Graduation Project at Croonwolter&dros

ON

"Potential Application of the Digital Twin in the Exploitation Phase of Infrastructural Projects"

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Preface

As part of the bachelor Industrial Engineering & Management, an assignment is conducted at Croonwolter&dros B.V. The assignment is introduced by the Asset Management department of the infrastructure business division. The question arose whether the Digital Twin, created for the design and construction phase of an infrastructure, could be of value for maintenance after commissioning.

Prior to this research, a project management document is created outlining the project background, problem description and approach, aiming to manage and control the graduation project. Subsequently, a literature review is conducted to the definition of the Digital Twin and the existing applications of the Digital Twin for maintenance in various industries. Moreover, a research proposal is formulated containing the planning and procedures to execute the project.

Concurrently with the internship, support was provided by Ms. Martens and Mr. Straver from Croonwolter&dros, and Mr. Wubben from Avans University of Applied Sciences. I would like to thank them for their assistance, feedback and the opportunity to complete my thesis at Croonwolter&dros. Moreover, I also wish to thank everyone that participated in the research or in any other way helped me with my project.

Finally, I hope that this research will contribute to the decisions that Croonwolter&dros makes regarding the Digital Twin for Maintenance.

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Executive Summary

The bachelor thesis assignment is executed at the Asset Management department of Croonwolter&dros. Croonwolter&dros supports clients in sustainable entrepreneurship with intelligent technical solutions for electrical and mechanical engineering, automation and information solutions. One of those intelligent solutions is the Digital Twin, which is presently utilized during the design phase of several infrastructural projects. The unknown value of the Digital Twin during the exploitation phase of infrastructural projects is the research topic of the assignment. For the purpose of this research, the RijnlandRoute, A16 Rotterdam and Sluice Eefde projects are investigated.

The Digital Twin for Maintenance is considered as a shared digital platform where information and data of the different assets converge through the use of linking applications, a central environment for management and maintenance information and a user interface. Moreover, the Digital Twin supports virtual training, education and testing purposes as well as data analysis. The Digital Twin for Maintenance coordinates the desired functionalities of the participants through the adaption of assigned features, the Digital Twin:

- Facilitates a connection with the technical management application, maintenance management system and document management system through Application Programming Interfaces;
- Offers a centralized environment for management and maintenance information including as-built documentation, supplier contact details, technical drawings, maintenance history, configuration data and construction plans by the creation of a Common Data Environment;
- Serves as virtual educate, train and practice environment offering multidisciplinary training for technicians, service engineers and emergency services with the use of Virtual Training;
- Provides test and simulation environment facilitating a safe environment to test updates before applying them to the real tunnel system through the preservation of the Test Environment;
- Performs data analysis through the use of a playback function for the purpose of failure diagnoses and decision making by integrating the Digital Twin with the Technical Management Application (TBA).
- Offers a user interface where an overview of the infrastructure's status is visualized based on relevant information which can be retrieved centrally, and sensor data can be presented by integrating a Graphical User Interface which include the 3D model and ArcGIS.

The effect of the Digital Twin on Maintenance Performance is an important indication to measure the possible added value of the Digital Twin during maintenance. Maintenance Performance consists of efficiency and effectiveness and through the utilization of KPIs and a Measurement system, improvements by the Digital Twin can be tracked and demonstrated.

Moreover, recent initiatives in the infrastructure industry possibly affect the advancement of the Digital Twin and can influence the decisions Croonwolter&dros makes regarding the investments and allows to set up pilots for Digital Twins more affordably in the exploitation phase.

The feasibility of the Digital Twin is determined by the number of changes and additions required, the willingness of stakeholders and the long-term benefits and strategic advantage of the adoption. The present Digital Twin utilized during the design phase significantly differs from the Digital Twin for Maintenance specified and therefore a considerable amount of additions and changes are required. Moreover, the maintenance teams are usually insufficiently involved with the development of the Digital Twin but appear to take an interest in the Digital Twin for maintenance application. However, the profits regarding the Digital Twin for maintenance are presently unidentifiable in terms of money due to lacking research and successful pilots or implementations.

In conclusion, the concept Digital Twin for Maintenance can noticeably improve the performance of maintenance through the adoption of the desired functionalities outlined by the participants. However, the success in terms of operational productivity and strategic advantage are strongly influenced by the developments of Rijkswaterstaat as well as other initiatives in and around the infrastructure sector and the involvement of the maintenance organization with the development of Digital Twins.

Lastly, the recommended actions for Croonwolter&dros include:

- To better arrange the handover of the Digital Twin from design to maintenance phase as well as to involve the maintenance team with the development of the Digital Twin;
- To create an explicit development path for the Digital Twin implementation and to monitor the improvements realized by the Digital Twin through the use of KPIs and the integration of a Maintenance Performance Measurement system;
- To collaborate with stakeholders on the advancement of Digital Twins or to join existing initiatives with Rijkswaterstaat as important player;
- To further investigate the features of the Digital Twin for Maintenance due to the insufficient knowledge of information technologies.

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List of Abbreviations

3B	Operation Control and Monitor (Dutch: bedienen, besturen en bewaken)
3D	Three-dimensional
API	Application Programming Interface
BI	Business Intelligence
BIM	Building Information Modelling/ Building Information Management
CDE	Common Data Environment
COB	Centrum Ondergronds Bouwen
CWD	Croonwolter&dros
DBFM	Design Build Finance Maintain
DMS	Document Management System
EAM	Enterprise Asset Management
ESB	Enterprise Service Bus
GIS	Geographical Information System
(G)UI	(Graphical) User Interface
I/O	Input/ Output
iFAT	Integrated Factory Acceptance Test
IoT	Internet of Things
iSAT	Integrated Site Acceptance Test
KPI	Key Performance Indicator
MTM	Motorway Traffic Management
OEM	Original Equipment Manufacturer
OMS	Maintenance Management System
OTL	Object Type Library
OTO	Educate, Train and Practice (Dutch: opleiding, trainen en oefenen)
PLC	Programmable Logic Controller
ROI	Return on Investment
SCADA	Supervisory Control and Data Acquisition
SIT	Site Integration Test
TAI	Technische Automatisering en Informatisering
TBA	Technical Management Application
TTI	Tunnel Technical Installations
PMS	Performance Measurement System
VR	Virtual Reality
WCM	World Class Maintenance

1. Introduction

The bachelor thesis assignment is conducted at Croonwolter&dros located in Rotterdam, as part of the Industrial Engineering & Management course. Croonwolter&dros is a project organization and 'Digital Twins' are currently applied in various infrastructural projects. For the aim of this research, the scope is limited to the applications of the Digital Twin in three recent projects, namely A16 Rotterdam, RijnlandRoute and Sluis Eefde. Croonwolter&dros and Mobilis, together TBI Infra, as well as Soltegro B.V. represented in these projects are the main focus.

The Digital Twin has an ambiguous definition in literature since it recently surged in popularity due to the massive technology push in the Internet of Things (IoT), cloud solutions and sensors. The Digital Twin is described by Forbes as 'a virtual model of a process, product or service. This pairing of the virtual and physical worlds allows analysis of data and monitoring of systems to head off problems before they even occur, prevent downtime, develop new opportunities and even plan for the future by using simulations' (Marr, 2017).

The assignment is introduced by the Asset Management department of the Infrastructure Technology business division. With the DBFM integrated contract type, Croonwolter&dros is besides designing and building the infrastructure, responsible for maintenance with lead times between 20 and 27 years. This contract type includes predefined service agreements and when these are not met, penalty clauses enter into force. These penalty clauses affect the repayment and finance structure adversely and are essentially based on the availability and reliability of the infrastructure together with the respective acreage. Minimizing these penalty clauses is crucial, given the profit target of the consortium and funding agencies.

The current capacity of technically trained personnel is insufficient to cope with the increasing need for replacement and maintenance of infrastructures (Kerkhof, Lamper and Fang, 2018). This shortage in technically trained employees is expected to continue or worsen since there is no quick solution (UWV, 2019). This insufficient capacity led to the need for innovative solutions since infrastructures are of significant importance to the economic development and prosperity of the Netherlands as well as the safety of the population. Thus, high reliability and availability of these structures is crucial and partially depends on the quality of maintenance.

Digital Twins are currently created during the design or construction phase of infrastructural projects. It is not evident what the Digital Twin could possibly yield after commissioning, during the maintenance phase. Moreover, it is not yet investigated which properties the Digital Twin should have in order to realize an added value during the exploitation phase.

The integrated contracts with lead times of around 25 years, a shortage in technically trained personnel and the application of the Digital Twin in the preceding phase of infrastructures resulted in question whether the Digital Twin could be of additional value during the exploitation phase of infrastructural projects. This thesis attempts to apperceive this through investigating the following research question: *'How could a Digital Twin improve the maintenance performance during the exploitation phase of infrastructures from Croonwolter&dros?*'

In order to answer the main research question stated above, sub-questions and corresponding objectives are created. These sub-questions and objectives help to structure the research and ensure that the main research question is answered well grounded. Questions I. and II. researched during the literature review, are shortly reiterated in the theoretical framework. The remaining five questions are outlined below. Moreover, the chapter in which the research questions and objectives are discussed are identified.

I. What is the definition of a Digital Twin? Chapter 2.1

II. Which successful applications of a Digital Twin in the exploitation phase of infrastructure technology projects can be found? Chapter 2.2

III. What is a Digital Twin for TBI Infra and what are the corresponding features and functionalities at present? Chapter 4

- Chapter 4.1 - An overview of all features, capabilities and applications of the current Digital Twin within TBI Infra;
- Chapter 4.2 - A comparison between the different visions on the Digital Twin of all relevant stakeholders;
- Chapter 4.3 - Introduction of one Digital Twin definition for TBI Infra.

IV. Which additional features and functionalities are necessary to effectively employ a Digital Twin for Maintenance? Chapter 5

- Chapter 5.1 - Research to the conceivable and desired applications of the Digital Twin within the exploitation phase of infrastructural projects;
- Chapter 5.2 - Analysis of the additional features needed such as hardware and software as well as the required data and smart industry technologies, to satisfy the needs of the stakeholders and to effectively apply the Digital Twin for Maintenance.

V. Which activities and steps are needed to implement the Digital Twin in the exploitation phase? Chapter 6

- Chapter 6.1 - An implementation plan to effectively apply the Digital Twin in the exploitation infrastructural projects including the requisites and restrictions.

VI. To what extend could a Digital Twin affect the maintenance performance? Chapter 6

- Chapter 6.2 - Research to the possible effects of the Digital Twin on the maintenance performance by evaluating the efficiency and effectiveness.

VII. What is the feasibility of the Digital Twin for maintenance? Chapter 7

- Chapter 7.1 - An identification of the current initiatives that can possibly affect the advancement of Digital Twins in the infrastructure sector;
- Chapter 7.2 - A feasibility assessment including the technical and organization feasibility as well as the strategic business viability of a Digital Twin for maintenance.

The research started with assessing the present position of the Digital Twin at the three projects. Next, the Digital Twin for maintenance is discussed including the demanded functionalities, features and a concept. Subsequently, the employment of this concept Digital Twin is elaborated, containing an implementation plan; the maintenance performance; recent initiatives regarding the Digital Twin and a feasibility assessment. Lastly, the conclusions and recommendations are presented, discussing the most important results, answering the main research question and providing recommended activities for the organization.

2. Theoretical Framework

In this paragraph, the descriptive research questions from the literature review are shortly addressed which state: ‘What is the definition of a Digital Twin?’ and Which successful applications of the Digital Twin the in the exploitation phase of infrastructure technology project can be found?’ Moreover, the tools and methods utilized during the research are introduced.

2.1 Digital Twin Definition

The definition of the Digital Twin appears to be ambiguous, thus open to more than one interpretation, since nearly every article introduced another definition. For this reason, the first sub-question ‘What is the definition of a Digital Twin’ could not be answered based on the executed literature review. Nevertheless, a new definition of the Digital Twin is introduced for Croonwolter&dros in the theoretical framework of the research proposal based on the definitions found in literature. An approved and clear definition of the Digital Twin is a requisite for the execution of the research.

Moreover, the elements of the Digital Twin also differ in the reviewed articles. The most consistently described elements are the physical mode, virtual counterpart and data network or Digital Thread between the physical and virtual spaces. Furthermore, three different types of Digital Twins are discussed namely the Digital Twin Prototype, Instance and Aggregate. The Digital Twin is created by employing computer-aided engineering and is integrated with Internet of Things, Artificial Intelligence, Machine Learning, Software and Big Data Analytics with Spatial Network Graphs and cloud-based access or a connected data environment.

2.2 Successful Digital Twin Applications

From the Digital Twin applications in the maintenance phase of the manufacturing, building and aerospace industries can be concluded that the Digital Twin facilitates numerous opportunities. The main capabilities focus on the connection with external data sources, integration of user data, provision of insightful information about the economic and production consequences of maintenance, optimized layouts, error elimination, simulation ability, malfunction predictions and asset tracking. The advantages of utilizing a Digital Twin for maintenance are improved energy and building efficiency; hybrid systems; increased sustainability; optimized heating, air-conditioning and area utilization as well as the reduction of downtime and lifecycle costs.

The articles describing the different application of the Digital Twins in the maintenance phase of infrastructures describe ‘potential’ applications of the Twin since it is frequently still a pilot project or experiment. Moreover, it can be concluded that most articles are concerned with the application of a Digital Twin on bridge structures.

The potential benefits of the applications include more efficient maintenance; organized lifecycle information; improved performance and reliability of the construction; increased lifetime; improved safety; generation of simulations to discover deficiencies or forecast potential problems and supporting strategic decision making. The requirements to apply the Digital Twin for infrastructure maintenance are the integration of sensors; algorithms to analyze the structure and condition; a realistic three-dimensional model; regular updates or real-time data; a knowledge base; parametric modelling; accurate big data management and guaranteed access to information.

3. Research Methodology

To investigate whether the Digital could improve the maintenance performance, qualitative research is chosen. The Qualitative research approach is preferred since it enables to verify new ideas, the perceptions of respondents are considered through focus groups between the different parties and because it allows to fine-tune the questioning during the interviews.

Moreover, qualitative research also allows to interrogate which results in more in depth answers and reasoning. This approach involves exploring and understanding the meaning individuals or groups ascribe to a social or human problem. It is concerned with the features, attributes and characteristics of a phenomenon, in this case the Digital Twin, that can be interpreted thematically [3]. The case study research design is chosen to investigate the application of the Digital Twin in the exploitation phase of infrastructural projects. A variety of data collection procedures are used to gather data, including interviews, a brainstorm session and existing documentation.

Narrative data is collected through conducting interviews using open-ended questions and a brainstorm session with the different roles indicated as participants. The first participants of the research were introduced by the company supervisor and maintenance engineer to gain much information in a short period of time. Moreover, at Croonwolter&dros, Mobilis and Soltegro, documentation exists on the Digital Twin technology. For the current projects, several presentations and articles are published together with the other stakeholders from the consortiums including the subcontractors and the client.

Semi-structured interviews are held with the participants and people from the three projects, who are concerned with the Digital Twin or have specialist knowledge. The interviews are split into three different parts with varying participants since it was noticed that the participants with knowledge on the Digital Twin are often not competent with maintenance management and vice versa. Moreover, each project organization is arranged differently making it difficult to use the exact same interview questions for each participant. In

Appendix 1 Interview Questions and Participants, the questions used during the interviews and the participants can be found.

Initially the present situation of the Digital Twin at the three projects is assessed through interviews with participants who are involved with this technology or oversee the project. Moreover, the existing documentation is utilized to better understand the present position of the Digital Twin.

Next, an ideal Digital Twin for maintenance within TBI Infra is proposed by questioning where the Digital Twin must comply with. Data is collected through interviews, brainstorm sessions and existing literature, aiming to coincide with one Digital Twin for TBI Infra. For this Digital Twin, corresponding functionalities are determined through interviews with the participants who are involved with the maintenance management of infrastructures. Academic journals and articles are utilized to research the features needed to fulfill these desired functionalities. This information will be organized in a Morphological chart which is discussed in chapter 5.

To analyse the present situation of the Digital Twin at the various projects, documentation is collected from the organization websites, technical journals, the SharePoint document management platform of Croonwolter&dros, internal presentations which are shared by the participants as well as project documentation.

The existing documentation is complemented with data obtained from interviews with 10 participants within a timeframe of 8 weeks. There is been made use of open and semi-structured interviews which are held to generate new ideas, more in depth answers and reasoning as well as the ability to still compare the questions to each other.
Moreover, to research the ideal Digital Twin for maintenance, a brainstorm session is held in week 12 with 7 participants through the use of a collaborative whiteboard called Miro. This platform allows all participants to work in the whiteboard simultaneously during the session. After this brainstorm, follow up interviews are held with participants that are involved with the maintenance activities at the various projects.

During the interviews, generally notes were made since it was not always possible to record the interview when for example the interview was held over the phone or the interview started spontaneously. The notes or transcription are included in the appendixes of the report.

The data gathered from the data collection activities, mentioned in the previous chapter, is analysed following a systematic approach to become useful for the research. The business analytics tool Power BI is utilized during the research for data visualization. Moreover, the journal of Ose (2016) is utilized to structure the qualitative data by the use of Excel and Word.

First, data is categorized by applying common codes. Next, themes, patterns and relationships are identified using qualitative data interpretations including word and phrase repetition, primary and secondary data comparisons and metaphors and analogues. The data is summarized by linking research findings to the research objectives and hypothesis (Dudovskiy 2018).

In order to propose a Digital Twin for maintenance, a morphological chart is created according to methodical design process (Siers, 2004). First, the desired functionalities of a Digital Twin for maintenance are researched where after the features to fulfill the function are investigated. A Digital Twin concept is created based on the input from the stakeholders and further elaborated in the implementation plan and feasibility assessment. The methods and tools utilized during the research are further elaborated in Appendix 2 Methods and Tools.

For the purpose of this qualitative research, the following validation strategies are applied:

- Respondent validation – this technique involves feedback from the participants about the accuracy of the data they provided as well as the interpretation of the researcher.
- Exclude alternatives – actively searching for alternative explanations to the research results enables to exclude the other scenarios.
- Multiple perspectives – participants of different levels within the organization as well as other organizations will be interviewed which includes multiple perspectives on the topics.
- Exclusion criteria – problems and solutions focused on the design phase of the projects are excluded from this research.
- Reproducibility – the participants, utilized interview questions and methods are specified to make the research better reproducible and more reliable.

4. Present Position Digital Twin Technology

Digital Twins are currently utilized during the design and construction phase of infrastructural projects at TBI Infra. As mentioned earlier, the A16 Rotterdam, RijnlandRoute and Sluis Eefde projects are included during the research. In this chapter, the projects are shortly introduced, and the third research question is addressed including the corresponding objectives.

The third research question states: '*What is a Digital Twin for TBI Infra and what are the corresponding features and functionalities at present?'* An overview of the present features and applications regarding the Digital Twin is created in order to map the present situation. Moreover, the different visions of the stakeholders on the Digital Twin are compared and an adequate specification of a Digital Twin for TBI Infra is created.

The existing documentation together with the information provided by the stakeholders through interviews is utilized to compare the different visions on the Digital Twin and to create an overview of the current situation.

4.1 Current Available Features and Applications

The current available features of the Digital Twin and the corresponding applications within the three projects are investigated. It is important to outline the present situation in order to analyze what is additionally needed to employ the Digital Twin for maintenance and to better estimate the feasibility of this Digital Twin. Moreover, the present features and functionalities of the Digital Twins differ per project since the application is not identical.

4.1.1 A16 Rotterdam Digital Twin Features & Functionalities

The A16 Rotterdam project consists of a new national highway of 11 kilometer including a tunnel in the 'Lage Bergse Bos', and connects the A13 at Rotterdam the Hague Airport with the A16 at the Terbregseplein as shown in figure 1. The commissioning company of the project is Rijkswaterstaat and the project team 'De Groene Boog Construction V.O.F.' consist of Besix, Dura Vermeer, Van Oord, TBI (Croonwolter&dros and Mobilis), John Laing and Rebel. The project has a DBFM-contract type which entails design, build, finance and maintain, with a 20-year maintenance contract. During the design phase, the consortium is also responsible for the present acreage. In 2017, the preparatory activities started, and the construction is expected to be finished in 2024.

Figure 1 A16 Rotterdam Trace

The TWIN16, the name of the Digital Twin at the A16 Rotterdam, mainly consists of three components, covering all the information and information systems of 'De Groene Boog'. First of all, the application landscape and information facility. Next, a Virtual Reality (VR)-model is created simultaneously, which is filled during its life cycle with information from the design, execution and maintenance phases. Lastly, a web platform is established which gives stakeholders access to relevant project information, for the purpose of process alignment (De Groen, 2017). These three components are further explained in Appendix 3 Digital Twin A16 Rotterdam.

The present functionalities of the TWIN-16 mentioned by the participants include:

- Demonstrate the functional behavior of the infrastructure;
- Bring forward interpretation differences between the stakeholders;
- Minimize rest points towards the completion of the project (De Groene Boog, 2020);
- Optimize and secure integration, validation with client and stakeholders to manage expectations;
- Facilitate insight in one another's work to avoid clashes in the design by ensuring there is spatial coordination between the different components;
- Stimulate integral design and high level of information and application management;
- Support the testing and training in a representative simulation world by integrating training in existing working methods (De Groen, 2017);
- Educate and train emergency services as well as personnel through the use of the game engine and virtual reality location;
- Simulate the possible tunnel scenarios which include the evolution of possible incidents;
- Disclosure of information as main objective which is more BIM focused;
- Improve and accelerate integrated Factory and Site Acceptance tests (iFAT and iSAT);
- Virtually test the software developed by Croonwolter&dros according to the Test Manager (Appendix 4 Interview with the Test Manager of A16 Rotterdam).

4.1.2 RijnlandRoute Digital Twin Features & Functionalities

The RijnlandRoute is a new road connection between Katwijk, via the A44, to the A4 nearby Leiden. The project team COMOL5 consists of Mobilis, Croonwolter&dros, Vinci Construction Grand Projects and DEME Infra Marine Contractors. The project is initiated by Rijkswaterstaat and Province South Holland. COMOL5 won the DBM contract for the first part and consists of design, realization and maintenance for 15 years of the new provincial road N343. The project covers the construction of two motorway junctions to connect the N434 to the national highways visualized in figure 2. Moreover, it also includes the road widening of certain parts of the existing road as well as the rearrangement of the Leiden-west junction (Mooyman, 2018). The RijnlandRoute is expected to be ready late 2022.

Figure 2 Aerial photograph of the activities COMOL5 RijnlandRoute (Linkedin, 2020)

The Digital Twin consist of the 3D-BIM, the Virtual Verification Tool and the test location in Eindhoven. In the 3D-BIM also the coordination model, some installations and civil aspects are modelled and from there a copy is made and behavior is added to each element. However, many installations are purchased and must operate according to their specifications and are not included in the Digital Twin.

Projects such as RijnlandRoute are too large to realize an exact digital copy in detail. Moreover, the verification tool includes a drive simulation for the perception of such an intersection and it does not include a validation of the software. It is linked to the 3D BIM and will be maintained until approximately 2024 according to the Software Architect of the RijnlandRoute (Appendix 5 Interview with the Software Architect of the RijnlandRoute). In Appendix 6 Digital Twin RijnlandRoute, the test location and software and hardware of the Digital Twin are addressed.

The above-mentioned features of the Digital Twin at the RijnlandRoute allow for:

- Focused consultations with the emergency services prior to the project;
- Providing direct insight into the impact of renovations on the entire construction preliminary to the project;
- Digitally test all operational tunnel processes prior to the project (Van Wijck, 2019);
- Operators and emergency services can virtually practice numerous scenarios, long before the actual tunnel is completed.
- After the tunnel object is completed, the Digital Tunnel Twin can be utilized to test software updates on beforehand and to implement new installations (Buijense, 2019);
- Calamities can be simulated;
- Demonstration of the operation of the tunnel systems in various scenarios;
- Validation of the driving behavior of the road users by creating a virtual driving experience of the different road phases (Peek, 2019);
- Validation of the positioning and the simulation of the behavior of installations including the working principle of the installation, which failure can occur and what is the effect of this failure according to the interview with the Software Architect (Appendix 5).

4.1.3 Sluis Eefde Digital Twin Features & Functionalities

The Sluis Eefde project consists of the expansion and large-scale maintenance of the present sluice as shown in figure 3. A second lock chamber will be constructed to increase the capacity for the shipping traffic on the Twentekanaal and after commissioning, the current sluice will go in major maintenance. The project is executed by Rijkswaterstaat and the consortium Lock to Twente which includes the TBI-companies; Mobilis, Croonwolter&dros and TBI PPP. The actual construction started in 2018 and this year the first ship can sail through the new lock (Rijkswaterstaat, 2020). The project entails a DBFM-contract and includes the maintenance of the new sluice for 27 year.

The 3D BIM model of Sluis Eefde is created with the Civil 3D, Revit and Inventor Autodesk software as well as the Allplan Engineering software. The model is not linked to any other applications or systems and is mainly deployed for interface management, verification of requirement and validation of the camera positions and the corresponding visibility coverage. According to the Asset Manager (Appendix 7 Interview with the Asset Manager of Sluis Eefde) documentation is linked to the objects in the 3D-model and the sensor data is first logged in this model where after it is sent to a local database.

Figure 3 Lock Complex Eefde (rtvOost, 2020)

A test arrangement has been built in Apeldoorn and will be preserved during the exploitation phase including the simulation model. This configuration can be altered according to the changes in the physical infrastructure and can be utilized for training according to the Project Manager at Sluis Eefde (Appendix 8 Interview with the Project Manager Sluis Eefde).

The detailed three-dimensional models are incorporated in the BIM model. Rijkswaterstaat arranged a building information management (BIM) data room whereby the traditional data room existing of only documents is extended with a BIM-component based on the Object Type Library (OTL) (Verbruggen, 2016). The data room and corresponding standards are further discussed in Appendix 9 Digital Twin Sluis Eefde.

The present Digital Twin at Sluis Eefde assist to:

- Avoid clashes of the various objects already in the design phase of the project;
- Provide decisive information of the sluice during the exploitation phase;
- Assess the maintainability of the components in the design phase, according to the Asset Manager (Appendix 7).
- Align with stakeholders by visualizing the future sluice with Virtual Reality;
- Communicate the progress and changes in the design of the sluice with stakeholders such as the various disciplines within the project, the local residents and the client;
- Test the software before its installed on the real sluice;
- Verify and validate the systems of the sluice through simulations of the dynamic behavior, in accordance to the Project Manager (Appendix 8);

4.2 Perception of the Digital Twin

From the literature review could be concluded that the definition for the Digital Twin is ambiguous, thus open to more than one interpretation. For this reason, the various perspectives on the Digital Twin from the different stakeholders within TBI Infra at the projects are investigated. Moreover, the associated terms including BIM, Virtual Reality and simulations are included.

4.2.1 Digital Twin of the A16 Rotterdam

The Digital Twin is one of the themes from the digital transformation challenge that the infrastructure sector faces (Fouchier, 2019). The Digital Tunnel Twin at the A16 Rotterdam project is called the TWIN-16 and is a joint project of Soltegro and Croonwolter&dros. Soltegro and Infranea develop the Digital Twin, commissioned by ‘De Groene Boog (Mooyman, 2019).

The Digital Twin refers to a digital replication of a prospective or existing physical assets, processes, users, systems and components which can be adopted for multiple purposes. This digital representation gives insight in the elements as well as the dynamic behavior of the object during its lifecycle. In the Digital Twin, the three-dimensional geometry, interaction of the systems and the virtual software congregate (De Groen and Kreuk, 2019).

The definition of a Digital Twin according to the interview with the TWIN-16 Coordinator (Appendix 10 Interview with the TWIN-16 Coordinator of A16 Rotterdam) of the A16 Rotterdam, is a digital environment of a (to be built) physical object or system. Whereby the worth is maximized over the lifecycle through better design and maintenance decisions based on simulations aided by data of the system or object, data from the outside world and algorithms or codes which describe the behavior or degradation. The challenges are the alignment of the various data sources and to ask the right questions to the Digital Twin.

The Test Manager at the Groene Boog project describes the Digital Twin in the interview (Appendix 4 Interview with the Test Manager of A16 Rotterdam) as the effort to make as much as possible of what you actually have, digital. This forces to think digitally and to link for example through the connection of files. A design is made of a tunnel and it is linked with what will be outside eventually. Everything existing in reality, can be found in the digital environment as well as the certificates and design documentation. Further details on the Digital Twin of the A16 can be found in Appendix 3 Digital Twin A16 Rotterdam.

4.2.2 Digital Twin of the RijnlandRoute

Digital Twin are not new but at the RijnlandRoute, a virtual copy is designed far before the construction is started. The various possibilities can be tested, and the proposals can be aligned with the expectations of the stakeholders well in advance. It appeared to be very clarifying for the involved parties to visually and step by step see how the safety protocols function. Croonwolter&dros gratefully makes use of game engines which are pre-eminently suitable to program action and reaction (Sminia and Pos, 2018).

One of the most important design and validation tools at the RijnlandRoute is 3D. At the project, various objects such as traffic lights and barriers are placed in the Digital Twin and their interfaces are tested in combination with the operation and control software. Moreover, at the RijnlandRoute, the intersection is simulated with Virtual Reality (Mooyman, 2019).

The Software Architect of the RijnlandRoute describes a Digital Twin in the interview (Appendix 5 Interview with the Software Architect of the RijnlandRoute) as a copy of the hardware and the implementation of the design, a one-on-one copy without having it physically but the behavior and the 3D model is supporting but not necessarily needed.

Furthermore, the BIM Coordinator defines the Digital Twin during the interview (Appendix 11 Interview with the BIM Coordinator of the RijnlandRoute) as a Digital Twin of the model and the functionalities are not definite. The best application of the virtual twin so far is testing the equipment of Croonwolter&dros and the situations. Thus, testing the software before it is built. It can also be said that for example 4D planning falls within the scope of a Digital Twin but then it will be made large.

At the RijnlandRoute, the physical objects already exist, and all signals of the real model are duplicated and the behavior behind the input and output (I/O) of the devices are retrieved from the supplier or from the lead engineer documentation. Thus, reconstructing what is already there whilst at the A16, the installations still need to be built.

In the tendering phase of this project, visualizations of the different junctions in the route are created which enables the client to look around 360 degrees. During the design phase, Mobilis made full use of the integral coordination model, which served as a basis for the Digital Twin (Peek, 2019). Moreover, the Building Information Management (BIM) models is acquired from this coordination model and these are converted to 3D-models which are suitable for the game engine. Thereafter, behavior is added, and it can be used as test stand in accordance to the interview with the Software Architect (Appendix 5). Further details about the Digital Twin of the RijnlandRoute can be found in Appendix 6 Digital Twin RijnlandRoute.

4.2.3 Digital Twin of Sluis Eefde

At Sluis Eefde, the 'Digital Twin' can be defined as three-dimensional building information management (3D-BIM). This 3D-model is developed in-house by Mobilis and Croonwolter&dros for the new lock chamber of the sluice. However, the weather condition simulations are developed by Movares Nederland B.V. according to interview with the Project Manager at Sluis Eefde (Appendix 8 Interview with the Project Manager Sluis Eefde).

In accordance to the Asset Manager of Sluis Eefde (Appendix 7 Interview with the Asset Manager of Sluis Eefde), the Digital Twin is a visual representation of the acreage to which information in linked. It enables to execute activities with all crucial information available when needed, which reduces the margin of error. In Asset Management it is all about information management.

The Project Manager indicates during the interview (Appendix 8) that the Digital Twin is a three-dimensional model with dynamic behavior, enabling to create simulations for validation and verification with the stakeholders. Moreover, virtual reality glasses are utilized during the design phase to align the interests of the stakeholders by visualizing the future sluice.

4.3 Digital Twin for TBI Infra

The information of the three projects is collated and it can be concluded that the perspectives of the various stakeholders as well as the documentation from the projects differ greatly. In Appendix 12 Present Functionalities of the Digital Twins, the current functionalities of the various Twins are presented in a table. The definition of the Digital Twin is different for every stakeholder and the functionalities vary at every project. The Digital Twin at the RijnlandRoute for example was only introduced at the beginning of this year while at the A16 Rotterdam, the Digital Twin was introduced at the start of the project. Therefore, not many people at the RijnlandRoute are familiar with this subject. The Digital Twin at Sluis Eefde can be specified as a 3D-BIM and not necessarily as a Digital Twin.

However, there are also similarities between the Digital Twins of the three projects. The Digital Twin of RijnlandRoute and A16 Rotterdam are both managed by Soltegro and both environments will be equated. At this moment, even virtual installations are mutually exchanged. Each project makes use of three-dimensional models and Building Information Modelling (BIM). Moreover, all three projects are equipped with a test environment that will be preserved after commissioning.

From all interviews, the visions of the various participants are gathered. Through the use of the qualitative data analysis method discussed in the methodology, the present Digital Twin for TBI Infra is specified as:

"A three-dimensional digital environment of a prospective or existing infrastructure. The Digital Twin runs on a game engine where dynamic operation and functions, including tunnel system scenarios and software models, congregate with the stationary geometry of integrated 3D-BIM models. The functional and physical behavior are simulated and supported by data and algorithms or codes which describe the behavior or degradation.

Virtual Reality is utilized for stakeholder management and has an important role during the design and testing of infrastructures. The Digital Twin allows for validation and verification of the interaction and operation of the system architecture. Moreover, it allows to offer training for emergency services and tunnel operators. Lastly, a test facility is created to support software tests before commissioning the tunnel”.

5. Digital Twin for Maintenance

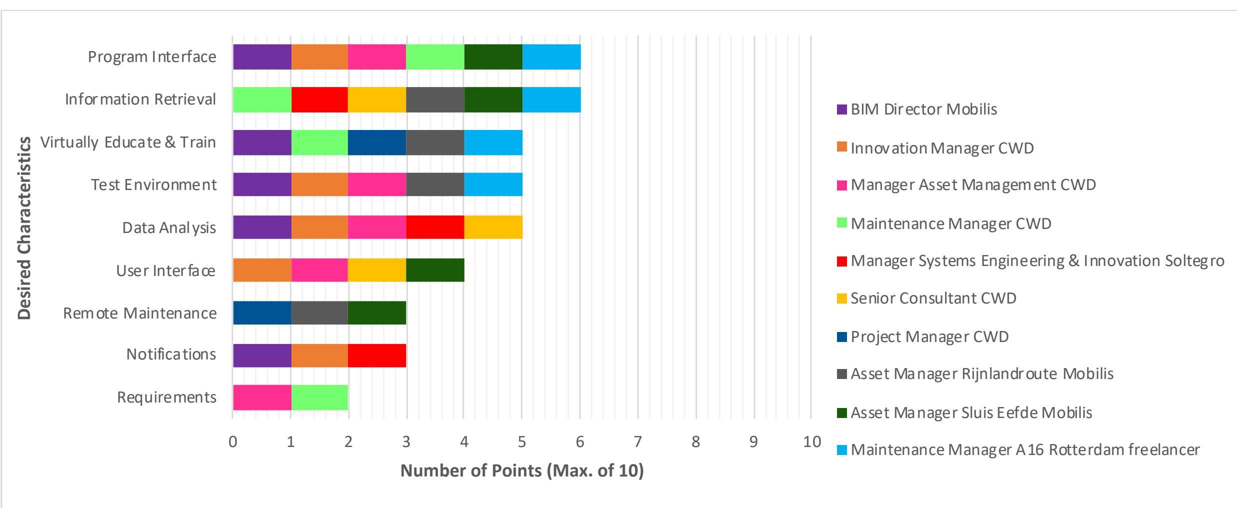
The desired functionalities and corresponding features of a Digital Twin for the maintenance phase are researched in order to answer the fourth research question which states *‘Which additional features and functionalities are necessary to effectively employ a Digital Twin for Maintenance?’* Information is obtained from the Asset Management department of Croonwolter&dros and Mobilis, Asset and Maintenance Managers of the projects through interviews and a brainstorm session. An overview of the Miro whiteboard can be found in Appendix 13 Miro Whiteboard Brainstorm Session.

During the brainstorm session, various functionalities introduced in literature are suggested to the participants in order to demonstrate the possibilities. The output of this brainstorm session includes a list with functionalities, advantages as well as preconditions and challenges to work with the Digital Twin. After this brainstorm, follow up interviews are held with the Asset and Maintenance Managers of the various projects.

During these interviews, the practicability of the functionalities introduced during the brainstorm session are analyzed and the presently faced obstacles during maintenance are identified together with the preconditions to utilize the Digital Twin for maintenance. The results of the brainstorm session can be found in Appendix 14 Results Brainstorm Session & Interview Asset Managers. The functionalities of the brainstorm session and interviews are categorized and the most frequently chosen characteristics of a Digital Twin are visualized in Table 1 Desired Digital Twin Characteristics.

The methodical design process provides a structured approach for the concept generation of the Digital Twin. The information gathered by above mentioned activities are presented in a morphological chart. It captures the necessary product functionalities researched in chapter 5.1 and explores the alternative means and combinations of features to achieve the functionalities in chapter 5.2.

Table 1 Desired Digital Twin Characteristics



5.1 Demanded Functionalities for Maintenance

In this chapter, research is done to the conceivable and desired applications of the Digital Twin within the exploitation phase of infrastructural projects, conducive to answer the fourth research question. The functionalities which are deemed valuable for maintenance are gathered in the morphological chart in Appendix 15 Morphological Chart Digital Twin Concept. The functionalities are prioritized based on the amount of people describing the same sort desired application.

A program of requirements is developed whereby a difference is made between the requirements and the wishes represented by the functionalities. The requirements represent the capabilities which the design must meet, and wishes are the desired and noncompulsory functionalities of the Digital Twin.

The functionality is classified as a requirement when more than three participants outline the functionality as valuable for maintenance. In consultation with the Asset and Maintenance Managers, the value of the functionality is discussed in more detail. The program of requirements is illustrated below in Table 2 Digital Twin for Maintenance – Program of Requirements.

Table 2 Digital Twin for Maintenance – Program of Requirements

Requirement	Wish	Functionalities
X		1. Facilitates a connection with the technical management application, maintenance management system and document management system(s).
X		2. Offers a centralized environment for management and maintenance information including as-built documentation, supplier contact details, technical drawings, maintenance history, configuration data and construction plans.
X		3. Serves as virtual educate, train and practice environment (OTO) offering multidisciplinary training for technicians, service engineers and emergency services.
X		4. Provides test and simulation environment facilitating a safe environment to test updates before applying them to the real tunnel system.
X		5. Performing data analysis through the use of a playback function for the purpose of failure diagnoses and decision making.
X		6. Offers a user interface where an overview of the infrastructure's status is visualized based on relevant information which can be retrieved centrally, and sensor data can be presented.
	X	7. Supports remote maintenance by an up-to-date model and relevant information. Enables to assist technicians with insufficient domain knowledge or to better prepare maintenance activities.
	X	8. Sends notification when behavior deviates and for predictive maintenance.
	X	9. Automatically demonstrate availability requirements.

5.2 Additional Required Features for the Maintenance Application

The additional features or methods necessary to comply with the requirements of the stakeholders to effectively apply the Digital Twin for maintenance are gathered in the Morphological chart (see Appendix 15 Morphological Chart Digital Twin Concept). The corresponding features are acquired through research and are shortly introduced below.

5.2.1 Functionality 1 – Middleware or Application Interface

It usually appears at the projects that many different software systems do not communicate with each other. The different stakeholders use the systems that fit for their purpose, but the data is often not available in another system. When the systems are not sharing data, information must be inserted manually into the different systems, making it difficult to guarantee that the information is up-to-date or to provide insight (Schopen, 2015).

To enable a connection between the different applications, the middleware concept can be utilized. Middleware is software that acts as a bride between an operating system or database and applications, especially on a network. For the purpose of this research, the modern integration infrastructure named Application Programming Interface (API) management software and Enterprise Service Bus are introduced (Luenendonk, 2019) Appendix 16 Application Interface – API and ESB.

5.2.2 Functionality 2 – Project Data and Document Management

Typical infrastructural projects generate a colossal amount of data and requires the creation and sharing of never-ending data during the lifecycle of the project. Unfortunately, the trouble is that information is often unstructured, poorly coordinated and difficult to find. Many project teams find it hard to manage and disseminate the information effectively over such a long period of time.

There is a wide range of possibilities in order to manage project information. For the purpose of this research, the Common Data Environment (CDE) and the conventional method, the Document Management System (DMS), will be discussed shortly in Appendix 17 Project Data and Document Management – CDE and DMS.

5.2.3 Functionality 3 – Virtual Training

Rijkswaterstaat is the largest tunnel manager in the Netherlands and ensures that the personnel are correctly prepared to perform the tasks required to guarantee the safety of the tunnel. For this reason, a national OTO-program is set up (Oto portaal, 2020). OTO is a Dutch abbreviation for educate, train and practice and denotes the multifaceted of the virtual environment. There is a structural need for continuous education and training.

For two other tunnel projects, a virtual training environment is built by Croonwolter&dros where the operation of the events in the tunnel are simulated in detail. Through the use of XVR, the tunnel can be virtually presented, and dynamic elements can be added. The XVR-software generates a realistic image, the hardware and controls in the test environment correspond to the original material (Bastiaanse, 2020).

Both tunnels have their own OTO-program and Croonwolter&dros added a simulator for the system control layer TuBeS. The TuBeS is the abbreviation for tunnel control system and is a graphical presentation for the control of the tunnel. The representation functions on the SCADA platform of Siemens. A duplication of the operational tunnel control system with simulations are realized in order to make the training as realistic as possible, this enables the user to interact with the tunnel (OTAR, 2020).

5.2.4 Functionality 4 – Test Facility

The Digital Twin is a virtual model and offers a safe digital design, develop and test environment where the 3D-geometry, interaction of systems and even the virtual software congregate. Within this virtual environment, improvements can be made by testing and simulating how the different components function (Croonwolter&dros, 2018).

Through the use of the Digital Twin, the required tests can be performed much earlier in the process. It can for example be checked whether the fire extinguishing system works correctly or if the ventilation systems turns on in time before the tunnel is commissioned. This can be attained when the real tunnel operates the same as the virtual twin (Jankovic and De Groen, 2020).

For the infrastructural projects, frequently test locations are set up in order to test the operation of the installations and the software before the tunnel is realized. For the Rottemerentunnel of the A16 Rotterdam, the virtual reality model is integrated in the test environment and improves as well as accelerates the integrated factory and site acceptance tests (iFAT and iSAT). Moreover, the representative simulation world allows to test the software developed by Croonwolter&dros virtually according to the interview with the Test Manager (Appendix 4 Interview with the Test Manager of A16 Rotterdam).

The complexity of the tunnel technical installations (TTI) can lead to substantial delay and extra costs for tunnel projects. For this reason, the integral tests of the TTI and corresponding operation takes place two years before the opening of the RijnlandRoute. In factory halls, various installations such as the cameras, display panels and transformers are placed. More information on the test facility of the RijnlandRoute can be found in Appendix 18 Test Facility.

5.2.5 Functionality 5 – Data Analysis

Data is currently acquired through corrective and preventive maintenance activities in the maintenance management system, usually Maximo. The activities include visual inspections, corrective and preventive maintenance as well as condition monitoring through instruments.

Moreover, a Technical Management Application (TBA) is currently being developed by the Croonwolter&dros venture 'Technische Automatisering en Informatisering' (TAI). The TBA should provide the monitoring for the long-term maintenance period of the RijnlandRoute, Sluis Eefde and A16 Rotterdam projects.

In TBA, real time signals from the infrastructure in the field will be analyzed and presented. It will enable to view failures, the running hours of the installation and the status of the assets. At present, it is discussed with the different parties at the projects which values of the different installations should be monitored. The additional information regarding the TBA and analytics can be found in Appendix 19 Data Analysis.

5.2.6 Functionality 6 – User Interface

At present, an overview is missing where all information about the assets of an infrastructure comes together. Ideally, there would exist one interface for the user where information about the asset from the different underlying systems can be extracted through one coordinating system. This objective can be achieved by a User Interface (UI) in the form of a platform.

A user interface is the point of human-computer interaction and communication on a device, webpage, or app. This can include display screens, keyboards, a mouse, and the appearance of a desktop. User interfaces enable users to effectively control the computer or device they are interacting with (Hannah, 2019). Moreover, a Graphical User Interface (GUI) is a type of user interface whereby the users interact with electronic devices through visual indicator representations.

‘Graphical user interface design principles conform to the model-view-controller software pattern whereby the internal representation of information is separated from the manner in which information is presented to the user. This results in a platform which shows the user which functions are possible rather than requiring the input of command codes (Omni Sci, 2020).

For the purpose of an interface, two options are researched, the three-dimensional (3D) model created during the design phase of the projects and the Geographic Information System (GIS) described in Appendix 20 User Interface – 3D and GIS. The interface serves as a dashboard or platform where all relevant information for maintenance management converge.

5.3 Proposed Digital Twin Concept for Maintenance

Based on this Morphological chart, a Digital Twin concept is proposed and elaborated. The concept consists of a logical combination of features to fulfill the desired functionalities. This combination of features is visualized in the morphological chart in Appendix 15 Morphological Chart Digital Twin Concept. For this Digital Twin, an implementation plan and feasibility study are created. This morphological chart can be supplemented with more functionalities and features enabling to create additional concept Digital Twins for Croonwolter&dros.

For the Middleware or Application Interface, Information Management and User Interface functionality, two alternatives are introduced and compared. In order to fulfill the middleware functionality, the Application Programming Interface is chosen. ESB and API share functionality and capabilities, however API management tools are more flexible and optimized for the recent advanced technology developments, the solutions are typically consumption-based while ESB have an exposure-based model and API tools usually have supplementary features.

Furthermore, the Common Data Environment is preferred over the traditional Document Management System. A CDE is a central and online single source of information during the projects. Contents of the CDE are not limited to assets created in a BIM environment but can include documentation, graphical models and non-graphical assets. At present, information management is crucial for asset management and the DMS lacks the capability to manage the various file types efficiently. Moreover, a DMS is usually not centralized over the project and the main sharing tool is email causing information to be scattered easily.

For the user interface functionality, both features are chosen since GIS and 3D both show their value as interface. ArcGIS gives a clear overview of the entire area and is provided by Rijkswaterstaat. At the A16 Rotterdam, the web application includes a route information map which allows to navigate through the acreage and shows panorama photographs of the present and future situation. The graphical information systems can be complemented with the 3D models by clicking on an area or module. In this model, the assets can be visualized, and information can be disclosed in the components.

For the virtual training, test facility and data analysis functionalities, the present situation is outlined in chapter 5.2. In the implementation plan, it is analyzed how these available features can be deployed and can be of added value during the maintenance phase.

The concept Digital Twin for Maintenance coordinates the functionalities. The concept is focused on the requirements assigned to the Digital Twin. The wishes are not incorporated due to the complexity of all technologies that congregate in a Digital Twin. A short introduction of the wishes introduced by the participants can be found in Appendix 21 Digital Twin – Additional Functionalities.

6. Employment of Proposed Digital Twin

In this chapter, the implementation of the concept Digital Twin in the exploitation phase is discussed together with the effect of the Digital Twin on the maintenance performance in order to answer research question five and six.

6.1 Implementation Plan

The starting point of the Digital Twin is the visualization in the three-dimensional BIM. The Digital Twin is a virtual model and offers a safe digital environment where the three-dimensional geometry, the interaction of the systems and or even the virtual software congregate The Digital Twin runs on a game engine allowing the simulate and visualize the dynamic behavior. In this Digital Twin, the stationary geometry of the integrated 3D model come together with the dynamic operation and functions including the software models and tunnel scenarios.

The selected features for the Digital Twin, outlined in chapter 5.3, are elaborated below, it is researched how these features can achieve the functionalities that are categorized as a requirement. Moreover, the restrictions and requisites of the implementation, identified by the stakeholders, are discussed. In order to answer research question five: *'Which activities and steps are needed to implement the Digital Twin in the exploitation phase?'*

6.1.1 Application Programming Interface

The Application Programming Interfaces (APIs) allows different (software) systems to communicate and exchange information. This feature allows for the congregation of the Maintenance Management System (Maximo), Technical Management Application and Document Management System(s). A concept of the system architecture is visualized in figure 4 indicating the connections between the systems. The selection of these three systems is based on the input of the participants, as described in Appendix 14 Results Brainstorm Session & Interview Asset Managers.

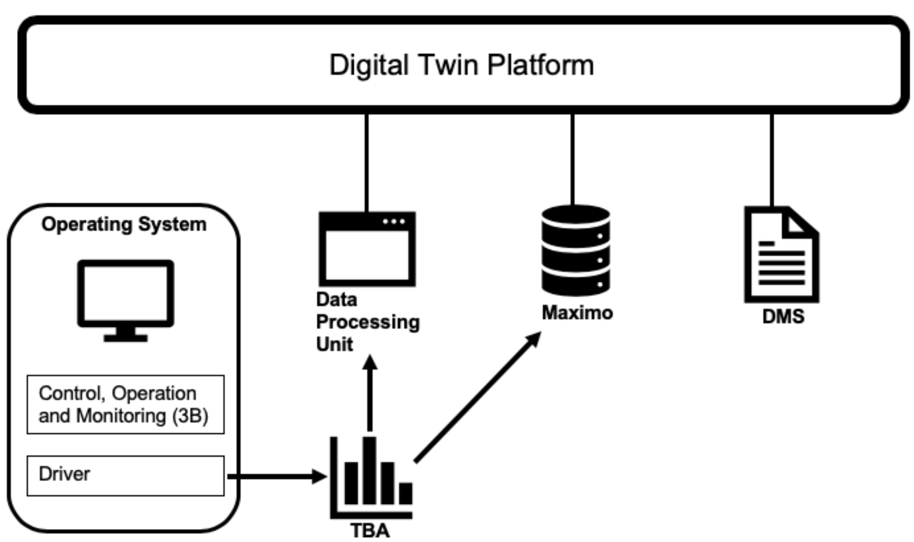


Figure 4 Concept Digital Twin - System Architecture

In order for the Application Programming Interfaces to communicate, a connection is required between the various systems. Some applications have additional built-in tools to make the connections work or an additional service can be purchased (Schopen, 2015). Examples of such tools include Zapier, Microsoft Flow and Integromat (Themeisle, 2019).

There exist four main types of APIs, namely Open APIs, Partner APIs, Internal APIs and Composite APIs. Moreover, different types of API protocols can be distinguished and include REST, SOAP an RPC (Castellani and Dorairajan, 2020).

In order to link the OMS, DMS and TBA with the Digital Twin, it must be ascertained whether those application already feature an application programming interface. Moreover, it must be decided whether a one or two-way integration is desired between the Digital Twin platform and the systems. The TBA, more extensively discussed for the data analysis functionality, will include a standard TBA interface mechanism and a link with GIS. TBA will send work orders to Maximo in the future which is visualized by the arrow from TBA to Maximo in figure 4.

Maximo presently delivers a REST API and with the release of Maximo 7.6.0.2 a new JSON API is available. The Document Management System utilized during the maintenance phase is not selected yet for the A16 Rotterdam and RijnlandRoute. For Sluis Eefde, DigiOffice is chosen and offers the ability to collaborate with various other applications for example through webservices with XML-messages (DigiOffice, 2020).

Moreover, the integrated systems should be synchronized, and a uniform language should be applied in the different systems to make it successful. It is important to investigate whether a real time synchronization between the systems is of value or whether a daily update is sufficient. Next, data should be classified based on uniform tagging. This can be achieved through applying a standard Object Type Library (OTL). The standardized object types allow to collaborate with the different parties with the same words in one language (RoyalHaskoningDHV, 2020). Data should be delivered from the different parties in a platform-agnostic, open file-format to standardize data utilized during the project.

6.1.2 Common Data Environment

Information of infrastructural projects is produced in many forms including drawings, documentation, lists or BIM-models. Moreover, this information is also collected through different communication channels including email or even scanned paperwork. In order to manage the overload of information, it is important to create a standardized manner of collaborating and structuring by adopting a Common Data Environment (CDE) (Allen, 2019).

At Schiphol for example, the CDE brings data together from a great number of sources and includes Building Information Models data, GIS-data and real-time data of project changes and incidents as well as financial information, documentation and project portfolio's (Baumann, 2020).

The British standard PAS 1192-2 provides a complete overview of the CDE and it is adopted to enhance interoperability using Building Information Modelling. This data sharing platform has been outlined for the first time, in an organic and defined manner, by British technical standards (Biblus, 2020).

The working principle of a CDE is visualized in figure 5 and shows a single and centralized source of information for all stakeholders during the entire lifecycle. The CDE specifically mandates that data is stored in a single location or repository.

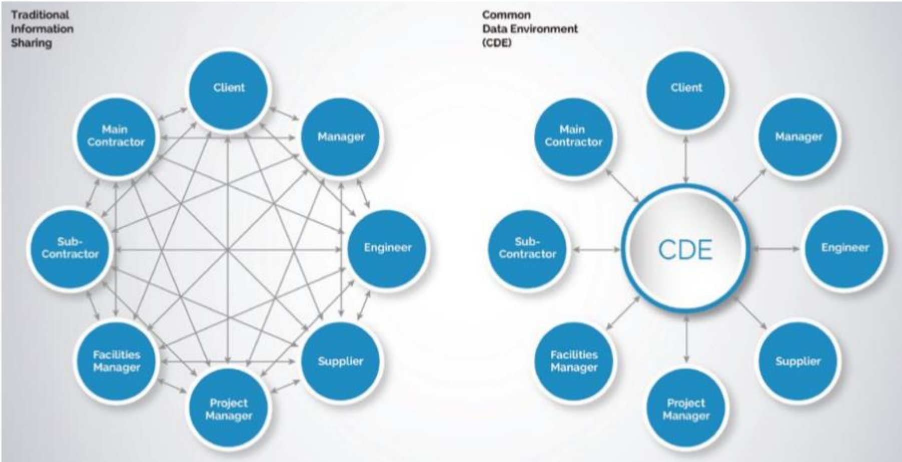


Figure 5 From traditional information sharing to a Common Date Environment

The single location can be facilitated by the Digital Twin which presently facilities the 3D geometry and interaction between systems. The BIM forms the basis for the Digital Twin, herein all physical properties as well as the positioning of the different installations are registered. In the course of the project, more data is generated, and this should be managed in the same location.

The information necessary during the exploitation phase include as-built documentation, configuration data, maintenance history and real-time monitoring information of the objects. This information is dispersed among the different applications and should be gathered in the CDE. The Digital Twin platform visualized in figure 4 can operate as such a Common Data Environment since information from the different systems is congregated here.

In order to benefit from the CDE, there are several preconditions which must be considered. When working in a central repository, permission levels and privileges management are of importance. Since not all stakeholders from the various organization are allowed to access or modify certain information that is available in the system (Building in Cloud, 2018).

Moreover, a workflow process is needed so it is clear which information remains work in progress, which has been shared following appropriate review and which is published following stakeholder sign-off (McPartland, 2016). Other attributes of the CDE include integration with the current systems and processes in order to increase the overall collaboration, allowing for standardized workflows and processes (Allen, 2019) and information security through for example ISO 27001.

The Common Data Environment can have many forms which will depend on the size or type of organization or project. It can be a project server, an extranet, a cloud-based system or a file-based retrieval system (McPartland, 2016) and (Designing Buildings, 2020). CDE platforms or services are widely offered including the Autodesk Construction Cloud (Allen, 2019), BiC-CDE from Building in Cloud (Building in Cloud, 2018) and EPLASS CDE from Think Project (2020).

6.1.3 Virtual Training

The present training environments are mainly created for the tunnel operators and emergency services, but it could also be of value for maintenance technicians and operators. For two tunnel projects, mentioned in chapter 5.2, the XVR represents the tunnel virtually. However, the training environment can also be integrated with the Digital Twin, this enables to offer 100% virtual simulations (Bastiaanse, 2020).

Individuals are visually oriented and making the events visible in a dynamic environment through Virtual Reality facilitates this. The scenarios are displayed in the 3D environment where the action and reaction can be shown. Moreover, with VR glasses practical exercises can be realistically recreated since it improves the perception in comparison to scenarios described on paper.

To provide virtual training for maintenance, the OTO program earlier mentioned is needed supplemented by maintenance related scenarios. These scenarios can include installation failure and repair including their consequences as well as preventive maintenance activities. The training environment can be of value during maintenance since it is not necessary for the infrastructure to be closed in order to show it to new personnel for example. Moreover, for the purpose of training it is not necessary to wait for a night when the infrastructure is closed for planned maintenance activities.

6.1.4 Test Environment

A test facility could also yield potential benefits during the maintenance phase of infrastructural projects. The virtual copy of the tunnel, 'Digital Twin' enables to perform tests extensively. For example, to validate how the systems responds after an update or modification, during patch testing and renovation activities. Software might be the most important element during the construction of the tunnel since it concerns the control and the heart of the tunnel.

For the testing of security patches, the Digital Twin offers advantages. A patch refers to a small adjustment to the code of the software being used. It updates one component of the software, perhaps to fix a bug or error discovered after product release. However, security patches address the vulnerabilities of software that cybercriminals might use to gain unauthorized access to devices and data. The adjustment to the software can first be authorized in the Digital Twin before applying it to the real tunnel software to ensure the new patch works properly.

During renovations, a vast amount of installations will be replaced preventively. In a test facility, the software of the installations can be connected to the virtual tunnel first before installing them in the physical tunnel. This allows to confirm whether the installations function as intended. In a paper of Centrum Ondergronds Bouwen (COB), an identification in made of the possibilities and boundary conditions to shorten the tunnel closure through virtual testing. The three basic facilities to perform tests are the power system, the data transmission and the 'common hardware' which includes the PLC where the 3B and drive are running (COB, 2017).

6.1.5 Data Analysis

Performing data analysis through the use of a playback function for the purpose of failure diagnoses and decision making is where the stakeholders see the value of the Digital Twin in the exploitation phase. The Digital Twin as a place where data is collected as well as analyzed to gain insight in the status of the asset and to support asset management decisions. Input data can include operational data, Original Equipment Manufacturer (OEM) data, control parameters and sensor data. With the increasing digitalization, the amount of available data grows at exponential rate. It is becoming easier to assess conditions and to store events.

The integration between the TBA and Digital Twin can be realized through the first functionality, application programming interface. The TBA will readout data from the driver and will forward this to a data processing unit. Possibly the Digital Twin could function as the user interface for the TBA where the data can be presented and potentially analyzed. The Digital Twin can be a tool to support the evaluation to smart maintenance. The roadmap of the Asset Management Team defines several stages of monitoring, data, analysis, insights and decisions.

Through the use of virtual reality, registered asset behavior and historical data, it should be possible to visually rewind or playback in the event of a failure for the purpose of diagnosis. In order to view and analyze data through time and improves the visualization of the results in the context of the project. Aiming to visualize the status of assets and analyze problem visually.

At Sluis Eefde, a ‘experimental garden’ is initiated where steps are made towards Smart Maintenance. This field lab of World Class Maintenance (WCM) is focused on measuring the status of infrastructures with the use of sensors and data analysis. All parties strive to practice new techniques and applications around Smart Maintenance to improve the performance and reliability of the sluice as well as to create effective maintenance schemes.

One of the data sources which is utilized to gain insight is SCADA (Supervisory Control and Data Acquisition), all movements and traffic at and around the sluice will be registered and it can be extremely valuable for condition monitoring (iMaintain, 2018). It should be analysed whether the results of this project could be of value for other infrastructural projects in order to improve the maintenance strategy of other projects.

6.1.6 Graphical User Interface

For the Graphical User Interface of the Digital Twin platform visualized chapter 6.1.1, both the GIS and 3D model can be utilized simultaneously. At the A16 Rotterdam and RijnlandRoute, only the tunnels are modelled in 3D. Various installations including the motorway traffic management (MTM) systems and lampposts are not completely incorporated in this 3D model and scattered over the entire acreage. However, the consortiums are also responsible for these installations during the maintenance phase and therefore must be incorporated in the user interface. In figure 6, an example of a GIS user interface is visualized where installations are denoted by a symbol.

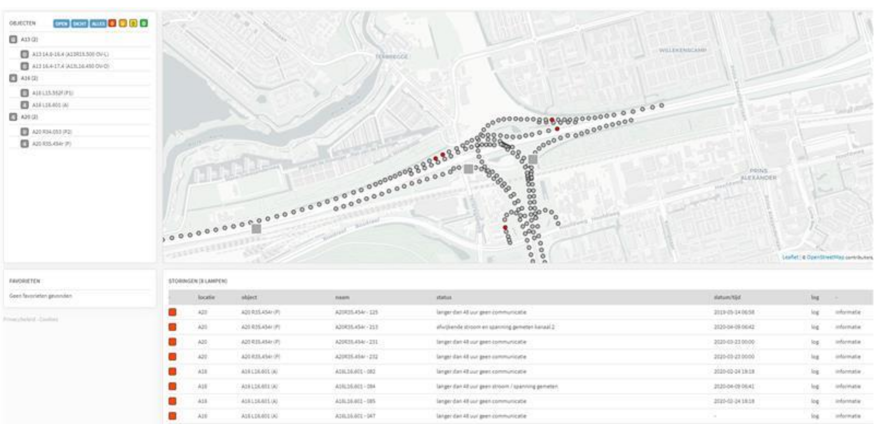


Figure 6 Example of a GIS-Interface

By linking the systems utilized during maintenance through the use of Application Programming Interfaces and the incorporation of a Common Data Environment, the user interface allows the stakeholders to retrieve information efficiently from one location. Thus, by clicking on the installations in the GIS and 3D interface, information and data that is available in the underlying systems can be retrieved in one single visual interface.

Sensor data from the technical management application can be visualized through various tools such as PowerBI which is available within Croonwolter&dros and capable for data visualization in the Digital Twin platform and IoT applications. With the aim to offer a dashboard including (real-time) sensor data to monitor the asset condition.

The main elements of a user interface include input controls, navigation components, informational components and containers. Input controls are interactive components and screen objects that accept the input from the user, such as text boxes and buttons. The navigation components allow the user to move within the interface, examples are search fields and tabs. Information controls display information and cover amongst others, notifications and message boxes. Lastly, containers group other controls for organization purposes. These controls indicate a relationship between grouped controls (Hannah, 2019). It is important to analyze how these elements should function and appear in the GUI to optimize the employment.

Important prerequisites of the GUI include that the interface must be user friendly, thus that all stakeholders can easily work with it and to understand. The needed information must be easy to find in a short amount of time. Moreover, the interface should be flexible or customizable. Not all roles and organizations need or are allowed to view the same data and information. Moreover, the interface must be accessible from various locations including on site and at the office but also most preferable available from a mobile device or tablet. Otherwise, people will try to avoid or bypass the system and start working again with the old methods.

6.2 Maintenance Performance

The sixth research question states: *'To what extend could a Digital Twin affect the maintenance performance?'* and it attempted to be answered by researching the possible effects of the Digital Twin by evaluating the efficiency and effectiveness.

6.2.1 Maintenance and Performance Description

Maintenance is defined as the combination of all the technical and administrative actions, including supervision, intended to retain an item, or restore it to a state in which it can perform a required function. A Digital Twin mainly impacts performance which appears to be more relevant during the use and maintenance stage (Tchana, Ducellier and Sebastien, 2019). Maintenance performance reflects to what degree the desired results of a particular event are accomplished. Performance measurement can be utilized to monitor the implementation of new ideas to determine the success and possible improvements (Tiddens, 2011).

In order to assess maintenance performance, maintenance efficiency and effectiveness are considered. Efficiency can be defined as performing or functioning to achieve a desired result in the best possible manner with the least waste of time and effort (Insight Squared, 2020), thus concentrating on how well the resources for maintenance are utilized. Effectiveness is the adequacy to accomplish a purpose, the ability to produce the intended or expected result, in other words how maintenance ensures that the user can deploy their assets in a desired manner. In contrast to efficiency, effectiveness is determined without reference to costs, whereas efficiency means "doing the thing right," effectiveness means "doing the right thing" (Business Dictionary, 2020).

6.2.2 Availability-Based Contract

For Croonwolter&dros, the most important benchmark for maintenance is the availability of an infrastructure which is demanded by the client, often Rijkswaterstaat. The consortium receives a fixed amount of money every quarter according to the DBFM contract. This amount of money can be curtailed if the availability requirements of the installations are not met. When an installation fails to meet the requirements, penalty points are issued either directly or after a given time to solve the failure. The recovery period and number of penalty points are based on the assigned failure category. The failure definition of an installation indicates when the 'logic function fulfiller' works insufficiently and therewith can form a potential risk for the road users. The failure definition helps the maintenance organization and tunnel operator to make decisions in case of failure (DON Bureau, 2020).

6.2.3 Potential Effect of the Features on the Maintenance Performance

A substantiation for the implementation of the Digital Twin for Maintenance is created through discussing how the six different features can positively influence the maintenance performance, and can be found in Appendix 22 Maintenance Performance Influenced by the Features of the Digital Twin.

The Digital Twin features have high potential to positively influence the efficiency and effectiveness of maintenance. Moreover, the Digital Twin for maintenance has the ability to reduce the costs of maintenance and the costs of unavailability of equipment. It not necessarily improves the direct availability of installations since the maintenance strategy, which at present incorporates a combination of corrective and preventive maintenance, remains unchanged.

6.2.4 Measurability of the Maintenance Performance

According to the Master Thesis of Tiddens (2011), Maintenance Performance can be calculated by multiplying maintenance efficiency with maintenance effectiveness as shown in Equation 1. Maintenance efficiency is determined by costs and scheduling and maintenance effectiveness is defined by health and availability. The health parameter classifies the ability of a system to perform its functions. The availability is the percentage of the time the equipment is available, and it should be compared to the requested availability of an asset. Maintenance costs refers to the ratio between the planned and actual costs. As last, the scheduling parameter which involves the grip on the process.

$$
\begin{aligned}
&Maintenaenc\ Performance \\
&\quad = Maintenace\ Efficiency\ (Costs\ \cdot Scheduling) \\
&\quad \cdot\ Maintenacne\ Effectiveness\ (Health\ \cdot Availability)
\end{aligned}
$$

Equation 1 Maintenance Performance

Another option to make the impact of the Digital Twin measurable, is by making use of key performance indicators (KPIs). New performance indicators can be introduced or the KPIs of the Asset Management departments can be of utilized to measure the consequences of implementing the Digital Twin, the KPIs of the Asset Management department include:

- Assets provided with the correct data in the Enterprise Asset Management (EAM) system in percentages;
- Productivity of (maintenance) technicians in percentages;
- Planned workorder completed in time in percentages;
- Realized savings over the contract duration in euros.

Measuring maintenance performance can be performed by implementing a Maintenance Performance Measurement (MPM) system. A performance measurement system is defined as the set of metrics used to quantify the efficiency and effectiveness of actions and an operational MPM acts like an early warning system. The characteristics of performance measures include relevance, interpretability, timeliness, reliability and validity (Aditya and Kumar, 2006). Different researches have observed that companies that utilize a performance measurement system perform better in comparison to those who do not measure performance (Tiddens, 2011).

7. Sustainability of the Digital Twin for Maintenance

The feasibility of the Digital Twin for Maintenance is assessed by first identifying current Digital Twin initiatives which possibly affect the advancement of the Digital Twin technology in the infrastructure sector as well as evaluating the technical and organizational feasibility as well as the strategic business viability of the Digital Twin for Maintenance. aiming to answer the seventh research question: *'What is the feasibility of the Digital Twin for maintenance?'*

7.1 Recent Initiatives Regarding the Digital Twin

The Digital Twin is a complex, relatively unfamiliar, multifaceted and relatively expensive technology in the infrastructure industry. Through the use of various initiatives, knowledge is shared, and it is tried to join forces to benefit optimally from the Digital Twin technology. A couple of those initiatives are shortly discussed below in order to identify whether those ideas can possibly advance the Digital Twin in the infrastructure sector.

During the project, maintenance and management platform meetings of 'Centrum Ondergronds Bouwen' (COB) where attended. COB organizes various platform sessions and the maintenance and management platform aims to combine and utilize the knowledge in the COB network. One of the recent topics are digital tools which include the Digital Twin.

Rijkswaterstaat wants to develop Digital Twins from the clients' side whereby the Digital Twin is delivered to the consortium in the contract phase. The contractor then enriches the model with new engineering data and after commissioning the Twin will be managed by Rijkswaterstaat and will remain property of Rijkswaterstaat. The Heinenoordtunnel renovation project serves a pilot for the development of the Digital Twin for Rijkswaterstaat and the decision was made to prescribe the Digital Twin in this contract. More detailed information regarding these two initiatives can be found in Appendix 23 Digital Twin Initiatives Infrastructure Industry.

Moreover, there exists a cooperation agreement between governments and the market called DigiDealGO. It is a national digitalization program for built environment which gives direction, provides guidance and moves towards the acceleration of digitalization in the construction sector. Proposing the Digital Twin for Maintenance as acceleration project enables to enlarge shared, smart and quick available professional knowledge. It gives the opportunity to experiment and to find potential sponsors or enablers (DigiDealGO, 2020).

Lastly, another initiative was discovered from NWO during the research, a Dutch research council which invests in curiosity driven research and research related to societal challenges. One of which, is the Digital Twin program which received a grant of 4 million euro. The Digital Twin is defined as the integration of data driven and model-based engineering in future industrial technology with value chain optimization. The participants include various universities and progressive organizations such as Philips, ASML and Altran (NWO, 2020).

The described initiatives of COB and Rijkswaterstaat are focusing on the application of the Digital Twin in Maintenance and the initiatives of DigiDealGo and NWO are not directly focused on maintenance but on digitalization and the Digital Twin in general. It can be concluded that in and around the infrastructure industry, forces are joined to advance the Digital Twin (for Maintenance). It is important to keep track of these advancements and opportunities to prevent unnecessary duplication of work as well as to take advantage of the initiatives where possible.

7.2 Feasibility Assessment

A feasibility study for the implementation of the Digital Twin is created to identify the practicality of the proposed concept. It aims to analyze and justify the Digital Twin in terms of technical feasibility and business viability.

7.2.1 Technical and Organizational Feasibility

The creation of an Application Programming Interface between OMS, DMS and TBA; a Common Data Environment and a Graphical User Interface can be outsourced to an external specialized organization or can possibly be realized by the TAI venture in cooperation with the Asset Management department and possibly Soltegro. TAI is a system integrator with knowledge of modern control systems, ICT and programming environments. As mentioned in the implementation plan, API's, CDE and GUI can be realized in various manners and it has to be decided which type or program suits the organization best. Thus, the exact requisites and steps to build the interfaces between the various systems are not defined.

For the training and test facility it is more about preserving the present test set up and training environment with additions to make it of value for the maintenance phase. Maintaining and updating the test and training facility as well as the additional maintenance scenarios are cost factors. However, the training environment can potentially be offered as a service for training institutes or vocational secondary education for example, to make it widely deployable and improve the exploitation. The data analysis functionality of the Digital Twin can most profitably be accomplished by the conjunction with the present TBA development. Merging these projects will initially bring extra costs for the TBA project but is probably more efficient and cost effective in comparison to implementing the two projects separately.

Besides the software, hardware, expertise and people needed to create the functionalities. The employees that are going to make use of the Digital Twin in the maintenance phase must be considered and involved carefully. This Digital Twin is essentially created for the maintenance organizations of the projects. For this reason, it is crucial that these persons approve and appreciate the Digital Twin and are willing to give their feedback for possible improvements along the implementation and utilization. Participation with employees is desired to create willingness to adapt their working behavior which is required when implementing the Digital Twin.

7.2.2 Business Economic Feasibility

The expected profit of the Digital Twin can be expressed by improved maintenance performance. Reduced effort and time needed to prepare and execute maintenance as the provision of information is improved; enhanced data quality due to decreased human error and first-time right repair or replacement activities.

Moreover, the time needed to close the tunnel can be reduced due to virtual training and testing in advance. Improved maintenance productivity can be achieved since the time needed for non-value adding activities and rework is reduced. The Digital Twin can eventually result in less penalty points when failures are fixed quicker or can be prevented by testing in advance. Data analysis can lead to better maintenance intervals, decision making and predicting failure by analyzing sensor data.

Participants involved with maintenance, generally view the Digital Twin as an information management tool whereas the Digital Twin in the design phase is presently deployed as a tool to verify and validate the design and functional behavior with the stakeholders; clash avoidance; software testing and training the emergency services and tunnel operator. This interpretation differences prompts that the present Digital Twin requires a considerable amount of modifications and additional features in order to be of value during the exploitation phase.

As mentioned in chapter 7.1, Rijkswaterstaat wants to provide a Digital Twin to the consortium in the future during the contract phase and after commissioning, Rijkswaterstaat wants to manage the Digital Twin and remain ownership. This can have the result that the investments made for the development of the Digital Twin possibly are not of value for future projects. Investments in gained knowledge and expertise in the Digital Twin technologies as well as additional hard- and software are possibly only of value for a small number of infrastructural projects which can make it more difficult to recover the investment costs.

Although it appears to be a promising technology, successful implementation stories are lacking. Profits are unidentifiable in terms of money due to lacking research and successful implementations or pilots. One possible explanation might be the dependency on large structured datasets which makes it hard to pilot. With complex technologies, pilot versions are needed to convince the client and employees of its value. Especially with innovations, the ‘Digital Twin for Maintenance’ is relatively unknown and there is no market for it yet, the demand from the client and users must be assessed.

As the economic benefits and costs of the currently utilized Digital Twin at the infrastructural projects are relatively unknown and mostly based on estimations, the costs for the possible Digital Twin for Maintenance are unidentifiable at present. Mainly due to the lack of research, pilot projects and successful of Digital Twins in the exploitation phase. Nevertheless, the Technical Innovation Lead of Soltegro and the A16 Rotterdam project, provide some estimations of possible savings and costs.

Soltegro presently develops a Digital Twin for virtual testing of software of a project and for the purpose of education and training. The problem with virtual testing, is that the reclaimed costs through the discovery of failures are not possible to trace back to the development costs of a Digital Twin. Another aspect includes that every Digital Twin is unique and complies to the additional wishes of the project. More information on the additional wishes and the application in maintenance can be found in Appendix 24 TWIN-16 Identification of the costs and potential cost savings.

For a tunnel project to development costs are estimated between 500.000 and 1.500.000 euros. A Digital Twin for a sluice project is expected to cost somewhere between 200.000 to 800.000 euros. The costs depend on the extra wishes of the project and the costs of a sluice are lower due to reduced complexity.

At present, the exact costs of the present Digital Twin of the A16 Rotterdam are competition sensitive and therefore confidential. The costs of the virtual simulation environment of the TWIN16 are based on several aspects which can also be found in Appendix 24.

An identification of the costs savings of the A16 Rotterdam Digital Twin is created. Based on the phase of the project, anticipated failure costs and amount of failures, an indication of the reduction of the failure costs by utilizing the Digital Twin is given. It is estimated that the Digital Twin can reduce 53% of the estimated failure costs during design, (i)FAT, (i)SAT and after completion as well as opening of the infrastructure. The failure costs increase concurrently with the development of the infrastructure, with failures after opening being the most expensive according to the TWIN16 Coordinator and Consultant at ‘De Groene Boog’.

This lack of information of the possible benefits and costs of the Digital Twin for Maintenance does not allow to create a well-reasoned Return on Investment (ROI) estimation. In order to create an ROI including the financial effect and payback period of the Digital Twin in the exploitation phase, pilots and implementations are necessary as well as a more accurate measurement of the present performance.

8. Conclusions

The purpose of this chapter is to discuss the most important and relevant results that support the decisions regarding the Digital Twin for Maintenance and to clarify the main research question: *'How could a Digital Twin improve the maintenance performance during the exploitation phase of infrastructures from TBI Infra?"*

The concept Digital Twin for Maintenance can noticeably improve the performance of maintenance through the adoption of the desired functionalities outlined by the participants. However, the success in terms of operational productivity and strategic advantage are strongly influenced by the developments of Rijkswaterstaat as well as other initiatives in and around the infrastructure sector and the involvement of the maintenance organization with the development of Digital Twins.

The Digital Twin for Maintenance is considered as a shared digital platform where information and data of the different assets converge through the use of linking applications, a central environment for management and maintenance information and a graphical user interface. Moreover, the Digital Twin supports virtual training, education and testing purposes as well as data analytics. The Digital Twin for Maintenance coordinates the different functionalities, that the participants assigned to it, through the adoption of the features.

Maintenance Performance is assessed by considering the efficiency and effectiveness of maintenance. The Digital Twin can influence performance through overall improved information provision with a central location to find, share, change and manage information, better prepared maintenance activities, reduced risks and test time in the tunnel and better trained and prepared employees. The performance is desirably measurable through assigned key performance indicators or a Maintenance Performance Measurement system in order to keep track of the objectives.

The feasibility of the Digital Twin is determined by the number of changes and additions required, the willingness of stakeholders and the long-term benefits and strategic advantage of the adoption. Since the present Digital Twin utilized during the design phase significantly differs from the Digital Twin for Maintenance specified, a considerable amount of additions and changes are needed. Stakeholders concerned with maintenance are at present limited involved with the creation of the Digital Twins at the projects but certainly take an interest in and acknowledge the potential value of the Digital Twin for maintenance.

The strategic advantages are partly dependent on the developments of other parties in industry. When Rijkswaterstaat wants to be the owner of the Digital Twin during the project, it would be more profitable to cooperate with Rijkswaterstaat on what should be included during the maintenance phase. Moreover, when introducing a pilot to assess the value of the Digital Twin during maintenance it would be favorable to collaborate with other organizations and initiatives then to develop it individually.

9. Recommendations

For Croonwolter&dros, follow up actions and recommendations are conceived regarding the development of the Digital Twin. It aims to take the results of this research further and to optimally benefit from the Digital Twin for Maintenance.

The handover of the Digital Twin to the maintenance organization is at present often unclear and an unspoken topic. Often this subject only originates short before the commissioning of the infrastructure. At this stage, most people are completing their work at the project and are usually already busy with an upcoming project. Much of the intelligence is lost during this handover. However, it should become a conscious decision, determining what to keep and what to omit. For this reason, it is of importance to consider the handover to the maintenance team carefully and well in advance.

Moreover, the maintenance teams are often limited or not involved in the development process of the Digital Twin. This often results in resistance to change from the maintenance teams since the technology and its functionalities are unclear. Hereafter, the maintenance teams do not see the potential benefits and remain working with the conventional means and processes. Thus, it is important to involve the maintenance organization at the start of the project with the progress around the Digital Twin. In order to stimulate the intrinsic motivation to participate and to collect input and functionality from the operational maintenance level to improve the Digital Twin.

In order to monitor the progress and improvements realized by the Digital Twin, it is recommended to make an explicit development path. The Digital Twin is a comprehensive technology where various technologies congregate. Steps with fixed deadlines should be arranged including go, no-go moments to decide whether to continue with the Digital Twin for Maintenance. Progress can be monitored by measuring the development against key performance indicators in terms of maintenance performance. Including improved effectiveness and efficiency in terms of costs savings, reduced time and effort required and improved productivity.

It is recommended to introduce a Maintenance Performance Measurement (MPM) system in order to analyze whether improvements are made by the Digital Twin. When the current situation is not determined, it is impossible to outline possible advancement. Furthermore, it has been researched that companies that utilize a performance measurement system perform better in comparison to those who do not measure performance.

The maturity of the Digital Twin in the infrastructure sector is still limited in contrast to other industries. The Digital Twin is not something that can be done by an organization independently due to its complexity, the immaturity of the market and the high costs to develop and preserve the Digital Twin over the extended period of time. Most profitably, it should be in collaboration with the client usually Rijkswaterstaat or provinces, specialized organization including consultants and service provides as well as the consortiums and contractors. Furthermore, another option includes joining the initiatives mentioned in chapter 7.1 or similar projects. The main focus is to remain sharing information and knowledge to accelerate the process so that all parties can benefit from the innovation. Additionally, in other sectors much more methods are developed, where the infrastructure sector should take advantage of.

At present, Rijkswaterstaat is working on pilots and attempts to make the Digital Twin part of the contract. Moreover, the initiatives discussed show that the vision, expectations, ambitions, goals of Rijkswaterstaat largely correspond to the functionalities determined by the participants of the brainstorm session and interviews. For this reason, it is highly recommended to collaborate with Rijkswaterstaat on the functionalities of the Digital Twin in the maintenance phase in order to corporate the interest of TBI Infra and other relevant parties to develop one Digital Twin centrally.

As part of a follow-up research, it is recommended for Croonwolter & Dros to identify the differences and similarities between the functionalities assigned to the Digital Twin created in this report and the Digital Twin described in the contract of Rijkswaterstaat. In order to evaluate the extent to which Rijkswaterstaat and the participants of the research coincide on the purpose of a Digital Twin for Maintenance. Thereafter, it is important to evaluate whether Rijkswaterstaat is open to collaboration.

When Croonwolter&dros prefers to develop the Digital Twin for Maintenance composed in this research, it is recommended to further research the applicability of the mentioned features to fulfill the desired functionalities, due to the insufficient understanding of information technology related topics. Possibly additional features can be introduced and compared to each other in the morphological chart to enhance the Digital Twin concept generation. Moreover, it is suggested to analyse the possibilities of linking to TBA project to the Digital Twin.

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Appendices

Appendix 1 Interview Questions and Participants

Present Situation

Current Features & Applications

- Where is the Digital Twin currently used for during the project?
- What are the functionalities of the Digital Twin?
- Where does a Digital Twin currently consists of at the project? (Features: Software, Hardware, Sensors, Data input, Integration, Connection)

Vision on Digital Twin

- What is a Digital Twin in your perception?
- What is your role regarding the Digital Twin?
- What is tried to achieve with the Digital Twin during the project?
- What is the relation and difference between a Digital Twin and BIM?

Digital Twin for Maintenance

Digital Twin for Maintenance

- What would be the ideal Digital Twin to support maintenance?
- What are in your opinion the opportunities of this Digital Twin for Maintenance?

Functionalities

- What are the desired functionalities or applications of this Digital Twin to assist maintenance activities regarding decision making, reducing claims, increasing availability of the infrastructure, increasing productivity of the maintenance execution?

Maintenance Application

- Which tools and systems are currently used for the execution of maintenance?
- What are the biggest cost drivers during the exploitation/ maintenance phase which could possible by prevented or reduced with the use of a Digital Twin?
- Which problems or hindrance do you encounter during the execution or preparation of maintenance which could possibly be solved by the Digital Twin?
- What are the prerequisites to work with the Digital Twin during Maintenance?

Feasibility

- What are the expected activities and costs to maintain the Digital Twin during the exploitation phase?
- What do you think are the risks to preserve the Digital Twin during the exploitation phase?

Participants

Interviews

- TWIN16 Coordinator A16 Rotterdam
- Test Manager A16 Rotterdam
- Maintenance Manager A16 Rotterdam
- Project Manager Sluis Eefde
- Maintenance Manager Sluis Eefde
- Asset Manager RijnlandRoute
- BIM Coordinator RijnlandRoute
- Software Architect RijnlandRoute
- Maintenance Manager Croonwolter&dros
- Maintenance Engineer Croonwolter&dros

Brainstorm Session

- Innovation Manager Croonwolter&dros
- BIM Director Mobilis
- Manager Systems Engineering & Innovation Soltegro
- Project Manager Rotterdam Region Croonwolter&dros
- Senior Consultant Croonwolter&dros
- Maintenance Manager Croonwolter&dros
- Manager Asset Management Croonwolter&dros

Appendix 2 Methods and Tools

The tools used during the research include PowerBI and Miro and to structure the conception creation of the Digital Twin, the methodical design process according to H.H. Van den Kroonenberg is used. The qualitative data is organized according to Ose (2016) and analyzed following the three steps of Dusdoskiy (2018).

Miro is an online collaborative whiteboard platform that allows teams to work together effectively. The tool features a digital whiteboard that can be used for research, ideation, building customer journeys, wire framing and user story maps and a range of other collaborative activities. Miro also offers video, presentation, chat and sharing collaboration capabilities. Furthermore, the toolkit enables to create mockups and schemes, to write down ideas and give feedback. Standard templates are available and can be converted into a presentation or saved as PDF file.

Power BI is a business analytics tool of Microsoft which enables to connect and analyse data and to easily visualize data through dashboards. PowerBI is a unified, scalable platform for self-service and enterprise business intelligence (BI) that is user friendly and aids to gain deeper data insight. The tool allows to collect and combine data from various information sources such as ERP systems and Excel to create visual reports.

The methodical design process, according Van den Kroonenberg, is utilized for concept generation. Methodical design is focused on the inventory of the needs, formulating a problem statement and devising alternative solutions, to eventually elaborate a definite conception (Siers, 2004). This method is chosen in order to structure and systematically organize the design process for the Digital Twin concept.

The qualitative data collected during the project is structured through the use Excel and Word according to Ose (2016). The method makes use of Microsoft Word and Excel and produces a flexible Word document of interview data separated into logical chapters and subchapters. All text is coded, and the codes correspond with headings in the final document. The purpose of the method is not to quantify qualitative data but only to sort and structure large amounts of unstructured data.

Furthermore, this data is then analyzed with the use of guide of Dusdoskiy (2018). The analysis can be performed through first developing and applying codes, then identifying themes, patterns and relationships including word and phrase repetitions and data comparisons. Lastly, summarizing data by linking the findings to the research aim and objectives.

Appendix 3 Digital Twin A16 Rotterdam

Current Available Features and Applications

The application landscape and information facility consist of the Documentation Management System SharePoint including the Cadac Organice Suite. ArcGIS is utilized for the geolocation of the components and corresponding documentation. Moreover, Relatics is a System Engineering Database and semi-automatically linked with Relatics. Primavera is a stand-alone planning tool. Furthermore, various two- and three-dimensional modelling software are applied during the project to model the various objects. Those models are integrated through various integration packages which are then transferred to the virtual model by the game engine.

The Virtual Reality Model is created with Unity Reflect and the Unreal Engine to transform the static components to dynamic components. The created two- and three-dimensional models are integrated in 3ds Max and then converted to the virtual model through the use of a game engine. The VR-model has a semi-automatic interface with the traffic model for TWIN-16 development and Enterprise Architect which is the design tool for technical tunnel installations (TTI) linking the functional model. Moreover, there is a manual interface between coordination model in Navisworks.

Lastly, a TWIN-16 web platform is established and consists of the graphics card with the location of objects in ArcGIS. Furthermore, Relatics gives an overview of the licenses and SharePoint contains the documentation to inform the stakeholders (De Groen and Kreuk, 2019).

Vision on The Digital Twin

The TWIN-16 Coordinator states that tor the TWIN16, the focus lies in the tender phase on the simulation of the behavior of the future system and to prevent failure costs in the realization phase where the system is designed, build and tested. This is done by adding simulated behavior of the installations to the BIM of the Rottemerentunnel. Moreover, to connect these installations with the intermediate products from the software development process of the operating system. Then, we are capable to virtually fine-tune the functional behavior and the interaction between the installations. Thereby, the emphasis in the field is on the commissioning and double checking the variables per installation.

In accordance to the Test Manager, a BIM could also solely consist of two-dimensional models where information is linked to. A Digital Twin is an environment where the information is linked to a three-dimensional model. The Digital 3D-environment can be used for more things such as testing. This environment makes the situation visual, at the test location, it is possible to exactly demonstrate what happens during various scenarios. The TWIN-16 Coordinator states that BIM consist of all aspect models, component properties and the requirements imposed by Rijkswaterstaat.

The Digital Twin builds upon the existing 3D models which are already employed in the construction and infrastructure industry for a while. This is then linked to documentation, requirements and processes resulting in a Building Information Model. Subsequently, the various incidents which can possibly occur in a tunnel are simulated and safety scenarios are applied to check the adequacy of the function. The virtual models will run on the software developed by Croonwolter&dros, a long time before the real tunnel is realized (Sminia and Pos, 2018).

Virtual Reality plays an important role during the design and testing of the new tunnel, by replicating the reality very precisely, costly faults can be prevented in an early stage. Moreover, the Digital Twin yields benefits during the management and training of emergency services. The main purpose of building a Digital Twin is to be able to test the physical characteristics as well as all functionalities and physical properties on beforehand. For this purpose, the actors and sensors are simulated (Fouchier, 2019). Furthermore, in collaboration with the RijnlandRoute project, a test location is developed. This test site remains operational during the exploitation phase for changes and testing and is integrated with a reality model according to the Test Manager.

Appendix 4 Interview with the Test Manager of A16 Rotterdam

Role: Test Manager	**Organization**: Groene Boog/ CWD
Project: A16 Rotterdam	**Date**: 1 April 2020
Location: Teams Meeting	**Version**: 1.0
Topic: Vision, Features and Functionalities Digital Twin	

Visie op de Digital Twin

- Wat is voor jou de defintie van een Digital Twin?

Proberen zoveel mogelijk wat je in het echt hebt, digitaal te maken. Dit dwingt je om digitaal na te denken en verbanden te leggen door bijvoorbeeld de bestanden te koppelen. Bijvoorbeeld als we een ontwerp maken van een tunnel en je koppelt dat wat er straks werkelijk buiten staat. Dan weet je dat je dit ook in een digitale omgeving hebt staan. Certificaten en ontwerp zaken kunnen teruggevonden worden.

- Wat is jouw rol in perspectief tot de Digital Twin?

Na het opleveren stopt mijn taak als testmanager. Ik moet ervoor zorgen dat alle documenten compleet zijn. Als je volgens system engineering werkt, wordt er bij wijzingen een ontwerpteam opgezet die teruggaan in het proces.

De testomgeving blijft bestaan voor wijzingen en testen tijdens onderhoud. Het 3D model maakt de Digital Twin toegankelijk tijdens de overdracht voor mensen die ermee moeten gaan werken. Het allerbelangrijkste is dat er in de documenten een goede structuur zit zodat de belangrijke documentatie snel teruggevonden kan worden, een digital twin hoort hierbij.

- Wat is het doel van de Digital Twin binnen het project, wat proberen jullie ermee te bereiken?

  - Hulpdiensten laten oefenen d.m.v. een game engine
  - Simuleren van mogelijke tunnel scenario's
  - Trainen, opleiden (VR locatie gebouwd in samenwerking met Rijnlandroute)
  - Ontsluiten van informatie (hoofddoel) op BIM gericht
  - Virtueel testen van de software die is gebouwd door CWD
  - iSAT/ iFAT testen versnellen/ verbeteren (first time right)

- Wat is de relatie en verschil tussen BIM en Digital Twin?

Een BIM zou ook alleen uit 2D modellen kunnen bestaan waar ook informatie aan is gekoppeld.

Digital Twin is een omgeving waar je alle informatie aan een 3D model koppelt. De digitale 3D omgeving kan voor veel meer dingen worden ingezet zoals bijvoorbeeld testen. Deze omgeving maakt de situatie heel erg visueel. Bij de test omgeving kunnen we exact laten zien wat er plaats vindt in plaats van dat een slagboom dicht is alleen 0 weergeeft en open een 1. De BIM bij de A16 is uitgebreider dan normaal.

Digital Twin voor Maintenance

- Wat zijn de mogelijkheden van de Digital Twin voor onderhoud, wat zou een ideale Twin zijn?

Het kan de grootste bijdrage leveren door het vinden van alle onderliggende documentatie. Als bron ideaal om snel dingen te kunnen vinden. Documentatie en tekeningen zoeken in schijven en databases kost heel veel tijd. Snel de goede informatie verkrijgen dus informatievoorziening.

Digital Twin kan ook een bijdrage leveren door als meet instrument te dienen. Data verzamelen en analyseren in de Digital Twin.

Scenario's in laten draaien. Bijvoorbeeld wat uitval (componenten en hoeveelheid in uren) kan betekenen voor de faaldefinities door het koppelen van faaldefinities aan de Digital Twin.

Een dynamisch omgeving maakt dat mogelijk en laat zien wat er gebeurt. Beter in gesprek gaan met de opdrachtgever over die faal definities, die zijn ook niet altijd helemaal duidelijk en toetsbaar. Boetepunten voorkomen. Verlichting simuleren. (Met camera's wordt dit al gedaan). Beter onderhoudsbeleid minder gericht op boetes aanvechten. Beter op de kwaliteit van de installaties.

Bijdrage kan leveren in het werk wat onze mensen doen. Monteur moet kunnen vertellen wat hij belangrijk vindt. Monteurs moeten ons vertellen wat zij nodig hebben. Een Gps-code die alle tekeningen toe stuurt wanneer ze bij de installatie in de buurt zijn zou heel waardevol zijn.

Ook bijvoorbeeld welke leveranciers zijn erbij betrokken (die informatie direct beschikbaar maken) in het model. Met als hoofddoel om de informatievoorziening te stroomlijnen. Tip: kijk goed naar de behoefte van de gebruikers.

- Welke risico's horen hierbij?

Snelle veroudering van de systemen in de tunnel, de databases en de software als overkoepelende schil. Systemen die we nu kopen, zijn verouderd als de tunnel opgeleverd wordt en de apparatuur moet dan snel weer vervangen worden door veroudering.

Vaak willen verschillende partijen heel veel data verzamelen maar ze weten niet wat het doel hiervan is en wat ze ermee kunnen bereiken. Het is belangrijk de vraag te stellen wat het daadwerkelijk gaat opleveren en of het zinvol is voor de organisatie.

Appendix 5 Interview with the Software Architect of the RijnlandRoute

Role: Software Architect	**Organization**: Soltegro
Project: RijnlandRoute	**Date**: 7 April 2020
Location: Teams Meeting	**Version**: 1.0
Topic: Vision, Features and Functionalities Digital Twin	

Huidige Features & Toepassingen

- Waar wordt de Digital Twin op dit moment voor ingezet tijdens het project?

In de literatuur wordt de twin heel breed getrokken en waar wij het eigenlijk voor gebruiken is specifiek. En dat is eigenlijk voornamelijk het testen van de software, validatie van de positionering. En niet per se om eigenlijk een hele berekeningen toe doen op het 3D model te doen zelf.

- Andere deelnemers beschrijven dat ze alles in de Digitale Tweeling zou kunnen zien en exact hetzelfde te houden als de werkelijkheid)

Daar heb je grotendeels wel gewoon 3D BIM voor, daar moduleren eigenlijk alle modellen uit en daar trekken wij dan een kopie van en stoppen gedrag aan elk element. Maar de omvang van projecten zoals a16 en RijnlandRoute zijn te groot om een 1 op 1 kopie ervan te maken.

Heel veel van de installaties zijn ingekocht qua hardware en die moeten gewoon volgens specificatie werken. Vaak heeft een leverancier een standaard hulppostkast en dan zeggen wij nou daar willen wij twee contacten of we willen hier een noodtelefoon i.p.v. daar en het contactje moet zo heten. Dan bouwt de leverancier de huidige kast net om dat het gewenste eruit komt. Digital Twins zie je vaak in industrieën zoals auto en robotica waarbij ieder boutje en moertje is gemoduleerd. Dat is bij infra niet van toepassing.

- Wat zijn de functionaliteiten van de Digital Twin?

Testen van de software, Validatie van positionering en Simuleren - gedrag van een installatie, bijvoorbeeld bij een afslagboom dan krijg je vanaf de besturing krijg je bepaalde signalen, die signalen verwerken we volgens wat de lead engineer voorschrijft en dan gaat een afslagboom wel of niet neer of stopt het. En aan de andere kant kunnen we zeggen dat de hardware in storing is of dat er een motor kapot is of de lampen zijn kapot en dan moet 3B (besturing, bediening, beveiliging) daar weer op reageren via bepaalde architectuur. En zo gaan we elke installatie af, wat kan je in het echt ermee, welke storing kan het geven en wat doet zo'n storing dan, en dat zetten we er allemaal in.

Bij de RijnlandRoute zijn nu 24 van de 40 type installaties gemoduleerd. Er wordt ook voor gekozen om bepaalde installaties niet te doen omdat het allemaal inkoop is. Dus bijvoorbeeld een beveilig systeem van een dienstgebouw is door een beveiligingsmaatschappij is dat gebouwd en die zeggen van dit moeten wij beveiligen en die komen het installeren en dan is het klaar. Wij doen echt alleen de hardware waar we de software zelf voor maken.

- Waar bestaat de Digital Twin op dit moment uit tijdens het project?

We hebben een Unity project dus een game engine waar het in gebouwd wordt en die maakt contact met de echte hardware door een OPC-server. Met deze server worden eigenlijk alle contactjes mee verzonden en binnen gehaald. Daarnaast heb je een Windows machine nodig en een grafische kaart en dat is het. Bij de a16 is een game server gekocht bij een Duits bedrijf en voor RijnlandRoute heb ik eigenlijk geen idee. Want dat heeft een ander bedrijf ooit gekocht waar we het project van hebben overgenomen. Dat zijn in principe twee game PC's als interface.

Worden signalen direct naar de Digital Twin gestuurd of zijn die niet met elkaar zijn verbonden?
Bij de RijnlandRoute staat er een grote PLC, daar staan alle contactjes vertaald naar de hardware en wat we eigenlijk doen daar is we snijden eigenlijk al die contactjes door en die zetten dan op onze digital twin. In de test hal heb je een kast (PLC) waar alle signalen binnenkomen en die vertaald al die contactjes naar digitale waardes en wat wij doen is, wij schrijven die waardes over dus onze digital twin vervangt eigenlijk alle contactjes van de echte hardware.

Bij de a16 werken ze niet met een PLC's maar met een Windows machine en daar draait het als een losstaand stukje software waar gewoon via internet contact mee is. Het hele idee is wel waar de hardware op het systeem inplugged dat wij daar ook op inpluggen. Dat de interface tussen de Twin en de echte hardware gelijk is.

Visie op de Digital Twin

- Wat wordt er verstaan onder een Digital Twin?

Eigenlijk een kopie van de hardware en de implementatie van het ontwerp, dus eigenlijk een 1 op 1 kopie zonder dat je het fysiek hebt met gedrag en het 3D model is eigenlijk meer ondersteunend maar hoeft in principe ook niet per se.

Bij de Groene boog is net wat anders dan bij de Rijnlandroute. Bij de groene boog zijn ze de installaties nog aan het ontwerpen dus daar is op dit moment de ontwerp documentatie eigenlijk de leidraad voor de implementatie van de twin. Bij de Rijnlandroute is eigenlijk het fysieke object er al omdat ze die test hal hebben. Dus zijn we alle contactjes langs gegaan van het echte model dus we hebben gekeken of we ook signalen geeft aan de hulppost kast, die hebben we gekopieerd en eigenlijk is het gedrag achter die I/O (Input/output) of contactjes die hebben of opgezocht bij de leverancier of uit lead engineer documentatie. Dus daar is het echt nabouwen van wat er al staat en bij de a16 is het eigenlijk maken wat er nog niet is. En dat ligt helemaal de fase waarin je zit, welke van de twee aanpakken kan doen.

- Wat is jouw rol in perspectief tot de Digital Twin?

Software architect. Ik heb de software architectuur opgezet en de eerste paar voorbeelden. Daarna zijn Marco en Nirish alle installaties aan het afgaan en ik controleer of ze volgens specificaties aan het implementeren zijn.

- Wat is de relatie en verschil tussen BIM en Digital Twin?

Coördinatie model is meestal het 3D BIM-model en bij de a16 wordt dit volgens mij door Infranea gedaan en dat zijn eigenlijk alle BIM-modelleurs die van elke installatie en van alle civiele aspecten 3D modellen maken en in dat programma ook alle documentatie en eisen eraan linken. Dan heb je eigenlijk dat 3D coördinatie model en dan heb je 3 Twin platformen en dat is meestal het webplatform en die hebben ook de linken naar alle documentatie die je dan weer uit de 3D model BIM-coördinatie model komen. Dan heb je ons model van het testen en dan heb je er nog een die ik altijd vergeet eigenlijk.

Wij krijgen het BIM-model uit het coördinatie model en die zetten we om naar 3D modellen die geschikt zijn voor een game engine. En daar zetten wij dan gedrag aan en gebruiken wij als testopstelling.

- Wat is de link tussen het 3D BIM, coördinatie model, testopstelling in Eindhoven en de virtuele verificatie tool (Soltegro). Zijn al deze ‘componenten’ onderdeel van de Digital Twin?

De virtuele verificatie tool bouw ik samen met Marco en Nirish. Wij proberen gelijk te lopen met het softwareteam dus als zij een installatie af hebben dan hebben hij het virtuele model van de installatie af. Zij kunnen dan hun software eigenlijk al gelijk testen voordat ze de echte hardware hebben. Dit is het eerste doel van de testopstelling. Uiteindelijk is het dus ook de bedoeling dat als ze een echt stuk hardware krijgen, dus ze hebben bijvoorbeeld een hulppost, dat zij de andere 160 hulpposten simuleren. Dan kunnen ze eigenlijk de hele tunnelsoftware testen, met een echte installatie. Die fysieke installatie staan in Eindhoven en alles wat er niet is simuleren wij. Vaak kunnen ze de test moeilijker afnemen als ze er een hebben staan want dan gaat het besturingssysteem in storing omdat de overige installaties er niet zijn.

Virtuele verificatietool van de diamanten kruising daar is echt een rijsimulatie gemaakt, de beleving van zo’n kruispunt en geen validatie van de software. De virtuele verificatietool is wel gekoppeld aan het 3D BIM. Dit wordt tot ongeveer 2024 of 2023 onderhouden.

Dus als je straks wel bij de digitale tweeling, als daar een software update komt van de besturing en er zijn installaties niet gewijzigd dan kunnen ze de huidige Twin ertegenaan hangen en opnieuw alle verificatie validatie doen. Maar als er een nieuw type hulpdienstpaneel in komt dan moeten wij een update aanleveren waaraan ze kunnen testen. Hoe dit proces is ingericht heb ik geen idee van.

- Bestaat er documentatie van de Digital Twin?

We zijn pas 2,5 maanden geleden mee begonnen met de Digital Twin bij de Rijnlandroute en die is gelijk meegenomen in het productieproces meegenomen en niet eerste geïntroduceerd bij iedereen. Hier wordt het echt als testtool gebruikt en bij e a16 ook als promotiemateriaal.

- Wordt er bij de Rijnlandroute al over nagedacht om de Digital Twin aan het onderhoudsteam door te geven?

Weet ik eigenlijk niet. Uiteindelijk moet deze opstelling als iFAT opstelling moeten gaan voldoen en daar zitten 20 of 25 jaar onderhoud aan vast. Alleen heb ik geen idee hoe dit is afgesproken en wie dit gaat doen. Want ik houd mij niet bezig met contract zaken.

Voor elk project hebben we gewoon documentatie van hoe het in elkaar zit, hebben we ook ontwerpdocumentatie gebruikt. Dus in principe moet het onderhoudbaar zijn. We zien nu bij de a16 dat we van DO naar UO overgaan en dat eigenlijk hetzelfde proces en code hergebruikt kan worden. Als er wijzigingen komen dat werkt eigenlijk precies hetzelfde als we nu van het DEO naar het UO gaan. De onderhoudspartij zal dit waarschijnlijk moeten gaan bijhouden.

Ik weet niet of we alles opleveren, Franc Fouchier weet hier meer van. Ik denk dat er op dit moment nog niks is afgesproken qua onderhoud en ook niet van wie eigenlijk het intellectueel eigendom is.

Als je kijkt naar de Velsertunnel dan staat daar ook een iFAT opstelling en dat is gemaakt zonder digitale tweeling maar met een ander systeem Xpro en dat is precies hetzelfde als wat wij nu hebben maar zonder 3D model en die wordt iedere keer geüpdatet aan de hand van software updates.

Appendix 6 Digital Twin RijnlandRoute

Current Available Features and Applications

The BIM Coordinator states in the interview (Appendix 11 Interview with the BIM Coordinator of the RijnlandRoute) that the added value of the Digital Twin lies in maintenance. The Digital Twin can be utilized to test for example when a camera is replaced. Moreover, the BIM is reveled in the Digital Twin whereby maintenance does not need a BIM model anymore.

Three years prior to the opening, the technical tunnel installations of the RijnlandRoute in the test location in Eindhoven are connected to the central operation of the traffic control center in Rhoon as shown in figure 7. This allows to test the remote operation with the tunnel control in an early stage (Oorthuis, 2019). The main purpose of this test location is to test the software of the installations before the hardware exists. The intention is when one real piece of hardware is realized, the other installations of the same kind are simulated allowing to test the entire tunnel software. According to the interview with the BIM Coordinator (Appendix 11 Interview with the BIM Coordinator of the RijnlandRoute), allows the test location to reduce the test time tremendously by a better preparation and to tackle problems before commissioning.

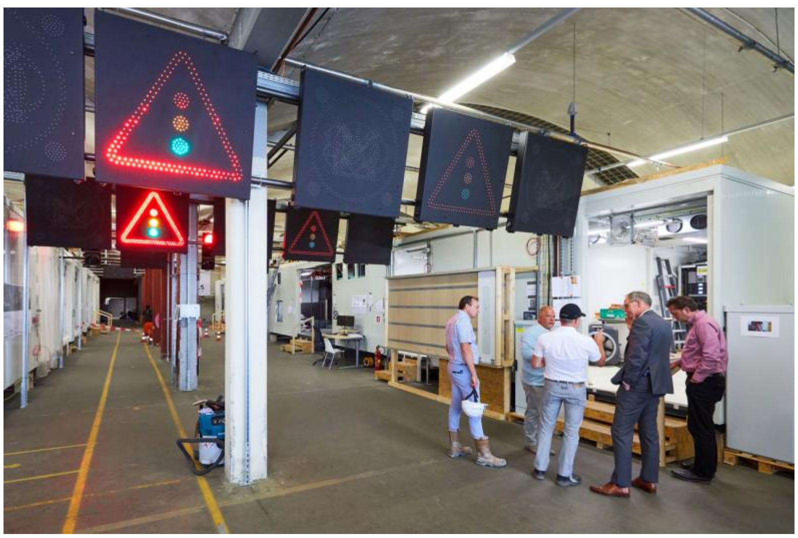


Figure 7 Tunnel installations of the RijnlandRoute compiled in the Test Location

The Digital Twin is built in a Unity project, thus a game engine which makes contact with the real hardware through an OPC-server. Besides, a Windows machine is needed as well as a graphical map. There is a large PLC at the RijnlandRoute with all the inputs and outputs translated to the hardware. The intersection of these contacts is linked to the Digital Twin. There is also a PLC at the earlier mentioned test location where all signals arrive. This PLC translates these contacts to digital values which are overwritten causing the Digital Twin to replace the inputs and outputs of the real hardware. Making the interface between the Twin and the real hardware identical according to the Software Architect of the RijnlandRoute (Appendix 5 Interview with the Software Architect of the RijnlandRoute.

Vision on The Digital Twin
Rijkswaterstaat is researching the possibilities of digitalization at the Heinenoord tunnel, the A16 Rotterdam and the RijnlandRoute. One of the innovations is the Digital Tunnel Twin which is created with the aid of 3D-BIM. The digitalization goes further, besides an extensive 3D-model, there are possibilities for simulations and virtual reality (Van Wijck, 2019).

At the RijnlandRoute, it is possible to drive through the tunnel virtually (Mol, 2019). All technical tunnel installations of the service building are constructed in modules on beforehand which are attuned to one another and tested in an industrial warehouse located in Eindhoven. Here after, the approved modules can be placed in the service buildings with the certainty that everything works properly. The virtual drive experience and modular configuration are enabled by designing all components in the integral 3D model upfront (Pos and Sminia, 2018).

The new provincial road is virtually built in a three-dimensional model. The BIM-processes reveal what the road will eventually look like and what obstacles must be faced (Mobilis TBI, 2018). Mobilis created their own BIM-environment where all information regarding the different project disciplines, during the entire construction process, is stored, shared, used and managed. Moreover, together with Croonwolter&dros the operation of certain systems is validated by connecting the system architecture to the virtual model, the so-called Digital Twin (Peek 2019).

ATBK digitally portrayed the tunnel of the RijnlandRoute with the use of aerial photography by a drone. With these aerial photographs, a digital point cloud (3D-model), a Digital Surface Model (DSM) and a digital orthophoto of the location can be generated. By means of the 3D model, accurate measurements and calculations can be performed such as the determination of areas, volumes, contour lines (elevation and/ or depth) and cross sections of, for example, the tunnel. The acquired data can be exported readily to the CAD or GIS environments. The georeferenced orthophoto can be used as digital basis for GIS or CAD software (ATKB, 2019).

Furthermore, Soltegro developed a virtual verification tool at the request of COMOL5 for the new road connection between Katwijk and Leiden. This verification tool is utilized to examine the specific, not yet common, road situation; the Diverging Diamond Interchange. COMOL5 uses the verification tool to research the driving behavior of users during various traffic scenarios at different times of the day and to consider the road safety and legislation with competent authority (Soltegro, 2019).

Appendix 7 Interview with the Asset Manager of Sluis Eefde

Role: Asset Manager	**Organization**: Mobilis
Project: Sluis Eefde	**Date**: 25 March 2020
Location: Teams Meeting	**Version**: 1.0
Topic: Vision, Features and Functionalities Digital Twin	

Visie

- Wat wordt er verstaan onder een Digital Twin?

Een 3D model met een visuele weergave van de omgeving/ areaal. Een digitale versie van wat er wordt onderhouden waar heel veel informatie aan wordt gekoppeld. Zodat werkzaamheden goed uitgevoerd kunnen worden. Die ervoor zorgt dat je cruciale informatie direct voor handen hebt waardoor de foutmarge naar beneden gaat, faalkosten)

In Asset Management draait om in mijn ogen voornamelijk om informatiemanagement. De juiste informatie op het juiste moment. Met data van sensoren of de constructietekeningen dat maakt dan eigenlijk niet uit als je maar de adequate informatie hebt.

- Wat is het doel van de Digital Twin binnen het project, wat proberen jullie ermee te bereiken?

Bij Sluis Eefde hebben we niet expliciet ingezet op een Digital Twin. Maar er is wel altijd gewerkt met een 3D model waarbij we de raakvlakken tussen verschillende disciplines duidelijk proberen te krijgen.

Tijdens sessies waarbij we met de verschillende disciplines rond de tafel zaten, waarbij we simpel weg met z'n alle door het 3D model zijn gegaan. Vooral als communicatiemiddel.

Vanuit de onderhoudskant is gekeken of we overal makkelijk bij kunnen komen, praktisch door het areaal heen te lopen om onhandigheid eruit te halen (maintainability). Maar verder ook om de clashes in het design er al uit te halen.

- Wat is de relatie en verschil tussen BIM en Digital Twin?

De 3D BIM-model en de Digital Twin zijn hetzelfde bij Sluis Eefde.

- Welke tools en systemen worden er op dit moment ingezet voor de uitvoering van onderhoud?

Systemen: Maximo voor het onderhoudsproces, een prestatie meet system (PMS) voor het aantonen aan de opdrachtgever dat we voldoen aan beschikbaarheidseisen van de sluis, die wordt geleverd door Soltegro. Een Document Management System (DMS) DigiOffice, Sensus Process Management System voor de lopenede processen. Een Relatics omgeving die heet Mobilizer voor het daadwerkelijk invullen van een aantal processen. (Integral digital management and information system of Mobilis).

Tools: Tablets zijn in bestelling om inspecties te doen, de jongens gaan het veld in om inspecties te doen. Op dit moment zijn we alle componenten aan het voorzien van QR-codes en kunnen we straks ook door het scannen van de QR-codes komen we direct in Maximo bij de juiste gegevens. Het is hier weer belangrijk accuraat te zijn van je gegevens. Bijvoorbeeld door de storingen op de juiste assets worden gemeld zodat we geschiedenis kunnen opbouwen.

- Wat zijn de grootste kosten factoren tijdens de exploitatie fase die mogelijk voorkomen of verminderd kunnen worden door het gebruik van een Digital Twin?

Het systeem moet blijven draaien en de sluis moet in beweging blijven, dat is van belang. Er zijn niet per se dingen waar we heel veel tijd aan kwijt zijn. Geen specifieke componenten, maar baggeren is er wel een waar eisen aan zijn i.v.m. met de toegang waar boetes aan gekoppeld zijn. Je weet zeker dat je om de zoveel jaar met een kraanschip in het water ligt om te baggeren zodat je voldoet aan de eisen. Beschikbaarheid en voldoen aan gestelde eisen, er zijn geen specifiek componenten.

- Tegen welke problemen of obstakels loop je aan tijdens het uitvoeren of voorbereiden van onderhoud die mogelijk opgelost kunnen worden door de Digital Twin?

Voornamelijk dat je de informatie hebt en houd, op afstand een monteur goed kunt helpen. En dat je gewoon het gedrag van je assets en componenten goed kunt monitoren. Maar daar heb je niet per se een 3D model voor nodig.

Het verschil met een sluis ten opzichte van een snelweg is dat een sluis eigenlijk soort postzegelwerk is waarbij op een locatie het hele apparaat staat en bij een snelweg is dit verspreid over een aantal kilometers.

Als er storing is kunnen ze gelijk naar de juiste plek rijden en dat het 3D-model de locatie van de storing aangeeft heeft dat niet veel toegevoegde waarde. De monteurs moeten zich toch altijd eerst melden bij de bedienaar.

Ik vind het echt heel mooi en ik denk dat het goed is om informatie in te overzien en intuïtief te houden maar ik denk niet dat alleen het 3D model een grote besparing oplevert. Vooral omdat het hele apparaat op een locatie staat.

- Hoe is de overdracht van de Digital Twin naar het onderhoudsteam op dit moment gepland?

Dat is wel de bedoeling maar het model heeft een tijdje stilgelegen en moet worden bijgewerkt uiteindelijk. Maar we willen het wel meenemen binnen de onderhoudsgroep.

Sander Ruiven is bezig om te kijken naar hoe de Digital Twin gekoppeld worden aan Maximo maar staat op laag pitje. Maar dat zouden we uiteindelijk wel willen doen om een up-to-date 3D model te blijven houden. Ook op het te koppelen met allerlei bestanden en dan kom je weer terug om informatiemanagement wat zo belangrijk is.

Functionaliteiten

- Wat zijn de gewenste functionaliteiten of toepassingen van de Digital Twin om onderhoudsactiviteiten te ondersteunen? Zoals het nemen van beslissingen, verminderen van boete claims, verhogen van beschikbaarheid of de productiviteit van onderhoud verbeteren.

Er zijn sensoren in de sluis, die meten van alles, dat wordt naar een database gebracht en dat zou wel gaaf zijn als we in het 3D model de verschillende waarde van de sensoren kunnen aflezen. Zodat het meer wordt gebruikt als een practical user interface. Wanneer er wijzingen worden gedaan en dat het systeem het automatisch herkent, dat zie ik voorlopig niet gebeuren, maar dat zou wel mooi zijn.

Sensoren data 3D omgeving gelogged en daarna wordt ook alle informatie naar een database gestuurd. En de database staat op locatie in Eefde en die is op afstand bereikbaar. Prestatie meetsysteem wordt pas aangesloten wanneer de sluis in operatie is

Haalbaarheid

- Wat zijn de verwachte kosten en activiteiten om een Digital Twin tijdens de exploitatie fase in de lucht te houden, voor bijvoorbeeld een jaar?

Ik heb daar totaal geen idee bij. Je hebt natuurlijk het model wat je moet bijwerken wat een paar dagen werk zal zijn voor de tekenaar. Vervolgens CMDB up to date houden waar toch al kosten aan zijn verbonden die we moeten maken om het dossier orde te houden. Ik denk niet dat er veel meer kosten zijn om het in de lucht te houden want het is contract technisch verplicht informatie bij te houden. Het 3D model zou dat een stuk makkelijker kunnen maken.

- Wat denk je dat de risico’s zijn om een Digital Twin te behouden tijdens de exploitatie fase?

Dat het niet up to date is en dat daarmee verkeerde keuzes worden gemaakt. Dat is dus ook wat je met zo’n systeem kan beheersen. Iemand moet het bijhouden en bij wijzigingen moet dit correct worden bijgewerkt, dit heeft te maken met de discipline van de mensen.

Het model en de CMDB up-to-date houden, anders gaat de hoofdfunctie verloren.

Appendix 8 Interview with the Project Manager Sluis Eefde

Role: Project Manager	**Organization**: Croonwolter&dros
Project: Sluis Eefde	**Date**: 23 March 2020
Location: Teams Meeting	**Version**: 1.0
Topic: Vision, Features and Functionalities Digital Twin	

Achtergrond Informatie Project
- De Digital Twin van Sluis Eefde is intern ontwikkeld door Mobilis en CWD
- Alleen de nieuwe sluis staat in het 3D model en heeft een DBFM-contract.
- De oude sluis is uit 1933 en er is nog geen contract voor het onderhoud. Paul verwacht wel dat dit wordt gegund. Eerst moet de grote onderhoudsbeurt gedaan zijn voordat het bekend wordt of ze verantwoordelijk worden voor het onderhoud van de oude sluis. (De PFAS moet bijvoorbeeld ook nog afgekocht worden).

- Wat wordt er verstaan onder een Digital Twin binnen Sluis Eefde en wat is uw definitie van een Digitale Tweeling?

Een 3D model met dynamisch gedrag waar simulaties in gedaan kunnen worden om te valideren en verifiëren met stakeholders. Alleen de nieuwe sluis in een gedetailleerd 3D model gemoduleerd

- Wat is het doel van de Digital Twin binnen het project, wat proberen jullie ermee te bereiken?

Voornamelijk voor het afstemmen met stakeholders door de toekomstige sluis de visualiseren met virtual Reality. Virtual Reality brillen zijn gebruikt om de opdrachtgever en omwonende een idee te geven hoe het er straks uit gaat zien (visualisatie)

En het verifiëren en valideren van de systemen en 3D visualisaties maken.

- Wat is de relatie en verschil tussen BIM en Digital Twin?

In de BIM, zijn alle 3D modellen in detail opgenomen (schakelkasten, damwanden). Ook is dynamisch gedrag toegevoegd, de BIM is een onderdeel van de Digital Twin

- Waar wordt de Digitale tweeling ingezet momenteel?

De digitale tweeling wordt voornamelijk tijdens het ontwerp gebruikt voor afstemming, clash avoidance (door inzicht in elkaars werk) en tijdens de realisatie voor het software testen voordat het op de echte sluis wordt aangesloten, simulaties en communicatiemiddel.

De testopstelling (Apeldoorn) wordt in de lucht gehouden inclusief simulatiemodel die aangepast kan worden bij wijzigingen en ingezet kan worden voor trainingen. Dit wordt overgedragen aan de onderhoudsclub.

- Wat zijn de functionaliteiten van de Digital Twin?

Verifiëren en valideren
Camera positie digital verifiëren
Digitale testen uitvoeren met de sluis bedienaars
Mist en regen simuleren (Movaris)

- Waar bestaat de Digitale Tweeling uit, VR-omgeving, Connectie met andere systemen, welke data input is er?

Het systeem is op dit moment alleen voor het afstemmen ingezet en zal overgegeven worden aan het onderhoudsteam die het eventueel kunnen uitbreiden.

Appendix 9 Digital Twin Sluis Eefde

Current Available Features and Applications

The data room complies to the prerequisites of transferring the information, consisting of objects and documents, through the VISI and COINS standards (Verbruggen, 2016). An OTL is a library with standardized object-types names and properties or specifications. The object is then described with its object type data, geometry data and specifications (Interlink, 2020). VISI is an open standard for communication management and COINS is a flexible standard for the interchange of BIM-information (Coins, 2020).

Appendix 10 Interview with the TWIN-16 Coordinator of A16 Rotterdam

Role: TWIN16 Coordinator	**Organization**: Groene Boog/ Besix
Project: A16 Rotterdam	**Date**: 9 March 2020
Location: De Groene Boog	**Version**: 1.0
Topic: Vision, Features and Functionalities Digital Twin	

- Wat is jouw definitie van een Digital Twin?

Een digital twin is een digitale omgeving van een (nog te bouwen) fysiek object of systeem, waarmee de waarde over de levenscyclus heen gemaximaliseerd wordt door betere ontwerp/ onderhoudskeuzes aan de hand van simulaties met behulp van data van het systeem/object, data van de buitenwereld, en algoritmes/code die het gedrag/degeneratie beschrijven. De uitdaging ligt in het aligneren van verschillende databronnen en het stellen van de juiste vragen aan de digital twin.

Voor de A16 ligt de nadruk van TWIN-16 zoals beloofd in tenderfase op simulatie van het gedrag van het toekomstig systeem & en het voorkomen van faalkosten in de realisatiefase, waarbij het systeem ontworpen/gebouwd/getest wordt. Dit doen we door aan het BIM van de Rottemerentunnel gesimuleerd gedrag toe te voegen van de installaties en deze te verbinden met tussenproducten uit het softwareontwikkelproces van het besturingssysteem. Zo zijn we in staat om virtueel het functioneel gedrag en samenspel tussen installaties te perfectioneren, zodat in het veld de nadruk ligt op het juist inbedrijfstellen en check-dubbel-check van de variabelen per installatie.

- Zijn er al meerdere Digital Twins gemaakt voor andere bedrijven?

Ik werk als Coördinator dus ik bouw zelf eigenlijk niks.

- Wat is minimaal nodig om een Digital Twin te creëren?

Afhankelijk van de toepassing/ gebruiker!
Elenaferyman.com (je hebt niet persee een model nodig, dit is alleen om het visueel aantrekkelijk te maken voor de gebruiker) (het kan ook een puntenwolk zijn)
Representatie (puntenwolk, Plaatje, etc.)
Data van fysieke asset of ontwerp zelf

- Met welke systemen wordt de Digital Twin model mee gekoppeld? TWIN16
  - 3D modellen
  - Stuurprogramma’s installaties
  - Besturingssysteem
  - MMI
  - Hardware van bedieningsplek (Video Wall)
  - Enterprise architect
  - Hardware van de fysieke installaties in de tunnel
  - ArcGIS (via 3D model)

- Waar wordt de Digital Twin (TWIN16) voor gemaakt, voor welke activiteiten?

Vooral Design fase, functionele gedrag, het gedrag visueel inzichtelijk maken

- Waar bestaat de BIM uit?

Alle aspectmodellen
Eigenschappen van componenten
Eisen die worden gesteld aan de objecten vanuit RWS (Informatie levering naar RWS)

- Welke kennis is nodig om een Digital Twin te maken

Soltegro autonome logica simuleren
Infranea (modelleren, VR interfacing)
TWIN16 Coördinator (samenbrengen van modellen, zorgen dat alles klopt)
Lead engineers (functioneel gedrag omschrijven)
Modelleurs deelgebieden (3D modellen)
Test managers
Softwareontwikkelaar besturing en MMI, bediening, stukje bedienplek, autonome logica, stuurprogramma’s (Croon zuidoost)

Appendix 11 Interview with the BIM Coordinator of the RijnlandRoute

Role: BIM Coordinator	**Organization**: Mobilis
Project: RijnlandRoute	**Date**: 21 April 2020
Location: Teams Meeting	**Version**: 1.0
Topic: Vision, Features and Functionalities Digital Twin	

Visie op Digital Twin

- Wat wordt er verstaan onder een Digital Twin?

Een digitale tweeling van het model en wat de functionaliteiten zijn staat eigenlijk niet vast. Ik vind de beste toepassing van de virtual twin tot nu toe altijd dat testen van de apparatuur van Croonwolter&dros, dan de situatie testen. Je software testen voordat het gebouwd wordt.

Je kan ook zeggen dat bijvoorbeeld een 4D planning er ook onder valt, maar dan ga je het weer heel breed maken. Ik vind het lastig om te zeggen.

- Wat is het doel van de Digital Twin binnen het project, wat proberen jullie ermee te bereiken?

Reduceren van je test tijd, van de opening zodat je beter voorbereid bent en problemen van tevoren getackeld hebt voordat je in die tijd komt.

Je maakt natuurlijk de hele tunnel en dan heb je vaak nog een best lang proces om de tunnel te openen, alles werkend te krijgen.

- Wat is de relatie en verschil tussen BIM en Digital Twin?

Het heeft overlap met elkaar, voor ons in de civiele wereld is het 4D plannen heel mooi maar de vraag is of je dat onder een BIM schakelt of onder een Digital Twin schuift, dat is voor een beetje een vraag.

Verder denk ik dat de Digital Twin voor maintenance heel handig is. Dat zou de plek zijn waar je hem zou verwachten daar waar je moet testen als je bijvoorbeeld een camera gaat vervangen om te kijken van tevoren of de camera ook werkt met het huidige systeem.

Daar zou het juist de meeste meerwaarde hebben. Want je maakt in je ontwerp je BIM-model, dat fluctueert heel erg dus daar hebben we redelijk goede software om het bij te kunnen houden maar het maken van een Digital Twin duurt vaak lang.

Bij de A16 doen ze het maar 3 of 4 keer, ze pakken 3 of 4 baselines en dan maken ze een model waardoor het model snel achterloopt.

Eigenlijk maak je het een keer aan het einde een goed model waarin je al je testen doet en die dan eigenlijk door moet naar maintenance om daar voordeel uit te halen.

Waarbij het BIM-model is opgegaan in de Digital Twin waardoor maintenance geen BIM-model meer nodig heeft.

Je hebt je BIM-model en wordt voornamelijk gebruikt bij ontwerp en uitvoering specifiek en als je het BIM-model in onderhoud wilt houden dan wordt het een Digital Twin en daar kunnen functies aan toegekend worden.

- Wat is de link tussen het 3D BIM, coördinatie model, testopstelling in Eindhoven en de virtuele verificatie tool (Soltegro). Zijn al deze ‘componenten’ onderdeel van de Digital Twin?

Heel vaak is het zo dat het coördinatie model, op basis daarvan wordt de Digital Twin gemaakt.

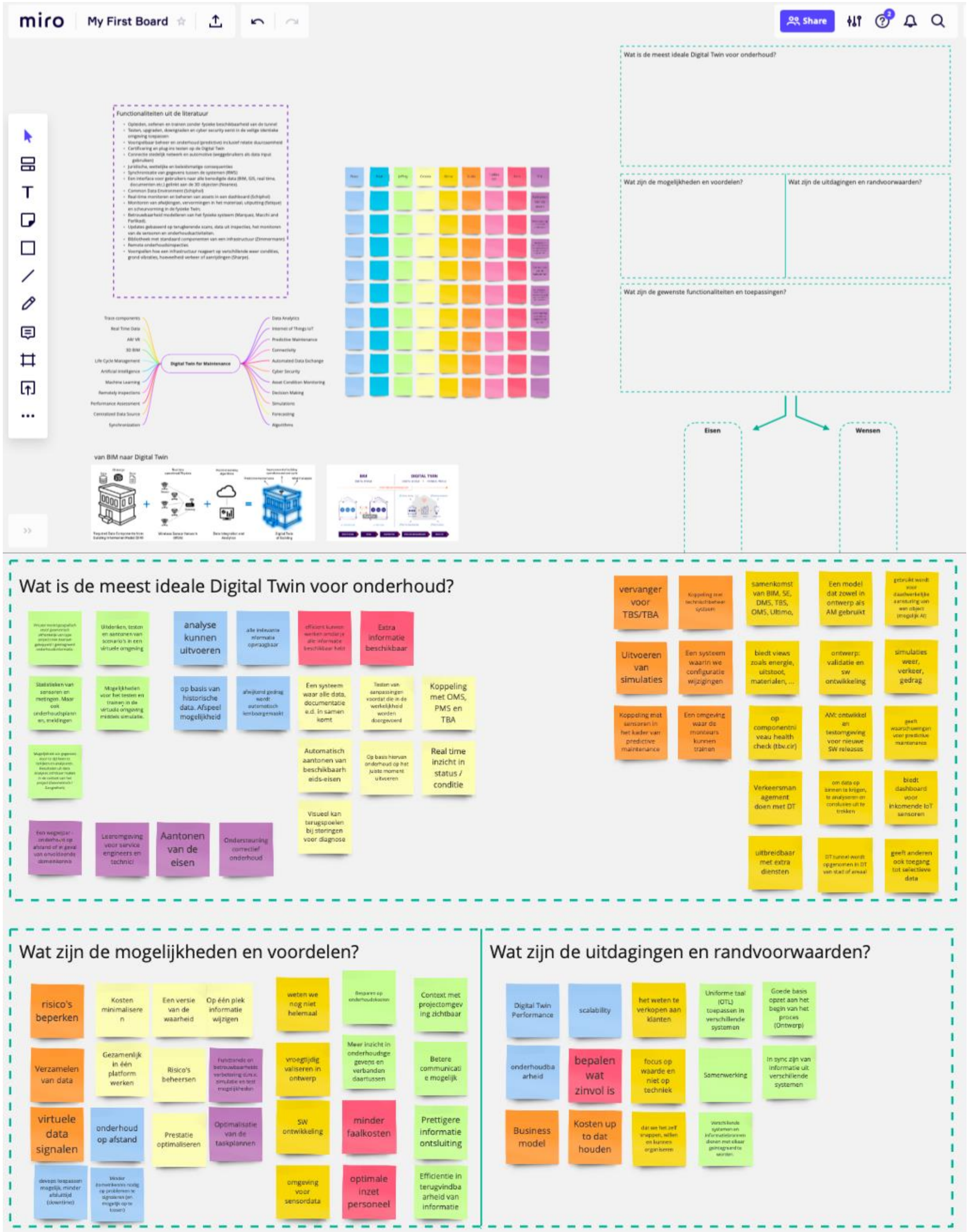
Relatie naar de tool van Soltegro hoor ik niet vaak langs komen.

Test opstelling: ik weet dat de containers in coördinatie model gezet zijn maar volgens mij stopt het daar zo’n beetje.

Appendix 12 Present Functionalities of the Digital Twins

Functionality	Sluis Eefde	Rijnland Route	A16 Rotterdam
Test software in advance	X	X	X
Clash avoidance	X		X
Train emergency services and operators		X	X
Information disclosure	X		X
System validation through the simulation of behavior	X	X	X
Assess maintainability of installations	X		
Demonstrate and test operation through scenarios		X	
Validation of design with stakeholders	X		X
Stimulate integral design			X
Minimize rest points towards the completion			X
Support iFAT and iSAT			X
Validation of the positioning			X
Assess the impact of renovations		X	

Appendix 13 Miro Whiteboard Brainstorm Session



Appendix 14 Results Brainstorm Session & Interview Asset Managers

Desired Functionalities

Middleware of Program Interface (API) - (6)

- Connection with OMS, PMS and TBA – Manager Asset Management
- Replacement or connection with TBA – Maintenance Manager
- Congregation of BIM, SE, DMS, TBA, OMS, Ultimo, etc. – Innovation Manager
- Virtual model linked or integrated to maintenance information – BIM Director
- Linking application with the Digital Twin; facilitating Digital Twin as TBA; linking DMS, Maximo and the OTO environment is already partly connected with the Twin – Maintenance Manager A16 Rotterdam
- Linking or replacing TBA, the DMS and test environment. It is not recommended to link PMS (keep it 'dull') or Relatics - Asset Manager Sluis Eefde

Information Retrieval - (6)

- Retrieval of all relevant information - Manager Systems Engineering & Innovation
- Ability to work efficiently because all information is available – Senior Consultant
- Collection of data – Maintenance Manager
- Information management and availability are crucial during maintenance - Maintenance Manager A16 Rotterdam
- Support the technicians through presenting the recent and right information to ensure that they can quickly solve the problems - Asset Manager RijnlandRoute
- Asset management is all about information management, having the adequate information at the right time - Asset Manager Sluis Eefde

Virtual Training (OTO) - (5)

- An environment where technicians can train – Maintenance Manager
- Learning environment for service engineers and technicians – Project Manager
- Possibility for training in a virtual environment through simulation – BIM Director
- The OTO environment or training system is partly linked with the Digital Twin at the A16 Rotterdam. – Maintenance Manager A16 Rotterdam
- Simulation of complex failures in order to train people and to visualize how the tunnel reacts to failures of systems – Asset Manager RijnlandRoute
- An environment where technicians can practice. If new people need to be educated, the 3D model or Digital Twin can be useful to visualize the tunnel and to show scenarios - Asset Manager RijnlandRoute

Test Environment - (5)

- Excogitate, test and demonstrate scenarios in the virtual environment – BIM Director
- Test modifications prior to applying it in reality – Manager Asset Management
- Test new software releases – Innovation Manager
- The test environment is of value when installations need to be replaced or during renovations - Maintenance Manager A16 Rotterdam
- Tests can be done to see how everything works, what happens for example when the tunnel is closed, do the procedures follow in the right sequence or to check whether the software is still correct. This allows to do a part of the tests virtually, reducing the time that the tunnel needs to be closed - Asset Manager RijnlandRoute

Data Analysis (playback function) - (5)

- Receive, analyze and draw conclusions from data – Innovation Manager
- Performing analysis based on historical data from a playback function – Manager Systems Engineering & Innovation
- View and analyze data through time and visualize the results from these analysis in the context of the project – BIM Director
- Contribute by serving as a measuring instrument to collect and analyse data – Senior Consultant
- Visually rewind in the event of a failure for the purpose of diagnosis – Manager Asset Management

Graphical User Interface (GUI) - (4)

- Provides dashboard for incoming IoT sensors and an environment with sensor data– Innovation Manager
- Offers a view where everything comes together (energy consumption, emission, materials on component level for the purpose of a health check and circularity – Innovation Manager
- One system where all data, documentation and such like comes together – Manager Asset Manager
- Real time insight in status or condition – Manager Asset Manager
- Contribute through finding all underlying documentation, as source ideal to be able to find things quickly – Senior Consultant
- There is a need for one interface, the 3D model – Asset Manager Sluis Eefde

Remote (assistance for) Maintenance - (3)

- A guidebook – remote maintenance or in case of insufficient domain specific knowledge – Project Manager
- An up-to-date 3D model can assist remote maintenance since someone else is in the ability to watch along - Asset Manager Sluis Eefde
- Supporting maintenance by determining your location and retrieving information with an iPad- Asset Manager Rijnlandroute

Notifications - (3)

- Automatically reveal deviant behavior – Manager Systems Engineering & Innovation
- Gives alerts for Predictive Maintenance enabled by a connection between the Digital Twin and sensors – Maintenance Manager
- Statistics of sensors and measurements but also maintenance plans and notifications – BIM Director

Requirements - (2)

- Automatically demonstrate compliance to the availability requirements – Maintenance Manager
- Demonstrate requirements – Manager Asset Management

The Desired Objectives

Risico's	Risico's beperken, operationeel door vooraf te testen/ simuleren	Maintenance Manager
	Risico's beheersen	Manager Asset Management
Kosten	Kosten minimaliseren	Manager Asset Management
	Besparen op onderhoudskosten	BIM Director
	Minder faalkosten omdat er veel meer informatie beschikbaar	Senior Consultant
Prestatie	Prestatie optimaliseren	Manager Asset Management
Een platform	Gezamenlijk in één platform werken	Manager Asset Management
	Een versie van de waarheid (op een locatie)	
	Op één plek informatie wijzigen	
Communicatie	Betere communicatie mogelijk	BIM Director
Inzicht	Context met projectomgeving zichtbaar	BIM Director
	Meer inzicht in onderhoudsgegevens en verbanden daartussen	
Informatieontsluiting	Prettigere informatieontsluiting	BIM Director
	Meer inzicht in onderhoudsgegevens en verbanden daartussen	
Domeinkennis	Minder domeinkennis nodig om problemen te signaleren (en mogelijk op te lossen)	Manager Systems Engineering & Innovation
Personeel	Optimale inzet personeel	Senior Consultant
Taakplannen	Optimalisatie van taakplannen	Project Manager
Correctief onderhoud	Ondersteuning correctief onderhoud	Project Manager
Functionele en betrouwbaarheidsverbetering	Functionele en betrouwbaarheidsverbetering d.m.v. simulatie en test mogelijkheden	Project Manager
Training als service	Dat de opdrachtgever er ook voor gaat betalen met als doel om hun personeel te trainen, brandweer te trainen en veiligheidsdiensten, herhalingstrainingen	Asset Manager RijnlandRoute
Modificaties	Modificaties goed kunnen doorvoeren	Asset Manager RijnlandRoute
Informatievoorziening	Mensen van de juiste informatie voorzien tijdens het werk	Asset Manager RijnlandRoute
Renovaties	Bij renovaties eventueel dat je je faseringen kunt zetten omtrent verkeersmaatregelen	Asset Manager RijnlandRoute

Expected Challenges and Boundary Conditions

Manager Systems Engineering & Innovation

- Scalability
- Digital Twin Performance
- Onderhoud-baarheid

Innovation Manager

- Het weten te verkopen aan klanten
- Focus op waarde voor de klant en niet op de techniek
- Dat we het zelf snappen, willen en kunnen organiseren (veel disciplines komen samen, het is van belang allemaal hetzelfde doel voor ogen te hebben) Ik ben bang dat wij conservatief zijn.
- Geeft anderen ook toegang tot selectieve data

Test Manager

- Bepalen wat zinvol is
- Risico's: snelle veroudering van de systemen in de tunnel, de databases en de software als overkoepelende schil. Systemen die we nu kopen, zijn verouderd als de tunnel opgeleverd wordt en de apparatuur moet dan snel weer vervangen worden door veroudering.
- Vaak willen verschillende partijen heel veel data verzamelen maar ze weten niet wat het doel hiervan is en wat ze ermee kunnen bereiken. Het is belangrijk de vraag te stellen wat het daadwerkelijk gaat opleveren en of het zinvol is voor de organisatie.

BIM Director

- Uniforme taal (OTL) toepassen in verschillende systemen – data classificeren op basis van uniform labelen.
- Samenwerken – Multidisciplinair
- Goede basis opzet aan het begin van het proces (ontwerp)
- Verschillende systemen en informatiebronnen dienen met elkaar geïntegreerd te worden
- In synchronisatie zijn van informatie uit verschillende systemen

Asset Manager RijnlandRoute

- Er moet goede support zijn voor de tools en de werking hiervan (centrale ondersteuning).
- Een goed wijzigingen beheer om alle informatie actueel te houden, het zou ideaal zijn om dit om een centrale plek te doen.
- Een scherpe business case om tegen argumenten te kunnen pareren en simpelweg investeringen doen die terug verdiend gaan worden.
- Strakke scope, een logisch ontwikkel pad, niet alles in een keer maar wat als eerst en welke ontwikkeling daarna.
- Resistance to change van mensen en daarom is het belangrijk in stappen te werken en te implementeren.

Maintenance Manager A16 Rotterdam

- Het moet gebruiksvriendelijk zijn zodat mensen het ook echt gaan gebruiken

Asset Manager Sluis Eefde

- Belang van cyber security als veel informatie op een locatie samenkomt.
- Go/ No Go momenten en niet jarenlang tijd aan besteden zonder resultaat.
- Goede business case om aan te tonen wat de toegevoegde waarde is.
- Overzetten van data moet eenvoudig en snel mogelijk zijn wanneer een systeem geüpdatet wordt of vervangen wordt.

Appendix 15 Morphological Chart Digital Twin Concept

Functionalities	*Option/ element A*	*Option/ element B*	*Option/ element C*	*Option/ element D*
Function 1	Application Programming Interface (API)	Enterprise Service Bus (ESB)		
Function 2	Document Management System (DMS)	Common Data Environment (CDE)		
Function 3	OTO-program	Virtual Reality (VR)	Maintenance Simulations	Three-dimensional (3D) model
Function 4	Power System	Common hardware	Data Transmission	Digital installations
Function 5	Technical Management Application (TBA)			
Function 6	Graphical Information System (GIS)	Three-dimensional (3D) model		

Appendix 16 Application Interface – API and ESB

Feature A: API
Application Programming Interfaces (API) enables different (software) systems to communicate and exchange information (Trivento, 2020). It is a set of rules that define how computers, applications or machines talk to each other (Park, 2020). More and more software applications have an API available nowadays (Schopen, 2015). An API makes use of a small part of the code from the original program. This code ensures that the client from outside can request particular information from the program. These requests are translated by the API to code in order to make it usable for the application. The API will subsequently return the answer to the request back to the client. Through the use of an API, it is possible to let various applications collaborate seamlessly or to create an all-in-one application (Trivento, 2020).

Feature B: ESB
Enterprise Service Bus (ESB) is a pattern whereby a centralized software component performs integrations to backend systems as well as deep connectivity routing, translations of data models and requests. ESB makes those integrations and translations available as service interface for reuse by new applications (IBM, 2019). ESB is a platform designed in order that underlying application can connect to each other univocally and to impart information (Bright answers, 2015).

An ESB is an essential component of SOA, or service-oriented architecture. The SOA defines a way to make software components reusable via service interfaces. These interfaces utilize common communication standards which enables them to rapidly incorporate into new applications without the need for deep integrations (IBM, 2019). The various functions assigned to an ESB include an operations and management, mediation, security, adapters and service hosting module. These modules form the basis for evaluating ESB products (Kress, et al., 2013).

Appendix 17 Project Data and Document Management – CDE and DMS

Feature A: CDE
A Common Data Environment is the single source of information during a project. It is used to collect, manage and disseminate documentation, the graphical model and non-graphical data for the entire project team. The CDE includes all project information whether created in a Building Information Modelling (BIM) environment or in a conventional data format (Designing Buildings, 2020). Moreover, many BIM protocols, in particular the CIC BIM Protocol propose the use of a common data environment. Collaboration to drive improved results and efficiencies is at the heart of implementing a BIM approach on construction projects (McPartland, 2016).

Feature B: DMS
A Document Management System is the utilization of a computer system and software to centrally store, access, modify, manage and track electronic documents and electronic images of paper-based information. It is defined as the software that controls and organizes documents throughout an organization (Aiim, 2020). Moreover, a DMS is designed to assist in managing the creation, storage, and flow of documents by providing a centralized repository. DMS incorporates document and content capture, workflow, document repositories, output systems and data retrieval systems (Aiim, 2020) and (Zammit, 2020).

Appendix 18 Test Facility

All items necessary for the operation of the tunnel and the adjacent sunken section of the RijnlandRoute are connected. Moreover, all equipment is installed in modules which are needed for the two service buildings. If the chance of failure during commissioning is large, all items are installed and for systems with a lower risk profile, only a part is installed. In the test facility, each component is mounted based on the 3D BIM-model.

By setting up the TTI in the test location, it enables to profoundly test the integral functioning and to remove possible start-up problems in an early stage. Moreover, a fiber optic connection is established between the test location and the road traffic control center in Rhoon since the tunnel will be operated from this location after commissioning (Nuhn, Jansen and ‘t Hart, 2019).

Appendix 19 Data Analysis

The TBA is introduced since the maintenance organization demands more detailed information than contractually requested by the client during projects. Moreover, there is no standardized nor centralized procedure of data analysis arranged thus far. The project is initiated in 2018 and recently, the decision for the operating system is made.

The most important goal of this applications is to support the maintenance organizations of Croonwolter&dros as well as Mobilis to effectively and efficiently analyze, deployment of preventive and corrective activities. Furthermore, to optimize the installations and maintenance through in depth analysis of the process measurements.

Four levels of analytics can be distinguished namely, descriptive, diagnostic, predictive and prescriptive analytics (Plurarsight, 2020) visualized in figure 8. At present, mainly descriptive and diagnostic analytics are applied within TBI Infra.

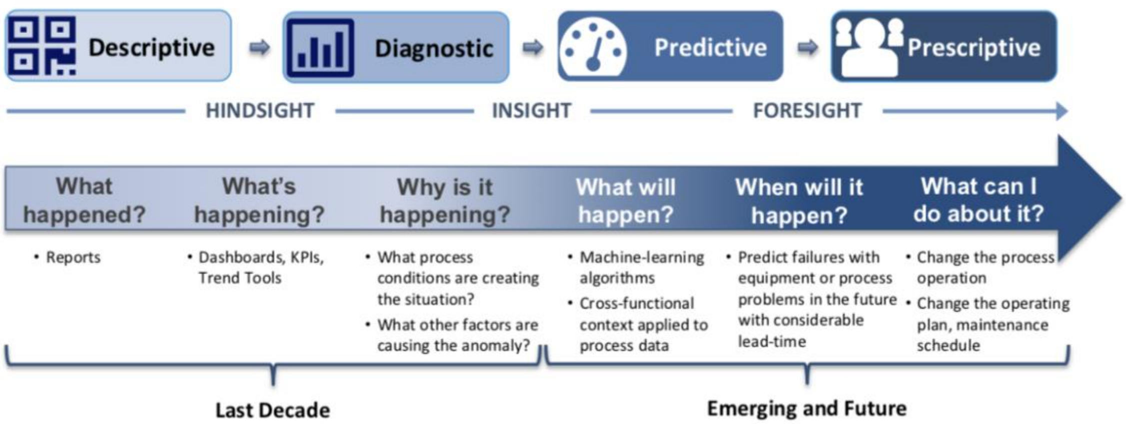


Figure 8 The four levels of Analytics (FitzGerald, 2018).

Appendix 20 User Interface – 3D and GIS

Feature A: 3D
Three-dimensional building information modelling of the infrastructures are created during the design phase of the projects and part of the present Digital Twin. This 3D BIM can be utilized as the user interface in order to find the underlying information about that asset, including documentation, sensor data and asset condition. The information is disclosed by clicking on the items in the model which generates an overview for the users. The information from the 3D BIM is complemented with information from the underlying systems through the use of the API discussed during the first functionality.

Feature B: GIS
The Geographic Information System ArcGIS is presently utilized during the projects and provided by Rijkswaterstaat. ArcGIS software includes a two-dimensional visualization and looks familiar to Google Maps. ArcGIS is a software that allows to manage and analyze geographic information by visualizing geographical statistics through layer building maps (Shaktawat, 2020). To each object extra information can be linked which can be requested which allows for diverse analysis (Rijkswaterstaat, 2020).

The software functions as a platform whereby geographical information can be linked, shared and analyzed. ArcGIS creates maps that require categories which are organized as layers. These layers are registered spatially which allows the program to line them up properly to create a complex data map. Data then can be correlated with these spatial layers and can be mapped and analyzed through demographic changes or via data tables. Operating as a platform enables resources to be available and to decrease and extract information from much bigger geographical data bases. It is a solution to manage and analyze data as filtered through map construction (Shaktawat, 2020).

Appendix 21 Digital Twin – Additional Functionalities

Functionality 7 – Remote Maintenance

The Digital Twin can support remote assistance during maintenance activities by an up-to-data 3D model. Technicians with insufficient domain knowledge can be assisted since someone is in the possibility to monitor the asset status through sensors and view the location of the assets. The model also allows the maintenance team to better prepare maintenance activities since the location of the failure can be better identified and a better prognosis can be made on beforehand.

Moreover, by determining the location in the model, the correct information can be extracted from the object on location. This is enabled by QR codes placed on the assets which is applied at Sluis Eefde or through the use of a GPS location.

Functionality 8 – Notifications

An integration with the TBA allows to visualize deviant behavior through alerts in the Digital Twin whereby the location is directly visible. This functionality is enabled by first identifying for which assets it is of importance to give alerts. Then, defining what the normal behavior pattern is and what deviant behavior is for the various assets. The notification can be in the form of an SMS, WhatsApp or email for example. Moreover, in the future when predictive maintenance is practiced, these notifications can also be communicated through the use of the Digital Twin.

Functionality 9 – Requirements

In order to demonstrate the availability requirements established by the client, possible an interface between the Performance Measurement System (PMS) and Digital Twin can be realized. This allows to display the requirements in the central interface and simplifies to establish a link the available information.

The PMS is used to record the performance, the corresponding evidence and reimbursement. Results of all relevant verifications, inspections, measurements, assessments and the updated availability data of the infrastructure are captured. Based on these elements with the contractually specified calculation rules which are implemented in the system, the availability compensation is determined (Soltegro, 2020).

Appendix 22 Maintenance Performance Influenced by the Features of the Digital Twin

First, the application of application programming interfaces ensures that the information between the linked systems is synchronized and computers rather than people manage the work. Information between the systems is automatically shared which improves the accuracy and reliability of the information and data. Moreover, the interface between the different systems allows the user to insert data centrally once-only which will reduce the chance for mistakes. An API partly facilities the creation of a Common Data Environment and Graphical User Interface discussed below.

The Digital Twin enables to retrieve information from the various data sources and systems centrally through the 3D or GIS interface and by integrating the systems. This centralized visual interface can provide improved insight in the data and information and the correlations between them. The existing documentation and maintenance history of the installations are better discoverable. Moreover, it allows the user to efficiently search for the needed information and the time needed for searching will be reduced significantly. The misconceptions will also reduce when all stakeholders are provided with the unequivocal and correct information

A Common Data Environment can drastically reduce the time spent looking for, sharing and coordinating information within a project. In a CDE, data is never compromised which offers a secure environment for confidential information and collaboration can be enhanced between the different parties. The single source of truth can improve decision making and lowers the risk with better transparency and insight in the information. Moreover, efficiency and data quality are improved since the need to manually recreate data is reduced thus less input errors and lost information (Allen, 2019).

Building in Cloud (2018) states that the Common Data Environment is necessary and essential to be able to efficiently and essential to more effectively carry out the activities of repair, maintenance, renovation and new construction with significant improvements in quality, delivery time and cost.

The hands-on-tool time for maintenance technicians can be increased when less time is needed to find the required information to execute the maintenance activity. The overall better information provision and management leads to less waste of time and effort for the maintenance personnel. Moreover, having the correct information at hand reduces the change of mistakes. In case of failure, it is of importance to restore the function of the installation as soon as possible to prevent or minimize the number of penalty points.

A training environment can offer benefits during the maintenance phase by making use of multidisciplinary training. The tunnel can be presented in the three-dimensional model and with the use of simulations, various scenarios can be shown. It is possible to bring the training to the user which makes it easier, cheaper and more efficient for the different parties. Moreover, the training environment also helps to better prepare the maintenance activities in advance. For example, the exact location of the installations can be determined, and obstacles can be identified. The main goal is offer realistic training without requiring the physical tunnel, to accelerate the function recovery of the installations and better prepared maintenance activities.

By testing the software on beforehand in the virtual test environment, the failure rate can be reduced, and testing time can be decreased. This will reduce costs, hinderance and improves the safety of the tunnel drastically by closing the tunnel for shorter periods of time and early verification of the software. The ultimate aim is to replace the physical installations through the use of simulations. An exact copy is required whereby the simulation work exactly like the reality. When the tunnel is ready, it only has to be checked whether the cables are correctly connected reducing the test time drastically.

Exploiting the Digital Twin as tool to analyze data during the lifespan of the installations can improve decision making regarding maintenance. Potentially, the replacement interval can be optimized, and failures can be predicted. A better identification of the type of failure enables to determine which discipline or service is required to restore the function. Moreover, an up-to-date status of the installations can prevent unnecessary visits.

Appendix 23 Digital Twin Initiatives Infrastructure Industry

‘Centrum Ondergronds Bouwen’ (COB) is a knowledge center for underground constructions. COB tackles issues that serve a common and social interest. To identify these issues, close contact with the network is maintained through coordinators, events and platforms. The goals of the maintenance and management platform are to create a safe environment where participants can ask questions and can share their concerns and experience; to identify challenges which are then explored together; and to develop a collective view and to solve problems. Besides the Digital Twin, other technologies such as VR/ AR, 3D BIM and OTO are addressed. These attended webinars of COB can be found on Youtube and the links are included below:

- https://www.youtube.com/watch?v=WKb558lHtIw&t=30s
- https://www.youtube.com/watch?v=9qJMLw6g2pM

Rijkswaterstaat is facing the biggest maintenance assignment in Dutch history, hundreds of infrastructures are in need of renovation or even replacement. This requires an innovative, sustainable and safe approach. Innovation refers to inter alia, the possibilities of digitalization. One of the innovations that underpin this, is the Digital Twin. Rijkswaterstaat plays an important role as client in the development of the Digital Twin.

During various projects, (parts of) Digital Twins are developed, but these are often the property of the contractor. At present, the contracts do not include the arrangement with regards to the transfer of the Digital Twin to Rijkswaterstaat. However, Rijkswaterstaat wants to develop Digital Twins from the clients’ side whereby the Digital Twin is delivered to the consortium in the contract phase. The contractor then enriches the model with new engineering data and after commissioning the Twin will be managed by Rijkswaterstaat and will remain property of Rijkswaterstaat.

The Digital Twin Pilot of Rijkswaterstaat at the Heinenoordtunnel renovation project makes use of 3D data capture, to completely map the as-is situation which is enriched in a 3D model. A dashboard is created with the Asset @ Your Desk solution of Smart AIS, which can include all data that is relevant for the project as shown in figure 9. Smart Asset Integrity Solutions B.V. has built a demo together with Rijkswaterstaat for the Heinenoordtunnel. Smart AIS is a specialized company in the field of independent design reviews, implementing and maintaining of Integrity management systems and inspections of contractors’ activities to ensure compliance with the clients and the legislative requirements.

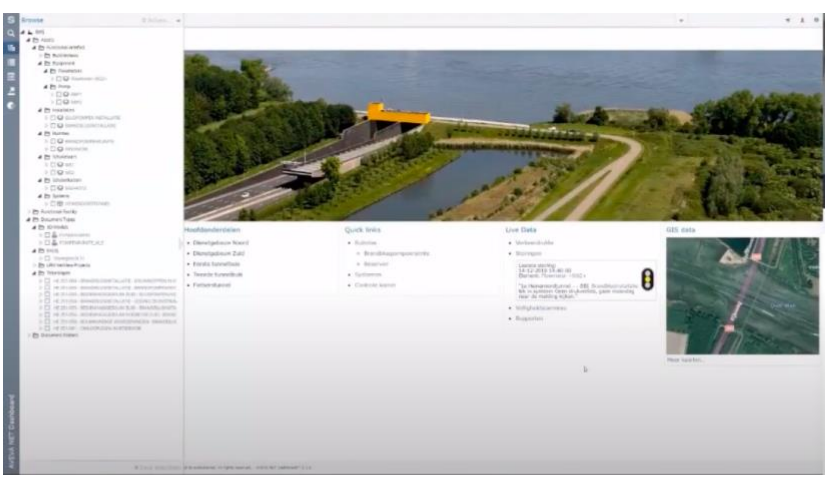


Figure 9 Asset @ Your Desk Demo Heinenoordtunnel

Appendix 24 TWIN-16 Identification of the costs and potential cost savings

The Technical Innovation Lead of Soltegro explains that every project usually has additional wishes, for example a traffic simulation or smoke and fire simulation; testing of the camera positions; or is the Digital Twin applied in a multi-player environment for a virtual Site Integration Test (SIT) with emergency services.

The Digital Twin application developed for virtual testing can often be applied, with small adjustments, for education and training. This allows to deploy the Digital Twin after realization and during exploitation of a project. It can be of use for the developed of software updates and is often part of the test set-up which is delivered with a tunnel. There are of course sporadic costs attached to required maintenance and updates.

It is expected that the costs can be reduced drastically in the future since reusable components are developed and the complexity of the work can be estimated and communicated better.

The costs for the virtual simulation environment of the A16 Rotterdam include:

- Development of the simulations (hours of software development);
- Conversion of 3D to a VR model;
- Linking the simulations to the control;
- Execution of extra (u)FATS and alignment;
- Maintenance of the simulation and interface with the control during the exploitation phase;
- Hardware to run the simulation on including computers, glasses, etc. and to develop. The iFAT setup can partly be used for this purpose.