6), and Simulation of Processes and Events (BU7).

The research then set out to identify the factors which work as barriers and drivers to the adoption of the BIM uses. Two case studies were done on maintenance and renovation projects of tunnels in the

South-Holland region of the Netherlands. These were the REHT (in Dutch: Renovatie Eerste Heinenoord tunnel) and PTZ (in Dutch: Programma tunnels Zuid-Holland). The research first identified barriers to the adoption of the BIM uses. One of the major barriers regarded the lack of a perceived relative advantage to the utilization of the BIM uses. Compatibility issues with the known way of working and, knowledge and experience of stakeholders were other major barriers. A lack of observable positive results of utilizing the BIM uses was further found to be a significant barrier, as the absence of such results failed to motivate stakeholders to adopt the BIM uses. The findings further showed that there was a lack of support from top management toward the adoption of the BIM uses for AM. Two barriers originated from variables which do not pertain to the developed framework. Based on the findings it can be concluded that the perceived time pressure and procedural agreements i.e. the lack of AIR also worked as barriers to adoption of the BIM uses.

The research hereafter identified drivers to the adoption of the BIM uses. A highly perceived relative advantage and good observability were found to be the most significant drivers to the adoption of the BIM uses. The perceived relative advantages were seen in the ability of the BIM Uses to reduce downtime of assets, shorten the project duration, and deliver an enhanced asset information management on the project. A good observability of the positive results of adopting the BIM uses further proved to be a major driver to the adoption of the BIM Uses as these positive results motivated stakeholders to adopt and overcome barriers. It was further shown that a high degree of trial-ability could also positively influence the adoption of BIM uses as the findings demonstrated how small-scale tests were a driver to adoption. Based on the findings it was further shown that a combination of a highly perceived relative advantage, good observability, and trial-ability of the BIM uses was capable of overcoming barriers relating from a highly perceived complexity and incompatibility.

The findings of this research study serve as a gateway to understanding the adoption of BIM uses for AM in the O&M phase. The research has contributed to filling the gap in the scientific literature and holds practical implications for project teams and asset managers in the construction industry to better select BIM uses for AM on their projects. These stakeholders are now better equipped to identify barriers on their projects and develop strategies to mitigate them, while fully utilizing drivers. By addressing barriers and leveraging drivers, stakeholders in the Dutch construction industry can achieve the highly sought-after efficiency gains in the O&M phase.

Table of Contents

Table of Figures

Table of Tables

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List of Abbreviations

#	Abbreviation	Meaning
1	AM	Asset Management
2	AIM	Asset Information Model
3	AIR	Asset Information Requirements
4	BEP	BIM Execution Plan
5	BIM	Building Information Modeling
6	BU	BIM Use
7	CAFM	Computer-Aided Facilities Management
8	CMMS	Computerized Maintenance Management System
9	COBie	Construction Operations Building Information Exchange
10	D&C	Design & Construct
11	DT	Digital Twin
12	DOI	Diffusion of Innovations
13	DMU	Decision-Making Unit
14	EHT	Eerste Heinenoord Tunnel
15	EIR	Exchange Information Requirements
16	FM	Facilities Management
17	GIR	Geometry Information Requirements
18	IM	Information Management
19	IDP	Innovation Decision Process
20	IFC	Industry Foundation Classes
21	ISO	International Organization for Standardization
22	MRQ	Main Research Question
23	O&M	Operations & Maintenance
24	OTL	Object Type Library
25	PTZ	Programma Tunnels Zuid-Holland
26	RAM	Reliability Availability and Maintainability
27	REHT	Renovatie Eerste Heinenoord Tunnel
28	RWS	Rijkswaterstaat
29	SHM	Structural Health Monitoring
30	SLR	Systematic Literature Review
31	SRQ	Sub Research Question
32	TA	Technology Adoption

1. Introduction

The first section of this report introduces the research project and provides information on the context of the study. The section begins with the background of the research, followed by the research problem and objective. Hereafter, an introduction is given to the research client, Witteveen+Bos (W+B). Then, follow the research questions that will guide the study. The first section continues with the scope of the research and ends with a reading guide.

1.1 Background of Research

A recent study into the adoption and usage of Building Information Modeling (BIM) in the Netherlands revealed a significant difference between the usage of BIM in the different phases of the project lifecycle (BIMLoket, 2021). BIMloket (2021) showed that 55% of the surveyed participants used BIM in the design and construction (D&C) phases, but only 10% of participants used BIM in the operations and maintenance (O&M) phase. This lower usage of BIM in the O&M phase is not unique to the Netherlands and has been observed in the UK, US, and Vietnam, among other countries (Hoang et al., 2020; McGraw Hill Construction, 2014; O. Olanrewaju et al., 2020). The lower usage of BIM in the O&M phase is peculiar, considering the numerous publications on BIMs' potential for cost savings and operational efficiency in the O&M phase (M. Al-Kasasbeh et al., 2021; Hellenborn et al., 2023). The O&M phase is accountable for a significant portion of the total lifecycle costs of projects, ranging between 60-80% (M. Al-Kasasbeh et al., 2021; Q. Lu et al., 2020). Recognizing the substantial financial implications of the O&M phase, it becomes imperative that research is done to advance efficiency in the management of assets during this crucial phase (Shemery et al., 2019). BIM, when combined with asset management (AM), might be the key to unlocking this sought-after efficiency in the O&M phase (Hayes, 2019; Hellenborn et al., 2023).

AM plays an essential role in the O&M phase, but current AM practices lead to substantial avoidable expenses due to a misalignment between the D&C and O&M phases (Maha Al-Kasasbeh et al., 2021). AM is defined by Al-Kasasbeh et al. (2021) as: "… a strategic and systematic approach of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. The backbone of AM is the information that asset managers use to make informed decisions. The higher the quality and readily available the asset information is, the better the decision-making process becomes, leading to more effective and efficient management of the asset. Considering the relationship between data quality and AM, a problematic situation becomes apparent, as Olanrewaju et al. (2022) point out how the construction industry is characterized by a lack of adequate information and knowledge management, which negatively impacts the project lifecycle.

The symbiotic relationship between BIM and AM becomes evident when considering the information-rich framework that BIM provides for developing, storing, and exchanging data on the asset (Sawhney, 2014). This feature of BIM is especially important when considering the vast amounts of data that are generated during the O&M phase of an asset, such as energy usage, maintenance data, and sensory data (Q. Lu et al., 2020; Yoon et al., 2019).

The utilization of BIM for AM goes far beyond functioning as an asset information model, and studies have shown different ways of using BIM for AM in the O&M phase (Sakr & Sadhu, 2023; Wijeratne et al., 2023). Wijeratne et al. (2023) showed how BIM can be used for enhancing facilities management (FM), and Sakr & Sahdu (2023) discussed the usage of BIM for conducting Structural health monitoring. These are just a few examples of BIM uses for AM, but while there are many possibilities, not all might be of equal interest to the Dutch construction industry. Currently, it is unclear which specific BIM uses for AM are interesting in the context of the Dutch construction industry.

Research has shown that just like when BIM was first introduced in the construction industry, there are currently a host of barriers that inhibit its adoption in the O&M phase of projects (Durdyev et al., 2022; M. Munir et al., 2021). In their study, Munir et al. (2021) showed how a misperception of BIM was one of the significant barriers to its adoption for AM. However, a gap exists in the literature regarding the specificity of barriers and drivers to distinct BIM uses for AM in the O&M phase. This gap is further signified by the geographical specificity of research studies, as barriers and drivers might differ per country or be specific to the context of a particular area (Al-Mohammad et al., 2023; Hafiz Muhammad Faisal Shehzad Roliana Binti Ibrahim & Ahmad, 2022; Ullah et al., 2019). The last widespread analysis on BIM adoption in the Netherlands provided a comprehensive overview of BIM adoption in general, however, it did not focus on the specific adoption of BIM for asset management (BIMLoket, 2021). Realizing the further adoption and benefits of BIM utilization for AM in the O&M phase in the Dutch construction industry requires the identification of specific barriers and drivers to the BIM uses.

1.2 Research Problem

The problem statement provides a brief summation of the information presented in the problem context:

Studies have shown that BIM usage in construction projects is significantly lower in the Operations and Maintenance phases than in the Design and Construction phases (BIMLoket, 2021; Hoang et al., 2020; O. I. Olanrewaju et al., 2022). Underutilization of BIM in the O&M phase is surprising, considering that BIM, especially when combined with AM, might hold the key to achieving greater efficiency in the O&M phase (Hayes, 2019; Hellenborn et al., 2023).

It is currently unclear what the BIM uses for AM are and which factors work as barriers and drivers to the adoption of BIM uses for AM in the context of the Dutch construction industry.

1.3 Research Objective

The objective of this research is to identify BIM uses for asset management in the O&M phase and the factors that work as barriers and drivers to their adoption in the Dutch construction industry.

1.4 Research Client

The research project is carried out for the Dutch engineering consultancy firm Witteveen+Bos (W+B). W+B was established in 1946 and has since grown to be one of the top engineering consultancies in the Netherlands. As a growing organization, W+B is continuously striving for innovation and ways to achieve a competitive edge in the dynamic landscape of the Dutch construction industry. The organization is structured in product-market combinations (PMCs), which are clustered in 4 business lines. This project is carried out for the PMC Life Cycle Management (LCM), which is clustered in the business line infrastructure and mobility. W+B is well-known for its involvement in governmental and private projects and its innovative solutions. These factors indicate the suitability of conducting a research project focused on identifying the factors that influence the adoption of a novel technology in the context of the Dutch construction industry at W+B.

1.5 Research Questions

This study was guided by a main research question and a set of 4 sub research questions, which are presented below:

- **Main Research Question (MRQ):**
  What are the BIM uses for asset management in the O&M phase, and which factors work as barriers and drivers to the adoption of these BIM uses in the Dutch construction industry?

- **Sub Research Questions (SRQ):**

1. What is a suitable theoretical framework for studying the adoption of BIM for Asset Management?
2. What are the BIM uses for Asset Management in the O&M phase?
3. Which factors work as barriers to the adoption of the BIM uses for Asset Management?
4. Which factors work as drivers to the adoption of the BIM uses for Asset Management?

1.6 Definition of Key Concepts

The research questions contain several key concepts. The following section will explain these key concepts to ensure a shared understanding amongst the readers of this report.

Building Information Modeling (BIM)

In this report, the key concept of Building Information Modeling (BIM) is defined along the lines of 4 principles: representation, collaboration, process, and life cycle (Bradley et al., 2016). BIM is the "...use of a shared **digital representation** of a built asset to facilitate design, construction, and operational processes to form a reliable basis for decisions" (International Standardization Organisation [ISO], 2019). BIM supports and facilitates **collaboration** on construction projects (Liu et al., 2017). Its utilization encompasses the **process** of creating and managing information on the built asset across its **lifecycle** (AutoDesk, 2023), which is further defined as the period from its earliest conception to its demolition (NBIMS-US, 2024).

Asset Management (AM)

The International Standards Organization defines asset management as: "A coordinated activity of an organization to realize value from its assets" (International Standardization Organization [ISO], 2014). The definition provided by the norm is too general for this research. As such, the study uses the more concrete definition provided by Al-Kasasbeh et al. (2021), who defined asset management specifically for building assets. They defined asset management as: "… a strategic and systematic approach of operating, maintaining, upgrading and expanding physical assets effectively throughout their lifecycle" (Maha Al-Kasasbeh et al., 2021). It is also important to define the relationship between asset management and facilities management, as these two concepts are often used inconsistently within different literature sources. The International Facilities Management Association (IFMA) defines facilities management as: "… an organizational function which integrates people, place and process within the built environment to improve the quality of life of people and the productivity of the core business" (van Sprang & Drion, 2020). This study sees the relationship between these two concepts as such that facilities management is an asset management component (Vahdatikhaki, 2023).

Operations and Maintenance (O&M)

The Operations and Maintenance phase represents the segment of the project lifecycle of an asset, following the construction phase (Messner, 2019) This phase entails the utilization of the asset by its owner for its intended purpose (Messner, 2019). The activities during this phase encompass operating the facility, conducting maintenance, replacing equipment, and implementing renovations to facilitate the asset's ongoing usage (Messner, 2019).

BIM Use

Rojas et al. (2019) explored the different definitions of the concept "BIM use" and noted that there is no universal definition. Different sources define the concept as either methods, applications, or actions (Rojas et al., 2019). This study is interested in exploring the different methods of using BIM models for asset management post-construction and as such utilizes the definition provided by Kreider and Messner, which state that the concept of "BIM Use" can be defined as "a method of applying Building Information Modeling during a facility's lifecycle to achieve one or more specific objectives"(Kreider & Messner, 2013, p. 6).

Adoption

Adoption is defined as: "the decision to make full use of an innovation" (Rogers,2003, p.21). Rogers (2003) describes the adoption process of innovations with the innovation-decision process (IDP), by which a decision-making unit seeks and processes information on the innovation, ultimately leading to the decision to adopt or reject the innovation. It is necessary to reflect on the relationship between the concepts of adoption and diffusion as these concepts are often used interchangeably in the literature. Rogers (2003) defines diffusion as the process by which an innovation is spread through a social system over time. As such, adoption can be seen as an individual or organizational process that results in diffusion (Kee, 2017). Kee (2017) describes how adoption and diffusion are processes on different levels, where adoption is on the micro and meso levels and diffusion is on the macro level. This study is centered on adoption because it focuses on the micro and meso levels.

1.7 Research Scope

The scope of the research project aims to provide a clear understanding of the context within which this study unfolds. Scoping the research project also ensures the feasibility of the study, as the adoption of BIM is a complex, multifaceted, and broad topic. The research scope is presented in Table 1. This table presents the scope along the lines of several categories, namely, the study participants, the geographical scope, the asset type, and the research focus. The delimitation of the categories will be further discussed below.

Table 1: In-Out-Scope of Research Project

Element	In-Scope	Out-Scope
Study Participants	Internal project stakeholders (such as Asset Owners, BIM Engineers, Asset Managers, Operations and Maintenance Engineers, Contractors)	External project stakeholders (such as Software Developers, IT-& Data Engineers)
Geographical Scope	The Research is to be conducted in the context of the Dutch Construction industry and is geographically limited to the Netherlands.	Projects and stakeholder groups beyond the borders of the Netherlands

Element	In-Scope	Out-Scope
Asset Type	Civil Works	Residential buildings, Non-residential buildings, Roads, and Railways
Life cycle Phase	The research is focused on the post-construction phase of the asset	Construction and pre-construction phases of the asset

Study Participants

The stakeholder groups mentioned in Table 1 will be contacted for this study as research has shown how BIM experts, asset owners, and contractors, amongst others, play a significant role in the adoption of BIM and, at times, can even work as barriers to adoption (Ullah et al., 2019). The stated participants are considered key figures in the process of using and adopting BIM for AM and are deemed crucial sources of information on the barriers and drivers to the adoption. While software developers and Data engineers might play a role in BIM implementation, no link was found in the literature between them and the adoption process. Restricting the study participants to the stated categories aids in assuring the feasibility of the study as a larger population would require significantly more resources for the study.

Geographical Scope

As stated in the problem context, barriers to and drivers to adopting BIM are often geographically specific (Al-Mohammad et al., 2023; Hafiz Muhammad Faisal Shehzad Roliana Binti Ibrahim & Ahmad, 2022; Ullah et al., 2019). The interest in specific BIM uses can oftentimes also be specific to a certain area. As such, this study will be confined to the Netherlands, as this aligns with the study objective.

Asset Types

This study will focus on the adoption of BIM for AM in Civil works. This decision to focus on civil works was made at the request of the research client, who stated that understanding the adoption of BIM for AM on civil works was the most interesting to their organization.

Lifecycle Phase

As stated in the research objective, this research aims to identify the BIM uses for AM and the barriers and drivers to their adoption in the postconstruction phase of the project's lifecycle. The problem context stated the necessity of focusing research efforts on this specific phase. As such, the earlier phases in the project lifecycle (the pre-construction and construction phases) are not in the scope of the research.

1.8 Reading Guide

This report is structured in 7 sections. The first section introduced the research project. The second section will discuss the methodology which was used for this study. The following section presents the development of the technology adoption framework which was deemed suitable for researching the adoption of BIM for AM. The fourth section of the report goes on to explore the BIM uses for asset management. The following section of the report will continue to present the findings of the case study research. The sixth section of the report will present a discussion of the research study. The final section of the report will present the conclusions of the study and recommendations for future research.

2 Research Design

In this section a detailed description is offered of the methodology that was used to answer the study's' research questions. In addition to this is also discussed what quality control strategies were used to guarantee the validity of the results of the study.

2.1 Methodology

This study used qualitative research, as this type of research has proven to be suitable for exploring the complex issues that arise from adopting BIM in the construction industry (Hochscheid & Halin, 2020). The methodology consisted of 4 phases (see Figure 2: Schematic Visualization of Methodology for a graphical overview of the methodology). The first two phases of the methodology aimed to answer SRQ1: "What is a suitable theoretical framework for studying the adoption of BIM for Asset Management?" and SRQ2: "What are the BIM uses for Asset Management in the O&M phase?", with the aid of the scientific literature. Knowledge gained during these phases was applied to the third phase of the methodology, which entailed case study research. The case study research aimed to explore and gather data to answer SRQ 3: "Which factors work as barriers to the adoption of the BIM uses for Asset Management? and SRQ 4: "Which factors work as drivers to the adoption of the BIM uses for Asset Management?". The data from the case study phase was analyzed in the fourth phase of the methodology. The 4 phases of the methodology will be explained in greater detail in the following text.

2.1.1 Phase 1: A theoretical perspective on BIM adoption

The first phase of the methodology entailed the development of a suitable theoretical framework for this research study. A theoretical framework provides a theoretical structure and basis, which will be used for the data analysis and interpretation of the findings of a research study (Kivunja, 2018; Omodan, 2022). The scientific literature was explored to find suitable technology adoption (TA) theories for studying BIM adoption. The study looked at publications that reviewed and summarized the known TA theories. From these publications, a list was comprised of well-established technology adoption theories for conducting BIM research. Utilizing one of these well-established theories in this research would benefit from building on a theory backed by sufficient empirical research. Out of the most well-established TA theories, the most suitable option was chosen for this research study. The motivations behind this choice will be further discussed in the section 3.1 .

2.1.2 Phase 2: The BIM Uses for AM

The methodology's second phase aimed to answer SRQ2: "What are the BIM uses for Asset Management?". The study used a systematic literature review (SLR) approach to answer this question. The methodology, as described by Zabin et al. (2022), was used for conducting the SLR, as they had previously successfully undertaken a similar endeavor to find BIM uses for Machine learning. A five-step methodology was employed: "(1) Formulating the research questions, (2) identifying relevant work. (3) assessing the quality of studies, (4) summarizing the evidence, (5) interpreting the results" (Zabin et al., 2022).

(1). The earlier stated SRQ2 guided this endeavor.

(2). The platform Scopus was used for the SLR. Renowned for being a prominent scientific database of peer-reviewed literature and due to its advanced search options, Scopus was a suitable platform for conducting the SLR. Additional works were sought after the SLR with Google Scholar to avoid missing any relevant and credible publications on BIM uses. Adding sources after the SLR is a common practice known as "snowballing," where additional works are found through references in the earlier identified sources (Zabin et al., 2022). This study also included additional papers as the knowledge on the different types of BIM uses grew and other relevant sources on BIM uses were discovered through expert recommendations.

(3). The study used the search terms "Building information modeling BIM," "Asset management," "operations and maintenance," and "BIM use." This combination of terms returned an initial number of results (exact details are presented in section 4.1). Then the process of refining the search occurred. The study only looked at peer-reviewed conference papers, journal articles, and only those published in English. The SLR limited itself to a period between 2019 and 2023. The reason for this is as this 5-year period is seen as a rule of thumb for relevant and current literature in the field of science. An exception to this rule was made for additional works that were found relevant through snowballing or expert recommendations after the initial search was done. The subject of publications was limited to Engineering due to its relevance to this study. The keywords "Asset Management" and "Building Information Management" were used to further refine the search due to their relevance to the research question. The refined search returned a second set of papers after the excluding factors were incorporated. Based on their titles and abstracts, these papers were then screened on their relevance to the study. Grounds for exclusion were: (1) the studies did not use BIM for AM, (2) the studies did not cover BIM uses for AM in the O&M phase, and (3) the studies were on an asset type not relevant to this study, such as railways. After the process of selecting and screening through the results, the set of papers was chosen for further analysis and extraction of information. The exact search string used for searching with Scopus is shown below:

TITLE-ABS-KEY ("Building Information Modeling" OR bim) AND TITLE-ABS-KEY ("asset management") OR TITLE-ABS-KEY ("operations & maintenance") AND PUBYEAR > 2018 AND PUBYEAR < 2024 AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p")) AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (EXACTKEYWORD , "Asset Management") OR LIMIT-TO (EXACTKEYWORD , "Building Information Modelling"))

(4). The final step entailed the process of summarizing and interpreting the results. Content analysis was done to identify patterns relating to BIM uses in the set of papers. Categories of BIM uses were formed based on their type of application.

The categories of BIM uses were hereafter discussed with stakeholders at W+B, as an act of validating the results. The study discussed the results with two AM and two BIM experts, who were the same ones contacted for the explorative interviews. This combination of stakeholders was deemed capable of having the knowledge to provide the necessary criticism on the categories of BIM uses.

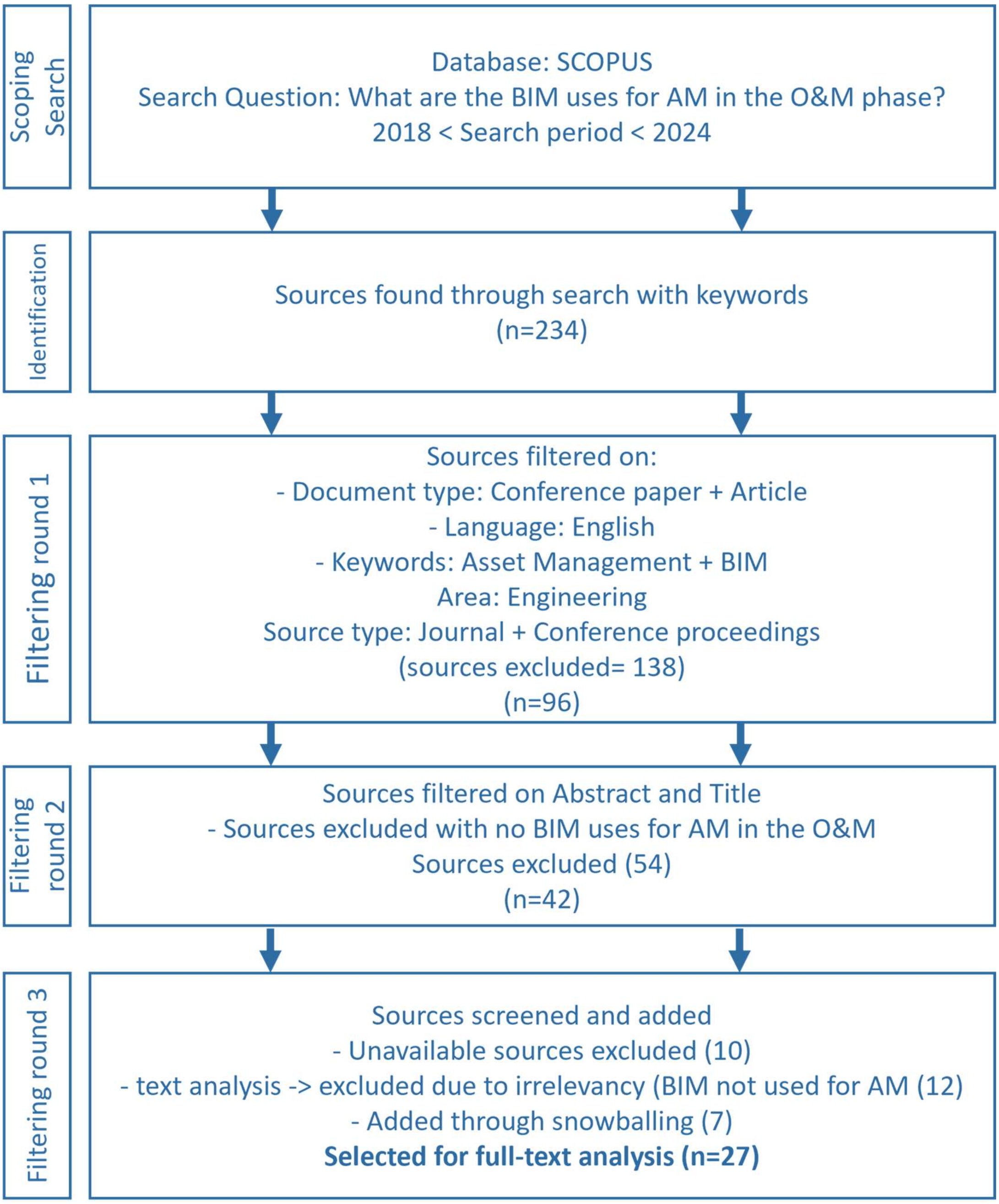

Figure 1: Flowchart of SLR

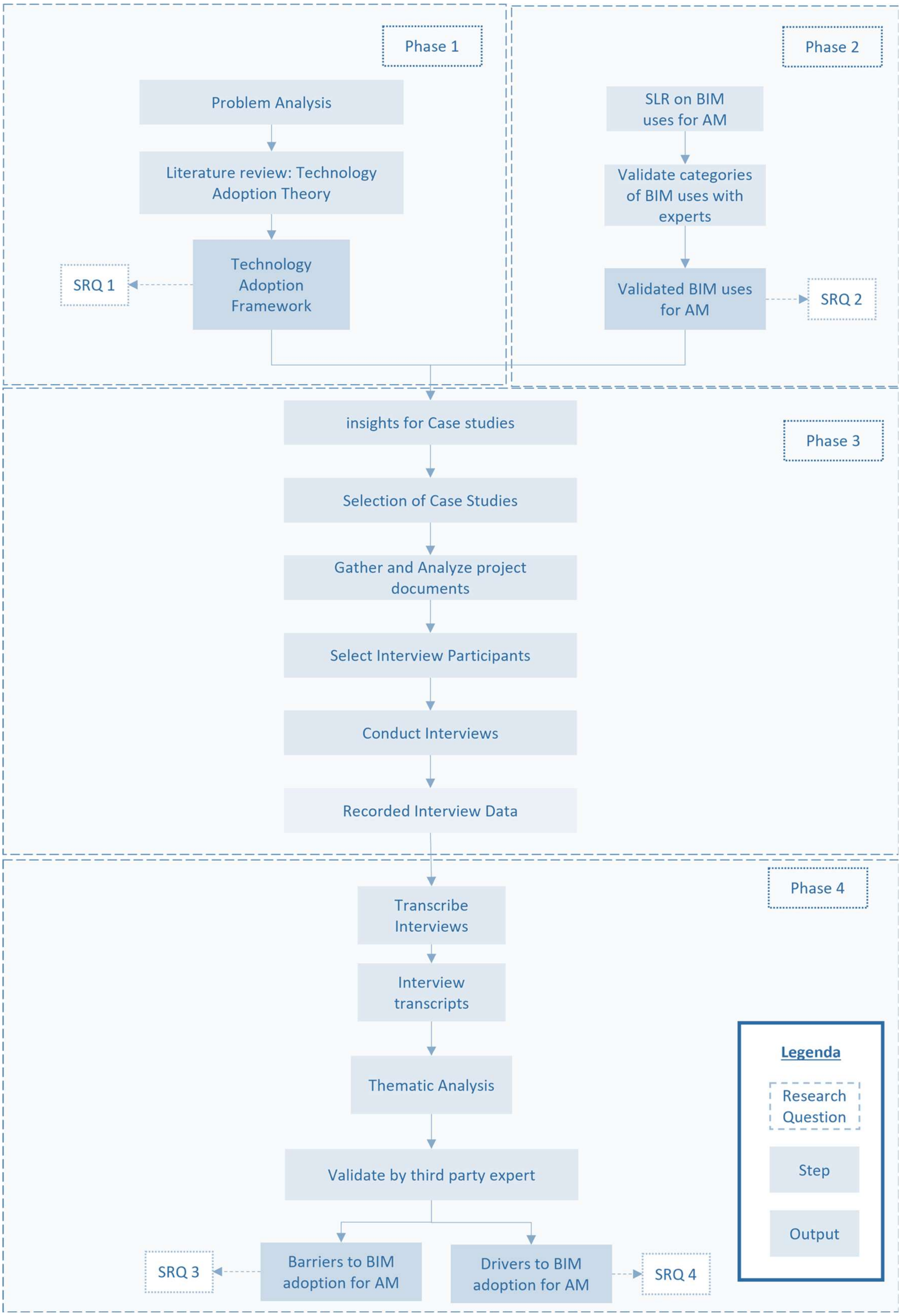

Figure 2: Schematic Visualization of Methodology

2.1.3 Phase 3: Case Study Research

The third phase of this research methodology entailed collecting empirical data through case study research. This activity gathered data for answering the third and fourth sub-research questions. The different elements of the case study research will be discussed below.

Rational behind case study research

Part of the objective of this study is to identify the factors that work as barriers and drivers to the adoption of BIM for AM in the O&M phase. The adoption of BIM is a complex and multi-faceted phenomenon. An appropriate research method for studying such phenomena is using case studies (Crowe et al., 2011) (R. K. Yin, 2009). Crowe et al. (2011) describe how this research method is suitable for obtaining an in-depth understanding of complex phenomena in the everyday context in which they occur. As such, studying the adoption of BIM through case studies will allow for the exploration and understanding of factors that worked as barriers and drivers to the adoption of BIM use in the cases. As the nature of this research is an explorative research project, the recommended strategy is to select two cases with minimal variety between them (Vershuren & Doorewaard, 2021).

Case study selection

Selection of the case studies is crucial to obtaining viable results from the research project. The selection of case studies was refined by focusing on 3 parameters. The parameters for the selection of case studies were:

1. BIM status
   Projects will be chosen where BIM uses have been or will be adopted for asset management. Projects will be selected with at least a BIM level 2 maturity[1] or higher as these higher-level BIM models are needed to study BIM uses for asset management.

2. Project Size and Complexity
   Projects of large size and complexity will be selected as they are more interesting and useful in gathering an in-depth understanding of the challenges faced when using BIM for AM. Project classifications can be done with a project classification matrix, as seen in the figure below.

Small Project	Medium Project	Large Project
• Project duration less than six months	• Project duration between six months and 12 months	• Project duration greater than 12 months
• Project budget less than $100,000	• Project budget between $100,000 and $500,000	• Project budget greater than $500,000
• Project team fewer than five people	• Project team between five and 20 people	• Project team greater than 20 people
• Minimal integration with other business units	• Moderate integration with other business units	• Significant integration with other business units
• Impacts fewer than 25 end users	• Impacts 25 to 250 end users	• Impacts more than 250 end users

Figure 1: Project Categorization Matrix adopted from (Burgan, S. C. & Burgan, 2014)

[1] categorization according to NEN-ISO- 19650-1

3. Project status and stage

Projects that are currently active and ongoing will be selected to ensure that all stakeholders are available to contact and can recall project details. Projects must be at least in the design phase to ensure that enough relevant project information is available for analysis.

The project database of Witteveen+Bos was hereafter searched on these parameters. The choice was made to focus on two renovation projects on tunnels in the region known as West-Netherlands South. The assets on these projects are well in the middle of their lifecycle and need renovations to keep their performance on an adequate level. The projects had been named the "Renovatie Eerste Heinenoord Tunnel" (REHT) and the "Programma Tunnels Zuid-Holland" (PTZ). This asset type was suitable as it offered the size, complexity, and multi-disciplinary environment needed to study the adoption of BIM for Asset management.

An overview of the projects, in terms of the parameters for their selection can be seen in the following table 1: Parameters of case studies. While each project in the construction industry is unique, it can be seen from the parameters that these cases had quit some similarities. Both projects had a BIM maturity of at least level 2. The project teams used 4D,5D BIM uses and several BIM uses for AM (more on the specific BIM uses will be explained in section 5.1 of the report). Both projects were classified as large projects as they both have a project duration of 12+ months, budget over half a million dollars, have a project team of more than 20 individuals and impact more than 250 end users (a more detailed description of the projects will be given in section 5.1 and 5.2 of this report). Further it should be noted that both cases have the same asset owner i.e. Rijkswaterstaat. This increases the comparability of the cases and a chance to discover similarities or differences in factors influencing adoption of the BIM uses. The social system in which adoption takes place can influence the adoption of innovations, as will be further illustrated in section 3 of the report. Therefore, it was also deemed beneficial to focus on two cases of RWS. The difference between cases is that the REHT project was the precursor of PTZ and in many ways a pilot project for utilizing BIM uses for AM by RWS. There is about a 4-year difference between the initiation of cases. Mistakes were inevitably made on REHT, and the adoption of BIM uses went with certain errors, that provided learning opportunities. These mistakes were learnt from, and a smoother BIM adoption process was seen for certain BIM uses for AM in PTZ.

Tabel 1: Parameters of Case Studies

Project	BIM status	Project size and complexity	Project status
PTZ	BIM maturity level 2	Large project	Active project
REHT	BIM maturity level 2	Large project	Active project

Projects for Case studies:

1. Case study of the Renovation of the Eerste Heinenoord Tunnel (REHT)
   The Eerste Heinenoord Tunnel (EHT) is in south-holland under the old Maas River. The tunnel was built in 1969 and is maintained by RWS region West-Netherlands South. The tunnel had a complete renovation of its installations and a reconfiguration in 2023.
2. Case study of the Programma Tunnels Zuid-Holland (PTZ)

PTZ encompasses the renovation of 8 tunnels in the West-Netherlands South area. The project is a follow-up and expansion of the REHT project, which is the first of the 8th to be renovated.

Data collection methods for case studies

The case study research will gather data via two data-gathering methods, namely, Document analysis and Interviews.

- *Document analysis:*

The first step of the case study research was to gather and analyze the relevant documents from each project. The document analysis was used to get an initial understanding of the utilized BIM uses on the two projects. The second goal of the document analysis step was to deliver insights, for which a list of interview questions would be prepared for the interviews with key stakeholders. The documents that will be studied are, but are not limited to, the BIM execution Plan (BEP), the program of requirements for the BIM model, and documents detailing the BIM uses on the projects. Interviews were conducted with key stakeholders on the projects. The interviews will be discussed below.

- *Interviews:*

The research will also gather data from the two selected case studies via semi-structured interviews. The desired output of the interviews is to attain the perception of stakeholders on utilized BIM uses, the BIM uses that were considered on the projects but not implemented, and possible barriers and drivers to the adoption of the BIM uses on the projects.

1. BIM managers/ coordinators
   The BIM manager of the two projects will be interviewed to determine which barriers and drivers were faced during the adoption of BIM uses for asset management during the projects and which strategies were employed. Also, it is important to gauge which BIM uses were (not/) used and why. Both the BIM manager from the contractor (***) and consulting parties (TEC) will be interviewed.

2. Project Managers
   The project manager of both projects (done by W+B) will be interviewed to identify how the workflow and collaboration are impacted due to the adoption of BIM for AM. This will most likely reveal barriers and drivers. Also, it is important to gauge with this stakeholder which BIM uses were (not/) used and why.

3. Advisor Technical Installations
   An advisor technical installation, who would be responsible for servicing the tunnel installations on the project, will be interviewed to investigate their perception of the BIM uses and how they can improve current practices (to find out which factors worked as barriers and drivers). Also, it is important to gauge with this stakeholder which BIM uses were (not/) used and why.

4. Asset Manager (Rijkswaterstaat (RWS))
   Interviews will be held with the asset manager responsible for drafting maintenance plans and strategies. This will shed light on the current practices of conceiving asset management

strategies and BIM's role in enhancing such practices. Researching which BIM uses were (not/) used and why is also interesting. The interviews will further reveal the relevance of BIM uses and possible barriers and drivers to BIM adoption for AM. It is interesting to gauge the long-term views on BIM data management.

The interview participants were selected beforehand. An overview of the selected candidates can be seen in the following Table 3: List of Stakeholder profiles for Interviews.

Table 2: List of Stakeholder Profiles for Interviews

ID	Project	Organization	Position/Area
1.1	PTZ	TEC	BIM Modeler
1.2	PTZ	***	Project Manager
1.3	PTZ	RWS	BIM Consultant
2.1	PTZ & REH	RWS	Asset Manager Regio West-Nederland Zuid
2.2	PTZ & REH	W+B	Project manager
3.1	REH	***	BIM Manager
3.2	REH	RWS	Senior Advisor infra-technical installations

The final step of the case study research entailed the process of analyzing and interpreting the results. This process will be explained in detail in the following section.

2.1.4 Phase 4: Data Analysis

The final phase of the methodology entailed the process of data analysis and data interpretation. Data analysis occurred in two steps. First, the recorded interviews were transcribed into written reports. After these written reports were derived and verified with the interviewees, an in-depth analysis of these conversations took place with thematic analysis.

Transcribing interview recordings into written reports

The collected interview recordings from the explorative and case study interviews were first transcribed. Transcribing interview recordings is not a straightforward process of creating a written form of an interview but rather the first step in qualitative data analysis, as it is a process that requires reduction, interpretation, and representation to ensure that the transcripts are readable and significant (Bailey, 2008). Bailey (2008) notes the importance of deciding on the right level of detail and the right person for creating the transcript. This is because there lies importance beyond what is said and how something is said, the so-called nonverbal communication. Hall et al. (2019) point out the significance of nonverbal communication and the need to analyze this alongside verbal communication to understand the true conveyed meaning (Hall et al., 2019). A transcriber should have adequate skill and knowledge of the study to distinguish between these subtle nuances. The author of this report was responsible for creating the transcripts as he also conducted the interviews and, as such, was capable of carrying out the interpretive process.

Thematic Analysis of Transcripts

The interview transcripts were hereafter analyzed with thematic analysis to gain insight into the barriers and drivers of the adoption of the BIM uses for AM. The thematic analysis concentrates on identifying and describing implicit and explicit notions within a data set, called themes (Guest et al., 2012). Codes represent the identified themes and link them to portions of text within the transcripts. This study uses the 6-step process for thematic analysis as developed by Braun & Clarke (Braun Clarke, Victoria, Newson, Lisa, 2022). A visualization of this process can be seen in the following figure 2: Visualization of Thematic Analysis.

Figure 3: Visualization of Thematic Analysis

The first step entails a process of reviewing and familiarization of the data. Hereafter the transcripts are screened, and codes are applied to certain portions of the text. This entails a process of labeling certain phrases of sentences. The third step entails looking at the codes and identifying patterns. Codes that follow the same pattern will be grouped in a certain theme. The fourth step entails reflecting on the generated themes and verifying that these represent the data correctly. Then the themes are defined and named. The theme might be a barrier or driver. The sixth and final step is to write up the findings of the analysis.

2.2 Quality Control Strategies

Ensuring the quality of the study was an important and ongoing process, which began at the immediate start of the research and lasted through each phase and each research activity. This section is structured around the different research activities of the study and depicts the strategies used to safeguard the quality and validity of the research.

Literature review

The first strategy for ensuring the quality during the literature review was to be mindful of the source selection of used literature. Special attention was given to selecting peer-reviewed sources. The second strategy was related to the relevance of the sources. A fundamental purpose of a literature review is to show the current state of our understanding of a particular research topic. While the APA Style guidelines do not state an age restriction for sources, they recommend using sources with the most current information (Greenbaum, 2021). However, a rule was used for the SLR on the BIM uses on AM, where sources could only be 5 years old. This 5-year period is in line with the rule of thumb for relevant and current research in the field of science. Older publications were incorporated after the SLR, but only if these older publications provided foundational knowledge or significant information to the study.

Data collection

Triangulation was used during the data collection and analysis of the study. This is a research strategy where a comprehensive understanding of the research problem is gained by incorporating a multitude of data sources and data collection methods, and by which the validity of the results is also warranted. Two of the four triangulation types were used in this research: method and data triangulation. Data

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was gathered using different data gathering methods, namely through interviews, document analysis, and observations during a site visit. Data was also gathered from stakeholders with different perspectives and functioning at various levels within their organization. The latter was to ensure that a dataset was gathered, which was a combination of elite and non-elite sources. In the context of interview participants for qualitative research, elite sources are defined as individuals who hold or have held a position of power by which they have gained unique knowledge or information in a particular field or organization (Natow, 2020). Non-elite sources are individuals who may not hold or have held this significant position. While researchers might be initially drawn to the unique information that elite sources have, they should be aware that this information could be filled with biases. It was necessary to combine both types of sources for the interviews to gain a complete understanding of the research topic, especially referring to the factors that may work as barriers. Lastly, all interview data was gathered through consent of the participants and the transcripts of the interviews were validated afterwards by the participants.

Data Analysis & Validation of Results

The quality of the data during the analysis phase was safeguarded through triangulation. There are multiple forms of triangulation available to researchers (see figure 4: overview of triangulation methods),which range from the use of multiple data sources and methodologies to multiple data analysis techniques and researchers (Natow, 2020). This research employed a combination of triangulation through multiple data sources and methodologies. During analysis, a comparison was made between the information gathered from elite and non-elite sources and data gathered through interviews and document analysis. Continuous reflection and self-awareness of the researcher's role were also used during the data analysis to prevent researcher bias.

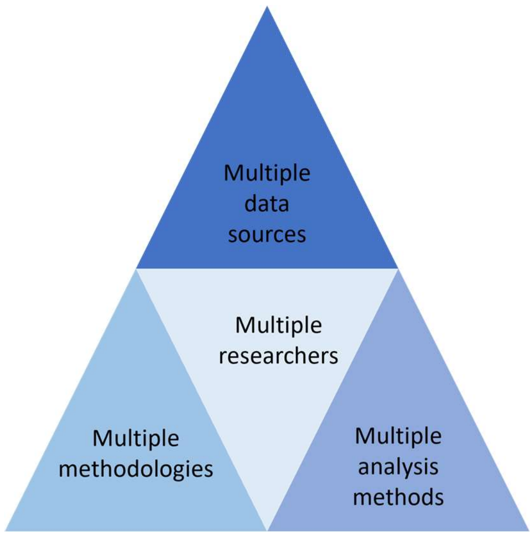


Figure 4: Overview of Triangulation Methods (Natow, 2020)

This section of the report discussed the methodology that was used in this research study. The following section will present a theoretical perspective on BIM adoption.

3. A Theoretical Perspective on BIM Adoption

This report section was guided by SRQ1: "What is a suitable theoretical framework for studying the adoption of BIM for AM?" The section starts by exploring technology adoption frameworks and their suitability for BIM adoption research in this study. It continues with a closer look at the selected technology adoption framework for this study and determines, based on previous studies, which components of the theoretical framework this study should focus on.

3.1 Theoretical Frameworks for BIM Adoption

Technology Adoption (TA) is multifaceted and occurs at the micro, meso, and macro levels, more commonly called the individual, organizational, and societal levels (Cunningham & O'Reilly,2018). At the individual level, TA is described by Tushman and Moore as a person's progression through various mental and behavioral states, ultimately resulting in the adoption or rejection of an innovation (Cooper,1985). At the organizational level, TA is a complex and dynamic process through which innovation gets integrated into a firm and can be influenced by factors such as organizational culture, organizational structure, the allocation of resources, and leadership (Saghafian et al., 2021). Compared to the previous levels, not much research has been done on the societal level of TA (Hooks et al., 2022). In their study, Hooks et al. (2022) stated that the macro level of TA aims to encourage the development of innovations in a country through the ability to promote TA in a society. The adoption of BIM has been studied at the individual, organizational, and societal levels of technology adoption (Chowdhury et al., 2024) (Murguia et al.,2021). BIM adoption has also been studied with a specific focus on certain phases of the adoption process (Chowdhury et al., 2024) (section 3.2 will delve more into the adoption process of BIM).

BIM has been described as a technological innovation, which implies that its adoption can be studied with the established technology adoption, diffusion, and acceptance lenses (Murphy, 2014). Many TA lenses have been developed over time, with some being more widely utilized and established than others (Xu et al.,2021) (Chowdhury et al.,2024). This study explored the well-established TA lenses. Exploring well-established TA lenses was a means of filtering through the plethora of options and identifying those scrutinized by researchers and backed by sufficient evidence from empirical studies that support their use (Z. Xu et al., 2021) (Taherdoost, 2018) (Dube et al., 2020). Figure 3 shows an overview of established technology adoption lenses (adopted from (Taherdoost,2018)). This figure captures the relationship between the established models but is not an exhaustive list of all TA lenses.

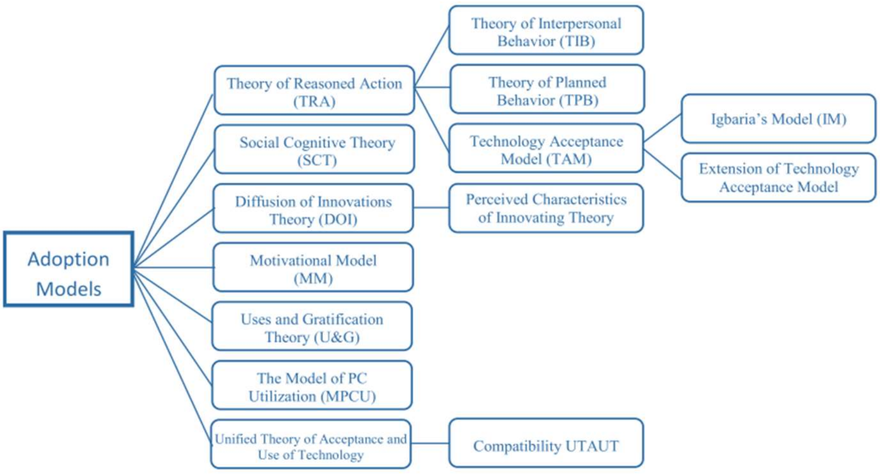


Figure 5: Overview of Technology Adoption Theories (Taderdoost,2018)

Previously conducted BIM adoption studies show certain preferences among specific models, contingent upon the level of adoption under investigation, or the specific research objectives (Chowdhury et al., 2024) (Murguia et al.,2021). The theory of reasoned action (TRA) and its iterations (most notably the technology acceptance model (TAM)), the Diffusion of Innovations Theory (DOI), and the Unified Theory of Acceptance and Use of technology (UTAUT) are frequently used to study BIM adoption (Chowdhury et al., 2024). The technology-organizational-environmental (TOE) framework and institutional Theory (INT) are also recurring options for studying BIM adoption in the construction industry (Chowdhury et al., 2024). Other theories, like the Uses and Gratification Theory (U&G) and the Model of PC Utilization (MPCU), are not often used in BIM adoption studies as they are more relevant for studying communication or personal computer usage (Taderdoost,2018). The Motivational Model (MM) and the Social Cognitive Theory (SCT) are also less frequently used for studying BIM adoption (Chowdhury et al., 2024). A study by Chowdhury et al. (2024) conducted a comprehensive review of BIM adoption and comprised a list of the most widely used TA lenses. The top five can be seen in Table 2: List of frequently used TA theories.

Table 3: Overview of Well-Established TA Theories (derived from Chowdhury et al.,2024)

#	TA Lens	TA Theory	Authors
1	Diffusion of Innovations Theory	DOI	E.M. Rogers
2	Theory of Reasoned Action	TRA	Ajzen & Fishbein
3	Technology Acceptance Model	TAM	Davis & Bagozzi
4	Technology Organizational Environment Framework	TOE	Tornatzky & Fleischer
5	Institutional Theory	INT	Meyer & Rowan

Even though multiple studies have found that TAM is the most widely used lens (Chowdhury et al.,2024) (Xu et al.,2021), it does not seem suitable for this study due to its focus on the micro adoption level. The same argument can be made for the TRA. BIM adoption not only involves the individual but also organizational structures, organizational norms, and social factors (Chowdhury et al.,2024). Wang et al. (2022) pointed out that TAM and TRA are more suitable for studying the characteristics of BIM as software. On the other hand, the INT focuses too little on the micro level of BIM adoption and is more focused on the internal and external pressures that influence the organization's adoption of BIM. BIM is an innovation that is integrated into the established processes of both the individual and the organization. For a complete comprehension of the adoption influencing factors research should touch upon both these levels. The DOI theory offers this perspective.

The DOI theory is suitable for this research because of its focus on both the micro and meso level of technology adoption research (Rogers,2003). Other studies back this claim up as they have stated that BIM adoption on the organizational level is suitable with the DOI theory or the TOE framework (Ritu Ahuja Anil Sawhney & Rakshit, 2020). TOE has, however, been criticized for being too general and not capturing the complexities of adoption in dynamic environments (Baker,2011). Other TA frameworks exist for studying BIM adoption at the organizational level, but they are not backed by as much empirical evidence or offer a balance between the social system dynamics and organizational factors as DOI. DOI has a widespread implementation, specifically for studying BIM adoption in the construction industry in other TA studies, which provides evidence of its suitability for research of this character (Xiaodong Xu et al., 2020) (Shirowzhan et al., 2020a) (Karampour et al., 2021)(B. J. Gledson & Greenwood, 2017). For example, Karampour et al. (2021) used DOI to study BIM adoption in the context of the Italian construction industry. The following section will explore the DOI theory and discuss studies that have previously utilized this framework for conducting BIM adoption research.

3.2 The Diffusion of Innovation Theory

The diffusion of innovations theory explains how innovations spread through communication channels among the members of a social system within a certain timeframe (Rogers, 2003). The DOI theory has been used to study BIM adoption in many countries, such as Italy, Nigeria, China, the UK, and the Netherlands (Karampour et al., 2021) (Hamma-adama et al., 2018) (Wang et al., 2022) (B. J. Gledson & Greenwood, 2017)(Papadonikolaki & Aibinu, 2017). It has proven useful in understanding the BIM adoption process in the construction industry (Gledson,2021) and in identifying factors that influence the adoption of BIM (Merschbrock & Munkvold, 2015) (Shibeika & Harty, 2015) (Karampour et al., 2021) (Oyuga et al., 2023). The findings of such studies are integrated and discussed in the following text which explains how innovations are adopted.

Rogers (2003) described the innovation adoption process in five steps and called this the innovation-decision process (IDP). Multiple researchers have modified the original IDP to better reflect the adoption process of BIM in the construction industry (Hochscheid & Halin, 2018) (Gledson, 2022). The original IDP, created by Rogers (2003), is shown in the following figure, and further discussed along the lines of BIM adoption below.

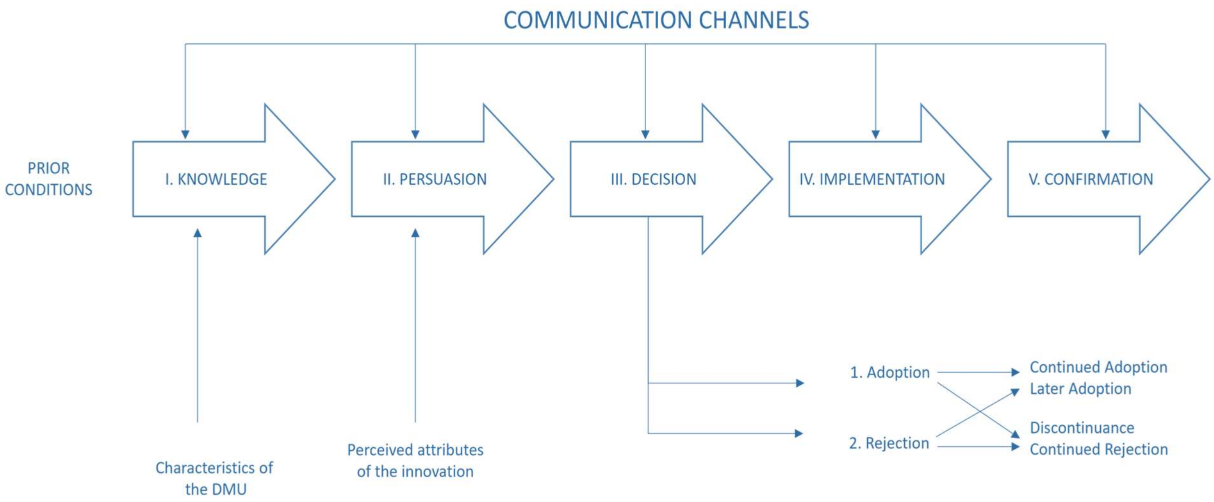


Figure 6: The innovation-decision process (Rogers,2003, p.170)

The innovation-Decision Process:

i. *Knowledge stage:* The initial stage of the innovation-decision process commences when the individual or decision-making unit (DMU) first becomes aware of the innovation's existence and its functionality (Rogers,2003). Rogers (2003) stated that DMUs tend to seek innovations that align with their interests, needs, and current views. However, Gledson (2022) revealed that DMUs in the construction industry exhibit passive behavior in seeking information and often become aware of an innovation by chance. An earlier study showed how individuals in the construction industry prefer to acquire awareness of innovations through their personnel network (B. J. Gledson & Greenwood, 2017), contradicting Rogers's (2003) theory, which stated that in the knowledge stage mass media communication is more effective at conveying information on the innovation as opposed to the interpersonal communication channels.

Awareness of BIM has been identified as a significant factor in the BIM adoption process, where lack of awareness hindered the adoption process of the innovation (Froise & Shakantu, 2014).

ii. Persuasion stage: The individual or DMU enters the persuasion stage when he starts actively seeking out information on the innovation and begins to form an opinion on the innovation, based on a general perception of the innovation (Rogers,2003). Gledson (2022) showed how the perceived attributes of the innovation play a key role in forming an opinion on the innovation. The innovation's trialability, compatibility, and relative advantage played a more significant role than complexity and observability in the study of (B. J. Gledson & Greenwood, 2017). Oyuga et al. (2023) underscored the role of trialability and relative advantage on the adoption rate of BIM and showed that observability also played a significant role in their study.

iii. Decision stage: The third step in the IDP is where the crucial decision is made to adopt or reject the innovation. Rogers (2003) describes four scenarios in which the decision is made for “continuous adoption, continuous rejection, discontinuance or later adoption.” Gledson (2022) argued that a more realistic outcome of the decision stage in the construction industry is a more nuanced scenario, as innovation decisions in the construction industry are more gradual or postponed, as opposed to being described as more immediate in DOI theory. The more applicable scenarios to the innovation decision in the construction industry are: “gradual adoption, postponed adoption, passive rejection, and immediate adoption or outright rejection” (Gledson,2022).

iv. Implementation stage: If the innovation passes the decision stage and is adopted, the innovation-decision process progresses into the implementation stage (Rogers,2003). Here, the individual or decision-making unit chooses to use the innovation. Gledson (2022) noted that the success of the innovation in this stage is quite uncertain in organizations, as the decision to adopt BIM is often made by individuals who do not implement the innovation, and implementers might oppose the decision to adopt BIM.

v. Confirmation stage: The final stage in the innovation-decision process occurs when the individual or decision-making entity seeks the validation of the choice to utilize the innovation. Rogers notes that during this stage, the individual might choose to differ from the previously made innovation decision if presented with conflicting information on the innovation (Rogers,2003).

The IDP has been utilized in previous BIM adoption studies and helped identify factors that influence the adoption process. Awareness and the perception of BIM throughout the IDP have been shown to influence adoption (Froise & Shakantu, 2014; B. J. Gledson & Greenwood, 2017). Gledson and Greenwood (2017) showed a notable lag between the moment that the DMU became aware of 4D BIM (the knowledge phase) and when the innovation was implemented. This lag was shown to be caused by the perceived attributes of the innovation (B. J. Gledson & Greenwood, 2017). Considering the similarities between those studies and the current one, attention will be paid to the awareness of BIM and where the adoption of the BIM uses is in the IDP.

While the innovation-decision process helps understand how innovations are adopted, the rate of adoption helps understand why and how specific innovations are adopted faster than others (Rogers,2003). The rate of adoption is measured as the number of individuals or units of adoption that choose to adopt an innovation within a certain specified period (Rogers,2003). Rodgers' original model for the rate of adoption consisted of 5 variables: the perceived attributes of the innovation, the type of innovation-decision, the communication channels, the nature of the social system, and the extent of the change agents' promotion efforts. The model for the rate of adoption is depicted on the following page and further discussed.

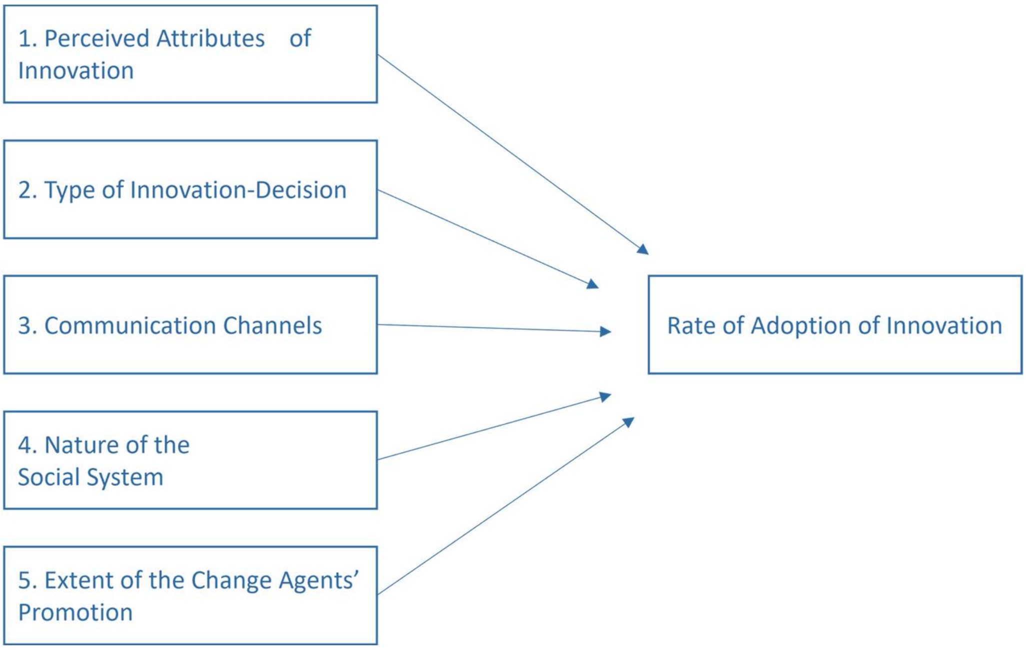


Figure 7: Model for the Rate of Adoption of Innovations (Rogers,2003, p.223)

1. Perceived Attributes of Innovation

The first variable that influences the rate of adoption is the innovation itself, specifically its perceived attributes. The perceived attributes of innovation can be seen as one of the most important variables for understanding the adoption rate and have been the point of focus in numerous BIM adoption studies (B. J. Gledson & Greenwood, 2017)(Xiaodong Xu et al., 2020)(Karampour et al., 2021)(B. Gledson, 2022) (Oyuga et al., 2023). Rogers (2003) noted that between 49 and 87 percent of the variance in the rate of innovation adoption can be elucidated by five attributes of the innovation: relative advantage, compatibility, complexity, trial-ability, and observability.

i. Relative advantage (RA)

The relative advantage has been described as: "the degree to which an innovation is perceived as being better than the one it supersedes" (Rogers, 2003, p.229) and often as the significant predictor of the innovations' adoption rate. As adoption units progress through the innovation-decision process (see figure: The Innovation-Decision Process), they are encouraged to acquire information on the innovation, which can lead to a decrease in uncertainty of the RA of the innovation (Rogers,2003). DOI states that "the RA of the innovation is positively related to its adoption rate" (Rogers,2003, p.233), meaning that a higher RA, as perceived by the members of the social system, will result in an increase in the adoption rate of the innovation. The relative advantages of BIM use in previous studies related to its benefits in enhancing architectural practices, facilities management, and financial planning (Shirowzhan et al., 2020). Oyuga et al. (2023) found a moderate correlation between RA of BIM uses, and their adoption, but other studies found a more significant role of RA in influencing BIM adoption behavior (Xiaodong Xu et al., 2020). Xu et al. (2020) stated the importance of studying the relative advantage of BIM to advancing BIM adoption.

ii. Compatibility

The compatibility of the innovation relates to "the degree that the innovation is perceived as being consistent with the current values, past experiences and needs of the potential adopters" (Rogers, 2003, p.240). An innovation perceived as more compatible will have a higher adoption rate than one that is not (Rogers,2003). Rogers (2003) advises that when implementing a host of innovations (such as different BIM uses for AM), starting with the most compatible innovation can be helpful as this will pave the way for other, less compatible innovations. The compatibility of BIM, so-called BIM-COM, has proven to be an influential factor in its adoption rate (B. J. Gledson & Greenwood, 2017) (Xiaodong Xu et al., 2020) (Shirowzhan et al., 2020a). Gledson and Greenwood (2017) found that the compatibility attribute of 4D BIM strongly influenced and delayed adoption in their study as only 5% of study participants found the innovation compatible.

iii. Complexity

The complexity attribute of an innovation is described as: "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers,2003, p.257). The complexity of the innovation is negatively related to its adoption rate, meaning that the more complex the innovation is perceived, the lower its adoption rate will be. Oyuga et al. (2023) noted that if a BIM use is perceived as simple to use, it will inspire an individual to learn more about its utilization, whereas if a BIM use is perceived as complex, it will deter the individual from engaging with the innovation.

iv. Trialability

According to the DOI theory, trialability is "the degree to which an innovation may be experimented with on a limited basis" (Rogers, 2003, p.258). Like relative advantage and compatibility, trialability is also positively related to adoption (Rogers,2003). Trialability has proven to be an essential attribute for understanding BIM adoption as a strong correlation between the trialability of BIM uses, and their adoption was found (Oyuga et al.,2023)(B. J. Gledson & Greenwood, 2017)(Xu et al.,2020). Gledson and Greenwood (2017) found that the trialability characteristic of 4D BIM strongly influenced and delayed adoption in their study.

v. Observability

The observability of the innovation relates to: "the degree to which the results of an innovation are visible to others" (Rogers,2003, p.258)., p.258). Observability of the innovation is positively related to adoption (Rogers,2003). The more the positive results of using an innovation are seen, the higher its adoption rate will be. Rogers (2003) noted that technological innovations have hardware or software components, and that observability might be a barrier to adopting software innovations as they have less observability. Oyuga et al. (2023) found a strong correlation between the observability of BIM uses and their adoption.

2. Type of Innovation-Decision

Decisions regarding the adoption of an innovation can be made either by individuals or by decision-making units within an organization. The rate of adoption is influenced by the number of individuals involved in making the decision to adopt the innovation (Rogers,2003). Rogers (2003) noted that the rate of adoption will decrease as more individuals are involved in the adoption decision process. DOI theory describes three types of decision types: optional innovation decisions, collective innovation decisions, and authority innovation decisions (Rogers,2003). In the construction industry, it can be expected that innovation adoption decisions are made by multiple individuals or a team rather than a single entity (Gledson & Greenwood, 2017). In their study, Gledson and Greenwood (2017) showed that the decision to adopt BIM was an authority type of decision. However, they proceeded to show no significant correlation between the innovation-decision type and the adoption of BIM in their study (Gledson & Greenwood, 2017).

3. Communication channels

The communication channels used to spread information about an innovation may also influence the rate of adoption (Rogers,2003). Rogers (2003) distinguishes between mass media and interpersonal communication channels, where mass media refers to using platforms such as radio or television, and interpersonal communication refers to the face-to-face spread of information from an individual(s) to the individual(s). The adoption rate is slower with interpersonal communication channels than with mass media. Gledson and Greenwood (2017) explored the effects of communication channels on the adoption of BIM. Their study showed no significant correlation between this variable and the adoption rate of BIM.

4. Nature of the social system

The adoption rate may also be affected by the nature of the social system within which adoption occurs. Rogers (2003) defined a social system as a set of interrelated units, such as individuals or organizations, working together to achieve a common goal. The 'social system' in which BIM is adopted is the construction industry, often described as a complex and dynamic system (Fernandez-Solis,2008). Elements that influence adoption by the social system are the structure of the social system, the norms of the social system, and the role of opinion leaders (Rogers,2003).

i. Social structure

Rogers (2003) describes social structure as "the patterned arrangement of units in a social system" (p.24). Organizations are known for their formal structure, where specific individuals may have a higher hierarchical position than others. The structure of the social system can either work towards or against the adoption of BIM (Aibinu et al.,2017) (Dao et al.,2021). Aibinu and Papadonikolaki (2017) researched the influence of organizational structure on the adoption of BIM and showed a correlation between these two variables. It was discovered that organizations with flexible structures were better equipped to handle the adoption of BIM (Aibinu et al.,2017). The importance of organizational structure in BIM adoption was further underscored by Dao et al. (2021), who showed the need for organizational change that stemmed from the adoption of BIM. The structure and size of the social system have been shown to influence BIM adoption rates. Aibinu et al. (2017) showed the influence of the size of the social system on BIM adoption. Their study found that organizations of smaller sizes were more successful in adopting BIM than their larger counterparts.

ii. Norms and culture of the social system

The Norms of the social system can be described as: "the established behavior patterns for the members of a social system" (Rogers,2003, p. 26). These norms can impede the adoption of innovations into a social system as members of the system might hesitate to deviate from the norms (Rogers,2003). Norms are a part of organizational culture (Scammon et al., 2014), which has extensively been researched and shown to significantly impact BIM adoption rates (Alankarage et al., 2023; Munianday et al., 2022).

iii. The role of opinion leaders

Rogers (2003) describes opinion leaders as members of the social system who are (informally) capable of influencing other individuals in that social system to change their attitudes or behaviors. In organizations, such individuals are often those in top management positions as they are (formally) capable of influencing others. The top management can facilitate the changes to the communication channels and free up other resources required to adopt the innovation ((Tavaelli et al, 2022). Aibinu and Papadonikolaki (2017) found that in their study, the support of top management was crucial to the successful adoption of BIM.

5. Extent of the change agents' promotion efforts

The innovation adoption rate can also be influenced by the extent of the change agents' promotion efforts (Rogers,2003). To successfully implement innovations in an organization, it is essential to have a group of individuals known as organizational change agents (Tavallaei et al.,2022). These agents are typically top management who play a critical role in defining the organizational context and norms for adopting the innovation. According to Tavallaei et al. (2022), top management support from the organizational change agents directly impacted the adoption of BIM. Change agents, who lack the organizational influence of top management, have proven to be less effective in facilitating BIM adoption in the study of Le et al. (2018). This study will, therefore, view top management as a change agent and gauge the willingness of top management to support BIM adoption for AM.

3.3 Theoretical Framework for BIM Adoption

This section presents the theoretical framework that will be used to study the adoption of BIM for AM used in this project. The original model by Rogers (2003) was designed to be universally applicable and required specification for this research. The specification was based on insights from previously conducted BIM adoption studies, which were discussed in the text above. A strong correlation has been shown between the "perceived attributes of the innovation," "the "nature of the social system," and the adoption of BIM (Karampour et al., 2021; Oyuga et al., 2023; Papadonikolaki & Aibinu, 2017). The following figure depicts the theoretical framework with its variables. This is hereafter discussed further.

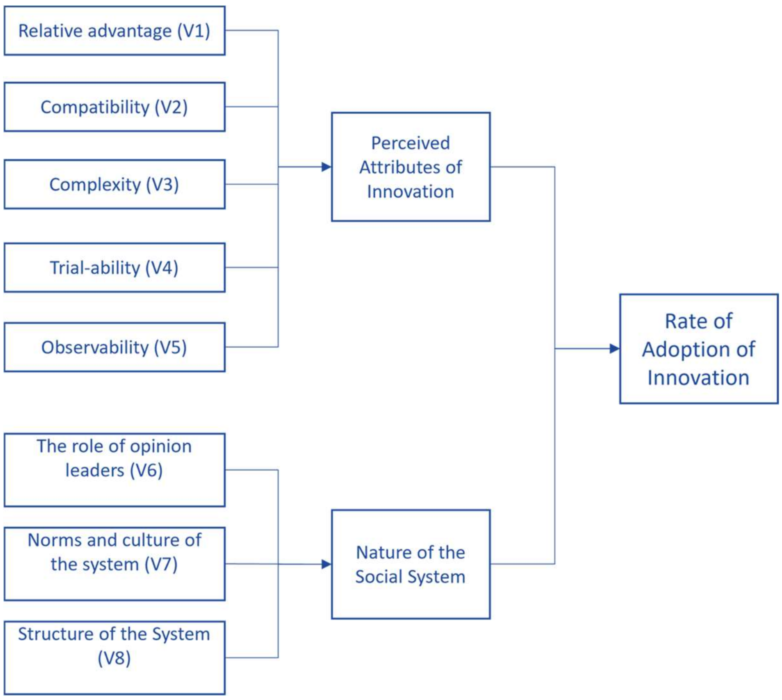


Figure 8: Theoretical framework for BIM adoption.

The first block of this model focuses on the perceived attributes of the innovation. It contains the five variables that influence its adoption: relative advantage, Compatibility, Complexity, Trial-ability, and Observation (Rogers,2003). These variables and their role in previous research studies were previously described. The perceived relative advantage, compatibility, and complexity of BIM have proven to have a significant role in previous BIM adoption studies (B. J. Gledson & Greenwood, 2017; Shirowzhan et al., 2020b; Xiaodong Xu et al., 2020). This research will build upon the work of these studies and explore the impact of the perceived relative advantage, compatibility, and complexity of BIM uses for AM in this study. The trial-ability and observability have been researched in previous BIM adoption studies as well and proven to significantly influence the adoption of the innovation (B. J. Gledson & Greenwood, 2017; Oyuga et al., 2023; Xiaodong Xu et al., 2020). This research will also investigate the role that these variables have on the adoption of BIM uses for AM.

The second block of the model focuses on the social system that adopts the BIM uses for AM. The variables that will be studied are the Structure of the social system, its Norms and culture, and the role of opinion leaders. Previous BIM adoption studies have focused on the size and structure of the social system and have been shown to influence adoption (Dao & Chen, 2021; Papadonikolaki & Aibinu, 2017). The norms, which are a part of the organizational culture, have also been shown to significantly influence adoption in previous BIM adoption studies (Alankarage et al., 2023; Munianday et al., 2022). An important factor in the social system is also the role of the opinion leaders of that social system (Rogers,2003). In the context of BIM adoption research, these opinion leaders are often individuals in top management positions, and their support is crucial to BIM adoption (Papadonikolaki & Aibinu, 2017; Tavallaei et al., 2022).

This research aims to comprehensively understand the adoption of BIM uses for AM. Rogers's (2003) original model on the factors that influence adoption was specified in the context of BIM adoption research by focusing on variables that were proven to have a significant role in BIM adoption in similar studies. This model was hereafter used to form an interview guide for semi-structured interviews. The results of using this model are further discussed in section 5 of the report.

4 BIM Uses for Asset Management

This section of the report was guided by SRQ2: "What are BIM uses for asset management in the O&M phase?" A systematic literature review was done to find the answer to this question. The methodology of that SLR can be seen in section 2 of the report. This section starts with the results of that systematic literature review. Hereafter the BIM uses for AM are individually discussed in greater detail. This section comes to and end with a summary on the BIM uses for AM and the corresponding barriers and drivers which were found in the scientific literature.

4.1 SLR approach to identifying BIM uses for AM

As the interest of academics has grown towards the utilization of BIM in the later phases of the asset's lifecycle, so has their desire to explore the possibilities of using these BIM models post-construction for asset management. The systematic literature review (SLR) was done on the published literature from 2019 until 2023 with the platform Scopus. The process of the SLR can be seen in Figure 8: Process of BIM uses for AM. The initial search resulted in 234 identified articles and research papers, which were filtered through 3 rounds (see Figure 8 for inclusion/exclusion criteria per round). After filtering and snowballing, a set of 27 papers was chosen for in-depth analysis and knowledge extraction. The final list of papers can be seen in the table 4: Literature sources on BIM uses for AM.

Table 4: Literature sources on BIM for AM

a	(M. Al-Kasasbeh et al., 2021)	h	(Qiuchen Lu, Xie, Parlikad, Schooling, et al., 2020)	o	(Matarneh et al., 2022)	v	(Guo et al., 2021)
b	(Jiang et al., 2022)	i	(X. Yin et al., 2020)	p	(Heaton et al., 2019)	w	(Nicola Moretti et al., 2021)
c	(M. Munir et al., 2020)	j	(J. Hull & Ewart, 2020)	q	(N. Moretti et al., 2020)	x	(Re Cecconi et al., 2017)
d	(Kaewunruen et al., 2023)	k	(Mohammadi et al., 2023)	r	(Chen & Lu, 2019)	y	(Wijeratne et al., 2023)
e	(Jofré-briceño et al., 2021)	l	(Heuser et al., 2022)	s	(Qiuchen Lu, Xie, Parlikad, & Schooling, 2020)	Z	(Opoku et al., 2021)
f	(Fang et al., 2022)	m	(Charlemagne et al., 2023)	t	(Wanigarathna et al., 2019)	aa	(Jensen, 2020)
g	(Morales et al., 2022)	n	(Rogage & Greenwood, 2020)	u	(Macchi et al., 2018)		

Through the process of backward snowballing 2 sources were identified which were published before the year 2019, but these were included due to their key insights. The following figure 8 provides an overview of when the works within the dataset were published. The most sources on BIM uses for AM in this dataset were published in 2020, followed by 2021 and 2022. The dataset was hereafter analyzed on its contents.

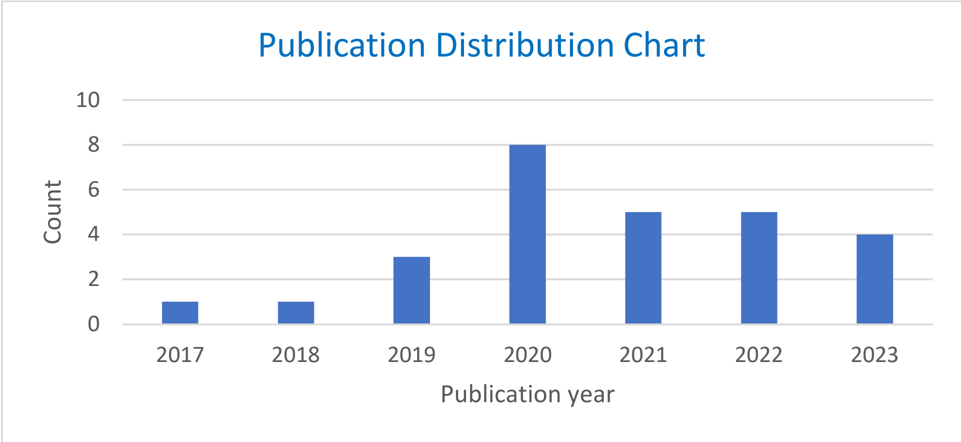


Figure 8: Overview of Yearly Sources SLR

Content analysis was performed to gather an in-depth understanding of the set of papers. Various methods of utilizing BIM for AM were described in the set, but recurring themes were identified. The similar themes were grouped together to form 7 categories of BIM uses for AM. The distribution of literary sources per category of BIM Use can be seen in the following figure 9. This chart shows that the majority of sources were on the topic of using BIM for asset information management (BU5). The second most prevalent theme in the dataset was on the usage of BIM for Facilities Management (BU6). Other BIM less frequently found BIM uses are the BIM use for RAMS analyses (BU1), Structural Health Monitoring (BU2), and Asset Performance Optimization (BU4) Lastly, are themes relating to BIM uses for Commissioning (BU3) and Simulation & Virtual Reality with BIM (BU7). These groups and the corresponding papers are shown in Table 5: List of BIM uses for AM. This table also mentions the frequency of the groups of BIM uses mentioned in the studied works.

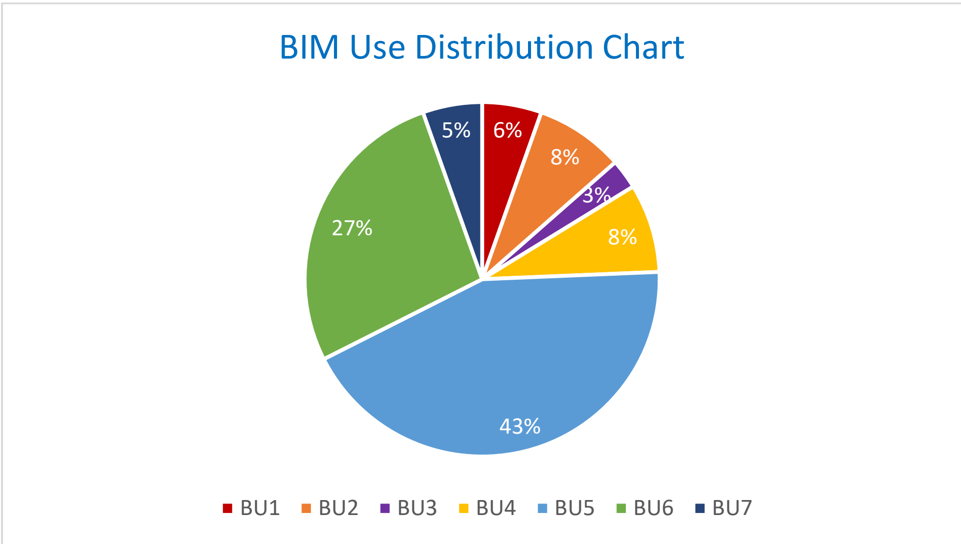


Figure 9: Distribution of sources per BIM use

It should be further noted that the order of BIM uses in AM in table 5 is not based on any prioritization of the BIM uses, but random. Each theoretical BIM use for asset management will be expanded upon in the following part of this section.

Table 5: List of BIM Uses for Asset Management

ID	BIM Use Name	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	aa	∑
BU1	Asset RAMS Assessment							•														•							2
BU2	Asset Condition Monitoring & Health Assessment				•																	•						•	3
BU3	Asset Commissioning																					•							1
BU4	Asset Performance optimization				•																		•				•		3
BU5	Asset Information Management	•	•	•		•	•		•	•	•	•		•			•	•	•						•	•		•	16
BU6	BIM-based Facilities Management									•					•	•		•		•	•			•	•	•	•		10
BU7	Simulation BIM and Virtual reality												•													•			2

4.2 Exploring the BIM Uses for AM

The following text explores the identified BIM uses for AM further in depth. A description of each of the BIM uses is provided as well as their purpose and the phase of the lifecycle to which they are applicable. The terms for the latter are adopted from the work of Kreider and Messner (2013) on the uses of BIM. The barriers and drivers that (/if they) were encountered in the literature are also discussed alongside the specific BIM uses to which they relate.

4.2.1 Descriptions, Barriers, and Drivers of the BIM Uses

BU 1) Asset Reliability, Availability, Maintainability and Safety (RAM) Analysis

- **Description:** The performance of a system or asset can be assessed based on its Reliability, Availability, Maintainability (RAM) aspects (Rijkswaterstaat,2018). Morales et al. (2022) points out how complex systems are being designed with the aid of BIM and RAM analyses, but that these processes are conducted independently from each either. There is currently a lack of a clearly defined procedure for sharing and utilizing the outcomes of these processes (Morales et al., 2022). Morales et al. (2022) provided a prove of concept for integrating BIM and RAM-analysis with the combination of Autodesk REVIT for BIM and RAPTOR 7.0 for the RAM. The BIM model functions as a data source for the RAPTOR software. RAM analyses proof to be valuable throughout the operations and maintenance phase of the asset for reconfiguring an asset, assessing its RAM performance, and calculating the total cost of ownership (Macchi et al., 2018). RAM is an important part of the asset management process and many large asset owners in the Dutch construction industry, such as RWS, deem it mandatory to perform RAM analysis (quantitative (IHP) or qualitative(P-IHP)) on their projects (Rijkswaterstaat, 2018).
- **Purpose:** To Analyze
- **Facility phase:** RAM analyses can typically be performed during various phases of the lifecycle of the asset such as the design and operations and maintenance phases (Rijkswaterstaat,2018) (Macchi et al., 2018).
- **Barriers:** The usage of BIM for RAM analyses is a novel approach, especially in the construction industry, as it is more often used in the oil & gas industry or manufacturing industry (Morales et al., 2022). While Morales et al. (2022) succeeded in developing a proof of concept, they point out that an improved communication between BIM and RAM-analysis software's is yet to be developed.
- **Drivers:** The first driver relates to an enhanced decision-making during the Middle of Life phase of assets (Macchi et al.,2018). The second driver relates to a more integrated and efficient process by conducting RAM analyses with BIM (Morales et. al., 2022). The third driver relates to the possibility of forecasting the performance and long-term behavior of the system (Macchi et al., 2018).

BU 2) Asset Condition & Health Monitoring

- **Description :** Structural Health monitoring (SHM) is defined as: "the analysis, localization and recording of the loading and damaging conditions of a structure by materials-integrated or structure-integrated sensing devices that permit a prediction in such a way that nondestructive testing (NDT) becomes an integral part of the structure and a material" (Systems & Bridge, 2010). This BIM use is focused on creating a SHM workflow by employing a combination of BIM and IoT sensors, which can be seen as a rudimentary Digital Twin (Sakr & Sadhu, 2023). Macchi et al. (2018) describe how such a DT can be used for asset diagnosis, aiding in the assessment of the health status of the asset based on the observed state. Sensing equipment doesn't need to be installed onto the asset. Sensors and camera technology can be used in combination with unmanned aerial vehicles (UAV) for SHM in monitoring the condition and performance of assets (Jensen,2020).

- **Purpose:** To Gather
- **Facility phase:** Monitoring of the performance and condition of the asset is described as an activity applicable to the Middle of Life of the asset (Macchi et al., 2018).
- **Drivers:** Drivers to this BIM use relate to the possibility to deliver real-time information on the asset with the aid of sensors and accurately locate damages (Kaewunruen et al., 2023). Further drivers relate to the possibilities of enhanced stakeholder collaboration and ease of estimating the capacity of materials through the BIM model (Kaewunruen et al., 2023).

BU 3) Asset Commissioning

- **Description**

Commissiong is described by (Djuric & Novakovic, 2009) as the structured procedure to guarantee that all building facility systems operate in accordance with their design specifications and goals. BIM has the ability of supporting the commissioning process by providing a database which covers all physical and functional aspects of the facility (Wu & Issa, 2012). Conventional commissioning is 2D-centered and paper heavy, whereas BIM offers a more efficient data sharing process (Wu & Issa, 2012). BIM further offers the ability to support the commissioning process of facilities through data analytics and advanced simulation, to achieve virtual commissioning of the asset (Macchi et al., 2018).

- **Purpose:** To Realize and communicate
- **Facility phase:** Asset Commissioning is an activity which is applicable to the Beginning and Middle of Life of the asset (Macchi et al., 2018). Commissioning typically occurs after the construction of new assets or renovation of existing assets (Wu & Issa, 2012). This study is only focused on the MoL applicability of BIM to commissioning due to its scope.
- **Barriers:** Wu & Issa point (2012) toward the legal and security issues which may arise from the commissioning-contained BIM models. There is a need to clearly define ownership of the models in the contracts (Wu & Issa ,2012).
- **Drivers:** The first driver to this BIM use is its capability of offering a centralized and structured database for the vast number of documents in certain complex assets such as operational manuals on building systems, MEP designs and other crucial building components (Wu & Issa ,2012. The second driver of this BIM use is its possibility of enabling virtual testing and simulation of the asset's components (Macchi et al., 2018). This spares downtime of the asset and can enable faster startup times.

BU 4) Asset Performance Analysis

- **Description:** Stakeholders are interested in how buildings perform and provide comfort in the operations and Maintenance phase. Utilizing BIM can help achieve the optimization of building performance, particularly concerning energy consumption and sustainability factors such as carbon-footprint (Opoku et al., 2021). Given that buildings are responsible for 19% of greenhouse gas emissions and 32% of global energy consumption (Xiaoxiao Xu et al., 2021), there is a growing focus on using BIM for sustainability analysis. Kaewunruen et al. (2023) studied the application of BIM for sustainability analyses of bridges by focusing on greenhouse gas emissions. Such performance analysis with BIM with regards to sustainability and energy consumption are also gaining attention as the focus is drawn to green building (Guo et al., 2021).

- **Purpose:** To Analyze
- **Facility phase:** This BIM use is appliable to the middle of life phase of the asset.
- **Barriers:** Barriers relate to the additional costs due to complex implementation and training costs for workers (Kaewunruen et al., 2023).
- **Drivers:** External pressures of society to focus on sustainable performance of assets due to the contribution of the construction industry to climate change (Guo et al., 2021). Second the evaluation and optimization of building performance has been found to be more flexible and effective with BIM (Guo et al., 2021).

BU 5) Asset Information Management

- **Description:** Using BIM use for information management (IM) is a enticing, but challenging matter (Chen & Lu, 2019). The attention to this BIM use is considerable as can be seen by its prevalence in our data set (see figure 9). A challenge to implementing asset management strategies is the timely availability of information on the built-asset (M. Al-Kasasbeh et al., 2021). Information in the)&M phase is often also incomplete or fragmented due to a separation between these two phases and an inefficient transfer of data between the phases (M. Al-Kasasbeh et al., 2021). BIM has the potential to greatly improve IM in construction (Chen & Lu,2019). Chen & Lu (2019) showed how BIM could satisfy IM requirements related to the quantity, quality, and accessibility of information; three central requirements for IM. A BIM model can further fulfil the role of link between the object hierarchy and the information which is specific to the elements of an asset (Jensen,2020). Information in BIM models can be captured through manual or automated methods. The emergence of scan-to-BIM is an example of technologies that has recently been rising in utilization and aids in the information capturing with BIM (Re Cecconi et al., 2017).
- **Purpose:** to gather and communicate
- **Facility phase:** This BIM use is applicable to the full lifecycle of the asset. Due to the purposes of the scope of this research it will be stated that its applicability is to the middle of life phase.
- **Barriers:** As this BIM use has been studied frequently over the past years, it has become quite clear what the barriers are to its adoption. First is a lack of BIM models with as-is condition information on existing assets (Joanna Hull & Ewart, 2020). This means that BIM models would need to be built before IM could occur with BIM. Establishing and keeping as-is condition BIM models up-to-date is hereafter another challenge (Mustapha Munir et al., 2021). The lack of interoperability between software systems due to a high variety in different systems and the presence of proprietary systems also acts as a significant barrier (Jiang et al., 2022). The large variety of different systems causes an issue to the end-users of these systems as they are required to have the technical knowledge for working with many different IM systems (Jiang et

al., 2022). Heaton et al. (2019 further point out that there is a gap in our understanding on how to effectively transfer information from BIM to asset information models. This is due to the fact that building owners and asset managers don't know what their asset information requirement are, which leads to BIM models which have little value in the O&M phase (Heaton et al., 2019). Asset information requirements relate to the information needed to operate and manage the asset as the managing organization intends.

- **Drivers:** This BIM use enables enhanced collaboration between stakeholders (M. Al-Kasasbeh et al., 2021). This BIM use also enables a more efficient capturing, storage and sharing of asset information (Jiang et al., 2022; Opoku et al., 2021).

BU 6) BIM-based Facilities Management of Asset

- **Description:** Another of the most researched BIM uses for asset management is the usage BIM for an enhanced facilities management, as can be seen by the number of publications on this subject (see figure 9). Some studies use a different definition of facilities management but in this study, it is defined as a part of the asset management process (see section 1.6 for the full definition). Wijeratne et al. (2023) write about integrating BIM with CAFM and CMMS systems, of which IBM Maximo is one of the most popular for enhancing asset management and the multiple benefits to be achieved from this assimilation of processes.

- **Purpose:** To Gather and Communicate
- **Facility phase:** This BIM use is appliable to the middle of life phase of the asset.

  Barriers: Despite the many benefits, this BIM use is not widely adopted yet, and researchers predominantly attributed this to a lack of BIM experts and high initial costs among a list of 26 barriers (Takyi-Annan & Zhang, 2023). Lu.et al (2020) researched the usage of BIM in the O&M phase and discovered limitations to the usage of BIM for the management of facilities. These primarily relate to the lack of integration of BIM with Computer Aided Facility Management (CAFM) systems. This issue is stated by numerous other academics (Mustapha Munir et al., 2021). Facility managers use specialized software for the management of buildings and other facilities. The data which is generated during the design and construction of the asset's lifecycle could for a long time not be transferred to the O&M phase for the usage with CAFM software's. The development of the Construction operations building information exchange (COBie) was an enabler to resolve this issue. This development acted as an adapter to aid the utilization of data generated through the D&C phases of the asset's lifecycle in the O&M phase for the use with facilities management software. COBie is a subset of the IFC model data and can be enriched by various stakeholders. Condotta & Scanagatta (2023) showed that COBie does have its limitations and drawbacks. They firstly note that the lack of automation in the input means that the process of using COBie is labor intensive and secondly that it is impossible to add all descriptive information due to the limitations of BIM models which cannot handle the data capturing. The third drawback noted by this study was that COBie results in too heavy files as not all data in the IFC subset is usable. A second limiting factor to BIM usage during the O&M phase for FM relates to the extensive amounts of data that are collected in this phase (Qiuchen Lu, Xie, Parlikad, Schooling, et al., 2020). If data on the temperature, humidity and air quality is continuously gathered through multiple sources and through multiple systems, it can become too complex of a dataset for asset managers to derive meaningful information from.

- **Drivers:** Through the usage of BIM for facilities management, a simplified and automated workflow can be created, resulting in time and cost savings and higher user satisfaction scores (Wijeratne et al., 2023) (Re Cecconi et al., 2017). A research study by Re Cecconi et al. proved that a BIM model with a low level of detail (LOD) and a high level of information can be used to create a BIM-based workflow for asset management but noted that early involvement of all stakeholders and facility management was crucial for the success of the endeavor (Re Cecconi et al., 2017).

BU 7) Simulation of processes

- **Description:** In addition to their capability for 3D visualization, BIM models can be used for animation and simulation(Wijeratne et al., 2023). This BIM use aids in analyzing and simulating the behavior of physical assets (Heuser et al., 2022). Simulation is desirable in case of reconfiguration or refurbishment of the asset to test the new situation (Heuser et al., 2022). The pottential of BIM for simulation can further be used in a gamelike environemt. Heuser et al. (2022) and Wijeratne et al. (2023) describe how BIM is used in a gamelike environment to train maintenance personnel and operators in the O&M phase.
- **Purpose:** To Analyze and Communicate
- **Facility phase:** This BIM use can be used in various stages of the asset's lifecycle. This study however only focused on the applicability of this BIM use to the middle of life of the asset.
- **Barriers:** The development of BIM models for game like environments comes with high costs (Heuser et al., 2022). Updating such models is then again high in costs and time-consuming (Heuser et al., 2022).
- **Drivers:** This BIM use offers the possibility for enhanced decision-making (Heuser et al., 2022). In addition to enhanced decision-making, this BIM use can also enhance the communication (Wijeratne et al., 2023).

4.2.2 Summary of BIM uses for AM

The preceding subsections have outlined the BIM uses for AM in the O&M phase, along with their specific barriers and drivers, as identified in the scientific literature. Table 6, overview of BIM uses for AM, encapsulates the aforementioned information, presenting the BIM uses alongside their corresponding barriers and driver.

Table 6: Overview of BIM Uses for AM

Code	BIM Use Name	Description	Barriers	Drivers
BU1	Asset RAM Analysis	Conducting Reliability, Availability, and Maintainability analysis with an integrated approach via BIM and RAM analysis software.	▪ Lack of BIM models on existing assets. ▪ Need for improved communication between BIM and RAM-analysis software's (Morales et. al., 2022).	▪ Enhanced decision-making during the Middle of Life phase of assets (Macchi et al.,2018). ▪ A more integrated and efficient process by conducting RAM analyses with BIM (Morales et. al., 2022). ▪ The possibility of forecasting the performance and long-term behavior of the system (Macchi et al., 2018).
BU2	Asset Condition Monitoring & Health Assessment	Using a combination of BIM and sensing technologies to analyze, localize and record the loading and damaging conditions of a structure.	(The studied papers from the SLR did not discuss barriers related to the adoption of BIM for SHM)	▪ The possibility to deliver real-time information on the asset with the aid of sensors and accurately locate damages (Kaewunruen et al., 2023). ▪ The possibilities of enhanced stakeholder collaboration and ease of estimating the capacity of materials through the BIM model (Kaewunruen et al., 2023).

Code	BIM Use Name	Description	Barriers	Drivers
BU3	Asset Commissioning	Supporting the commissioning of newly constructed or renovated assets with BIM.	▪ Security issues which arise from information in the BIM models for commission (Wu & Issa, 2012) ▪ Legal issues surrounding the unclear ownership of BIM models used for commissioning (Wu & Issa, 2012).	▪ A centralized and structured database for the vast number of documents in certain complex assets such as operational manuals on building systems, MEP designs and other crucial building components (Wu & Issa ,2012). ▪ The possibility of enabling virtual testing and simulation of the asset's components (Macchi et al., 2018).
BU4	Asset Performance Analysis	Analyzing and Optimizing Asset Performance in terms of Energy consumption or sustainability aspects such as carbon footprint with BIM.	▪ Additional costs due to complex implementation & ▪ Training costs for workers to use this innovation.	▪ External pressures of society to focus on sustainable performance (Guo et al., 2021). ▪ More flexible and effective evaluation and optimization of building performance with BIM (Guo et al., 2021).
BU5	Asset Information Management	Enabling information management of assets through the utilization of BIM	▪ A lack of BIM models with as-is condition information on existing assets (Joanna Hull & Ewart, 2020) ▪ Challenges in establishing and Maintaining as-is	▪ Enhanced collaboration between stakeholders (M. Al-Kasasbeh et al., 2021). ▪ More efficient capturing, storage and sharing of asset information (Jiang et al., 2022; Opoku et al., 2021; X. Yin et al., 2020) ▪ Timely access to asset information (Wijeratne et al., 2023)

Code	BIM Use Name	Description	Barriers	Drivers
			models (Mustapha Munir et al., 2021) ▪ The lack of interoperability between software systems due to a high variety in different systems and the presence of proprietary systems (Jiang et al., 2022). ▪ Challenging usage for end-users of IM systems as they are required to have the technical knowledge for working with many different IM systems (Jiang et al., 2022). ▪ A gap in our understanding on how to effectively transfer information from BIM to asset information platforms, such as AIM's (Heaton et al., 2019).	▪ Time and Cost savings due to the avoidance of duplicated work processes (Wijeratne et al., 2023).

Code	BIM Use Name	Description	Barriers	Drivers
			▪ Lack of knowledge on asset information requirement (Heaton et al., 2019). ▪ BIM models are not built for O&M and have little value in the O&M phase (Heaton et al., 2019).	
Code	BIM Use Name	Description	Barriers	Drivers
BU6	BIM-based FM	Supporting the management and daily operations of facilities with the aid of BIM.	▪ A lack of BIM experts High initial costs (Takyi-Annan & Zhang, 2023). ▪ The lack of integration of BIM with Computer Aided Facility Management (CAFM) systems (Qiuchen Lu, Xie, Parlikad, Schooling, et al., 2020; Mustapha Munir et al., 2021) ▪ The lack of automation in input when using Cobie resulting in labor	▪ Establishing a simplified and automated workflow (Re Cecconi et al., 2017; Wijeratne et al., 2023) ▪ Time and cost savings and higher user satisfaction scores (Re Cecconi et al., 2017; Wijeratne et al., 2023)

Code	BIM Use Name	Description	Barriers	Drivers
			intensive processes (Qiuchen Lu, Xie, Parlikad, Schooling, et al., 2020). ▪ COBie results in too heavy files as not all data in the IFC subset is usable. ▪ The extensive amounts of data that are collected in the O&M phase, resulting in a complex dataset (Qiuchen Lu, Xie, Parlikad, Schooling, et al., 2020).	

Code	BIM Use Name	Description	Barriers	Drivers
BU7	Simulation of Processes and Events	Utilizing BIM for animation and simulation. By employing BIM for animation and simulation, the opportunity is created to assist in training operations and maintenance personnel in a game like environment.	▪ High initial costs for development of game like environments for training (Heuser et al., 2022). ▪ High costs and time-consuming process of	▪ Enhanced decision-making (Heuser et al., 2022). ▪ Enhanced communication (Wijeratne et al., 2023). ▪ Training of Staff via a BIM based game like environment (Heuser et al., 2022; Wijeratne et al., 2023).

Code	BIM Use Name	Description	Barriers	Drivers
			updating BIM models (Heuser et al., 2022).	

5 Case Studies

This section of the report presents the findings of the case study research and is guided by the research questions SRQ 3: "What are the barriers to the adoption of BIM uses for AM?" and SRQ 4: "What are the drivers to the adoption of BIM uses for AM?" The first part of this section presents the findings on the case of the First Heinenoord tunnel. Hereafter the findings on the South-Holland tunnel program are presented. In the third part of this section a comparison is drawn between the two cases. The section comes to an end with a summary of the encountered Barriers and Drivers to the BIM uses for AM on these projects.

5.1 Case 1: The First Heinenoord Tunnel

5.1.1 Background Information

The First Heinenoord Tunnel (in Dutch "Eerste Heinenoordtunnel (EHT)) is located in the South-Holland region of the Netherlands and forms an important link in the A29 highway. The tunnel facilitates the connection between North-Brabant and the city of Rotterdam. The tunnel goes under the Maas River, as can be seen in figure 10: Aerial view of Heinenoordtunnel, which provides an image of the North side of the tunnels entrance and the Maas River behind it. The EHT is a standard tunnel, consisting of 2 tunnel tubes for accommodating traffic, and 2 service buildings on either side of the tunnels exits. The tunnel was opened to the public in 1969 and is after operating for nearly 50 years due to maintenance and renovations work.

Figure 10: Aerial view of First Heinenoordtunnel

Stakeholders on project

The Renovation First Heinenoordtunnel (In Dutch: Renovatie Eerste Heinenoordtunnel (REHT)) project was initiated in 2018 by the tunnel's owner, Rijkswaterstaat, and is projected to be completed in 2024. Maintenance of the tunnel falls under RWS-WNZ but is outsourced to *** until 2026. The project was brought to the market with a Design, Construct and Maintain (DCM) contract. A two-stage approach was used where the design, planning and costs were determined with the contractor. The contractor on this project is ***, a collaboration between the organizations ***, *** and ***. The engineering services were provided by TEC, a collaboration between the engineering firms Witteveen+Bos and ***. Many other stakeholders were involved on this project, but this report limits itself to the ones who were closely involved with the BIM uses for AM. An overview of relevant stakeholders on this project can be seen in table 7: Stakeholders on REHT Project.

Table 7: Stakeholders on REHT Project

Stakeholder Role	Name	Note
Owner	Rijkswaterstaat	
Asset Administrator	Rijkswaterstaat-WNZ	Daily maintenance outsourced to ***
Contractor	***	A collaboration between *** , *** and ***
		Collaboration between *** and Witteveen+Bos
Engineering	TEC	
Engineering	***	Responsible for BIM Modelling

Scope of project

The project aimed to revamp both the civil engineering components and the tunnel technical installations. This involved upgrading the tunnel's road surface and introducing a central tunnel channel for emergency use (see figure 11: Middle tunnel channel of EHT). Additionally, the lighting, fans, and technical systems were replaced. The control, monitoring, and security systems (known in Dutch as: Besturing, bewaking, Beveiliging (3BT)), were similarly updated. The 3BT system, a novel and standardized innovation for all RWS tunnels, underwent its inaugural implementation in the EHT. The transition from old to new hardware and software for these systems had to occur in parallel, ensuring minimal downtime of the tunnel. This was a major theme during this project as it was imperative to limit downtime of the asset. The final major element of the scope was a digital approach to capturing and storing the asset information. A BIM model was at the heart of this approach and facilitated the storage of information via various techniques. One of such was the coding of components of the tunnel and linking this to the BIM. Figure 12: Coding on cables of EHT depicts such coded elements in the tunnel. This BIM model had the aim of supporting maintenance of the tunnel in the remainder of the O&M period of the tunnel.

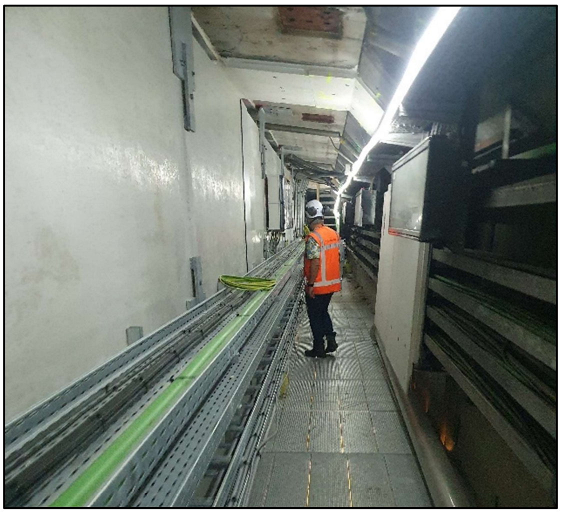


Figure 11: Middle Tunnel channel of EHT

Figure 12: Coding on Cables of EHT

BIM usage on project

The usage of BIM for asset IM on the REHT project was initially driven by the lack of (useable) information on the tunnel in its as-is condition at the start of the project. This issue is encountered on numerous asset management projects involving assets dating back to the 1960's and 1970's. Information on the assets is oftentimes inaccurate, incomplete, or fragmented between multiple departments of the organization. The same issue also arose at the REHT project. The asset information was outdated, fragmented and in some cases unreadable. This issue had led to substantial budget overruns in previous projects of RWS. Rijkswaterstaat would be confronted with a request for adaption (in Dutch: verzoek tot wijziging (VTW)), which results from additional work which is assigned to the contractor.

A second driver for the usage of BIM was the complexity of the project. As stated earlier, downtime of the asset had to be kept to a minimum, as it facilitates upward of 100.000 vehicles going to and from Rotterdam daily. In contrast to other projects, there was little room for surveying the tunnel and assessing the as-is situation with the traditional methods. There was also little room for commissioning of the asset and training of the tunnel operators. Rijkswaterstaat wanted to prevent additional costs and delays to the REHT project and as such decided on a novel approach; the utilization of various BIM uses for AM.

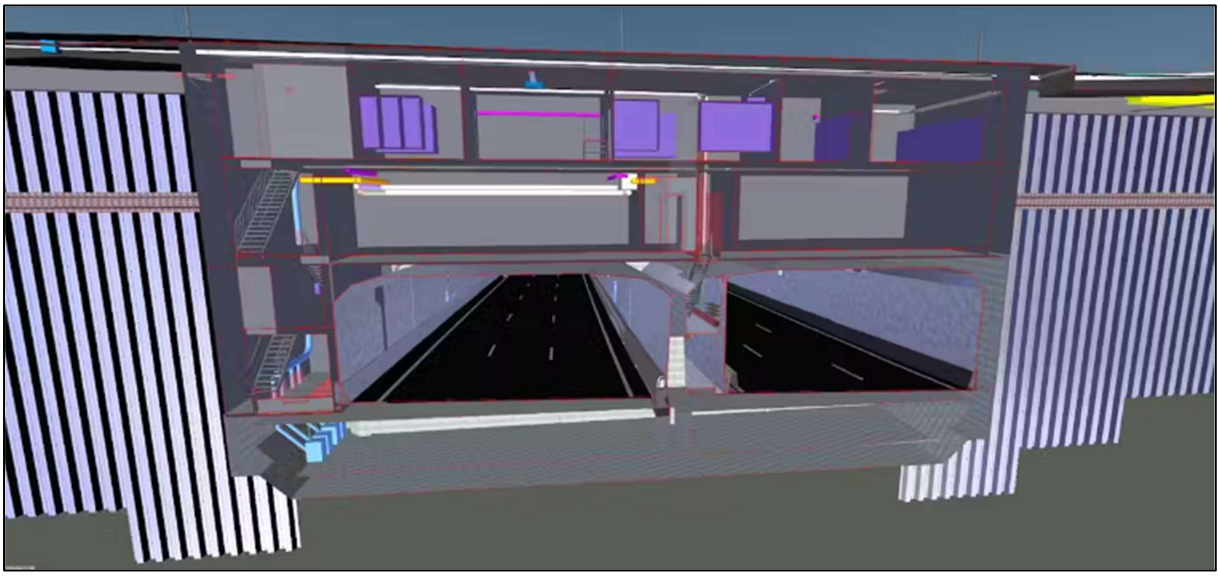


Figure 13: Depiction of BIM Model EHT (Sourced from (Rijkswaterstaat, 2022))

To address the issue of the lacking asset information it was decided to compile information on the asset in its as-is condition. This would be done before the tendering stage of the project. The strategy of RWS entailed the development of a BIM model, which would capture the current as-is condition of the asset, and then be handed over with other information on the asset to the contractor. The contractor would then enrich the BIM model and deliver this back to Rijkswaterstaat for use during the remainder of the O&M phase of the asset. Taking it a step further, the team of Rijkswaterstaat aimed at creating a BIM-based "digital twin" to support the remainder of the O&M phase of the tunnel (see figure 14: BIM applications on REHT for overview of BIM applications). The "digital twin" was to be built around the BIM model and connected to different computer programs. The BIM model was then used to facilitate the commissioning process of the asset and training of the tunnel operators.

The as-is BIM models were first built with the aid of Scan-to-BIM technology. This technology entails the method of transferring data from laser scans into BIM models (Bosche, Ahmed, Haas, Haas.,2015). Scan-to-BIM has emerged as a favorable solution to address the issues stemming from inaccurate, inadequate, or missing building information, as it is used to capture geometries and textures of a built asset (Wang et al.,2019). The tunnel was scanned, and a model was created from the point cloud. The working files for this model were created in the program Autodesk AutoCAD and these AutoCAD files were merged into a coordination model in Autodesk Navisworks. The model would later however be rebuilt by the contractor in Autodesk REVIT. More on this will be discussed in the following section. The REVIT model would ultimately be used for the remainder of the REHT project. The following figure 14 presents an overview of the BIM applications on the REHT project. A larger and clearer image of this can be found in appendix E: BIM Applications REHT.

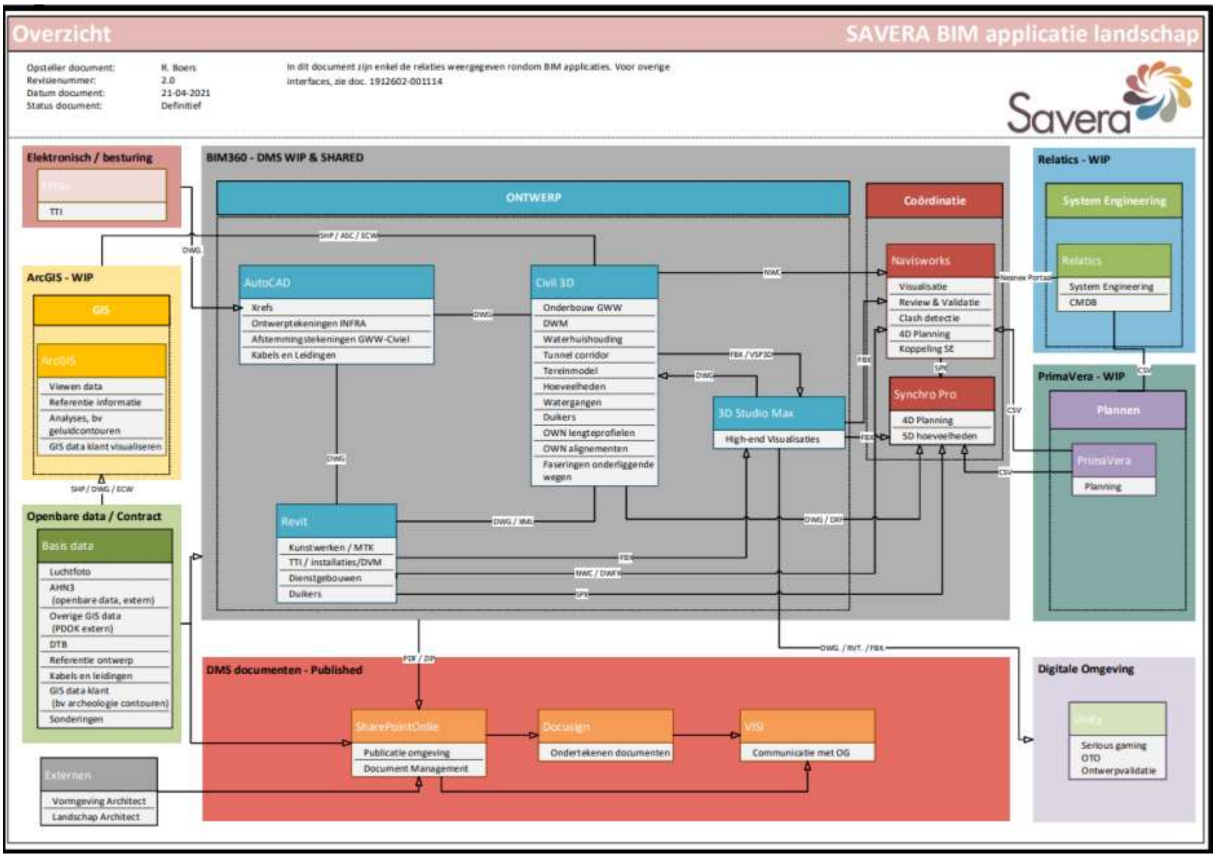


Figure 14: Overview of BIM Applications on REHT

Figure 14 shows the BIM Model at the heart of the processes and the flow of information of the project to different software platforms. The asset information is mainly captured in the Autodesk BIM 360 environment. A connection was most notably established between the BIM environment and the programs ArcGIS and UNITY. The program UNITY was used for visualizations of different scenarios and to create a game-like environment which was used to train the operators and administrators of the EHT.

The project team considered a host of other BIM uses for AM on the REHT project, but not all were eventually utilized. Table 2 shows an overview of the BIM uses which were considered for this project and the ones which were eventually utilized. It also shows the BIM uses for AM that were not considered. The interviews which were held with the key stakeholders on this project also probed into why the BIM uses were not considered/implemented and tried to identify why they were not considered/implemented.

Tabel 2: List of BIM uses for AM on REHT

BIM Use	Description	Code
BU1	Asset RAM Analysis	C
BU2	Asset Condition Monitoring & Health Assessment	B
BU3	Asset Commissioning	A
BU4	Asset Performance Analysis	C
BU5	Asset Information Management	A
BU6	BIM-based FM	B
BU7	Simulation of Processes and Events	A
Code	Meaning	
A	considered and implemented in case studies	
B	considered but not implemented in case studies	
C	not considered in case studies	

The research will predominately focus on the BIM uses that were both considered and potentially disregarded. It can be assumed that the stakeholders were aware of the existence of these BIM uses and can present arguments on why they were (not) chosen to be utilized. Their statements can shed light on the barriers and drivers to these BIM uses for AM. The following subsection will present the findings on studying the REHT project.

5.1.2 Findings from case REHT

The subsequent section presents the findings of the case along the lines of the developed framework in section 3 of the report. It elucidates how each of the 8 variables influenced the adoption of the BIM uses, including the associated barriers and drivers. An additional, non-variable related category of findings was included in this list. An overview of the variables and BIM uses can be found at the end of this subsection. Finally, an analysis is given on the influence of the combination of variables on the adoption of the BIM uses.

- **Relative advantage (V1)**

The first variable to be discussed is the relative advantage. This variable was earlier defined as: “the degree to which an innovation is perceived as being better than the one it supersedes” (Rogers, 2003, p.229). The relative advantage played a significant role in influencing adoption of the BIM uses in the REHT project. Among the stakeholders, there was a clear sense that the BIM applications chosen for adoption offered a significant relative advantage, while of those not chosen for adoption, the relative advantage was unclear.

As such, a high relative advantage was perceived in the usage of the BIM use for commissioning. Commissioning of the EHT tunnel entailed the process of checking that the facilities of the tunnel functioned as intended and training the tunnel operators. Stakeholder from RWS underscored the importance of testing the tunnel and the lengthy period that is conventionally associated with this process. The conventional commissioning process of the tunnel requires the asset to be closed, which in the case of the EHT would mean a cost of around 2 million euros[2] in economical loss to society per

[2] This figure was sourced from a RWS interviewee who stated that the organization used such an amount to make downtime cost calculations for the REHT project.

day of downtime. In contrast to the traditional testing method, the team tried to move as much of the process to the front end, to reduce the risks associated with commissioning and thus limiting the chance of unnecessary downtime of the asset. The stakeholders noted that using BIM for commissioning had saved the project team a significant amount of time. How much time exactly was not known to the interviewed participants, but they stated that this was a crucial factor in deciding to implement the BIM use. The efforts of training operators were aimed at reducing the downtime of the asset. In contrast to the traditional method where the tunnel operators were trained after construction on the tunnel had finished, operators were now trained parallel to construction with the BIM model. The contractor also noted the relative advantage of using BIM for training of personnel as they trained the construction crew via the BIM model. These trainings were needed to familiarize the crew with the complex maintenance tasks and installing middle channel elements in the existing EHT tunnel. The contractor had a small available timeframe for carrying out the maintenance work and wanted to minimize the risk of uncertainties. BIM helped in preparing the construction team. Preparations for this exercise were finalized with a physical test on site. The project manager from RWS attributed the successful completion of the task to the usage of BIM for training the crew and operators.

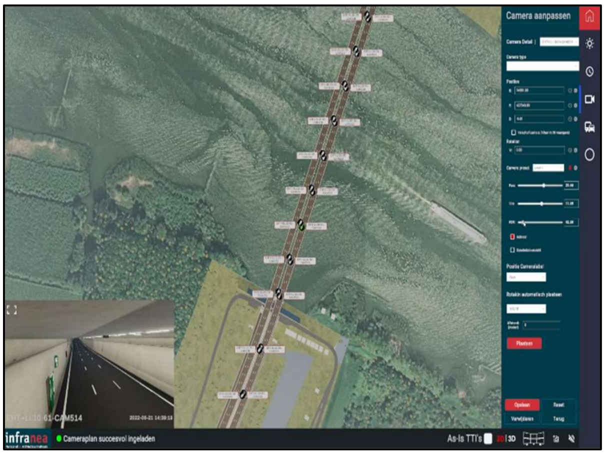
A high relative advantage was furthermore noted in the usage of the BIM use for asset information management. All interview participants stated that BIM can greatly improve the management of information, by delivering this information better and faster. The participants from Rijkswaterstaat described throughout the interviews how the "traditional method" of asset information management was lacking and had resulted in a situation of fragmented, inadequate, and outdated asset information. This traditional method of asset information management has resulted in cost overruns and time delays in previous projects. The following snippet out of an interview with an *** participant contextualizes this:

"If you were to start a new project, like Rijkswaterstaat did, the whole set of drawings wouldn't be correct. Good luck with that. The first thing the contractor did was to write a contract change… this alone costs 1 million euros and a year delay… and rightly so, because there was one huge mess and there still is one huge mess."

The participants from *** continued by stating that the project team had the aim of fixing the asset information by building a 3D model of the as-is condition of the tunnel. The process of gathering information on the as-is condition of the asset was done through scan-to-BIM, which was also stated as a relative advantage of using BIM for asset information management. This method could be used to gather information in less time, compared to the traditional method of surveying the tunnels, and resulted in less down time of the asset. These models were hereafter used to virtually guide various stakeholders around the tunnel, which again saved asset down-time. The contractor and engineering consultants also stated the relative advantages of using BIM for asset information management. These parties described how currently plenty of time is lost on projects by searching for the right information and recognized how BIM could resolve this issue by enhancing the way that data is shared. While the *** had stated that they recognized the relative advantage of using BIM for asset IM, they regarded this as an unrealistic option due to the complexities and incompatibilities associated with using BIM for asset IM. This will further be discussed under the variables of complexity and compatibility. The following text snippet contextualizes this.

"… I think you should be realistic in that. And of course it has many advantages, but I don't see it as a realistic picture. I think you should take a step forward with 2D, but digital 2D. For example, a GIS platform and then take the step towards 3D solutions".

Lastly, a high relative advantage was noted in the usage of BIM for simulation of processes and events. Safety plays a crucial factor through the design and operations of tunnels and RWS recognized the value of BIM in developing this. RWS described during the interviews how BIM was used to simulate the camera angles in the tunnel and to run simulations of the system behavior. As such, the project team used simulations to test and validate the reconfiguration of the tunnels camera system (see figure 8: Visualization of camera system with BIM. Emergency scenario's, such as that of fire in the tunnel (see figure 9: simulating system behavior with BIM), were used to access the system behavior. These simulations helped enhance the safety of tunnel.



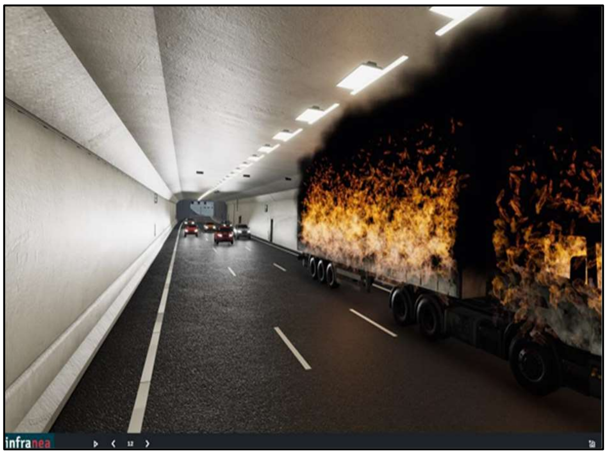


Figure 9: Visualization of Camera system with BIM

Figure 10: Simulating system Behavior with BIM

These activities were also methods of trying to minimize downtime of the asset, as in the traditional way of working the camera angles would be tested and validated after construction was finished. The relative advantage of this BIM use was clear to all stakeholders. The stakeholders from RWS had expressed their desire of the contractor to further utilize this BIM use, as they noted the relative advantage of using simulation BIM to inform the public. The contractor had stated that a lot more could have been done with the BIM model as well.

A low relative advantage was perceived of the usage of BIM for RAM analysis and directly stated to inhibiting its adoption on the REHT project. RWS stated that it is currently unclear what the relative advantage is of using BIM for RAM analysis and that this novel method would require much adjusting of processes (more on this in compatibility). The following snippet illustrates this lack of a perceived relative advantage of using BIM for RAM analysis.

"But there is no focus on that. This has always worked. I don't think it is clear what will yield more in terms of the old method and possibly the new method (RAM analysis with BIM) and it entails a lot of new processes. so, you must make choices. Is it just that the old method works, and we will not use it? no, in principle, we are looking at the low-hanging fruit. We look at that, and this (RAM analysis with BIM) is something that might never come to light".

A positive relative advantage was a driver to the BIM uses but was on its own not enough to lead to the adoption of all BIM uses with a highly perceived relative advantage. The BIM uses for facilities management, structural health monitoring, and performance analysis had a high relative advantage too, but were not adopted because of factors which outweighed the relative advantage. These will be discussed further on. One of such factors was their incompatibility with current processes, software's, and standards. The perceived compatibility of BIM uses played a significant role in influencing adoption. The following text will discuss the influence of this variable.

- **Compatibility (V2)**

The "compatibility" was defined as: "the degree to which the innovation is perceived as being consistent with the current values, past experiences and needs of the potential adopters" (Rogers, 2003, p.240). During the interviews, two themes emerged on the topic of compatibility, namely: the compatibility with existing processes and the compatibility with software systems. A lack of compatibility was noted in both themes, and this had a limiting effect on the adoption of the BIM uses on the REHT project.

The incompatibility with current processes was significant for all BIM uses, as could be expected, as researchers have previously pointed out how BIM requires a completely different way of working (Ahmad et al., 2016). The stakeholders were noticed to being hesitant toward BIM uses which didn't align with their past experiences and importantly of which the relative advantage was also unclear.

This was for example the case with the BIM use for RAM analysis. This requires such a different approach that the utilization was not considered by the project team. The stakeholders from RWS and the contractor in charge of conducting the RAM analysis both noted the vast differences in processes and their faith in the established method. Developing these processes would take considerable efforts, and with the relative advantage of this BIM use unclear, this led to this BIM use not being considered for the project. With the BIM uses of which the relative advantage was clearer, the compatibility proved less of a barrier and efforts were made to develop these new processes. When asked where the bottlenecks were on using BIM for commissioning, a RWS participant stated that there is a lack of knowledge at the organization on testing and commissioning (with BIM) and that these test protocols are currently still being developed. The following snippet illustrates this lack of knowledge at the organization and their confidence in current work processes and the in the market. RWS has booked progress in developing processes for commissioning, but as stated by the ***, more research needs to be done to make these processes clearer.

"Q: What were the bottlenecks to using BIM for commissioning?"

"A: The way we work now, and the market knows more. We have more confidence in the market. We have a lot of knowledge, but we don't know how it works. It's a lack of knowledge. We work the way we work. If you are going to request a test, or if you are going to do a commission, you need to know what you want in return. Do you want validation in return? But not necessarily in good terms"

The implementation of the BIM use for asset IM involved new processes as well. The compatibility issues were noted to being greater on the side of RWS than for the contractor or engineering firms. One of the most crucial steps in this new process of asset IM with BIM, as stated by the ***, was to develop the decomposition of the asset at the start of the project and put this in an agreement. This ensures that the data is structured and transferred in a specific way such that it enables a smooth integration of the data into the asset management systems of the RWS. This step in the process prevents compatibility issues later in the O&M phase. The decomposition of the tunnel was arranged with the NEN2767-4 and the SATO coding. The NEN2767-4 was used for the civil environment. A combination of NEN2767-4 and SATO were used for the mechanical and the electrical systems. The following snippet illustrates how strongly the RWS felt on the importance of this step:

"…The decomposition of the systems, how are you going to name them, how are you going to number them…what coding are you going to use? That is something that I think you should really put as a mega big statement, that you must make an agreement about that at the start of the project. That it is being implemented and that it (the data) is delivered in this way. So that it can be integrated one-on-one into the management systems"

These codes were included in the BIM model, the asset management systems, and the engineering packages. This was a unique key, which enabled querying of the different data sources. The process of data handover remains a difficult issue however and still needs further development. The *** illustrated this by stating that the software systems of RWS are not capable of facilitating 3D models.

This introduces the second theme of compatibility issues, revolving around the software systems, most notable for the usage of BIM for asset information management. The widely used software for asset information management at RWS is IFS Ultimo and a shift had to be made to working with BIM software's. As stated earlier, the asset decomposition is structured to realize an integration between the data in the BIM models and the IFS Ultimo software. The issue is however that currently employees of RWS have plenty experience with IFS Ultimo, but few have experience with working with the BIM software's.

Compatibility issues occurred between the contractor and the team of RWS on the software's used. The first 3D model of the EHT, which captured the as-is condition of the asset was built in AutoCAD. This model proved to be of less value to the contractor as they stated that they required REVIT models, REVIT families etc. The following snippet illustrates this:

"The Heinenoord was also scanned by the RWS. They made a 3D model of it and we as a contractor couldn't do anything with it, because it was of such low quality. It was of such a low quality that there were just 3D objects in AutoCAD. We couldn't do anything with that, we just needed REVIT Model… We literally threw away the model and started all over again."

A participant from the *** stated his doubts on the adoption of BIM for asset IM, as they noted that the systems of RWS are not compatible with 3D models and saw it as a futile effort to deliver the BIM models back to the asset owner. A stakeholder from RWS confirmed this lack of compatibility of current systems with 3D models at RWS but mentioned that the organization was taking steps to address this. The organization is currently capable of storing 3D models in an operational environment, but further integration is still required, as not all employees have access to this environment. Progress has already been made in removing barriers related to hardware at RWS. This was due to the implementation of air-BIM, which eliminated the barrier created by the requirement of supplying laptops capable of running BIM software. The contractor finally stated that they themselves had no compatibility issues with working in BIM as they noted that they had plenty of experience with the software.

- **Complexity (V3)**

The complexity of an innovation is described as: "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers,2003, p.257). Complexity had a significant influence on the adoption of BIM uses for AM on the REHT project. The complexity of certain BIM uses i.e. the BIM use for RAM analysis or performance optimization were perceived as too complex, and this hindered their adoption. As discussed above, these BIM uses are not compatible with the current way of working and require new processes to be developed; a process which is perceived as complex by participants. The stakeholders are also not very knowledgeable with these BIM uses and this creates an additional degree of perceived complexity. The usage of BIM for asset IM also suffered from perceived complexities. The first of such involves the perceived complexity of the software's interface. The contractor described how BIM is less useful in practice as in their experience asset managers have difficulties with navigating through the 3D interface. The contractor stated that currently most asset managers still use 2D drawings and that the jump to a 3D interface is too big for them. Navigating through these 3D interfaces has shown to be especially complex and unpractical in the field, such as in tunnels. The following snippets of an interview with the *** illustrate the complexity of the 3D interface of using the BIM models for asset IM:

"...I wonder if a 3D model for the management and maintenance phase offers a lot of added value, because if you are working outside with management and maintenance ...it is very difficult to navigate through a 3D model. To really click on an object and see what information is attached to it."

"...they (RWS) are still used to working with drawings. Then the step to a completely 3D environment is very large".

The participants from *** shared the opinion that the 3D interface is perceived as complex by asset managers. RWS did however make asset managers test working with the 3D environment in the design phase of the asset and stated that this worked quite well. The asset managers stated that it was worth working with the software. This test was however done on the3D models in the AutoCAD cloud environment. Repeating this test in a 3D environment with a dedicated BIM software could prove more complex. The contractor perceived (2D) GIS as a more realistic option for storing asset information as they perceived this interface to be less complex for asset managers.

- **Trial-ability (V4)**

According to the DOI theory, trialability is "the degree to which an innovation may be experimented with on a limited basis" (Rogers, 2003, p.258). The more an innovation can be tested with on a smaller scale, the higher the likelihood that it will be adopted. This variable was of significance on the adoption of the BIM uses on the REHT project, as extensive testing of BIM for asset IM within RWS gave stakeholders the confidence for its adoption. As shown above, one of such tests included familiarizing the asset managers with working in a 3D BIM environment. RWS participants stated that it was relatively easy for them to organize such a test, as they already had the BIM model and not much else was required. These participants continued by revealing that currently other BIM uses are still being tested within the organization and if these are successful, they will be adopted on other projects as well. The organization is still testing the BIM uses for asset condition monitoring and health assessment and facilities management internally and on other projects. Because these are still in the testing phase, they were not chosen to be implemented in the REHT project. The contractor had also stated that they are testing the BIM use for facilities management within their own organization. The ability to test and experiment with the BIM use within the organization gives confidence to its widespread adoption in projects. Interview participants could however not explicitly comment on the degree of trial-ability of the last two BIM uses as they were not involved in their testing.

- **Observability (V5)**

The observability of the innovation relates to: "the degree to which the results of an innovation are visible to others" (Rogers,2003, p.258). The observability has had a significant role in the adoption of the BIM uses for AM. Participants stated that the BIM use for commissioning, where the training of personnel occurred with a BIM model linked to a Unity environment, was observed at multiple conferences in the Netherlands. This visibility of the BIM use was a driving factor for the project team of RWS to implement it. The positive results of using BIM for commissioning had also been noted on other projects. i.e. the tunnel project in Amsterdam known as AWA (in Dutch: aanpak wegtunnels Amsterdam). The adoption of this BIM use had resulted in significant shortening of the AWA project. The visibility of such a positive result of adopting the BIM use acted as a driver to its adoption on the REHT project. The following snippet contextualizes this as a *** from the engineering firm explains how the BIM use for simulating the camera angles and training new operators were first observed at AWA and later adopted on the REHT project.

"AWA was the main one. A few road tunnels in Amsterdam. The tunnels in the Piet Heijn tunnel, Arena tunnel and the Michiel de Ruiter tunnel. They made the design for those, and they also made a camera module. So, before you place the cameras, because the cameras are important for the operator, they first made a 3D model. And after that, the 3D model is used, which is what they do at Heinenoord, to use it for new users, training, also when the functionalities are adjusted. Then you must operate the tunnel in a different way"

- **Norms of the system (V6)**

The norms of the system were previously defined as: "the established behavior patterns for the members of a social system" (Rogers,2003, p. 26). Rogers (2003) stated that the norms of a system might act as barriers to the adoption of innovations as the members of the system might be hesitant to deviate from the established norms. This phenomenon was brought up during the interviews on the case. It was especially the participants from RWS which noted that other members of their organization were inclined to stick to their regular way of working and did not want to deviate from this.

This phenomenon forms a barrier to the adoption of the BIM use for RAM analysis as there exist clearly defined and well-known processes for conducting RAM analysis (developed and prescribed by RWS). The interview participants from RWS and the contractor in charge of the RAM analysis for REHT stated their confidence and familiarity with the established process and are hesitant to deviate from it. This holds true for the BIM use of commissioning as well as RWS participants stated that much lobbying was required to convince people to deviate from the established process and adopt this BIM use. Deviating from the established processes were said to bring more risk to projects and increase their complexity.

The motivation of the stakeholders was further noted as being an influencing factor on the adoption of the BIM uses. The RWS participants stated that motivation is needed to make people embrace working with BIM use for asset IM, stating that certain people within their organization are afraid of deviating from the established way of working and moving forward. This fear stems from their perception of losing their job as a negative side effect of progress, as the adoption of the BIM use will lead to a more efficient work process with less employees required. The RWS participants stated that this is common among asset managers, as some are ambitious, but others are fearful of losing their jobs. This also shed light on an underlying issue which is a difference in motivation between the project teams and the asset managers which will be responsible for the asset in the remainder of the O&M phase. RWS participants noted that they've built the BIM models and systems, but that they are not responsible for the remainder of the O&M of the asset. The systems that they've built should ultimately be used by the asset managers of the region WNZ and they should have the intention to use these systems. The RWS participants were not sure of this intention of the asset managers. This doubt in the asset managers motivation to ultimately use the BIM models was shared by the contractor as well.

The stakeholders from RWS perceived a lack of motivation to utilize the BIM uses on the side of the contractor, to which the contractor agreed and stated regretting not taking bigger risks to innovate on the project. The following snippet from the interview with a stakeholder from the contractor illustrates their regret of not innovating more on the REHT project and their perceived lack of motivation in the asset managers of RWS to use their BIM models in the future:

"I think that we have taken too little risk on the Heinenoordtunnel. So, we set up a digital twin… We only made it because it had to be done from the contract and not because of the added value. You can do so much with it. So that's a shame. And of course, it's a shame that nothing will happen to it in the future, it will be delivered and that's done. All the time, all the effort for nothing".

The contractor noted that the high investment costs associated with innovating with BIM were the main cause of them not having innovated more. A lack of motivation to adopt the BIM uses was noted at different stakeholder parties. This lack of motivation to innovate and a tendency to stick to the preestablished behavior patterns formed a barrier to the adoption of BIM uses for AM on the REHT project.

- **The Role of Opinion Leaders (V7)**

Opinion leaders were previously defined as members of the social system with the ability to alter the behavior of other members within the social system toward a certain innovation (Rogers,2003). In the context of this research, such individuals were defined as the individuals within the upper management. The role of opinion leaders has been shown to have a significant influence on the adoption of the BIM uses. This was the case on the side of RWS, as the interview participants from the contractor and the engineering firm stated a willingness from their side to support the adoption of the BIM uses for AM. The participants from RWS stated that their management was less receptive of the innovations, however. In the interviews an explicit example was given of their hesitation toward BU3, but it can be assumed that this is the case for all BIM uses, as these innovations bring the same perceived risks and uncertainties and interview participants stated that the management was hesitant to support innovation in general.

Even though the relative advantage of the BIM use for commissioning was clear, it still required a lot of convincing to gain the support of the management. The following snippet of the interviews with *** illustrates this:

"Q: Was the upper management and other team members in support of this BIM use (BIM use for commissioning)?

A: Oh no, no, it's a lot of lobbying to get this done. It's definitely lobbying... So, this story you hear from me (about the advantageous of using the innovation), you have to constantly tell. And then it goes on to project management, or program managers. Then it goes on to thinking about it.… it is not self-evident."

The *** from *** noted a difference in attitude toward innovations between the middle- management and top management. While upper management, in charge of the renovation and replacement task (V&R opgave) stimulate innovation and take chances, the middle management has a more reserved attitude. The following snippet contextualizes this:

"The middle management doesn't want to hear about it, doesn't want to know about it. They don't like the way it works. So, they will also brake innovations and improvements in the organization. The people who have an interest in it, they see it and they stimulate it a lot. So, it's a bit of a two-way street with the organization."

*** of *** attributed this hesitation to support BIM uses to a lack of knowledge and familiarity with the innovation on the side of the middle management. This creates a perception of a more complicated project, filled with more risks. The middle management were said to be incapable of perceiving the added value of the BIM uses due their lack of knowledge on the subject, which led to them not allocating the required resources. The contractor faced another barrier when dealing with upper management on the asset owner's side and attributed this lack of support to the high costs of developing BIM models. They stated that the high initial costs make it difficult to justify the investment, when the benefits are not immediately seen, but years later in the O&M phase.

- **Structure of the social system (V8)**

The structure of the social system was described as the "the patterned arrangement of units in a social system" (Rogers, 2003, p.24), where not only the arrangement of the social system was under analysis, but also the size. During the interviews in this study there came no significant findings to light which pointed to a link between this variable and the adoption of the BIM uses on the REHT project.

- **Non-variable related findings (N-V)**

The text above presented the findings of the case along the lines of the variables in the framework. It should be noted that other discoveries were made during the interviews that do not necessarily fit the framework. An important issue that was discussed during the interviews was the lack of asset information requirements (AIR). The AIR is crucial for the BIM use of asset IM as it delineates the data and information requirements for establishing an asset information model (Munir et al., 2020). Without having this data need clearly defined, it is not possible to build BIM models which are optimized to support the asset management activities in the O&M phase. This fact was underscored by Munir et al. (2020) who state that the AIR forms a prerequisite for deriving full BIM business value. At the time of the interviews, the project manager from RWS was still waiting on the asset owner to deliver the AIR. This brings along the risk that a BIM model was built on the REHT project, which does not specifically cater to the data requirements of the asset owner in the remainder of the O&M phase. This barrier creates uncertainty and increases the perceived risk of adopting the BIM use. The following snippet from the interviews illustrates this:

"He (asset manager from RWS-WNZ) is my client from the digital twin. I have to ask him what information he wants from me. I hope that he is so far now, because we have been asking this for 4 years now."

The following table summarizes the previous text and shows the influence of the variables on the adoption of the BIM uses in a matrix. The matrix plots the BIM uses on the horizontal axis and the studied variables on the vertical axis. A positive influence is colored green and a negative influence orange. More nuanced findings were coded with yellow. The blank cells in this matrix indicate that no significant findings were made.

Table 8: Influence of variables on Adoption

		BIM uses on REHT						
		BU1	BU2	BU3	BU4	BU5	BU6	BU7
Variable	V1	Negative		Positive		Positive	Positive	Positive
	v2	Negative	Negative	Negative	Negative	Mixed	Negative	Mixed
	V3	Negative	Negative	Negative	Negative	Mixed	Negative	Positive
	V4	Negative				Positive	Negative	
	V5	Negative	Negative	Positive	Negative	Positive	Positive	Positive
	V6	Negative	Negative	Negative	Negative	Negative	Negative	Mixed
	V7	Negative	Negative	Negative	Negative	Negative	Negative	Negative
	V8							
	N-V					Negative		

The barriers and drivers that were discussed throughout the previous text are summarized in the following Table 13: List of Barriers and Drivers on PTZ. This table shows the relationship between barriers and drivers and the individual BIM uses.

Table 9: List of Barriers and Drivers on REHT Project

ID	Barrier	BU1	BU2	BU3	BU4	BU5	BU6	BU7
1	No perceived relative advantage of BIM use	x						
2	Challenge of keeping BIM models up to date decreases perceived relative advantage					x	x	
3	Stakeholders lack the knowledge and experience to utilize BIM use	x	x	x	x	x	x	x
4	BIM use is incompatible with needs of stakeholders	x						
5	BIM use incompatible with current practices, requiring new procedures	x	x	x	x	x	x	x
6	Lack of protocols for utilizing BIM use			x				
7	Challenges in asset information handover between project phases			x		x		x
8	Software systems of RWS are not fully capable of facilitating 3D models	x	x	x	x	x	x	x
9	Perceived complexity of working in a 3D software interface			x		x	x	
10	Lack of observable successes of BIM use on previous projects	x			x			
11	Stakeholders' resistance to change from known ways of working	x		x		x		
12	High initial costs of BIM models make top management hesitant to adopt BIM use			x		x		x
13	Lack of asset information requirements			x		x	x	
ID	**Driver**	**BU1**	**BU2**	**BU3**	**BU4**	**BU5**	**BU6**	**BU7**
1	Lack of usable information on the asset in its current condition creates a need for better asset IM					x		
2	High dependency on asset availability and operability (drives the adoption of innovations to reduce downtime)			x		x		x
3	Ability to gather as-is condition data faster through scan-to-BIM					x		
4	Training personnel using BIM models			x				x
5	Centralized and faster information management with BIM			x		x		x
6	Virtual guide through the asset via BIM					x		x
7	Simulating system behavior with BIM enhancing safety trainings					x		x
8	Ability to reduce downtime of the asset			x		x		x
9	NEN2767-4 and SATO offering structure for asset decomposition			x		x		
10	RWS upgrading systems to store 3D models in an operational environment	x	x	x	x	x	x	x
11	Contractors' experience and knowledge in using BIM			x		x	x	x
12	Stakeholders' familiarity with 3D work interfaces encourages innovation adoption			x		x	x	x
13	Observability of BIM successes on previous projects motivates stakeholders to adopt innovation			x		x	x	x
14	Good trial-ability of the BIM Use					x		

The following text provides an analysis of how the combination of variables, and the barriers and drivers associated with them, influenced the adoption of BIM uses on the REHT project. This analysis will be conducted per BIM use and is presented below:

1. BIM use 1: Drawing a comparison between the barriers and drivers of BU1 it is clear that the adoption of this BIM Use is heavily influenced by barriers. The stakeholders reported not perceiving a relative advantage of the BIM use. The innovation was further noted not being compatible with the needs and experience of the stakeholders. The stakeholders were further stated not willing to deviate from the known way of working i.e. conducting RAM analysis on the traditional method. This can be attributed to the lack of a perceived relative advantage. There were further no observations of the BU being successfully utilized in other projects. This lack of observability fails to motivate stakeholders to adopt BU1. Furthermore, was stated that the BIM use was not supported by the top management of RWS. It can therefore be assumed that this combination of predominately barriers is what caused BU1 not to be adopted on the REHT case.

2. BIM use 2: Continuing the analysis with BU2, results show that the stakeholders perceived a positive relative advantage to BU2, but failed to explicitly state what this perceived relative advantage was. This BIM use was perceived to be complex and incompatible with the current work processes and experience of the stakeholders, requiring the development of new processes. The success of its utilization on other projects was also unknown. Noteworthy is that this BIM use was stated as being developed and tested within RWS. It can be assumed that this BIM use was not yet ready for adoption on the REHT project, as it is in an earlier phase (phase 2) of the IDP as described Rogers (2003). The presence of only barriers and no drivers further explains why the BU failed to be considered for adoption on the case.

3. BIM use 3: The findings on BIM Use 3 show a multitude of barriers and drivers. The relative advantages of BU3 were perceived in its ability to reduce downtime of the asset and facilitating the training of personnel as part of the commissioning process. These drivers were what attracted stakeholders to the BU and managed to overcome barriers related to inexperience with the software and the new way of working. The observability of the success of adopting the BIM use on previous projects further drove the adoption of BU3 as they motivated stakeholders to use the innovation. The support of top management was limited though, and stakeholders had reported that much lobbying was needed to gain support for the adoption of the BIM use. This lack of support was attributed to the inability of top management to perceive the relative advantage of BU3. Nevertheless, the net result of the adoption influencing factors was positive and the relative advantage and observability can be attributed as the major factors that drove adoption of BU3 on the REHT case.

4. BIM use 4: Interviews stated that this BU was perceived as very complex, incompatible and they had not observed its implementation yet. Interviewees further indicated that they lacked the experience and expertise on BU4, which led to not as much in-depth insights being gathered for this BIM use. There responses on relative advantage and trial-ability were omitted from the findings as it was not clear if interviewees possessed the expertise to provide valid information on these. From the interviews it can be stated however that the perception of severe complexity and incompatibility alongside a lack of observable success of adopting BU4 were working as barriers to the adoption of the BU.

5. BIM use 5: Continuing the analysis of barriers and drivers with BU5, it is clear that a multitude of adoption influencing factors surrounded the adoption of the BIM use. The relative advantage of BU5 played an important role in influencing adoption as its perceived ability to gather information on the asset in its as-is condition and manage this in a more efficient and reliable way where what drove adoption initially. The BU was further perceived to be able to reduce downtime of the asset. Factors such as good trial-ability and observability were able to gain the support of stakeholders for adoption. This support was needed as the BIM use was also surrounded by compatibility issues which relate to the incompatibility of knowledge and experience of stakeholders. The asset managers were reported to having difficulties with the 3D interface of BIM software as they are not familiar with this type of program, but rather with IFS ultimo. As of the time of the case study, RWS systems were not capable of supporting BIM models in an operational environment, further pointing to compatibility issues. Furthermore, the challenge of keeping BIM models up to date during the O&M phase decreases the perceived relative advantage of this BIM use, as reliable and accurate information is critical to asset management activities. This issue persists and must be solved in the future as the interviewees had not reported that a solution to this problem is still not found. Nevertheless, the factors relating to the relative advantages and observability of BU5 were what drove adoption and were capable of overcoming the barriers.

6. BIM use 6: The findings revealed a positive perception of the relative advantage of using BU6. The BIM use also had a high observability and trial-ability as stakeholders had noted to having observed and tested this BIM use within their own organization. The BIM use was perceived to be complex and incompatible however with existing processes and experience of stakeholders. Furthermore, stakeholders and opinion leaders were hesitant to support BU6. Important to note it that the BIM use was stated to being developed and tested in house and at RWS. The contractor was further with their implementation of the BIM use as it was already fully utilized by them at their own head office. A difference can be noted between stakeholder's experience and expertise on BU6, because the asset owner lacked in experience and expertise in comparison to the contractor and had a lesser perception of the trial-ability of the BU. As such, these factors worked as barriers on the side of the asset owner. It can be assumed that this combination of barriers, in combination with the fact that this BU was still being developed inhouse, resulted in the BIM use not being considered for adoption.

7. BIM use 7: The presence of a multitude of barriers and drivers can be noted around the adoption of BU7. First, it is important to note that stakeholders perceived the relative advantages of this BU in its ability to reduce downtime of the asset, simulate system behavior leading to support for safety trainings, and the ability to train operational and maintenance personnel. The observability of the BIM use further drove its adoption. It must further be noted that the contractors had perceived the BIM use to be relatively easy, compatible and as having good degree of trial-ability. No data could be collected from the asset owner's perception as they outsourced the utilization of this BIM use to the contractor. Nevertheless, it can be concluded that this combination of mostly drivers led to the adoption of this BIM use on the case.

As can be seen, the REHT project was filled with innovative BIM uses, which were driven by a combination of their relative advantage, observability, and perceived lack of complexity, among other variables. The following section will discuss the case study on the South Holland Tunnels Program.

5.2 Case 2: South Holland Tunnels Program (PTZ)

5.2.1 Background information

The South Holland Tunnels Program (in Dutch: Programma Tunnels Zuid-Holland, PTZ) is a comprehensive initiative aimed at maintaining and renovating seven major tunnels in the Netherlands. These tunnels, which are spread out through the West Netherlands South (in Dutch: West Nederland Zuid, WNZ) region, include the Noordtunnel, Drechttunnel, first and second Benelux tunnel, 2e Heinenoordtunnel, Thomassentunnel, and Sijtwendetunnel. The following Figure 15, locations of tunnels of PTZ, depicts the position of the tunnels on a map of the WNZ region. The project will be carried out with a programmatic approach, where the first tunnels to be renovated are the Noordtunnel and then the Drechttunnel and Benelux tunnel. This programmatic approach was chosen by the asset owner as an initiative to stimulate innovation and cross-project learning. Innovations from one tunnel project will be carrier over to the sequential projects.

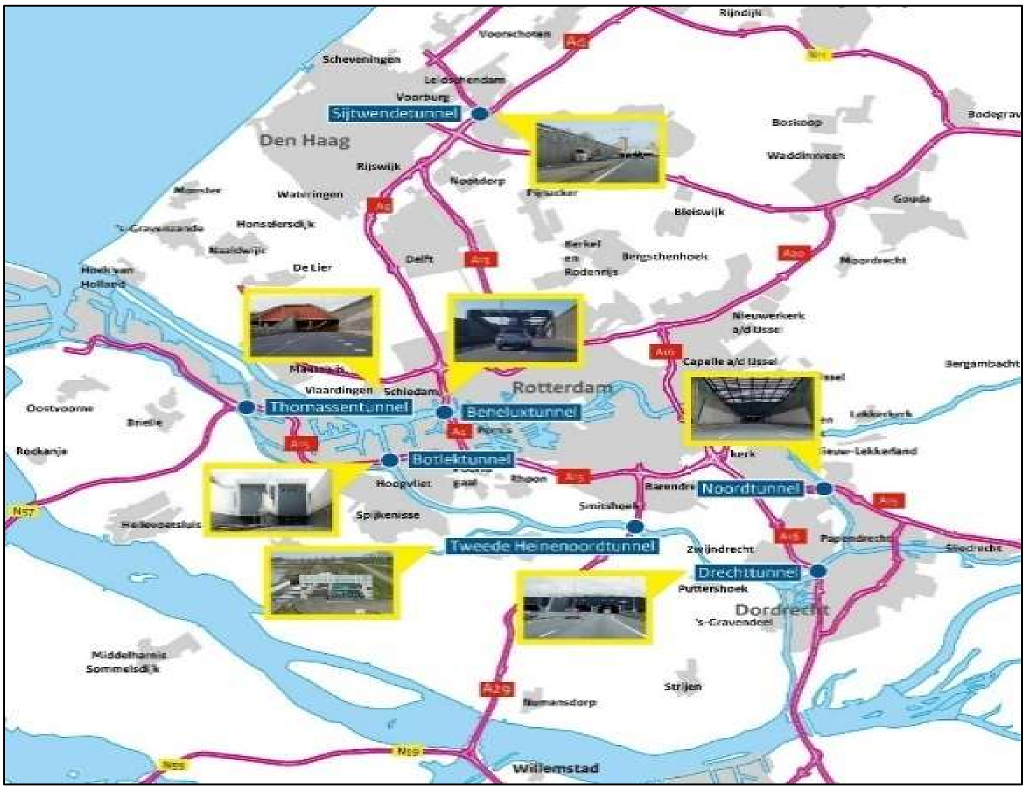


Figure 15: Locations of Tunnels of PTZ (sourced from: (Rijkswaterstaat, 2024))

Project stakeholders

The owner of the tunnels is Rijkswaterstaat. The tunnels are maintained by the asset management team of Rijkswaterstaat known as RWS-WNZ. The management of the tunnels is outsourced to Croonwolter & Dros until 2026. RWS launched PTZ in 2022 and once again contracted TEC for the engineering services and preparations of the tendering stage. Building upon the successful precedent set by the First Heinenoord tunnel project, RWS decided to utilize BIM for the maintenance of the tunnels. As no preexisting BIM model existed, one needed to be built first. This endeavor also served the purpose of fixing the asset information and establishing a trustworthy database for the as-is condition of the asset. Similar to the REHT project, a BIM model was built with the aid of scan-to-BIM technology. The engineering firm *** was responsible for building the BIM model and the scanning of the tunnels was done by the company ***. Table 8 presents an overview of the key stakeholders on PTZ.

Scope of projects

The scope of the projects entails maintenance and renovation of the tunnel technical installations and the civil engineering components. The scope further contains the development of a BIM-based digital twin to support asset management in the remainder of the O&M phase of the asset's life cycle.

Table 10: List of Key Stakeholders on PTZ

Stakeholder Role	Name	Note
Owner	Rijkswaterstaat	
Administrator	Rijkswaterstaat-WNZ	Outsourced to ***
Engineering Services	TEC	Collaboration between *** and W+B
BIM Modeling	***	Scan-to-BIM conducted by ***

BIM use on project

BIM was first used to capture the as-is condition of the tunnels. Scan-to-BIM and BIM modeling were tested in a smaller scale on the Noord tunnel to ensure that the quality of the scans was up to the standards of RWS. The Noord tunnel, the first of the seven tunnels to undergo renovation, holds a significant place in the PTZ program. Located on the A15 highway and lying under the Noord River, the tunnel has been in operations since 1992. Once this proved to be successful, the directive was given to proceed with building the BIM model for the whole tunnel. Just like with the EHT, the project team of RWS has the aim of using the BIM model for the tendering of the work and to support the remainder of the O&M phase. Learning from the REHT project, the BIM model of the Noord tunnel was directly built with the program Autodesk REVIT.

The RWS project team requested the same BIM uses for AM from the BIM model as on the REHT project. In addition to capturing and storing the asset information, BIM would be used to support the commissioning of the asset. The tunnel operators and maintenance personnel are to be trained in a game like environment with BIM. The following table provides an overview of the BIM uses which were considered and are (to be) implemented in this project.

Table 11: BIM Uses on PTZ

BIM Use	**Description**	**Code**
BU1	Asset RAM Analysis	C
BU2	Asset Condition Monitoring & Health Assessment	C
BU3	Asset Commissioning	A
BU4	Asset Performance Analysis	C
BU5	Asset Information Management	A
BU6	BIM-based Facilities Management	B
BU7	Simulation of Processes and Events	A
Code	**Meaning**	
A	considered and implemented in case studies	
B	considered but not (yet) implemented in case studies	
C	not considered in case studies	

The research will predominately focus on the BIM uses which were considered and (not) utilized as it can be certain that the stakeholders knew of their existence and the arguments on why they were (not) selected to be utilized can shed light on the barriers and drivers to these BIM uses for AM. BIM uses which were not considered will be touched upon. The following subsection will present the findings from the interviews with key stakeholders on the PTZ project, with a specific focus on the Noord tunnel, Drechttunnel and Benelux tunnel.

5.2.2 Findings from case PTZ

The subsequent section presents the findings of the PTZ case along the lines of the developed framework in section 3 of the report. It elucidates how each of the 8 variables influenced the adoption of the BIM uses, including the associated barriers and drivers. An additional 9th, non-variable related category, is discussed at the end of the sub-section to encompass findings that did not align with the other 8 categories.

Relative advantage (V1)

The first variable to be discussed is the relative advantage i.e. the degree to which the innovation is perceived to be better than the technology or process that it replaces (Rogers,2003). This variable played a significant role in influencing the adoption of the BIM uses on the PTZ project.

The perceived relative advantage in using the BIM use for commissioning and the BIM use for simulating processes and events was seen in their ability to reduce the project duration and prevent downtime of the asset. These BIM uses enable Rijkswaterstaat to simulate certain events and situations without having to close the tunnels. Contrary to the traditional method of commissioning and training of personnel, which only occurs after the work in the tunnel has been completed, the utilization of this BIM use means that this activity can be done during the construction. BIM is further used to simulate and configure the camera angles of the asset, which are a crucial element to safely operate the asset. In the conventional method, these angles are configured only after the renovation or construction of the tunnel is completed, but this could now be done in parallel to the renovation and maintenance work. This activity allows the project team to reduce down time of the asset. An *** from the engineering firm stated that it was difficult to state the relative advantage of these BIM uses in financial terms, but that the time savings could be made concrete. The following snippet from the interview with *** illustrates the perceived relative advantage in using BIM for commissioning of the tunnels with an anecdote of a previous project:

"The costs are always high (of the BIM model), they are immediately visible, but what does it deliver now? That is of course very difficult to express in euros. I don't know if you remember the example of the digital twin with the car modules. It made sure that we could open the Piet Hein tunnel 3 months earlier than a traditional process. Yes, also because of the training process. When the tunnel is completely renovated, and everything is gone...all the residents think, why can't I drive through it? I don't see anything happening... everything is gone. But then those people (tunnel operators, maintenance, and safety crews) are being educated. They must do an exam and it must be planned. But now we did that during the renovation and maintenance work. That's something you can make concrete. You can save three months with that."

The perceived relative advantage in using BIM for asset IM was seen in its ability to deliver information faster and more reliable in a centralized place. It was further stated to enhance communication as the 3D interface was a more eloquent solution to facilitate communication between stakeholders, compared to the conventional 2D drawings. The interview participants from the engineering firm perceived this BIM use to deliver cost savings to the project, as less time is needed to search for the correct information and there is no need to re-do certain data gathering activities in the field. It is noteworthy that the relative advantage of using BIM for asset information management, particularly in terms of cost savings, was not entirely clear to an interviewee from RWS, who was an asset manager.

To his knowledge, no business case existed that demonstrated the cost savings associated with using BIM for asset information management.

In summary, the interview participants perceived a high relative advantage of the BIM uses for commissioning, asset information management and simulation of processes and events. This perception was stated as being a driver to the adoption of the BIM uses on the project. Conversely, the unclear relative advantage of BIM uses, i.e. the BIM use for RAM analysis, acted as a barrier to its adoption. Lastly it can be reported that the relative advantage of using BIM for facilities management was noted by the different stakeholders, but that this BIM use is still in development and as such is not (yet) implemented on the project.

- **Compatibility (V2)**

The following findings relate to the variable compatibility, which was described as the degree to which the adopted innovation matches the experiences and needs of the adopter (Rogers,2003). Compatibility was found to have influenced the adoption of BIM uses in PTZ. The BIM uses for commissioning, simulation of processes and events, and asset information management were compatible with the needs and experiences of the individual units of adoption, which drove their adoption.

A stakeholder from the engineering firm TEC stated that these three BIM uses support 3 basic needs of the asset owner on such a tunnel renovation project i.e. to communicate the renovation and maintenance tasks through to other stakeholders and to test and simulate scenarios and the camera angles of the tunnels. In addition to these three, other BIM uses, such as BIM for Facilities management are under discussion, but these have not yet been formalized. The engineering firm is currently still determining with the asset managers how the digital twins of the tunnels i.e. BIM models should facilitate them in their asset management activities in the remainder of the O&M phase.

The experiences of the different units of adoption were also found to be compatible with the implemented BIM uses. The stakeholders from RWS and TEC had gathered experience with these BIM uses on previous projects; most notably the REHT and AWA projects. Learning from the project REHT, the models of the tunnels were directly built with the software Autodesk REVIT. *** has also gathered experience with these BIM uses on previous projects but stated that this was their first tunneling project. This lack of compatibility between this stakeholder's experience with implementing BIM on this asset type led to difficulties on the project. These difficulties will be discussed more under the following variable: complexities.

For the stakeholders from the other engineering firms, a higher degree of compatibility was observed. Firstly, the experience of these stakeholders was compatible with the asset type. The compatibility was further noticed in the processes and software's which were carried over from previous projects. While these stakeholders had a higher degree of compatibility due to their experience, it is worth noting that they also faced some challenges related to compatibility, stemming from the asset type and the rapid evolution of software. The rapid evolution of technology was stated as causing a degree of incompatibility between the experience of using BIM on previous projects and PTZ. The following snippet from an interview with a *** from *** illustrates this:

"Even if it is a tunnel, it is a tunnel on itself; that is a lesson learned. It can be just a bit different, and just a bit different can lead to a lot of things. So, we see for a part that we can reuse a lot of Heinenoord on PTZ, but we also see that PTZ has a different approach from the customer. The technology is years further... Heinenoord was launched in 2018, and PTZ in 2022, so 4 years later. Time is passing by quickly,

even though it seems like a conservative market. But 4 years is a big difference to say we can use everything one on one."

Regarding software, it is also important to note the requirement of asset managers from RWS to build a connection between the BIM model (in Autodesk REVIT) and the software program IFS Ultimo. This is caused by a lack of compatibility between the experience of these asset managers and the Autodesk REVIT software. Asset managers of RWS have experience with using IFS Ultimo for asset information management and lack experience in using BIM software. Although this connection solves the immediate challenge of asset managers lacking experience with BIM software, it may nevertheless hinder the full adoption of the BIM use for asset information management.

Certain incompatibilities were observed during the interviews; however, it is important to highlight that these did not prevent the adoption of the selected BIM uses. Instead, they added a degree of complexity to the process. The relative advantages of the BIM uses were stated as outweighing the compatibility issues.

- **Complexity (V3)**

The third variable within the developed framework is that of the complexity. This variable has been described as "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers,2003, p.257). This variable had influenced adoption of the BIM uses in PTZ. The perception of complexity of the BIM uses differed per stakeholder group and per BIM use. The stakeholder from the firm TEC perceived the implementation of the BIM uses as relatively easy. TEC had reportedly sufficient experience with working with the BIM uses and working with BIM software was not an issue. The stakeholder from *** by contrast stated that the firm had perceived the implementation of the BIM uses for commissioning, and asset information management as complex. They attributed this perception of complexity to their lack of familiarity with utilizing the BIM uses for the asset type of tunnels. The following snippet from the interview with *** from *** illustrates the challenges that they faced with building the models in BIM:

*"…for us, it was complex because we had not yet done a tunnel project at ***. We did make BIM models, but not for tunnels…so the object was new to us. And you noticed that you must know the tunnels… We ran into the fact that people don't know what the tunnels look like. If you are building a BIM model, it is difficult to predict how it will look like… we also assumed that the scan data could be imported into the BIM model. But that was not possible. Because of the areal data, a number of connections had to be made manually. A lot of things had to be done manually. It was not that easy to implement scan-to-BIM. That was not the case with most tunnels or, not with any tunnel. Then you must figure out how to do that. It is manual work to get the lines together. They do depend on a certain accuracy with the BIM models, and we did not reach that".*

As evident from the snippet above, constructing the BIM models of the tunnels posed a complex and time-consuming challenge for ***. The utilization of BIM for asset information management proved frustrating, primarily because asset information had to be inputted and aligned manually. Despite these challenges, the project manager emphasized that these complexities did not discourage the team of *** to implement the BIM uses. This persistence was attributed to the perceived relative advantage of the BIM uses, which outweighed the encountered barriers.

Finaly, it is noteworthy that *** involved the asset managers from RWS at the front end of the process to evaluate the commissioning of the asset using BIM. During their assessment, it became apparent that the asset managers found working with BIM to be complex. This complexity was attributed to a perceived lack of knowledge and experience in working with BIM software.

- **Trial-ability (V4)**

The variable "trial-ability" relates to the degree to which an innovation can be tested in a smaller scale, prior to its full adoption (Rogers,2003). This variable had a significant influence on the adoption of the BIM uses, as the BIM uses for commissioning and asset information management were tested on a smaller scale prior to their full-scale usage on the different tunnels. Through this activity stakeholders from the engineering firm and RWS gained more confidence in the adoption of the BIM uses and associated less risks with their adoption.

*** had built a test setup in the North tunnel for testing the BIM use for commissioning. During these tests the asset managers of *** were also included. The interview participant from *** stated that the scan-to-BIM functionality was also tested on the Benelux tunnel prior to its full implementation. This was done to validate that *** could deliver the desired results from the full-scale scanning activities to RWS and remove the risk of something going wrong. Testing the process was crucial, because the project team had a short window of time for executing the real scanning of the tunnel, which left little room for mistakes. The interviewee of *** illustrated the need and advantage of testing the scan-to-BIM in the following snippet from the interview:

"A big challenge is also the tunnel closures, because that has a lot of impact on the environment. For the Benelux tunnel you must have arranged that half a year in advance. Before you have one night to do the work... And if something happens that you haven't tested enough. If it doesn't work, you have to wait another half a year. So that's a very big challenge in the tunnel world".

Once these tests were concluded and the desired results had been achieved, the green light was given by RWS to scan the remainder of the tunnel. It was noted that the BIM uses for commissioning and asset information management had a high degree of trial-ability. The trial-ability of the implemented BIM uses was stated as being a driver to their adoption. While a high degree of trial-ability was stated as a driver, the lack of trial-ability was not explicitly stated as a barrier to the adoption of BIM uses.

- **Observability (V5)**

"Observability" is the fifth variable of the developed framework. This variable was described as "the degree to which the results of an innovation are visible to others" (Rogers,2003, p.258). This variable was a significant influence on the adoption of the BIM uses on PTZ, with successes on the REHT and AWA projects being stated as motivating stakeholders at PTZ to utilize them as well. The successful implementation of the BIM uses for commissioning, simulation of processes and events, and asset information had a high observability and were observed in these previous projects. The interview participants further stated that they had observed these BIM uses on national (BIM) days and were from that point onward motivated to adopt the innovation. Such was the case of developing a car module for the tunnels via simulations and BIM. Simultaneously, a lack of observability of other BIM uses was highlighted as inhibiting the adoption of BIM uses. Stakeholders from the engineering firm were uncertain of the positive results of using the BIM use for RAM analysis for example, as they had no prior exposure to this BIM use. It can therefore be noted that a high observability of the BIM uses for commissioning, simulation of processes and events, and asset information worked as a driver to their adoption while a low observability of the BIM use for RAM analysis worked as a barrier to its adoption.

- **Norms & culture of the system (V6)**

The variable Norms & culture of the system relates to "the established behavior patterns for the members of a social system" (Rogers,2003, p. 26). The norms and culture of the social system can have an impeding or driving effect on the adoption of innovations, depending on if the units of adoption are willing to deviate from the established behavior patterns or not (Rogers,2003). From the interviews it could be noted that this variable was a driver for the adoption of the BIM uses on the side of the engineering firms. The variable was noticed as being more nuanced on the side of RWS as certain stakeholders from this party were hesitant to deviate from the established way of working, while others had an intrinsic motivation for innovation.

The interviewee from *** had stated *** team's willingness to deviate from their familiar way of working and explore new processes stemming from the implementation of the BIM uses for commissioning and asset information management on an unfamiliar asset type to them. Even though there were compatibility and complexity issues on the side of this stakeholder during the project, the team was motivated by the perceived relative advantages of implementing the BIM uses. This resulted in a good collaboration between the parties of ***, RWS and *** (the organization responsible for the scanning of the tunnels) during the implementation of the two BIM uses.

As stated earlier, this variable was more nuanced on the side of RWS. Certain people and groups within the organization are more likely to embrace the BIM uses and deviate from the known way of working than others. A *** interviewee described how certain people, who recognize the relative advantages of the BIM uses support their adoption, while others, who are unfamiliar with the relative advantages, were more hesitant to deviate from the known way of working. Interviewees from the engineering firms suggested this to originate from a lack of knowledge on the BIM uses on the side of some stakeholders at RWS, which made it difficult for those people to perceive the relative advantages of adopting the BIM uses. An interview participant from RWS stated that many asset managers at RWS lack knowledge on the usage of BIM to perceive the relative advantages of the BIM uses. This lack of a perceived relative advantage, paired with a situation of a high workload, results in people being less likely to deviate from the established way of working.

- **The Role of Opinion Leaders (V7)**

The final variable in the developed framework is "the role of opinion leaders". This variable was shown to have a significant influence on the adoption of the BIM uses. Opinion leaders were described as members of the social system with the ability to alter the behavior of other members within the social system toward innovations (Rogers,2003). In the context of this study, these figures were previously stated as the individuals within the upper management, yet during the interviews it became apparent that the technical manager on the project was also an opinion leader. This figure possessed the capability of altering the behavior of the other members in the social system toward the adoption of the BIM uses.

It was stated by an *** interviewee that the upper management of RWS was in support of digitization and by extension the BIM uses for AM. Further came to light how the technical manager on the project drove the adoption of the BIM uses. This was illustrated with the development of the BIM use for facilities management on the project. At the start of the project, it was the desire of RWS to develop this BIM use on PTZ. From interviews with a RWS stakeholder it became clear that the (upper) management had freed up a budget to develop this innovation. But when a key player, in this case the technical manager driving the innovation left the project, the development slowed down. The following snippet from this interviewee from *** illustrates this:

"...In principle the budget has been allocated to get this going within the first few years, but you see that if nobody is focusing on it anymore... I don't know if it ever will be at PTZ. But it is a pretty hard demand that this is done well, and it has to do with the technical manager, so if the technical manager puts the focus on. It always has to do with the people. If … (name of technical manager) was involved, it would have been developed further. But if you don't have knowledge of it… You don't know what the importance of it is... then it dies with the departure of an important player."

- **Structure of the social system (V8)**

The following variable to be discussed is the structure of the social system i.e. the size and arrangement of adoption units in the social system. During the interviews in this study there came no significant findings to light which pointed to a link between this variable and the adoption of the BIM uses on the PTZ project. It can be noted however that there was a good collaboration between the adoption units.

- **Non-variable related findings (N-V)**

The text above presented the findings of the case along the lines of the variables in the developed framework in section 3 of the report. Non-variable related findings came to light during the interviews which were stated to have an influence on the adoption of the BIM uses. These findings are discussed in the following text:

An important finding was related to the need to develop Asset Information requirements (AIR) for PTZ. An interviewee from the engineering firm stated that this was not yet known to the asset managers and posed a major problem to the development of the BIM uses, especially for the BIM use for asset information management. As currently these AIRs are unknown, there exists the risk that BIM models are being built for asset management in the O&M phase, which are not capable of fulfilling the information needs of the asset managers. The engineering firm is currently developing the asset information requirements with the asset managers of the tunnels of PTZ.

The second finding was not (yet) encountered as barrier to the BIM uses on the project, but interviewees from the engineering firm and RWS stated its influence on the adoption process of innovations in previous projects. This finding relates to the influence of the time pressures of the project on the adoption of BIM uses. The time pressure causes the project team to divert its attention from innovations and focus on the primary processes i.e. the maintenance and renovations work to the tunnel. The stakeholders expressed the importance of incorporating the BIM uses for AM in the contract of PTZ as this would ensure that they are not neglected to focus on the more immediate demands to finish the project in the available time. The following snippets from the interviews illustrate this with a reflection of a project engineer from the engineering firm on the adoption of BIM uses on previous projects:

"What I say about AWA, luckily it worked there. It's not always possible, and if it doesn't work, it's often that the project's time span gets the highest priority. So that other things that aren't needed immediately for the end result, can take a little longer and go into the icebox".

The following table summarizes the previous text and illustrates the influence of the variables on the adoption of the BIM uses in a matrix. The matrix plots the BIM uses on the horizontal axis and the studied variables on the vertical axis. A positive influence is colored green and a negative influence orange. More nuanced findings were coded with yellow. The blank cells in this matrix indicate that no significant findings were made between the variables and their influence on adoption of the BIM use.

Table 12: Influence of Variables on Adoption on PTZ

		BIM use PTZ						
		BU1	BU2	BU3	BU4	BU5	BU6	BU7
Variable	V1	Negative		Positive		Positive	Positive	Positive
	V2	Negative	Negative	Positive	Negative	Positive	Negative	Positive
	V3	Negative	Negative	Negative	Negative	Negative	Negative	
	V4	Negative		Positive		Positive		
	V5	Negative	Negative	Positive	Negative	Positive	Positive	Positive
	V6	Negative	Negative	Mixed	Negative	Mixed	Negative	
	V7	Negative	Negative	Negative	Negative	Negative	Negative	Negative
	V8							
	N-V					Negative	Negative	

The barriers and drivers that were discussed throughout the previous text are summarized in the following Table 13: List of Barriers and Drivers on PTZ. This table shows the relationship between barriers and drivers and the individual BIM uses. The following text provides an analysis of how the combination of variables, and the barriers and drivers associated with them, influenced the adoption of BIM uses on the PTZ project:

BU 1: Results show that all the variables negatively influenced the adoption of BU1. Interviewees had stated not perceiving a relative advantage to implementing BU1. The BIM use was further perceived to be incompatible with the needs and experience of stakeholders and viewed as complex to use. Stakeholders had noted that they had not observed the success of this BU yet on other projects and perceived it to have a low trial-ability. The performance of these 5 variables alone, according to Rogers (2003) DOI theory, can already be indicative of an innovation that will fail to be adopted. Furthermore, stakeholders and opinion leaders were hesitant to deviate from the traditional way of working i.e. conducting RAM analysis via the established methods. Therefore, it can be assumed that the combination of a lack of a perceived relative advantage and multitude of compatibility issues among other mentioned factors, was responsible for BU1 not being adopted on the PTZ project.

BU2: The interviewees perceived a relative advantage of using BU2 but could not explicitly state this. The BIM use was further perceived to be complex to use and incompatible with the experience of stakeholders and current way of working. This BU was still being tested and developed in the organization (RWS). Interview participants were not involved with testing of the BU and therefore could not comment on the trial-ability of BU2. The successes of using the BIM use had furthermore not been observed on other projects and stakeholders and opinion leaders were observed to be hesitant to use the BIM use. This combination of predominately barriers can be contributed to BU2 not being adopted.

BU3: The utilization of BU3 was perceived as having a positive relative advantage. The ability to reduce downtime of the asset and potential to shorten the project duration drive stakeholders to its adoption. This BIM use was further perceived to be compatible with the experiences and needs of the stakeholders. Stakeholders had stated having experience with utilizing the BIM use in the past on other projects (most notable the REHT and AWA projects). While the BIM use was perceived as complex to adopt, the contractor stated that the complexity stemmed from the asset type and not the innovation itself. The BIM use was perceived to have a good trial-ability and observability as BU3 was tested on smaller scale prior to its full-scale utilization and the positive results of using BU3 were observed on other projects.

Table 13: List of Barriers and Drivers on PTZ

ID	Barrier	BU1	BU2	BU3	BU4	BU5	BU6	BU7
1	Unclear relative advantage of using BIM	x	x					
2	Incompatibility with needs of stakeholders	x						
3	Incompatibility with experience of stakeholders	x	x			x		
4	Rapid change of technology causes compatibility issues with BIM software					x		
5	Asset managers of RWS are more familiar and experienced with IFS Ultimo then BIM Software					x		
6	Adoption of BIM use perceived as complex due to unfamiliarity with asset type			x		x		
7	BIM software (interface) perceived as complex by asset managers			x		x		x
8	Lack of observable successes of implementing BIM uses	x	x					
9	RWS stakeholders are hesitant to deviate from known way of working	x		x		x		
10	High workload for asset managers leaves little room to innovate					x	x	
11	RWS top management hesitant to support BIM uses	x	x	x	x	x	x	x
12	Perceived time pressure causes stakeholders to deviate from innovation					x	x	
13	Unknown asset information requirements					x	x	
ID	**Driver**	**BU1**	**BU2**	**BU3**	**BU4**	**BU5**	**BU6**	**BU7**
1	Potential to reduce project duration			x		x		x
2	Ability to reduce downtime of asset			x		x		x
3	Ability to deliver information faster and more reliable in a centralized place					x		
4	Ability to enhance communication as 3D models were better communication tools than 2D drawings					x		x
5	Ability to reduce costs with more efficient information management and readily available information					x		
6	compatibility with needs and experience of stakeholders			x		x		x
7	BIM use not perceived as complex due to familiarity with BIM use and/or asset type			x		x		x
8	Good trial-ability of BIM use			x		x		
9	Observability of the successes of implementing BIM use on previous projects motivates stakeholders			x		x		x
10	Stakeholders from engineering firm were intrinsically motivated to deviate from known way of working			x		x		
11	Technical manager supported adoption of BIM use and positively influenced adoption			x		x	x	x

Motivation adopt BU3 were also mixed as participants of the contractor and engineering firm were willing to use the BIM use, but some stakeholders of RWS were hesitant toward the innovation. Especially the role of the opinion leaders at RWS was reported as being hesitant to support the adoption of the BIM use. Nevertheless, the combination of drivers relating to the relative advantage, compatibility, observability etc. outweighed the effects of the barriers and can be attributed to driving the adoption of BU3.

BU4: The interviewees perceived a relative advantage to using BU4 but could not explicitly state this. The BIM use was perceived to be very complex and incompatible with the experience of stakeholders and the current way of working. Interviewees were further not capable of giving deep insight into BU4 due to a perceived lack of knowledge on the BIM use. As such, interviewees had trouble commenting on the trial-ability of BU4. Interviewees had further not observed the positive results of BU4 stakeholders and opinion leaders were hesitant to support the BIM use. Information regarding, its relative advantage, complexity etc. were further omitted, because the interviewees did not seem to have a good comprehension of the BIM use.

BU5: Stakeholders perceived the relative advantage of this BU in the more efficient means of asset information management and time and cost savings. BU5 was further perceived to be compatible with the needs and experiences of stakeholders. The perception of the complexity of the BIM use differed per stakeholder as the engineering firm perceived the utilization of the BIM use as less complex as RWS and the contractor. Noteworthy is that the contractor attributed this complexity to the unfamiliarity with the asset type. The BIM use was perceived to have a good trial-ability as it was successfully and relatively easy tested on smaller scale prior to its full-scale implementation. The successes of adopting this BIM use were observed on previous projects, which motivated stakeholders to adopt BU5. The stakeholders were further reported to having a mixed attitude toward the innovation as stakeholders from the engineering firm and contractor noted being motivated to use BU5, but certain stakeholders at RWS were hesitant to support the utilization of the BIM use. The role of opinion leaders at RWS was further noted as hesitant to support the BIM use. Time pressure was stated as a potential barrier as project teams might be pressed to focus on primary processes and neglect BIM models. Even though these barriers exist, and no solutions were yet found to them, the combination of drivers relating to the attributes of the innovation outweighed the influence of the barriers. This is in line with Rogers (2003) DOI theory, as he states that the perceived attributes of the innovation are of major influence on the adoption of an innovation.

BU6: The interview participants noted a positive relative advantage to the utilization of BU6. The BIM use was however perceived as complex and incompatible. The BIM use is still in the early phase of development on the project and stakeholders could not comment on the perceived degree of complexity, because they were not involved with this. Stakeholders stated that they had observed the utilization of the BIM use before. The attitude of the stakeholders toward the innovation varied as the stakeholders from the engineering firm and contractor were more willing to deviate from the established way of working than those of RWS. The role of the opinion leaders was also more nuanced as the middle management at RWS was reported as hesitant to support the BIM use. Noteworthy was the role of the technical manager on the project, which was stated as being an opinion leader as well. Non variable related findings were also noted on BU6 and the same as BU5. The challenge of keeping BIM models up to date in the O&M phase and unknown asset information requirements were noted as factors which work as barriers. The time pressure of the project was also stated as a barrier to BU6 as it was noted that pressure on the team to deliver the project could lead to stakeholders focusing on primary processes and the neglection of development of BU6.

BU7: The interview participants reported a positive relative advantage toward the utilization of BU7. This relative advantage was perceived in the cost savings and limited downtime which result from the usage of the BIM use. The BIM use was perceived to be compatible with the needs and experience of the stakeholders and further noted to having a good observability. The positive results of utilizing the BIM use had been observed on previous projects (most notably AWA and PTZ). The opinion leaders at RWS were reported to be hesitant to support the BIM use. This combination of mostly drivers can be assumed to have resulted in the adoption of the innovation.

The PTZ project aspires to stimulate innovation and has shown to incorporate many innovative BIM uses. The programmatic approach of this project provides a foundation for cross-project learning and offers an opportunity for gradual advancements in the adoption of the BIM uses across subsequent tunnelling projects. It was observed that the adoption of the BIM uses on PTZ were driven by a host of influencing factors relating to their relative advantage, observability, trial-ability, and compatibility. A host of factors such as the perceived “complexity” and “role of opinion leaders” were also found to work as barriers to the adoption of the BIM uses.

The following paragraph will draw a comparison between the findings on the REHT project and PTZ. It will analyze how the factors which influenced the adoption of the BIM uses developed across the two cases.

5.3 Cross-Case Analysis

This paragraph provides a comparison between the two case studies and delivers insights into the factors which worked as barriers and drivers to the adoption of the BIM uses on both cases.

The following table: Comparison of selected BIM uses shows which BIM uses were considered and implemented on the two cases. This table shows that similar choices were made on the implementation of BIM uses on both cases, which is quite logical, as PTZ built forth on the successes and lessons learned from the preceding REHT project. Most notable is that BU2 was not considered on PTZ, but hard steps were taken to implement BU6. The latter is still in development and has not been implemented yet on PTZ. Interviewees had stated that the market had developed between the two cases and advances were made in technology and knowhow. This led to the development of more ambitious, but also more realistic goals for adopting BIM uses on PTZ.

Table 14: Comparison of selected BIM Uses

BIM Use	Description	REHT	PTZ
BU1	Asset RAM Analysis	C	C
BU2	Asset Condition Monitoring & Health Assessment	B	C
BU3	Asset Commissioning	A	A
BU4	Asset Performance Analysis	C	C
BU5	Asset Information Management	A	A
BU6	BIM-based Facilities Management	B	B
BU7	Simulation of Processes and Events	A	A
Code	**meaning**		
A	considered and implemented in case studies		
B	considered but not (yet) implemented in case studies		
C	not considered in case studies		

The influence of the variables on the adoption of the BIM uses on both cases is illustrated in Table 15: Cross-Case matrix of influencing variables on adoption of BIM uses. Many similarities exist between both cases, except for a few distinct differences. The significant similarities and differences will be discussed in the following text:

Comparing both cases, it can be seen that the perceived relative advantage of the BIM uses was a major driver to the adoption of the BIM uses on both cases. The perceived major benefits of utilizing the BIM uses on both cases were seen in their ability to decrease downtime of the asset, shorten the project duration and importantly, result in a faster, more efficient, and reliable management of information of the asset. These relative advantages drove adoption of the BIM uses and motivated stakeholders. On both cases, this factor was capable of outweighing barriers and furthered adoption. A good observability of the successes of utilizing the BIM uses was further noted as a strong driver on both cases and further motivated stakeholders. Noteworthy is that the observable successes of the REHT project were directly responsible for the continued adoption of the BIM uses on PTZ.

The next interesting point from the comparison between the two cases can be seen in the change of perception of compatibility and complexity of BU3, BU5 and BU7. While these BIM uses were perceived as incompatible with the knowledge and experience of the stakeholders on REHT, they were now perceived as compatible on PTZ. In the period between the two cases, stakeholders had gained more experience with these BIM Uses. Interviewees had further stated that the market had developed a lot between both cases resulting in greater compatibility of the BIM uses on PTZ. This change in perception of compatibility of the BIM uses was a driver to their adoption on PTZ, instead of a barrier on REHT. Having gained more experience with the BIM uses also resulted in a reduced perception of the complexity of their adoption. While some interviewees had reported on PTZ that working with the BIM uses was perceived as complex, this complexity was associated with a lack of experience with working with the asset type and not the BIM uses. The perception of complexity was nevertheless a driver on PTZ as opposed to on REHT.

The trial-ability of the BIM uses had a more prominent role on PTZ, as more testing of the BIM uses occurred on a smaller scale, prior to their full-scale implementation. This was a direct result of issues relating to the scan-to-BIM activities on REHT. More testing was done to ensure that stakeholders were implementing the innovation correctly and reduce risks of the full-scale implementation of the BIM uses. Stakeholders perceived a good trial-ability of BU3 and BU5 on PTZ. Furthermore, the role of the opinion leaders on both cases was one of hesitation and low support of the BIM uses. Noteworthy is that these opinion leaders in question were on the side of the client i.e. RWS and defined as figures in the upper (and middle) management. Comparison of the cases showed no significant influence of the variable V8 (structure of the system) on adoption of the BIM uses. The role of this variable will further be reflected on in the discussion section of the report.

Finally, it is important to note that non-variable related findings were uncovered on both cases. The issue of a lack of asset information requirements was brought up on both REHT and PTZ. This suggests that across the period between both cases little advances were made in the development of these AIR's, of which their absence results in an increased risk that BIM models are currently built, that cannot effectively support the asset managers in the remainder of the O&M phase of the asset. Interviews on PTZ added an additional non-variable related findings i.e. the influence of the perceived time pressure on the adoption of the BIM uses. This might be explained by the perceived time pressure that stakeholders experienced on the PTZ project as they were rushing to bring the renovation projects to the market. The following section will discuss this issue further.

Table 15: Cross-Case matrix of influencing variables on adoption of BIM uses.

	Variable								
	V1	V2	V3	V4	V5	V6	V7	V8	Non-variable
BU 1									
REHT	negative	negative	negative	negative	negative	negative	negative		
PTZ	negative	negative	negative	negative	negative	negative	negative		
BU 2									
REHT		negative	negative		negative	negative	negative		
PTZ					negative	negative	negative		
BU 3									
REHT	positive	negative	negative		positive	negative	negative		
PTZ	positive	positive	negative	positive	positive	Mixed	negative		
BU 4									
REHT		negative	negative		negative	negative	negative		
PTZ		negative	negative		negative	negative	negative		
BU 5									
REHT	positive	mixed	mixed	positive	positive	negative	negative		negative
PTZ	positive	positive	negative	positive	positive	mixed	negative		negative
BU 6									
REHT	positive	negative	negative		positive	negative	negative		
PTZ	positive	negative	negative		positive	negative	negative		negative
BU 7									
REHT	positive	mixed	positive		positive	mixed	negative		
PTZ	positive	positive			positive		negative		

6 Discussion

This section of the report presents a discussion of the research findings and the overall. The first part offers a reflection on the results and places them in the context of existing literature. The following part explorers the implications of these findings and their potential applications. The section concludes with a reflection on the study's limitations.

6.1 Reflecting on the study

This research developed a framework to study the adoption of BIM uses for AM. The framework consisted of 8 variables and was based on Rogers Diffusion of innovations theory (Rogers,2003). The findings of the case study research have shown that 7 out of these 8 variables were indeed confirmed to influence the adoption of the BIM uses for AM on our selected cases. These findings are a good validation of the developed framework.

The variable "relative advantage" has shown to strongly influence the adoption of the BIM uses on the two cases. Interviewees had stated that they did not perceive a relative advantage to BU1, and this was a main contributor to the BIM use not being adopted. Conversely, interviewees perceived a high relative advantage of using BU3, BU5 and BU7 on the case studies and this was noted as a strong driver to their adoption. The relative advantage of these BIM uses was seen in their potential to limit downtime of the tunnels, shorten the duration of the projects, and enhance the overall asset information management. The high relative advantage was an important driver to the adoption of the BIM uses on both the REHT project and PTZ, especially in the case of BU3 and BU5. These findings are supported by previous studies, which indicate that the variable "relative advantage" is an important influencer on adoption (B. J. Gledson & Greenwood, 2017; Oyuga et al., 2023; Xiaodong Xu et al., 2020).

The second variable which strongly influenced the adoption of the BIM uses was "observability". During the interviews it was stated multiple times that the observability of the positive outcomes of utilizing the BIM uses BU3, BU5 and BU7 on previous projects and on conferences is what motivated stakeholders to adopt the BIM uses on the cases. The observable positive results of implementing BU3, BU5 and BU7 on the REHT project were a significant driver to their adoption on PTZ. A low observability or absence of observable positive results, such as in the case of BU1, BU2 and BU4 worked as barriers to the adoption of these BIM uses. These findings are supported by Oyuga et al. (2023) who also found a strong correlation between the variable observability and the adoption of BIM in the context of the Kenyan construction industry.

It's further worth noting that the combination of a highly perceived "relative advantage" and high "observability" were observed on the BIM uses that were adopted on the cases. This combination seemed to help overcome the barriers posed by a high degree of "complexity" and low "compatibility" among other barriers on the REHT project and PTZ. This is interesting as the variables "complexity" and "compatibility" proved to be significant influences on adoption in previous studies rate (B. J. Gledson & Greenwood, 2017; Shirowzhan et al., 2020a; Xiaodong Xu et al., 2020). Gledson and Greenwood (2017) had demonstrated that a lack of compatibility was responsible for major delays in the adoption of innovations in their study. Even though "complexity" and "compatibility" were noted as barriers to the adoption of the BIM uses on our cases, stakeholders chose to push through when the previously named combination of drivers was noted. This suggests a smaller influence of "complexity" and "compatibility" on adoption of BIM in our study, contrary to other studies (B. J. Gledson & Greenwood, 2017; Shirowzhan et al., 2020a; Xiaodong Xu et al., 2020). A similar finding regarding the influence of "complexity" on adoption of BIM had also been demonstrated by Oyuga et al. (2023) albeit called simplicity in their study, had little influence on adoption of BIM in the Kenyan construction Industry.

The influence of the variable "trial-ability" on adoption of the BIM uses was also noted during the interviews. Testing the BIM uses BU3 and BU5 on the case PTZ was used to address and remove risks associated with the adoption of these BIM uses, and ultimately gave stakeholders the confidence to move to full-scale implementation. Stakeholders further perceived it as relatively easy to arrange tests for BU3 and BU5 on both the REHT project and PTZ. An example of such tests entailed familiarizing and accessing the ability of asset managers to navigate through the 3D environment for utilizing BU5. The findings on "Trialability" in this study are supported by previous studies, which had also demonstrated the significant influence of this variables on adoption (Oyuga et al.,2023)(B. J. Gledson & Greenwood, 2017)(Xu et al.,2020).

The influence of the variables "norms and culture of the system" and "the role of opinion leaders" were also noted on both cases. These variables worked as barriers to the adoption of the BIM uses as issues pertaining to a lack of motivation to use the BIM uses as well as a fear of change were noted during the interviews. These results are supported by the findings of previous studies, who also demonstrated that lack of motivation and a fear of change are significant barriers to the adoption of BIM (Elhendawi et al., 2019). The role of opinion leaders at RWS was especially noted as a barrier to the adoption of the BIM uses as these figures were hesitant to support the adoption of BIM uses on both the REHT project and PTZ. Interviewees had stated that much effort and lobbying was required to convince the top management to support the adoption of the BIM uses. This result is backed by previous studies who found that the support of top management was of significant influence on BIM adoption (Abbasnejad et al., 2021; Babatunde et al., 2021; Ritu Ahuja Anil Sawhney & Rakshit, 2020; Tavallaei et al., 2022). Tavallaei et al. (2022), Ahuja et al. (2020) and Elhendawi et al. (2019) showed that, just like on this study, top management's endorsement and capability of allocating resources was an important factor for BIM adoption and that their lack of support was conversely a significant barrier.

Variable V8, the "structure of the social system" performed unexpectedly, and no significant influence was found of this variable on the adoption of the BIM uses on the two cases. The lack of influence of this variable might be explained by contextual factors in the two case studies. The case studies were focused on examining the adoption of BIM uses on two renovation and maintenance projects i.e. on the project level. Previous studies had discussed the influence of this variable in the context of organizations (Dao & Chen, 2021; Papadonikolaki & Aibinu, 2017). It might therefore still be expected that this variable will have a more significant influence on the adoption of the BIM uses in another context i.e. when focusing on the organizational level of adoption. This assumption could be tested in future research. Another explanation for this result might be a methodological issue i.e. the method of measuring this variable was insufficient and could not deliver results. It might be that the interviewees did not comprehend the questions surrounding variable V8 during the interviews. This research tried to avoid interviewees having difficulties with comprehending the questions, by first having trial interviews and testing the interview questions. Despite these efforts it is still possible that interviewees did not comprehend the questions. Future research could take further measures to try and avoid this issue by sending questions beforehand to the interviewees to allow them more time to comprehend the questions. Another measure could be to collect data on this variable via another data collection method.

The findings of this research further showed the existence of non-variable related influences on the adoption of the BIM uses. These findings showed that “a lack of asset information requirements (AIR)” and “perceived time pressure” work as barriers to the adoption of BIM uses for AM on the REHT project and PTZ. The lack of AIR was mentioned as barrier to the adoption of BU5 and BU6.Interviewees had stated that it was difficult to build BIM models that will adequately fulfill the data needs of stakeholders (asset managers, facility managers) in the O&M phase for these BIM uses, without first knowing which data should be captured and stored in the BIM models. These findings are supported by previous research, that agrees that a lack of appropriate asset information requirements is working as a barrier to the utilization of BIM for facilities management (BU6) (Cavka et al., 2017; Eadie et al., 2013).

The time pressure has been shown to influence adoption of digital innovations in previous studies (Adriaanse, 2007; Sugandini et al., 2020). Adriaanse (2007) showed that the “perceived time pressure” influenced the personal motivation to use ICT and that a highly perceived time pressure can act as barrier to adoption of innovation. Those results are in agreement with the findings of this study.

6.2 Limitations of the study

The first limitation of this research concerns the systematic literature review (SLR) used to identify BIM uses for AM in the O&M phase. This study relied solely on the SCOPUS platform to search for relevant literature, potentially leading to the omission of relevant information on BIM uses for AM. The decision to focus on a single platform for the SLR was driven by feasibility considerations, as incorporating additional platforms in the scope of this search, was impractical given the time constraints for the research project. The scope of the SLR was further set on publications from 2019 to 2023. This choice was also driven by feasibility considerations and based on the assumption that the launch of the NEN-ISO 19650 in 2019 which was a key development for BIM use across its entire lifecycle. This choice however may also have excluded relevant literature from the SLR.

The following limitation of this research concerns the classification of BIM uses for AM. The BIM uses were identified, classified, and described along with their barriers and drivers. The research could not further develop the classification of these guidelines however due to time constraints. To aid project teams in the selection of BIM uses at the start of the project, the BIM uses characteristics as defined by Kreider & Mesner (2013) should be further developed. These characteristics include, but are not limited to the facility element, facility phase, discipline, level of development etc. (Kreider & Messner, 2013).

The third limitation of this study concerns the selection of interview participants on the case studies. Participants were chosen based on their key roles on the case studies and in the adoption of the BIM uses on the cases. Limited attention was given to the level of familiarity with the BIM uses prior to the interviews. This proved to be a significant factor, as the ability of interviewees to provide insights on barriers and drivers to the BIM uses was contingent on their comprehension and familiarity with the BIM uses. This is reflected in the findings of the case studies. Participants who possessed greater knowledge on the BIM uses, provided more detailed and insightful data. Conversely, interviewees with limited familiarity with the BIM uses could offered limited or no insights on the barriers and drivers effecting their adoption. As such, participants were unable to provide in-depth insights on BU1, BU2, BU4 and BU6 as they lacked the expertise and experience on working with these BIM uses. Conversely richer findings were uncovered on BU3, BU5 and BU7 as they interviewees had experience of working with them on the case studies or other projects.

The following limitation of this research concerns the comparative importance of variables. This study revealed insights into the variables which work as barriers and drivers to the adoption of the BIM uses for AM. It became apparent that a certain combination of the variables working as drivers, could outweigh the negative effects of barriers on adoption. It can therefore be assumed that certain variables exert a more significant influence on the adoption of the BIM uses than others. This phenomenon is also stated in the literature, as Rogers (2003) noted that the perceived attributes of the innovation for example account for 49-87% in the variance of the adoption rate. While this study provided qualitative insights, it did not provide quantitative results on the comparative strength of the variables. More research would be needed to address this limitation.

The final limitation of this research concerns to the selection of case studies. This study conducted case study research on two governmental projects in the Netherlands, specifically two large projects managed by Rijkswaterstaat. While this did offer insights into barriers and drivers to the BIM uses for AM, it must be noted that these barriers and drivers might differ from the ones which are encountered on non-governmental projects. While it can be expected that the findings pertaining to the attributes of the innovations are similar, the influence of variables such as organizational size and structure, norms & culture, and the role of opinion leaders might be expected to have a different effect on adoption rates in such a context. During talks with stakeholders in the firm W+B it became clear that non-governmental organizations such as Tennet were also heavily investing and exploring the BIM uses for AM in the O&M phase. The geographical scope of the study might also pose a limitation as barriers and drivers in the context of the Dutch construction industry might differ from those encountered in other countries. Al-Mohammed et al. (2023) had illustrated how factors affecting BIM adoption can differ between countries with different income levels for example. Although this research specifically aimed to address the gap in literature concerning barriers and drivers to the adoption of BIM uses in the Dutch construction industry, this choice of scope imposes limitations on the study's results. The generalizability of the findings and the developed framework is consequently affected. This limitation can be addressed with future research.

6.3 Implication of findings

The findings of this research have a host of implications. These range from developing strategies to adopt BIM uses for AM in the O&M phase to recommendations for future research. The recommendations for future research are addressed in the next section of the report. The following list will present the implications of the findings:

1. The findings of this study can aid project teams in the selection of BIM uses for future projects in the O&M phase. The study has identified BIM uses for AM and their specific barriers and drivers. Based on these results, project teams can make better informed decisions on adopting BIM uses on their projects. Based on the findings it can currently be recommend that project teams consider BU3, BU5 and BU7 for adoption, as they have successfully been adopted on our case studies and a host of drivers exist which outweigh the barriers to adoption of these BIM uses.
2. The findings of this research can further be used to recognize barriers and drivers to the adoption of BIM uses and develop strategies to mitigate these barriers. As the strong influence of the variables relative advantage and "observability" were shown, it can be recommended that more awareness needs to be created on the benefits and success of utilizing the BIM uses for AM. It was further noted during the interviews that a perception of complexity and incompatibility surrounds the BIM uses. This stems from a lack of knowledge and experience with the BIM uses. It is therefore recommended that more trainings are given to develop the knowledge and skills of stakeholders (Abbasnejad et al., 2021).
3. This research has uncovered through the case studies how decades of neglecting asset information management has currently impacted AM projects. All stakeholders agreed that

this is a significant problem which the Dutch construction industry faces now and in the coming years with the V&R task (in Dutch: vervangings en renovatie opgave). This research has shown how BU5 can contribute to resolving this issue and lead to an enhanced asset information management with BIM.

4. This study finally contributes to the sustainable development goals (SDGs), specifically SDG9, by stimulating innovation in the construction industry. By identifying barriers and drivers and developing a framework which helps understand the adoption of BIM uses for AM in the Dutch construction industry, this research hopes to contribute to a more sustainable infrastructure in the Netherlands.

The following section of this report shall present the conclusions of this research and provide recommendations for future research.

7 Conclusions

The final section of this report presents a summary of the main results and the conclusions of this study. Alongside these conclusions are also recommendations presented for future research, which are based on the discussion in the preceding report section.

7.1 Conclusions

Combining BIM with AM might hold the key to unlocking significant efficiency gains in the O&M phase of assets, but a gap in the scientific literature existed on the BIM uses for AM and their distinct barriers and drivers in the context of the Dutch construction industry. This study set out to fill this gap in the scientific literature. The research was guided by the following main research question (MRQ): "What are the BIM uses for asset management in the O&M phase, and which factors work as barriers and drivers to adopting these BIM uses in the Dutch construction industry?". This MRQ was further supported by 4 sub research questions (SRQ's). The following text will present the answers to these sub research questions.

SRQ1: "What is a suitable theoretical framework for studying the adoption of BIM for Asset Management?"

The first SRQ of this study sought to find a suitable framework for studying the adoption of BIM for AM. A literature review on technology adoption theories let to the development of a theoretical framework (see the following figure). The developed theoretical framework consisted of 8 variables and was grounded in Rogers (2003) Diffusion of Innovations (DOI) theory. The choice for the DOI theory was based on multiple factors. First, DOI theory was deemed suitable for this research as it is backed by sufficient empirical evidence which demonstrates its suitability for studying BIM adoption in the construction industry. Second, BIM adoption not only involves the individual but also organizational structures, organizational norms, and social factors. The DOI theory offers a balance between the social system dynamics, organizational factors and the individual. The chosen variables for the framework were: the relative advantage (V1), compatibility (V2), Complexity (V3), trial-ability (V4), Observability (V5), The role of opinion leaders (V6), Norms and cultures of the system (V7) and the structure of the system (V8). After applying the theoretical framework to two case studies in the Dutch construction industry, it can be concluded that the framework is suitable for studying the adoption of BIM uses for AM. The findings had shown that 7 out of the 8 variables in this framework have indeed influenced the adoption of the BIM uses on both the REHT project and PTZ. The only variable which was not found to influence the adoption of the BIM uses was the structure of the social system.

SRQ2: "What are the BIM uses for Asset Management in the O&M phase?"

The following SRQ sought to find the BIM uses for AM in the O&M phase. Identifying these BIM uses was realized via a systematic literature review (SLR). This SLR was conducted on the SCOPUS platform and finally chose 27 sources for data analysis. The findings revealed 7 BIM uses for Asset management in the O&M phase i.e. the BIM use for RAM analysis (BU1), Asset Condition Monitoring & Health Assessment (BU2), Asset Commissioning (BU3), Asset Performance Analysis (BU4), Asset information management (BU5), BIM based FM (BU6) and Simulation of Processes and Events (BU7). Based on the information gathered through the SLR, it can be concluded that these BIM uses have the potential to increase the efficiency in the O&M phase by enhancing asset management.

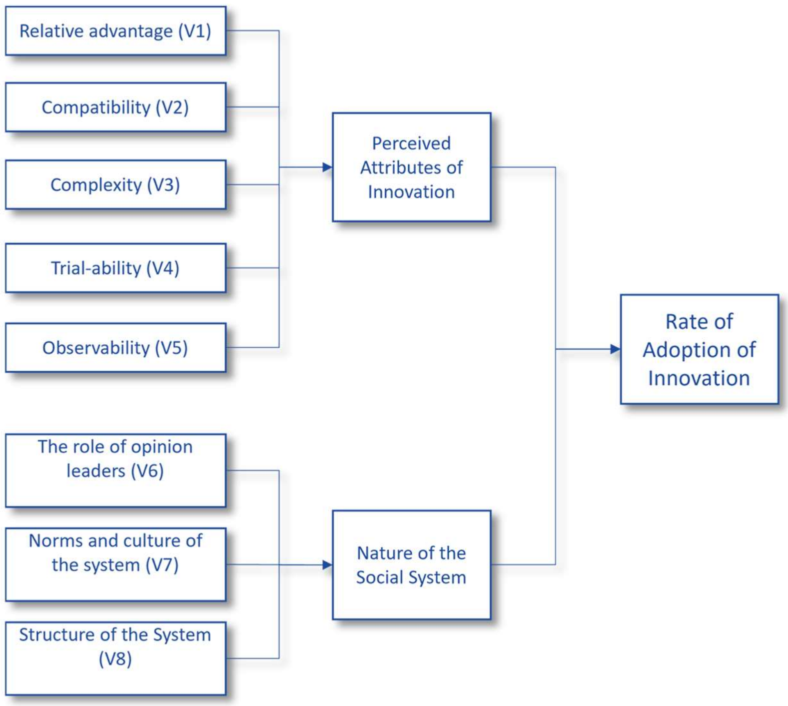


Figure 16: Theoretical Framework for BIM adoption.

SRQ3: "Which factors work as barriers to the adoption of the BIM uses for Asset Management?"

The third SRQ had the aim of finding the factors that work as barriers to the adoption of the BIM uses for AM. This was done via case study research on two cases in the Dutch construction industry. The research looked at the adoption of BIM uses for AM on the REHT project and PTZ project, two tunnel renovation and maintenance projects in the south-holland region of the Netherlands. This research activity resulted in the identification of 13 barriers on both the REHT project and PTZ. A major barrier regarded the lack of a perceived relative advantage to the BIM uses. This barrier was directly responsible for BU1 not being adopted on both cases. Compatibility issues with the known way of working and needs, knowledge, and experience of stakeholders were other major barriers to the adoption of the BIM uses. A lack of observable success of utilizing the BIM uses was also found to be a significant barrier, as the absence of such positive results fails to motivate stakeholders to adopt the BIM uses. Based on the findings, it can further be concluded that there is currently a lack of support from top management toward the adoption of the BIM uses for AM and that factors such as fear of change, and stakeholders' unwillingness to deviate from the known way of working are further working as barriers to the adoption of the BIM uses. Two barriers originated from variables which do not pertain to the developed framework. Based on the findings it can be concluded that the perceived time pressure and procedural agreements i.e. the lack of AIR also worked as barriers to adoption of the BIM uses, specifically BU5 and BU6. Especially the lack of AIR was stated as a growing barrier on both cases as it results in the risk of BIM models being built which will not effectively support asset management in the remainder of the O&M phase.

SRQ4: "Which factors work as drivers to the adoption of the BIM uses for Asset Management?"

The final SRQ had the aim of finding the factors that work as drivers to the adoption of the BIM uses for AM. This was also done via case study research on two cases in the Dutch construction industry. The research also looked at the adoption of BIM uses for AM on the REHT project and PTZ project. This research activity resulted in the identification of 11 drivers on PTZ and 14 on both the REHT project. It can be concluded however that a highly perceived relative advantage and good observability were key drivers to the adoption of the BIM uses. This perceived relative advantage differed per BIM use, but significant drivers were their ability to reduce downtime of assets, shorten the project duration and deliver an enhanced asset information management on the project. This driver was capable of overcoming barriers to adoption and played an important role in the adoption of BU3, BU5 and BU7 on both cases. A good observability of the successful utilization of the BIM uses further proved to be a major driver to the adoption of the BIM Uses as these positive results motivated stakeholders to adopt and overcome barriers. The successful utilization of the BIM uses on the REHT project were strong drivers to the continued adoption of the BIM uses on PTZ. It can also be concluded that a high degree of trial-ability can positively influence the adoption of BIM uses for AM as the findings demonstrated how small-scale tests with BU3 and BU5 on case study PTZ were a driver to their adoption. Based on the findings it can further be concluded that a combination of a highly perceived relative advantage, good observability and trial-ability of the BIM uses was capable of overcoming barriers relating from a highly perceived complexity and incompatibility, ultimately driving adoption of BU3, BU5 and BU7 on the two cases.

To conclude, this research explored the BIM uses for asset management and the factors which work as barriers and drivers to their adoption in the Dutch construction industry. The research developed a theoretical framework, which was proven to be suitable to study the adoption of the BIM uses for AM. The research identified 7 BIM uses for asset management, of which three of them were found to already be adopted in the construction industry. As could be seen from the case study research, these BIM uses for AM have the potential to significantly improve efficiency on projects in the O&M phase. A wide range of barriers and drivers exists that influence the adoption of these BIM uses. As could be seen on the case studies however, the drivers to the adoption of the BIM uses were able to outweigh their barriers and continue to forward innovation in the Dutch construction industry! The practical implications of this research are that project teams and asset managers now have a foundational framework to guide the selection of BIM uses for AM in their future projects. This research provides stakeholders the ability to identify barriers to BIM uses for AM on their projects and develop strategies to mitigate these, while fully utilizing drivers. The implication of this research also concerns direction for future research. These will be provided in the following text.

7.2 Recommendations for Future Research

As previously acknowledged, this research has its limitation, and future research is needed to address these. The following text outlines recommendations for future research, grounded in the findings and limitations of this research. These recommendations are:

1.) Future research should test the developed framework in various contexts. This research should be done in other countries, at other adoption levels of technology adoption (at the organizational level), and within non-governmental and semi-governmental organizations. These studies might show different results, as variables related to the social system of non-governmental originations might differ substantially from governmental organization such as RWS. Non-governmental organizations are known for their difference in structure, culture, but also goals and drivers. Barriers and drivers are oftentimes geographically bounded and to improve the generalizability of the findings it is important to conduct research in other countries. Testing the developed framework in the various contexts will improve the robustness and applicability of the framework.

2.) Future research is needed to investigate possible expansions of the developed framework as the findings indicated the existence of non-variable related findings. Previous research had shown how "perceived time pressure" can influence adoption of innovations in the Dutch construction industry (Adriaanse, 2007). This could be one of possible additions to the framework.

3.) There is a need for future research to further develop the identified BIM uses for AM. This research was only capable of describing the BIM uses and showing barriers and drivers to their adoption. Further development of the BIM uses can be done along the lines of the BIM use classification and selection guide by Kreider and Messner (2013). This will enhance the implementation of these BIM uses and aid project teams in the selection of BIM uses for AM on future projects.

4.) Research is further needed to quantify the benefits of the adoption of the BIM uses on the REHT project and PTZ. The importance of the variable “observability” has been shown through the findings of this research. Therefore, it would greatly help the adoption of the BIM uses if the benefits of their adoption on these two projects were quantified and used to increase awareness of stakeholders.

5.) Future research should be done on the barriers and drivers of the BIM uses at RWS, with a focus on the social system, and particularly the opinion leaders (Department managers and technical managers). The results of this study revealed that barriers and drivers persisted across both cases relating to the role of the opinion leaders. More insights into the underlying behavior of these opinion leaders might help resolve their hesitation to support the adoption of the BIM uses.

6.) Research should be done to determine the strength of the individual variables. The findings of this study provided qualitative insights into the influence of variables but could not provide quantitative insights on the strengths of the variables. Future research could employ a quantitative or mixed method approach to gain insights into the comparative strength of variables as this information is needed to further understand the influence of variables on adoption. This will aid the development of strategies to resolve barriers and utilize drivers to adoption of the BIM uses.

This study serves as a gateway to understanding the adoption of BIM uses for AM in the O&M phase. It has explored the BIM uses for AM in the O&M phase and found factors which work as barriers and drivers to their adoption. By addressing these barriers and leveraging drivers, stakeholders in the Dutch construction industry can achieve the highly sought-after efficiency gains in the O&M phase.

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Appendix

Appendix A: Analysis of BIM Maturity in the Dutch Construction Industry

For the purpose of advancing BIM usage for asset management throughout the later phases of the assets lifecycle it is important to have an understanding of how the adoption process of BIM in general progressed for the earlier (Design and Construction) phases. This section will discuss key stakeholders and events in the adoption process of BIM in the Dutch construction industry and the status quo of BIM maturity in the Netherlands.

BIM made its way to the Netherlands in the early 2000s and has over the course of 2 decades transformed the way the construction industry works (Dijk, 2018). The sectors interest in BIM grew due to its many benefits, such as the potential for lower failure costs, increased productivity, and enhanced collaboration (Siebelink et al., 2018). BIM has facilitated a shift from storing and sharing building information in conventional 2D drawings towards comprehensive 3D digital models, that not only incorporate geometric information of built objects, but also integrate semantic data (Gao & Pishdad-Bozorgi, 2019). Despite the numerous benefits of BIM, it was not immediately embraced by the construction industry, but rather met with numerous obstacles to its adoption. Considerable amounts of research had been conducted by academics to identify and characterize the barriers to BIM adoption in the construction projects (Adriaanse et al., 2010) (Chien et al., 2014)(Siebelink et al., 2021). Through the efforts by academics and multiple initiatives the technology gained traction and gradually began to diffuse in the construction industry. The DigiGO BIMloket, BIMregister and Bouw Digitaliserings Raad (BDR) (previously Bouw Informatie Raad (BIR)) are examples of visionaries in the Dutch construction industry, who committed themselves to digitization and accelerated adoption of BIM into the construction industry. The efforts of the DigiGO BIMloket, which was founded in 2015, to establish standardization and open standards in the BIM processes were aimed at enhancing the adoption of BIM in the design and construction phases. In 2019, the NEN-EN-ISO-19650 was released, which is the official Dutch version of the international guideline for managing the information of a build asset with BIM across its entire lifecycle. The release of this guideline was a means to guide organizations in their BIM implementation process and help standardize working with BIM across the industry. This approach has drastically improved collaboration among stakeholders, resulting in improved communication and facilitating better planning of construction activities, among other notable benefits that Lidelow et. al writes about (Lidelöw et al., 2023).

Analyzing the status quo of BIM in the Dutch construction industry can be assessed along several dimensions. First amongst the lines of the adoption rate of BIM and the maturity of BIM users. Secondly, a model with BIM levels was designed in the Netherlands by the BIR with a 4 level scale from 0 to 3 (see Figure 11: BIM Levels in the Netherlands), which was based on the classic British BIM maturity model (BIMM) from Bew and Richards (Bouw Informatie Raad, 2014). It is important to note that this model is a growth model and not an organizational maturity analysis tool, such as that of Siebelink (Siebelink et al., 2018). The UK made it a rule in 2016 that all government projects were to be executed at a level 2. No such mandatories exist in the Netherlands, but an estimation can be made (by the author as no concrete evidence exists in literature) that currently the Dutch construction industry works on a level nearing 2 on this scale. This means that currently collaboration with different stakeholders is enabled through the BIM model, oftentimes in the same organization or working unit, and 4D and 5D BIM uses are exploited, which refer to clash detection and cost estimations with BIM. This level is an average of the whole industry however as some parts of the industry are lacking. Henceforth not a full level 2 score can be given to the whole Dutch construction industry. This can be estimated on the results of the analysis of the adoption rate and especially maturity of BIM in the Netherlands which are discussed further on.

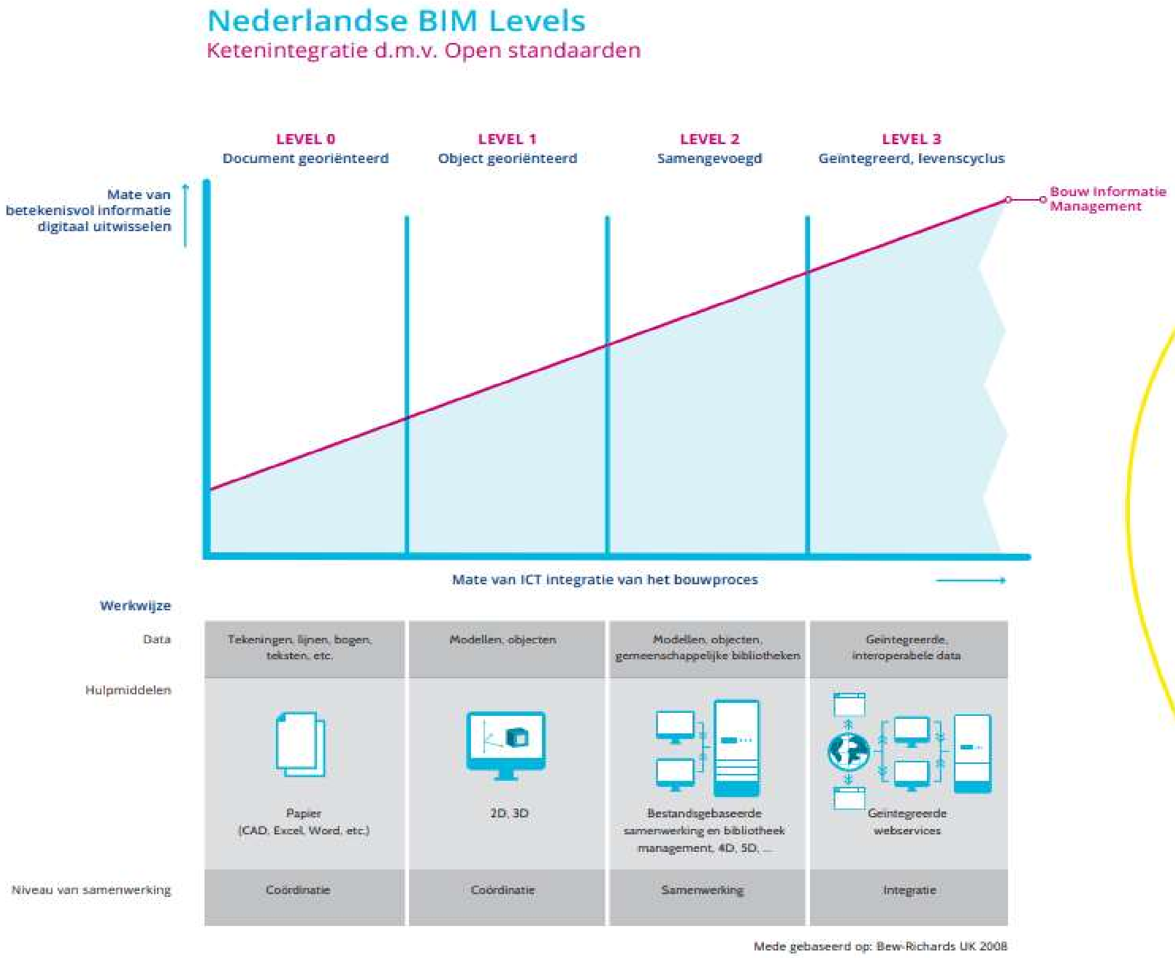


Figure 11: BIM Levels in the Netherlands (source: BIR)

BIM has become quite integrated in the Dutch construction industry, as can be judged by a 2021 study for the BIMLoket (Graas et al., 2021). This study showed that on average 79% of surveyed stakeholders in the Dutch construction industry knew of BIM, 32.4% were BIM users and 57.1% of projects were conducted with BIM (see Figure 12: Overview of BIM adoption in the Netherlands in 2021). A large discrepancy was noticed between the stakeholder groups however, which can possible be explained by the fact that not all stakeholders stand to gain the same immediate benefits of BIM usage and as such are not equally invested into it. Results showed that 67.4% of architects and 59.3% of suppliers were reported as BIM users, but only 21.6% of contractors and 19% of mechanical engineers. Interesting was also that 47.2% of respondents noted that they were aware of BIM but did not use it for whichever reason may be. The last group of 20.4% of respondents noted being unaware of BIM.

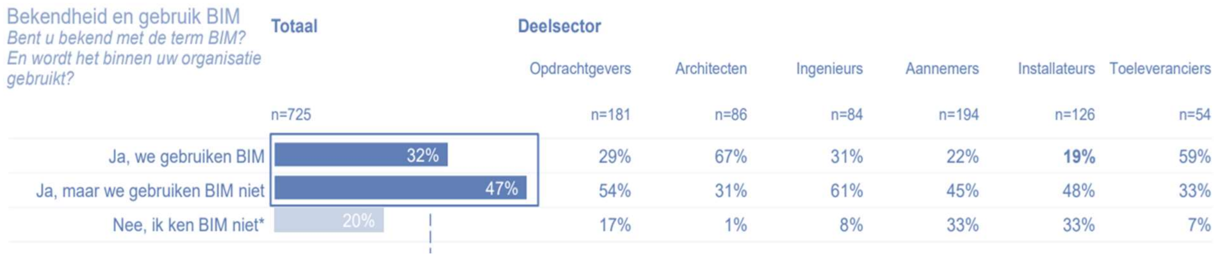


Figure 12: Overview of BIM adoption in the Netherlands in 2021 (source: Report Nationale BIM Monitor 2021)

The study by Graas et al. assessed BIM Maturity of BIM users with an adjusted BIMMM from Siebelink. (Siebelink et al., 2018) which scored BIM maturity on a 3-point scale; Not mature, partially mature, and adequately mature. Once again different stakeholder groups were surveyed and BIM maturity was assessed on 6 dimensions namely, Data structure, ICT, BIM-processes, people and culture, Strategy and Organization and project structure. When looking at the maturity of BIM users the study revealed that 46% of BIM users were adequately mature and 54% partially mature. Interesting was the observed discrepancy between maturity dimensions, showing that ICT and Data was leading in BIM maturity and BIM-processes and organization and project structure were lacking behind. The findings of this study paint a picture of the fairly recent state of BIM adoption in the Dutch construction industry and deliver crucial insights which will be used for designing the research strategy.

The BIMloket ordered an inventory of the most prevalent BIM uses in the Dutch construction industry in the year 2021, which revealed that designing and visualizing of designs in 3D, were the most popular BIM uses (53% and 39% respectively). The same inventory showed that current BIM usage for maintenance and management of assets was only at 10% (BIMLoket, 2021). Even though BIM is nowadays scarcely implemented in the Netherlands for the maintenance and management of assets, it could be quite a suitable option for this purpose, due to its object-oriented and integrative approach to data management.

The Dutch organization Rijkswaterstaat (RWS), who is the executing organization of the Dutch Ministry of Infrastructure and Water Management, sees the potential of more data driven processes. This organization can also be accreted for accelerating BIM use in the Netherlands. Now it has the ambition to improve its asset management through smarter and data driven processes (Tjeerd de Jong, n.d.), as it is making the move to data driven asset management. Data-driven asset management is asset management that is based on continuous adjustments on a basis of data from the environment (CROW, 2022). From 2023 on, RWS has 6 pilot projects running, in which it will incorporate data driven asset management on its assets, ranging from locks, bridges and tunnels (Tjeerd de Jong, n.d.).

The provinces and the municipalities of the Netherlands share the same desire for data-driven asset management and state that BIM could be a tool for achieving this goal (CROW, 2022) (Corstens, 2019). In a report by the "Interprovinciaal Overleg" (IPO), which is the association of the 12 provinces of the Netherlands, a roadmap is described for data-driven asset management and BIM as tool for achieving the objectives of the provinces. The IPO states that the entire process of building, constructing, and managing assets in the public space and infrastructure is becoming increasingly digital and data driven. These development affect provinces and municipalities, as they are the are oftentimes the primary client and manager of infrastructure and policy maker, licensing authority, supervisor, and registrar.

In the context of laws such as the Environment Act, the Climate Act and the Building Quality Assurance Act, more data will be shared digitally. It is clear that currently different stakeholders from the asset owners' side in the Dutch construction industry are becoming interested in improved asset management processes and are taking notice of BIM for achieving this goal. It might be however that they don't fully understand the usage of BIM for asset management and that the way in which they fully perceive the technology is unclear. This can be hypothesized by the fact that the study by BIMloket revealed that the stakeholders with the lowest BIM usage (29%) and the lowest BIM maturity were the asset owner group (Graas et al., 2021). Currently there is no information in the literature on how stakeholders in the Dutch construction industry perceive the usage of BIM for asset management specifically and this might be crucial to gaining insights into the adoption process of BIM uses for asset management. The perceived attributes of a technology by the target audience are linked to the adoption rates of said technology by aforementioned group, as is described by Roger's diffusion of innovations technology.

Appendix B: Profiles of Interview Participants

ID	Name	Profession	Organization	Position	Experience at Organization (years)
R-1	*****	Asset Management	*****	Consultant	4
R-2	*****	Civil Engineering	*****	BIM Director	5
R-3	*****	Asset Management	*****	Asset Manager	6
R-4	*****	Civil Engineering	*****	BIM Manager	17
R-5	*****	Civil Engineering/ Project Management	*****	Project Manager	27
R-6	*****	Asset Management / Project Management	*****	Project Manager/ Senior Technical Advisor	16
R-7	*****	Civil Engineering/ Project Management	*****	Project Manager	5

Appendix C: Interview structure

The following presents the semi-structured question list which was used during the interviews of the case studies. Important to note it that the interviews were conducted in Dutch. The following question list is translated and presented in English.

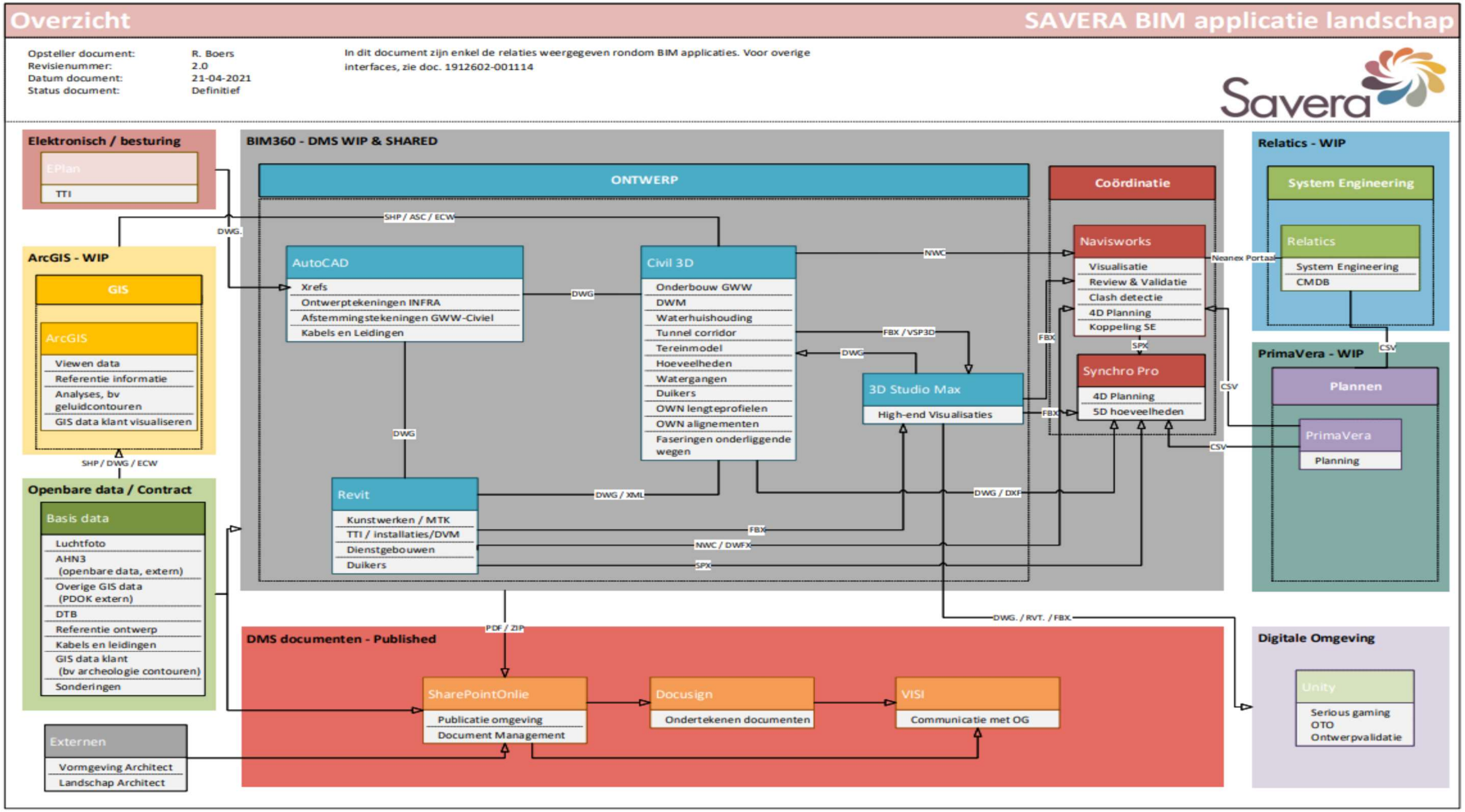
Date:
Location Interview Format: Interviewer: Interviewee ID: Organization:

ID	Question	Purpose
Q 1	How long have you been working at your organization?	Warm up
Q 2	What was your role on the project?	
Q 3	What does BIM mean to you?	Familiarity with key concepts
Q 4	What does Asset Management mean to you?	
Q 5	Was BIM Use (*insert BIM use*) considered on the project? Why (/not)?	Status of BIM Use on project
Q 6	How did you perceive the relative advantage of using BU (*insert BIM use*)?	Perception of variable
Q 7	Was the BIM use compatible with your experience and way of working?	
Q 8	How complex did you perceive it to use the BU (*insert BIM use*) on the project?	
Q 9	Was there a possibility to trial the BUx before full scale implementation? How easy did you perceive this?	
Q10	Have you observed the success of using BU (*insert BIM use*) before?	
Q11	How receptive were your coworkers and partners on the project of this BIM use?	
Q12	To which degree do you think that the arrangement and structure of organizations on the project effected the adoption of the BIM use?	
Q13	How did you perceive the support from your upper management toward the BIM Use?	

Appendix D: Transcripts of Interviews

Removed from this version of the report due to sensitive information and confidentiality agreements.

Appendix E: BIM Applications REHT



13: BIM applications on REHT (sourced from: Rijkswaterstaat)

Appendix F: The Relationship Between BIM and Digital Twin for Smarter Asset Management

When conducting research into enhancing asset management and creating smarter processes it is necessary to discuss the concept of the digital twin (DT). The DT relates to the BIM in the sense that it offers a broader range of analytical capability and information richness. The DT addresses an important limitation of BIM in the sense that it not only is a digital model of the physical built object, but it also supports the automatic and real-time data transference which is much needed for asset management. The concept of DT shares similar characteristics to that of BIM.

Just like with BIM there is no consensus on a definite definition of DT, but an effort was made by Trauer et al. to develop a broadly accepted definition, based on a literature review which revealed key characteristics of the concept (Trauer et al., 2020). They succeeded in deriving a consistent and overarching definition for DT where the concept can be defined as: "..a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange" (Trauer et al., 2020). As can be derived from this definition, BIM is similar to the DT in the sense that they are both virtual representations of physical systems, but the DT differentiates itself in the sense that it is aimed at automatic bidirectional data exchange and can be seen as a broader tool based on different use cases that it is designed for. LU et al. discusses how DT can help with overcoming these limitations of BIM by utilizing additional technologies such as machine learning, artificial intelligence etc.

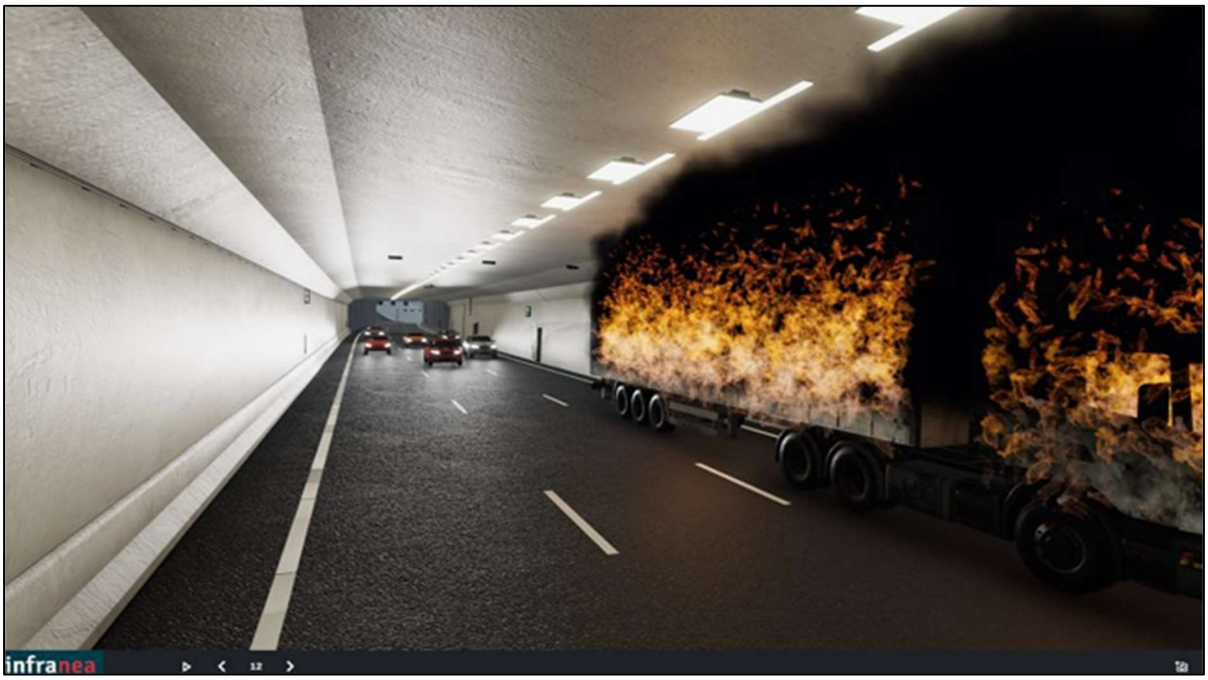
DT can be a valuable tool especially in the O&M phase of the lifecycle of assets, where the vast amounts of data need to be analyzed. BIM would be useful for being an integrative platform and data repository. A recent development is the creation of DTs with a BIM as basis, so-called BIM-enabled Digital Twins. This study is interested in these BIM-enabled Digital Twins, and they are included in the scope of the research focused on solving the issue of the disuse of BIM models post construction and improving asset management with BIM.

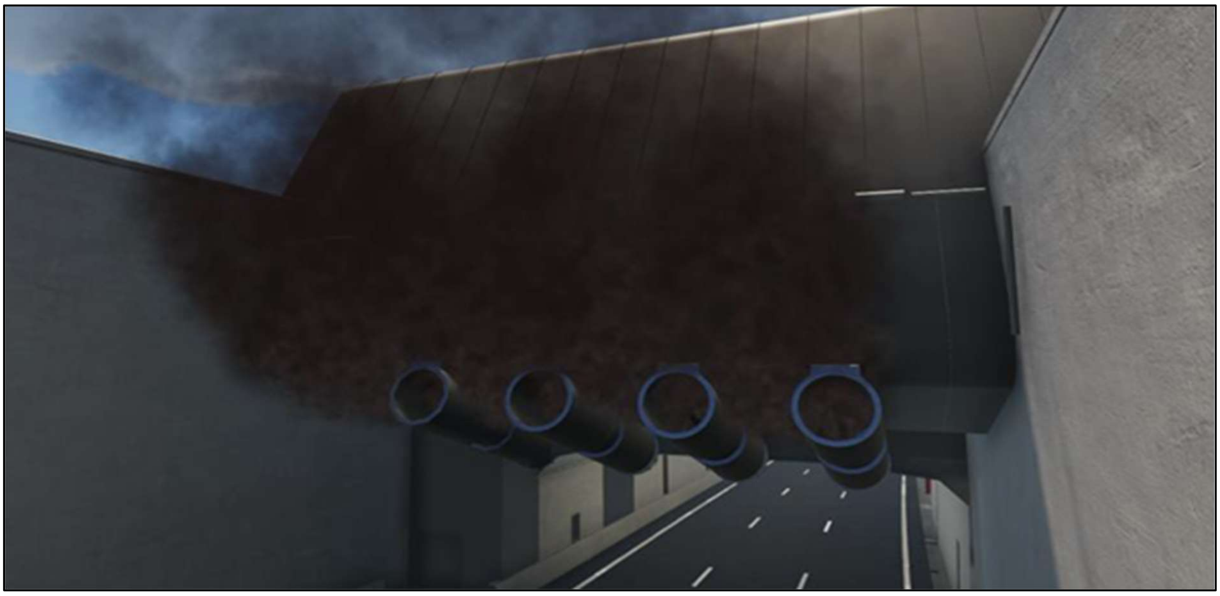
Appendix G: Overview of BIM-Based Digital Twin in EHT

14: Overview of BIM-based Digital Twin (sourced from: Rijkswaterstaat)

Appendix H: Images of utilizing BIM Uses on REHT

The following images depict the BIM uses of visualization and training of personnel on the REHT project. The images were sourced from Rijkswaterstaat.






Opleiden Trainen en Oefenen(OTO)