Investigation and development of a Digital Twin for the Maeslant barrier

Exploring the application of digital twins in the maintenance and operation of storm surge barriers

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Digital Twin for the Maeslant Barrier

Luc Ponsioen

2023

Investigation and development of a Digital Twin for the Maeslant barrier

Exploring the application of digital twins in the maintenance and operation of storm surge barriers

By

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in partial fulfilment of the requirements for the degree of

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface and Acknowledgements

This work on “Investigating and developing a digital twin for storm surge barriers” presents the final report of the Engineering Doctorate (EngD) programme at the Delft University of Technology (TU Delft). This EngD represents an intense two-year collaboration between the TU Delft, Rijkswaterstaat and Aveco de Bondt, which has resulted in the development of a digital twin prototype for the Maeslant barrier.

The past two years have been incredibly intriguing and educational, with occasional moments of intensity. The EngD program at TU Delft has provided me with numerous fresh perspectives on my strengths, weaknesses, interests, and ultimately, what brings me happiness. It has taken me to fascinating locations and introduced me to inspiring individuals who, each in their unique way, have expanded my self-awareness and my understanding of life as a whole. I would like to convey my heartfelt gratitude for these valuable new insights.

I would like to take a moment to sincerely thank Alexander, Bas and Hans, the supervisors of my research, who have supported and helped me in more ways than I could ever wish for.

Alexander, it was an absolute pleasure to work together. The dedication you had in guiding me through my research was inspiring. You pulled me through times where things weren’t going as they should, and your expertise kept me on track, preventing me from straying. Not only that, we often had good laughs during our weekly meetings, which made the work very enjoyable!

Bas, I frequently admired the insightful, sharp, and very rapid feedback you provided on the work I submitted. Writing did not always come easy for me, but you definitely challenged and inspired me to improve my skills, and gave me a push in the right direction when I needed it. Additionally, I hold fond memories of our visit to Houston and New Orleans, for which I am still grateful for the invitation.

Hans, your technical insight into the Maeslant barrier is unparalleled! This research wouldn’t have come nearly as far without your technical contributions. Whether it was about the data, models, documentation, or simply understanding how the barrier works, you were always willing to help, and I greatly appreciate that. Our phone calls were never dull, and actually never shorter than 15 minutes, which I think says it all about the assistance you provided.

This research would not have been feasible without the support and enthusiasm of the colleagues at Rijkswaterstaat, as well as my associates at Aveco de Bondt, who generously provided me with the time and freedom I needed. They played an instrumental role in facilitating my research, for which I am sincerely grateful. Moreover, I must express my appreciation to my fellow EngD candidates. We shared wonderful experiences and offered each other support when it was needed. While I won't attempt to list names, as I'm sure I would unintentionally omit someone, I want to convey that each of you is an outstanding colleague and friend. It was a true pleasure collaborating with you. I hold in high regard your enthusiasm and willingness to assist, highlighting the significance of teamwork in achieving success.

Finally, and most importantly, I want to express my gratitude to my friends and family for your boundless love, positivity and unwavering support. Sometimes, all you require is someone to talk to, share a drink with, bring laughter into your life, spend quality time with, or to just give you a hug. You have consistently been there for me when I needed it, and I am deeply thankful to have each of you in my life!

Luc Ponsioen
Rotterdam, October 2023

Executive summary

A Digital twin, a digital replica of a physical entity or system, encapsulated in a software model, represents a promising technology that has demonstrated its effectiveness for asset management in various industries. Rijkswaterstaat has gained interest in investigating the possibilities for digital twin integration in the asset management of storm surge barriers. Therefore, in this Engineering Doctorate (EngD) research, the application and development of a digital twin for a storm surge barrier is investigated, with the Maeslant barrier serving as the case study.

Storm surge barriers are technically complex systems that fulfil a vital role in the flood protection of the Netherlands. A strict form of risk based asset management (ProBO) is applied to keep the barrier operational. However, the complexity and infrequent use of the barrier makes this form of asset management highly knowledge intensive. Currently it is a large asset management challenge for Rijkswaterstaat (the organization responsible for operation and maintenance of the storm surge barriers in the Netherlands) to maintain the necessary expertise at the right level. The goal is therefore to explore the following question:

"How can a prototype digital twin support in investigating the application of a full-scale digital twin for storm surge barriers, to strengthen the knowledge and information in support of their maintenance and operations?"

A prototype of a digital twin for the Maeslant barrier has been designed and constructed by the writer of this report, with a particular focus on the barrier's retaining walls. For the design of this prototype (see Figure 1), knowledge from three fields had to be integrated: 1) organizational & user needs; 2) functioning of the barrier (civil and mechanical engineering); 3) ICT architecture design.

As a first design step the user needs were investigated by conducting interviews with Rijkswaterstaat employees. These were translated into four applications the digital twin should fulfil to provide added value:

1. Enhancing efficiency in knowledge and information management
2. Avoiding unnecessary costs through better barrier status monitoring
3. Improving risk management with models and data analysis
4. Providing insights into barrier behaviour

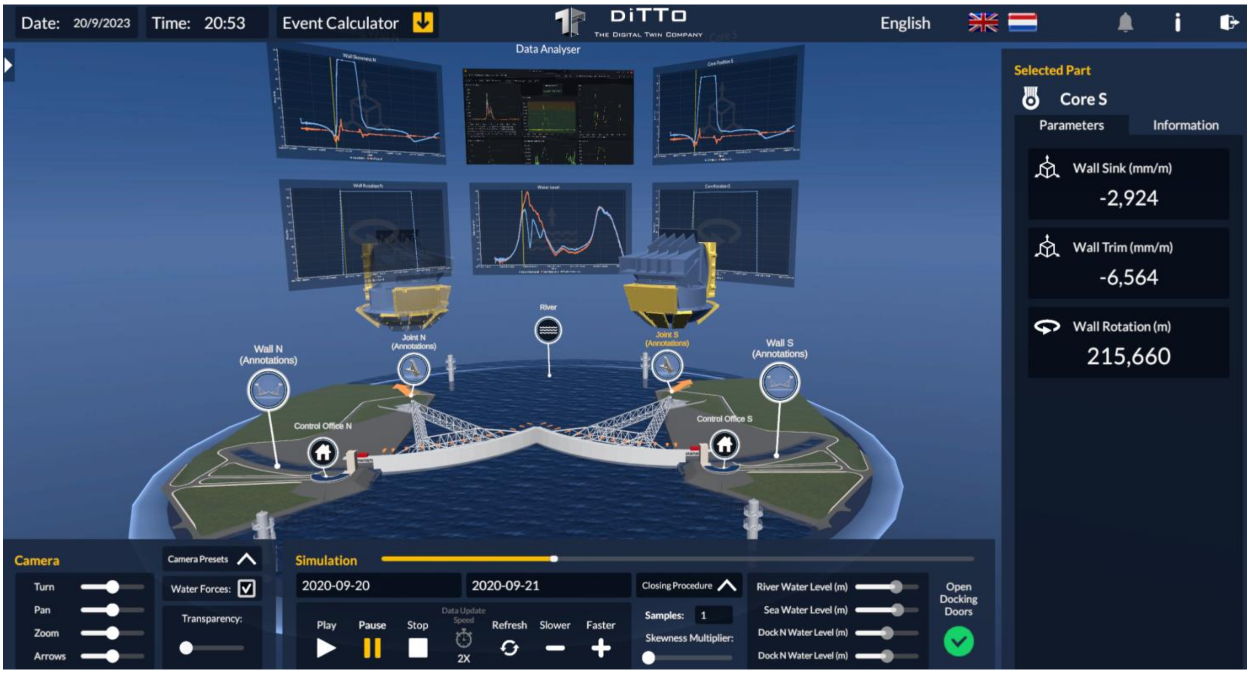

Figure 1: A visualization of the digital twin prototype. It shows the animation of the barrier closing for the actual 2020 test closure (centre), control panels for the simulation or replay of the closure (lower panel), clickable panels for data visualization and further data analysis including water levels, barrier position, pump data and status of valves (top panels) and 'live' values of the animated parameters including the option to search for more information (right side)

The user requirements were translated into design requirements to build the digital twin prototype, which is developed using Unity and Python scripts. The scripts are used for data calibration purposes and to make a connection between the digital twin model and existing models. For this prototype, a connection is made with a hydrostatic force model, a failure probability model and a pump discharge model. The Unity model acts as the user interface for the digital twin model in which a 3D data animation model of the barrier is integrated combined with data visualization panels.

The functional application of the prototype is illustrated by means of three use cases:

- Case 1 - *Analysis of closing procedures based on observations.*
  Quickly accessible and direct available data put users in the position to analyse the barrier closures and monitor its status by means of data visualisation, animation and model calculations.
- Case 2 - *Knowledge conservation and transfer: hydrostatic forces example.*
  Increasing knowledge transfer, illustrated by an example in which hydrostatic forces acting on the barrier are animated and supplemented with visualized data that can be analysed.
- Case 3 - *Observing abnormal behaviour and including risk management.*
  Using the digital twin to observe abnormal pump performances and directly calculate the impact of possible measures on the failure probability, to avoid unnecessary quick and costly decisions.

The prototype is tested among 14 potential users within Rijkswaterstaat to investigate the perceived added value and the organizational feasibility of a full implementation. The results of the tests demonstrate that digital twin users recognize clear value to enhance knowledge and information management. The current prototype exhibits potential in this regard, especially for the sake of information sharing and education, suggesting significant possibilities for a full-scale (i.e. of the entire barrier) digital twin. In the long term, it is expected that the digital twin could add value in increasing the barrier's asset management. An important notification, however, is that the reactions of respondents was diverse. The respondents with a more practical role at the barrier (e.g., the operational technical specialists) were less enthusiastic about the prototype for direct use for asset management than the higher management.

The development of the prototype demonstrated the feasibility of a small-scale digital twin of the barrier. However, it does not guarantee a successful implementation of a full-scale digital twin within the Rijkswaterstaat organization. Therefore, the challenges and obstacles in implementation have been further investigated through a technical, economic, and organizational feasibility study.

The prototype indicates that the available technology in the market, both at hardware and software level, is sufficient to develop a full-scale digital twin for the Maeslant barrier. However, the current state of hard- and software within Rijkswaterstaat is insufficient for full-scale implementation. Especially on cyber security, challenges need to be overcome to be able to use the maximum capacity of a full-scale digital twin.

A full-scale digital twin is expected to be financially feasible: a business case study indicates that a digital twin could be cost effective within five years. The economic added value of the digital twin is estimated based on expected savings in time and maintenance cost for Rijkswaterstaat. The costs are estimated by extrapolating the development cost of the prototype.

The Maeslant barrier organization is, resulting from the questionnaire, enthusiastic about implementation of a full-scale digital twin. However, achieving a digital twin with added value to the entire organization necessitates further development of the existing prototype, and a better connection to the user needs of the respondents that rated the prototype less positive. Subsequently, for successful implementation, the technically oriented Rijkswaterstaat employees need to be heavily included in the development process and must be given time to support in the implementation.

All points considered it is concluded that a full-scale digital twin is, under reasonable assumption of several surmountable challenges, feasible to implement for the Maeslant barrier.

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1 Introduction

Storm surge barriers are vital components of flood protection systems, strategically positioned at river mouths, tidal inlets, and estuaries. The barriers spring into action when water levels reach alarmingly high levels, playing a pivotal role in safeguarding regions from devastating floods. Notably, the Netherlands, home to six prominent storm surge barriers, heavily relies on these kinds of barriers, of which the Maeslant and Eastern Scheldt barriers are prominent examples. The operational reliability standards set for the barriers are strict. Therefore, these complex engineering structures demand a wealth of specialized knowledge for their maintenance, which aligns with the Performance Based Risk (or ProBO) method[1] [1] [2].

The maintenance procedures, in this context, are inherently knowledge-intensive, presenting a challenge in maintaining the requisite expertise and ensuring its accessibility to colleagues. Regrettably, Rijkswaterstaat[2] faces difficulties in effectively managing knowledge and information concerning their storm surge barriers at the necessary maintenance level [1]. Often, crucial knowledge remains implicit, fragmented, and poorly documented, complicating data interpretation and model simulations. This inefficiency leads to suboptimal asset management decisions and impedes the transfer of knowledge to new team members, resulting in a time-consuming onboarding process that can extend up to five years.

Since many employees transition to different roles before completing their training, the organization risks losing valuable knowledge. Especially with the effects of climate change and sea level rise in mind, it becomes more crucial to maintain the knowledge level of the barriers. While efforts have been made to conserve information and enhance knowledge transfer, navigating the complexities of finding and interpreting this information remains a significant challenge within Rijkswaterstaat [1]. As a response to these challenges, Rijkswaterstaat is exploring innovative technologies, including *digital twins*, to improve their asset management processes.

Digital twins represent a promising technology that has demonstrated its effectiveness for asset management in various industries. A digital twin serves as a digital replica of a physical entity or system, encapsulated in a software model. It enables the aggregation of data from multiple instances, providing a composite view across real-world objects and their associated processes [3], therefore addressing the knowledge and information or asset management challenges faced by organizations like Rijkswaterstaat. In the case of a storm surge barrier, a digital twin could offer insights into the operation of the barrier itself, and within a broader water management system.

In industries like aviation, offshore operations, and manufacturing, digital twins have proven highly effective. They have facilitated data and information management through dashboards, employed models to detect anomalies in machine behaviour, identified component degradation, and predicted failures [4] [5] [6]. Recognizing their success in other sectors, Rijkswaterstaat has expressed interest in leveraging digital twins to enhance the asset management of their infrastructure. They have outlined their vision in a document that includes a comprehensive roadmap [7].

Within civil engineering, numerous studies have explored the development and application of digital twins for various purposes [8]. In the realm of hydraulic engineering, digital twins have found applications in port development [9], drainage systems [10], offshore pipelines [11] and dams [12]. While several exploratory initiatives have investigated the potential of digital twins for storm surge barriers, to the best of knowledge, there has been no systematic investigation into the effectiveness of digital twins in enhancing knowledge management and asset management practices for storm surge barriers. This research aims to fill this gap and explore the untapped potential of digital twins for storm surge barriers, which is done by designing, developing and testing a digital twin prototype of a storm surge barrier.

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[1] a Risk-based asset management methodology based on an expectation (calculated or estimated by expert judgement) that objects will satisfy set requirements in terms of performance. [2]

[2] Rijkswaterstaat is the Dutch governmental organization responsible for operating and maintaining the storm surge barriers.

Objective

The goal of this EngD research is to explore the following question:

"How can a prototype digital twin support in investigating the application of a full-scale digital twin for storm surge barriers, to strengthen the knowledge and information in support of their maintenance and operations?"

To find an answer to this objective, several more detailed research questions are defined. These research questions are formulated as:

I. What are the design requirements for a digital twin of the Maeslant barrier and how can these be translated into a developed prototype digital twin?
II. Can a digital twin enhance the efficiency in knowledge and information management?
III. Can a digital twin support better monitoring of the barrier to avoid unnecessary maintenance or replacement costs?
IV. Does a digital twin improve risk management?
V. Does a digital twin provide better insight in the barrier's behaviour during closures?
VI. Is the implementation of a digital twin for a storm surge barrier technically, economically, and organizationally feasible?

Research approach

The research questions are answered by designing, developing and testing a *prototype digital twin*, which is achieved by integrating knowledge from three fields: 1) organizational & user needs; 2) functioning of the barrier (civil and mechanical engineering); 3) ICT architecture design. The application of a digital is researched within the Rijkswaterstaat organization by needs of interviews with potential users. This research provided a set of user requirements, based on which a prototype is developed. This prototype is tested in several use cases (covering engineering performance, reliability, and knowledge management of the barrier) and evaluated with the stakeholders. This led to an evaluation of the potential application and the organizational, economic, and technical feasibility of a full-scale (i.e. of the entire barrier) digital twin. This process is schematized in Figure 3, indicating the chapters of this thesis including the development steps.

The prototype is developed for the retaining walls of the Maeslant barrier (see Figure 2). The Maeslant barrier is chosen as earlier digital twin explorations for this barrier showed high potential and the object generates large amounts of data. The retaining walls (the white walls on the right side of Figure 2) are a crucial component of the Maeslant barrier, as they contain a ballasting system actively controlled during closures. They contain unique elements, and a significant amount of data is provided through monitoring of the retaining walls (e.g., pump power, water levels and valve positions). This makes it an ideal subsystem to test the contribution of a digital twin.

This EngD research thus has **two main deliverables:**

1) The *present report*, which describes the development, architecture, functioning and feasibility of the digital twin.
2) The actual *prototype digital twin*. This prototype is designed and built by the writer and is accessible through an app (supported by an instruction film).

It is highly recommended that the readers of this report, also review the actual protype and the supporting film. In case of limited time, the film could be a good starting point.

The digital twin prototype is developed in Unity, supported with Python scripts. The scripts are used for data calibration purposes and to make a connection between the digital twin model and calculation or simulation models. For this prototype, a connection is made with a hydrostatic force model, a failure probability model and a pump discharge model. The Unity model acts as the user interface for the digital twin model in which a 3D data animation model of the barrier is integrated combined with data visualization panels.

Figure 2: The Maeslantbarrier. The retaining walls are the large curved white element at the (in the picture) most right side of the Maeslantbarrier.

Thesis outline

This thesis is structured as follows: The research methodology is further elaborated upon in Chapter 0, and Chapter 3 provides background information for digital twins and the case study in this research: the Maeslant barrier. The reader interested in the design process of the digital twin prototype (see also the example in Figure 4 and Figure 5) is advised to focus on Chapter 4 to 6, in which chapter 4 elaborates the user requirements, which results in the digital twin design requirements (Chapter 5). Chapter 6 is a more technical chapter in which the design of the digital twin prototype is described in detail. For the use cases for the digital twin prototype, the reader can focus on Chapter 7. Chapter 8 documents the testing procedure of the prototype and its results. In Chapter 9, an evaluation of the technical, economic, and organizational feasibility of a full-scale digital twin is described. Finally, the methodology and results are discussed in Chapter 10, after which conclusions are drawn in Chapter 11.

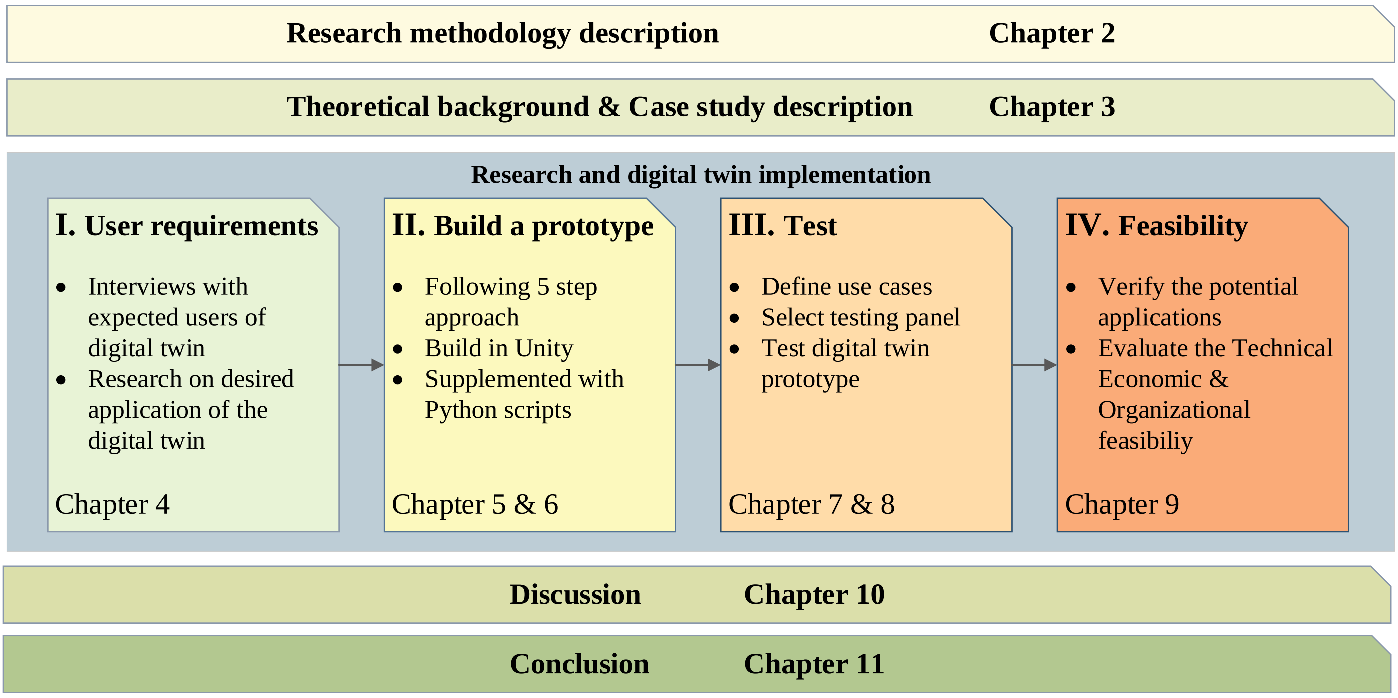


Figure 3: An outline of the chapters discussed in this thesis, including a flowchart for the methodology used in this EngD study

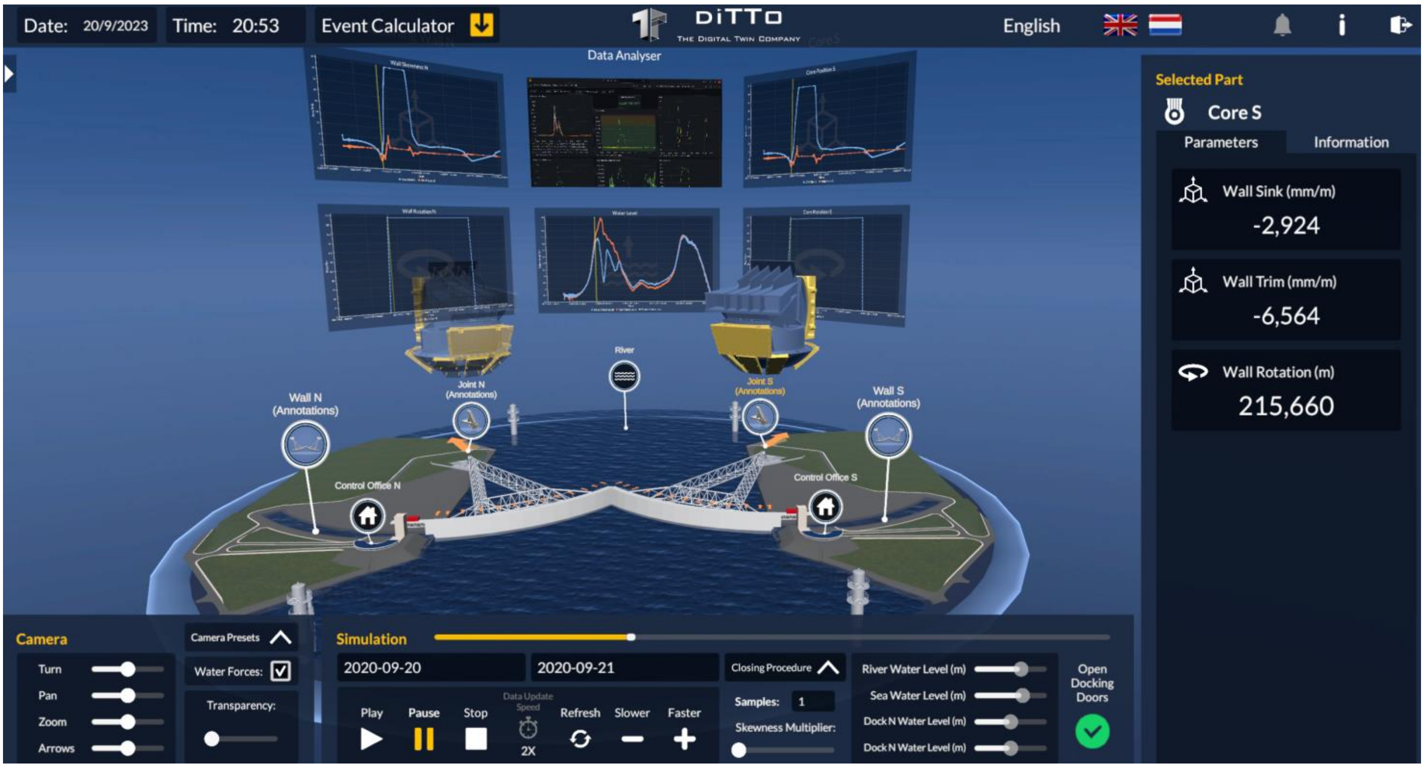


Figure 4: A visualization of the digital twin prototype. It shows the animation of the barrier closing for the actual 2020 test closure (centre), control panels for the simulation or replay of the closure (lower panel), clickable panels for data visualization and further data analysis including water levels, barrier position, pump data and status of valves (top panels) and 'live' values of the animated parameters including the option to search for more information (right side)

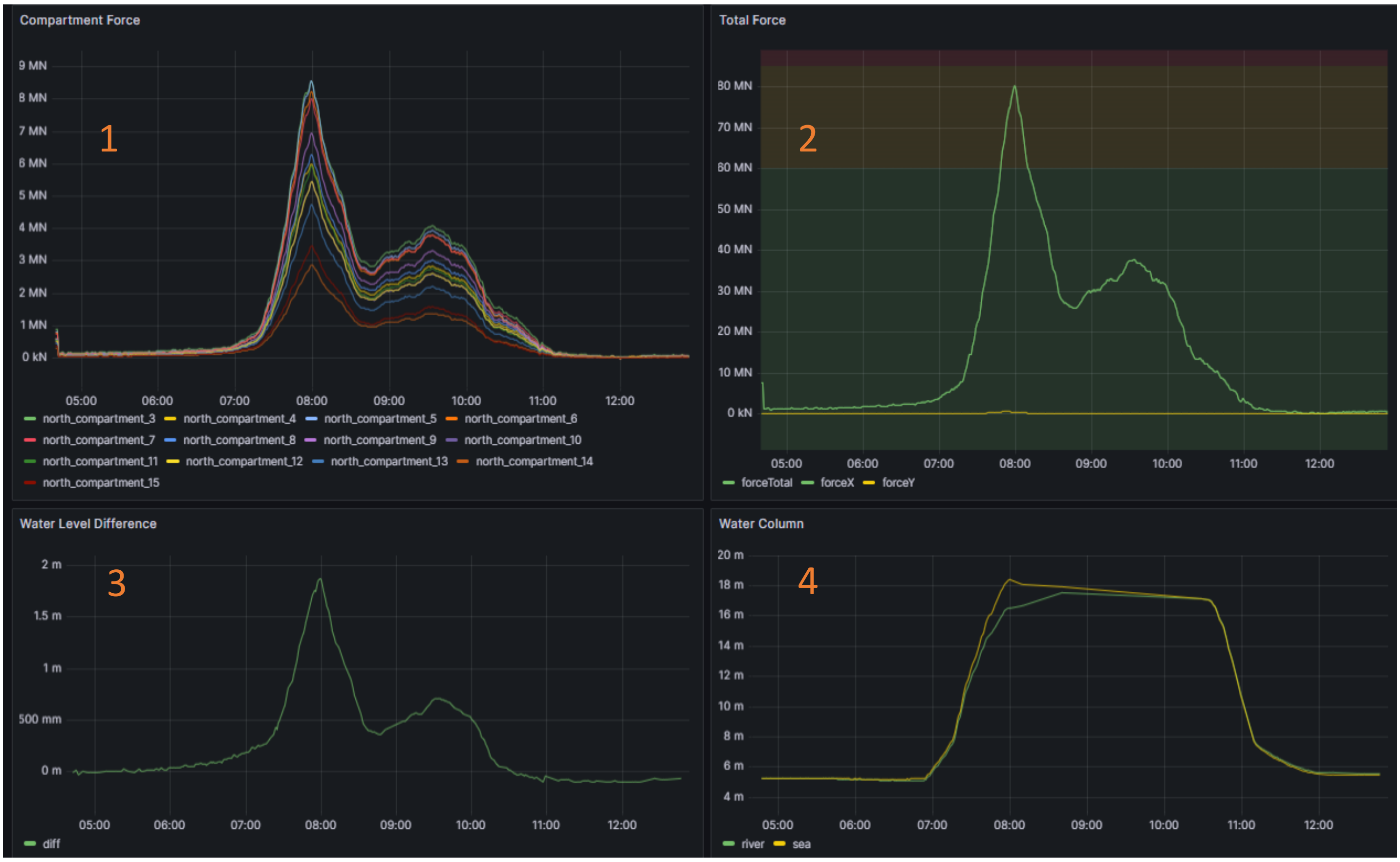


Figure 5: An example of a data analysis panel to show/explain how forces work and which parameters are involved. In this figure 1) represents the hydrostatic force of each compartment in the retaining wall, 2) represents the total radial and tangential force, 3) is the water level difference between the seaside and river side of the barrier and 4) represents the water head on the sea- and river side of the retaining wall.

2 Methodology for developing a digital twin

To assess the efficacy of employing a digital twin for a storm surge barrier, a structured methodology comprising four sequential phases has been proposed (see also Figure 6). This chapter elaborates further upon this methodology. Commencing with an exploration of the user requirements using stakeholder interviews among potential digital twin users (see Section 2.1), a prototype is developed for a digital twin tailored to a specific test case, in this research the retaining walls of the Maeslant barrier (see Section 2.2). Subsequently, this prototype undergoes empirical testing among potential end-users (see Section 2.3). This evaluation is conducted via a controlled test panel, tasked with actively engaging with the digital twin, subsequently completing a comprehensive questionnaire. The resultant outcomes of these empirical assessments provide valuable insights into the plausibility and viability of a comprehensive digital twin realization for the targeted storm surge barrier (see Section 2.4). This approach is explained in this chapter and implemented for the Maeslant barrier in chapters 4-9 of this thesis.

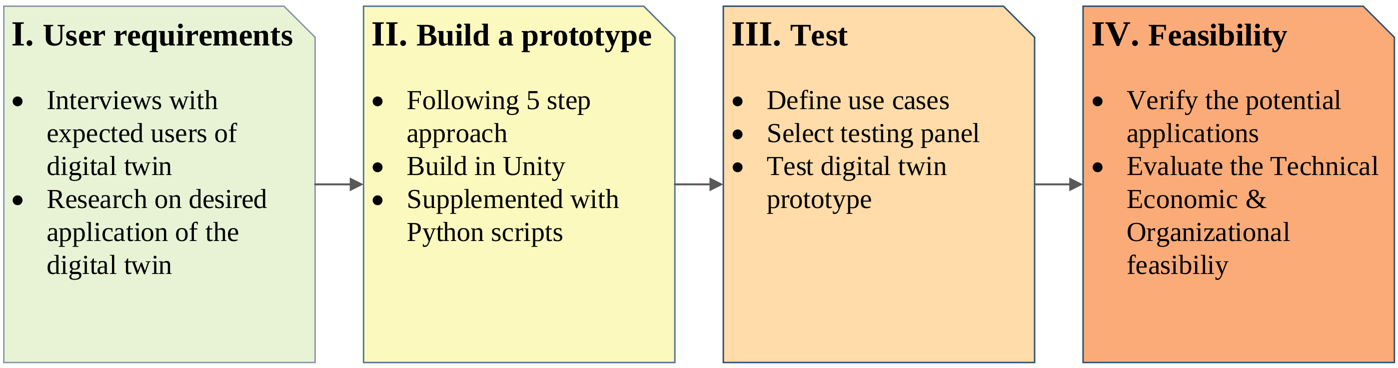


Figure 6: A flowchart for the methodology used in this EngD study.

2.1 User Requirements and potential application

The research starts by investigating the potential application of a digital twin for a storm surge barrier. These applications were investigated by means of interviewing potential users. The types of potential users were determined with the Zachman framework [13], that gave indications for the roles in the organization that have a stake in the development. The Zachman method provides a framework in which the organization is tested on several business purposes the organization is involved in, viewed from different levels in the organization. The term ‘business’ is in this case not entirely in place since a storm surge barrier is operated and maintained by a governmental organization. Therefore, in the context of the storm surge barrier it is interpreted as the core task for Rijkswaterstaat: Operating and maintaining the barrier in a safe and economically efficient way. When finished, the Zachman framework also provides a basis for the design architecture of the digital twin prototype, discussed in Section 6.1.

The most recent Zachman framework (version 3.0) has six different roles (Executive, Business management, Architect, Engineer, Technician and Enterprise) and six different purposes (What, How, When, Who, Where, and Why) [14]. Putting these aspects together as a matrix leads to a total of 36 different viewpoints. During the interviews, the six purposes formed the base line in the conversation, meaning the framework could be filled afterwards. In Section 4.1 the Zachman framework is further applied and elaborated for the case study for this research: the Maeslant barrier’s retaining walls.

2.2 Building a prototype

The prototype digital twin for the storm surge barrier is one of the main deliverables of this research. This prototype, however, is a complicated product to develop, it must include many different elements and requires a structured development method to guarantee all required elements are included. Therefore, an approach is set up to build the prototype based on the required elements of a digital twin presented in Section 3.1.2. Implementation of these elements has led to a five-step approach for developing a digital twin.

An indication of the elements the prototype contains are:

- Medium detailed level 3D model of the Maeslant barrier including terrain around the barrier
- A dashboard function for showing:
  - Historical retaining wall data of closing procedures
  - Retaining wall data of simulated closing procedures ('what if'-scenarios)
  - Calculated data from connected domain models
- Several connected calculation models using measured data for calculating:
  - The 'live' probability of failure of the barrier (focussing on the retaining wall)
  - Visualization of the hydrostatic forces on the retaining wall and ball joint
  - Pump discharges
- Data analysis models for:
  - Indicating deviant behaviour of components in the retaining wall

2.2.1 Five step approach

In this approach, step 1 starts with an investigation towards the service the digital twin should provide, subsequently what the design requirement to fulfil this service are. Each next step represents the addition of one of the elements defined in Section 3.1.2. After all elements have been added, when step 5 is reached, a full digital twin is built and ready to be tested. The five steps are summarized in Table 1, a more extended explanation of each of the five steps is given in Appendix D.

Step	**Description**	**Added element (see 3.1.2 for definition)**
1. Design requirements & Architecture	Investigate the required service the digital twin must provide and determine the design requirements. Then convert this into an Architecture.	Define the *service* the digital twin should provide
2. Data monitoring platform	Set up the first version of the digital twin application is set up with a 3D visualization of the real-world counterpart. This includes a data visualization aspect that is directly linked to the components in the 3D model.	Determine the *data & visualization* the digital twin will use
3. Integration of existing models	The digital twin is built by making a digital environment that connects the incoming data to existing models. Users can analyse and replay scenarios that have occurred or simulate scenarios that could occur.	Determine how the digital twin makes a *connection to models* & *controls* the real-world object
4. Capture and conserve knowledge	Essential knowledge elements are added to the digital twin and connected to the corresponding component in the digital twin application.	Define which static *data* is included in the digital twin
5. Sub-system integration (Not deeply investigated in this research, therefore not included in the digital twin prototype)	More advanced data analytics functions are added to the digital twin, including Artificial Intelligence and Machine Learning.	Determine how the digital twin can *control* the real-world object better

Table 1: A summation of the 5 steps that are developed to lead to a full-scale digital twin.

The intent is for each stage within the five-step plan to follow sequentially from its predecessor. Nonetheless, the integration of computational models (step 3) and the assimilation of knowledge (step 4) into the digital twin prototype can be concurrently undertaken. These stages are not mutually exclusive and, as such, can be developed in parallel. Upon completion of both these phases, the final step can be executed, facilitating the subsequent testing of the prototype. A schematization of these five steps is given in Figure 7. In Chapter 6, the design method is further elaborated for the case study.

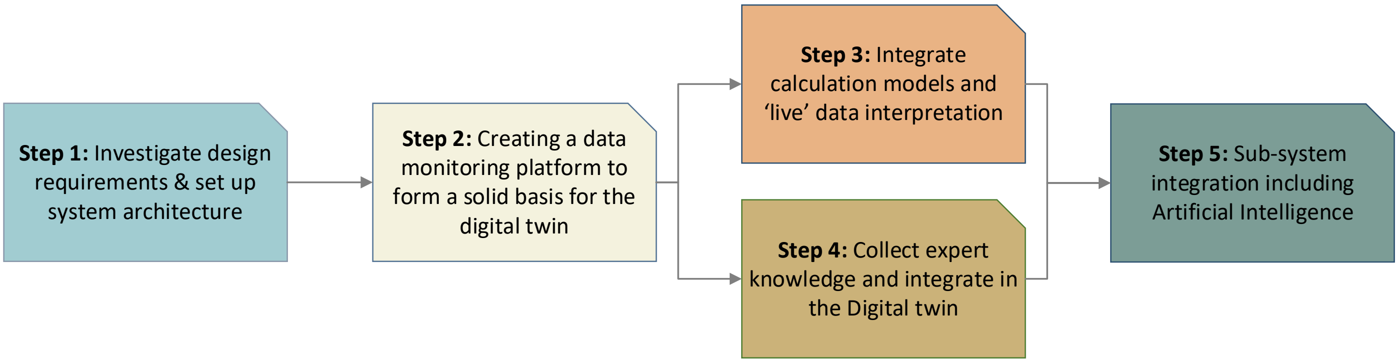


Figure 7: A 5 step approach for the development of a digital twin applied on the Measlant barrier's retaining walls.

2.3 Testing the prototype

For the testing phase of the digital twin prototype, several use cases have been elaborated upon, wherein a narrative explanation has been provided for the potential applications of the digital twin prototype. Subsequently, these use cases were utilized to expound upon the functioning of a full-scale digital twin of the Maeslant barrier. Following this, the members of the test panel are tasked with executing various actions using the digital twin prototype, after which they are requested to complete a questionnaire pertaining to their experience. Chapter 8 provides a further elaboration of the testing phase for the case study.

2.3.1 Use cases

For the testing of the digital twin prototype, three use cases have been developed, which describe how the digital twin could be employed based on user requirements and potential application. These use cases serve as an introduction for the test panel, which is instructed to use and explore these cases as a part of the test and evaluation procedure. Chapter 7 provides an extended description of the use cases.

2.3.2 Test panel

For the testing phase of the digital twin, the objective is to verify whether the potential applications, which were examined in Section 2.1, can indeed be achieved. This is accomplished by engaging a diverse group of Rijkswaterstaat employees who are routinely involved with storm surge barriers. They are requested to perform a series of tasks using the digital twin prototype and subsequently complete a questionnaire based on their experience. These tasks are to be executed after the EngD candidate provides an introductory presentation explaining how the digital twin user interface operates. This presentation not only covers instructions for navigating through the prototype but also employs the use cases to delineate specific functionalities of the digital twin.

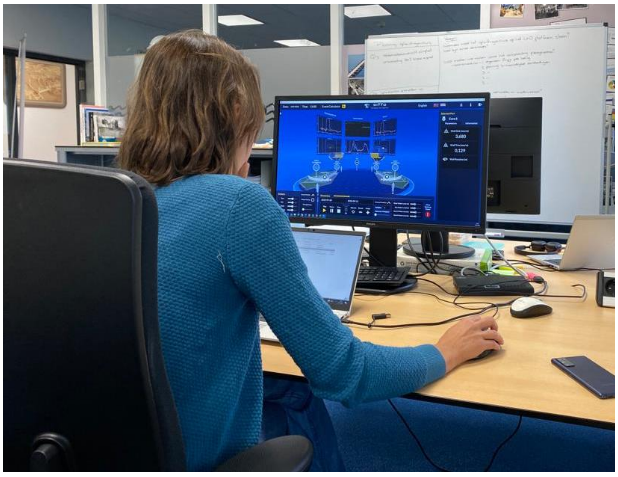


Figure 8: One of the participants of the test panel operating the digital twin prototype

2.4 Evaluation of the feasibility

The development of the digital twin prototype and test outcomes are supplemented with three kinds of feasibility studies, to draw a conclusion regarding the feasibility of a full-scale digital twin of the Maeslant barrier. This conclusion is drawn for four aspects which are explained below: application, technical feasibility, organizational feasibility, and economic feasibility.

Figure 9: An indication of the elements that are researched on order to determine the feasibility of a full-scale digital twin for the Maeslant barrier

Application

The potential applications for the digital twin, derived from the interviews with Rijkswaterstaat employees according to the Zachman framework (see Section 2.1), are compared with the outcomes of the questionnaires. The questionnaire is designed in such a way, that the panel members are asked explicitly to provide scores to their experience in relation to the applications. The scores provided by the panel members serve as an indicator of the feasibility of achieving these potential applications. From this, an initial conclusion can be drawn regarding the potential that a digital twin holds within the Rijkswaterstaat organization.

Technical feasibility

The applications outline the prerequisites for the successful technical implementation of a digital twin. Based on these prerequisites and an independent investigation into these technical aspects within the Rijkswaterstaat organization, a conclusion is drawn regarding the technical feasibility of a fully developed digital twin of the Maeslant barrier.

Organizational feasibility

To successfully integrate a digital twin within an organization, it is crucial that the organization is mentally prepared for it as well. Working with a digital twin often requires a different mindset in various fields of work. Many tasks can now be supported by the digital twin, thus facilitating processes. However, it is essential for the individuals within the organization to have sufficient confidence in the digital technology that provides this support. Therefore, this section conducts an inquiry into the organization's maturity concerning the adoption of digital transitions. The score resulting from this assessment serves as an indication of the feasibility of a successful implementation of the digital twin of the Maeslant barrier within Rijkswaterstaat.

Economic feasibility

To assess whether a full-scale digital twin of the Maeslant barrier is financially interesting for Rijkswaterstaat, it is examines whether a digital twin is a worthwhile investment. An indicative and preliminary business case is elaborated to determine whether the investment in a digital twin can be recouped within a reasonable timeframe.

3 Theoretical background and use case description

To test the method presented in Chapter 2, it is applied to a specific storm surge barrier: the Maeslant barrier. The theoretical background of both the digital twin and the Maeslant barrier is discussed in this chapter. Section 3.1 gives a general overview of digital twins, followed by a description of the Maeslant barrier (Section 3.2) and its challenges (section 3.3 & 3.4).

3.1 Digital twins

This section provides a brief description of the digital twin concept. It provides a theoretical background (Section 3.1.1), a definition (Section 3.1.2) and a summary of the application (Section 3.1.3).

3.1.1 General background of digital twins

Digital Twin is a relatively new but highly emerging concept that is increasingly used in sectors such as Aircraft, Aerospace, Construction, Energy or Manufacturing industry [4] [5] [6] [15] [16] [17] [18]. The concept has also found its way in Civil Engineering [17] [8], however for a more specific domain such as the Hydraulic Engineering industry the reported application is still limited. Publications regarding Hydraulic Engineering are for instance focussed on port developments [9], drainage systems [10], offshore pipelines [11] or dams [12]. Since the digital twin technology seems to be further developed in other industries, this literature research focussed on a broader set of domains, also publications about digital twin experiences in engineering sectors outside civil engineering were considered useful to provide input.

A digital twin is a cyber-physical representation of a physical entity, system, or process that encompasses both its geometric and functional attributes. It operates in real-time, dynamically mirroring the behavior, status, and interactions of the corresponding physical counterpart. This happens through continuous data exchange, simulation, and analytics, thereby enabling virtual experimentation, analysis, optimization, and decision-making to enhance performance and outcomes. The digital twin is designed to provide a real-time simulated representation of the physical object or system, using computer models to simulate its behavior. The goal is to create a more efficient and effective physical object or system by optimizing its performance in the virtual world.

Digital twins exist at many scales and levels of complexity, from a single component (e.g. a pump or valve) or asset (e.g. bridge, sea lock or storm surge barrier) to systems of connected digital twins (e.g. a vessel's digital twin sending signals to an offshore wind farm's digital twin), up to an ecosystem of connected digital twins (e.g. networks of service-based assets, such as healthcare facilities or transport) [19]. On every level, digital twins tend to improve performance and use a data-driven and knowledge-based approach with five types of application [3] [20]: (i) optimize supply and demand; (ii) operations and performance, i.e. support monitoring and predictive maintenance, as well as early-warning and disaster preparedness; (iii) live data management to support in optimizing processes, planning, decision-making and budgeting; (iv) simulate prototypes and scenarios; (v) optimize knowledge and information management. As a result, digital twins are perceived to improve efficiency, security, safety, reliability, decision-making and flexibility. These combined effects lead to time saving for workers and better control of risks, therefore reducing costs.

The term *Digital Twin* first occurred in several papers around 2002 [4] , but the *twinning* technique itself appeared earlier in history, for instance during NASA's Apollo program in the early 70's of the 20th century by using *physical* twins [6] [15]. Development in digitisation has since then led to a new revolutionary innovation era called Industry 4.0 [3], which completely digitized twinning techniques. Since 2002, the technology of *digital* twin has developed itself in the industry without many scientific publications. After 2016 the number of publications of digital twins (in earlier times named "product avatar") increased significantly [4] [6]. By now digital twin has become an upcoming paradigm with applications in many different industries. This makes it complicated to make a single definition of a digital twin however, in the next paragraph the vital elements of a digital twin (as found in the literature) are discussed which finally leads to an own definition for the concept of digital twin.

3.1.2 Digital twin definition

A digital twin doesn't come 'in a box', meaning it is a product that is not easily standardized for different kinds of situations. However, a digital twin should contain several basic elements in order to be rightly called a digital twin. Based on publications by Tao, et al. [21], Glaessgen and Stargel [22], Grieves and Vickers [23], Rosen, et al [24], Kritzinger, et al. [5] and Teugel, et al. [25] five basic elements of a digital twin are derived that form the basis for the digital twin designing process in this research, which are:

- **Service**
  A digital twin should provide a (or multiple) specific kind of service(s). It should be a contribution to the solution for an existing problem or improve existing processes. This service could for instance be a support aspect for better control or improve information related processes.
- **Data Interaction**
  It involves continuous data exchange (preferably real-time) between the digital twin and its physical counterpart, ensuring up-to-date synchronization and informed decision-making.
- **Accurate Representation**
  A digital twin must faithfully and visually replicate the physical entity, capturing its geometry, structure, and behaviour in a virtual environment.
- **Simulation and Analysis**
  The digital twin employs simulation, modelling, and data analytics to simulate behaviour, predict outcomes, and provide insights for optimization and operational improvement.
- **Control**
  The digital twin can control the real-world object or the processes around it. This could either be directly by the digital twin, or via an intermediate step by the operator of the physical object based on information from the digital twin application.

Based on the consulted literature, a schematization is made for a digital twin (see Figure 10) and its interactions with external sources, to indicate the difference between a digital twin and the external sources. The digital twin (represented in the middle of the figure) has a connection with all kinds of data sources, models, analysis tools and/or other digital twins. The digital twin is the model that connects these elements to each other to form the representation or simulation of the physical counterpart. The results are continuously sent to the digital twin user interface, where the user can give commands to the digital twin or view results created by the digital twin.

Many publications of digital twins, appear to lack the data interaction or simulation aspects to make them an actual digital twin [4]. A common observed confusion in the definition of a digital twin, is when the visualization/representation component is the digital twin. This, however, often only describes the front-end *user interface*, including a visualization of the physical object (for instance an interactive 3D model or GIS model), not the digital twin itself. The *digital twin* is the model that is capable of synchronizing and integrating data and domain specific models (that may be of an AI or ML[3] nature) to make information from this data.

The information created by the digital twin is used to make decisions regarding the real-world object, either directly by the *digital twin* with no human intervention, or by humans based on some advice from the digital twin brought to them via the *user interface*. The changes on the real-world object caused by these decisions are automatically changed in the digital twin as well. This makes a digital twin something 'alive' that changes, improves and evolves in time by maintaining the link between physical and virtual space.

[3] AI = Artificial Intelligence and ML = Machine Learning

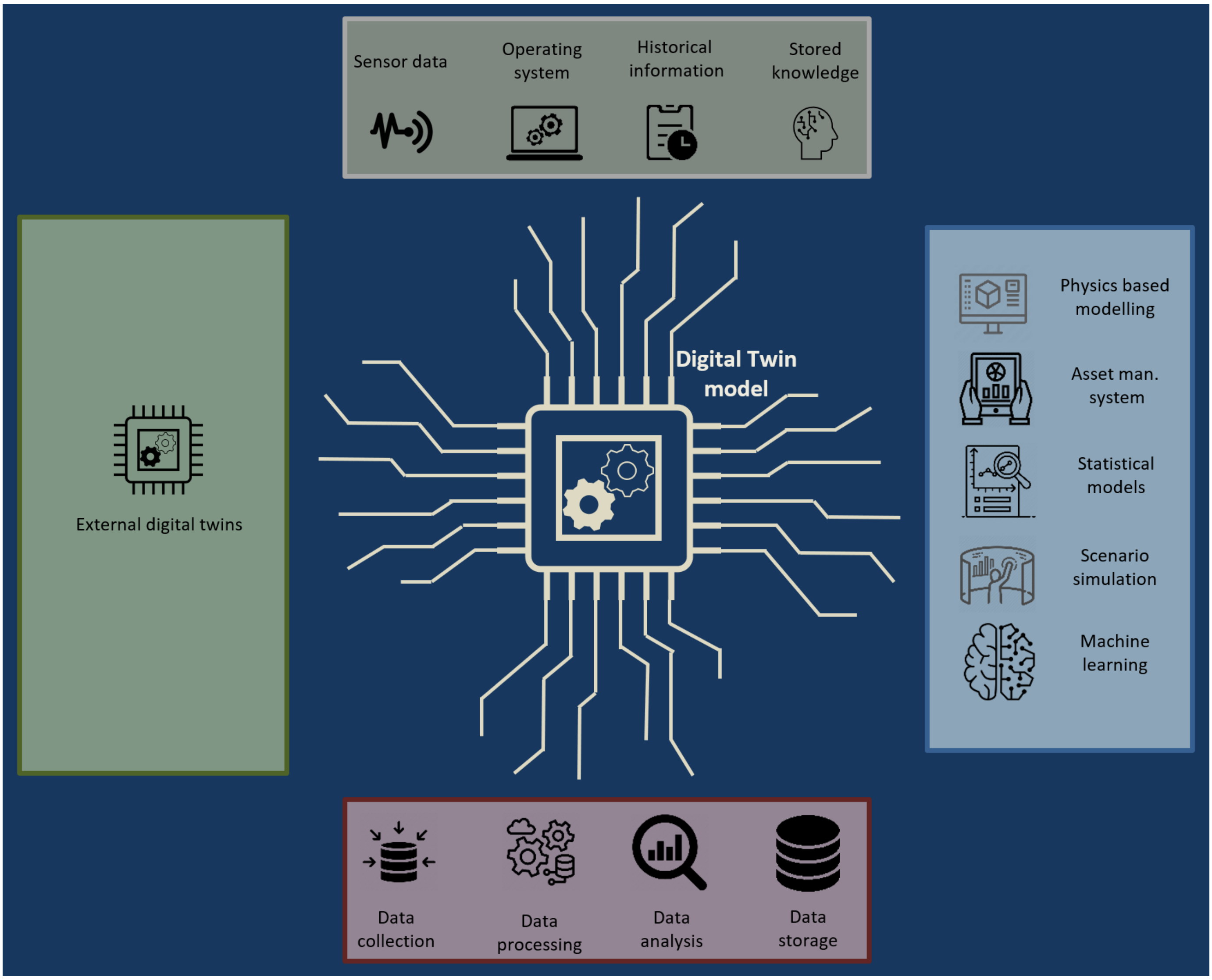


Figure 10: A schematization of a digital twin. The digital twin model acts as a spider in the web of several sources of information: data from the real world object (top), models to create new information from these data sources (right), data science (bottom) and other digital twins (left).

Interaction and convergence with other models, as well as the self-evolution and automated data flows are in some literature mentioned to be key aspects of the digital twin [4]. This, however, is the case when a more advanced digital twin is developed. It is not in every case possible to include all these elements. For more general cases, one describes the key aspects as follows: a digital twin is not merely a visualization of observed data, it includes algorithms describing behaviour and come to support, or decide on actions [26].

3.1.3 Summary of digital twins

The concept of the digital twin is a developing technology primarily applied in industries such as aircraft, aerospace, construction, energy, and manufacturing. In contrast, its utilization in the field of Hydraulic Engineering remains limited. Digital twins are cyber-physical representations of physical entities or processes, mirroring their behaviour and interactions in real-time. They enable virtual experimentation, analysis, optimization, and decision-making to enhance performance and outcomes.

Digital twins can encompass various scales and complexities, from individual components to ecosystems of interconnected Twins. They offer five primary applications: optimizing supply and demand, enhancing operations and performance, managing live data, simulating prototypes and scenarios, and improving knowledge management.

A digital twin should comprise five fundamental elements: service, data interaction, accurate representation, simulation and analysis, and control. The implementation of digital twins has proven successful in reducing costs, optimizing designs, enabling predictive maintenance, and enhancing safety. They are now being applied to larger objects like factories, airports, offshore platforms, and bridges. Additionally, they play a crucial role in the development of "smart cities" by combining geospatial and measured data with AI.

Successful implementation of digital twins relies on three boundary conditions: hardware, software, and organizational maturity. In terms of hardware, the industry offers advanced components, including data-collecting devices, computing power, and networking infrastructure. Software plays a pivotal role in modelling, simulation, data integration, analytics, visualization, user interfaces, connectivity, and security. Software developers continuously innovate to cater to various industries' needs.

As technology evolves, digital twin software is expected to become even more sophisticated, integrating with emerging technologies like AI and IoT. Overall, digital twins have become an asset in various industries, with promising growth on the horizon.

Appendix A provides a more elaborate description of the implementation of digital twins.

3.2 The Maeslant barrier

The Maeslant barrier is a storm surge barrier located in the Dutch Nieuwe Waterweg canal, close to the town of Hoek van Holland. It is the final project of the famous Dutch Deltaworks [27] and was built between 1991 and 1997. It can close off the “Nieuwe Waterweg” canal during a storm surge, thus protecting the areas around Rotterdam and Dordrecht from storm surge flooding. Together with the Hartel barrier and the dyke reinforcement around the town of Rozenburg, the Maeslant barrier forms the Europoort barrier [28]. See also Appendix B for a more elaborate description of the storm surge barriers.

The Maeslant barrier has been in operation since 1997 and has never been closed according to its original design requirements (a storm with expected water levels exceeding NAP[4] +3.00m near Rotterdam or NAP+2.90m near Dordrecht). If no storm closure has taken place for seven years, the closure level is temporarily lowered to 2.60m+NAP (near Rotterdam) to verify the fully automatic closure after which the closure level is reset to default. Due to this rule, the barrier has closed twice for moderate storm conditions (in 2007 and 2018), where the barrier closed based on the lowered storm criteria. Besides these storm closures, a test closing procedure is executed on a yearly basis as well.

3.2.1 Retaining walls and ball-joint

The Maeslant barrier exists out of two floating sector doors, each 210 m wide, that rotate towards each other when the barrier closes. During this procedure, the barrier is initially in a floating mode, during which the doors are pushed out by the so-called ‘Locomobile’. As soon as the doors are in position to close off the canal, the ‘Retaining walls’ (see Figure 11) sinks towards the bottom to retain the water. Figure 11 indicates the difference between a barrier arm in sunken position (top part of the figure) and in floating position (lower gate) during a closure.

The sinking process of the retaining walls happens according to a controlled protocol. When the retaining walls are in position, it sinks itself by opening valves to let water into the compartments until it reaches its final position on the bottom of the canal. To do so, the wall exists out of 15 individual compartments, of which 13 can be filled with water. To reverse this process, the water is pumped out of the compartments until it is afloat and can be brought back into it’s the dock, where the barrier is at rest. Figure 12 provides an indication of a cross section of one of the compartments in the retaining walls and indicates the position of the wall from a top view.

[4] All heights in the Netherlands are measured relative to the same level, the Normal Amsterdam Level (NAP). A NAP height of 0 m is approximately equal to the average sea level of the North Sea. [92]

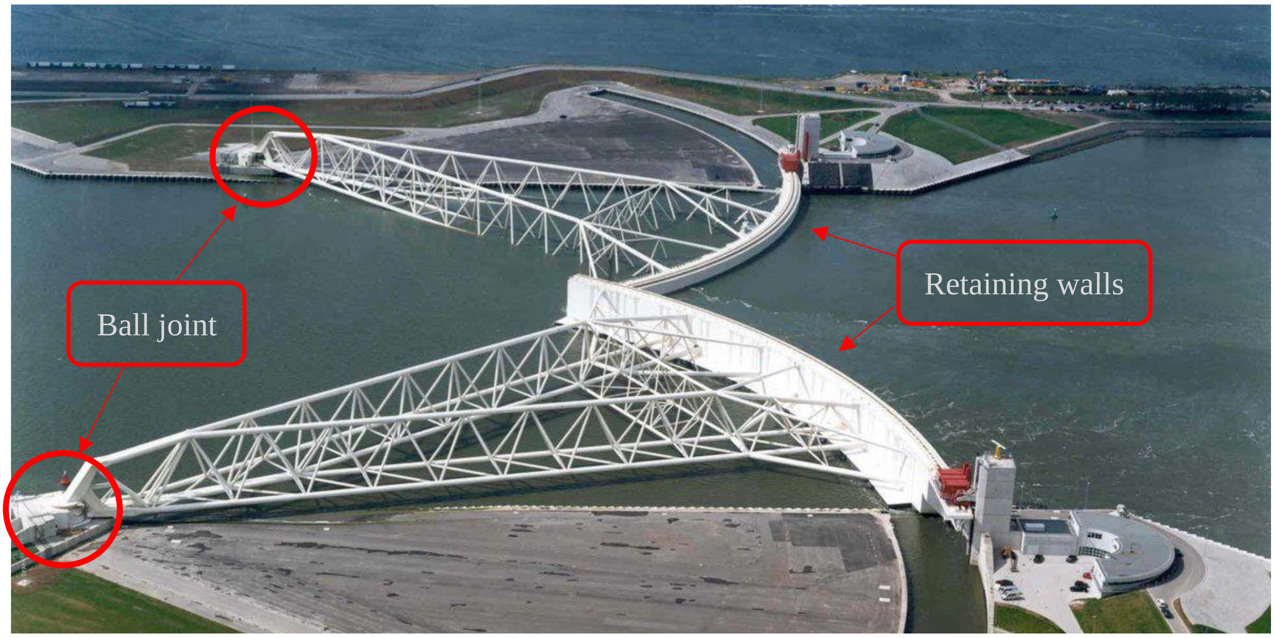


Figure 11: The Maeslant barrier with one arm in sunken mode (the top one in this picture) and one arm in floating mode (the bottom one in this picture). The main purpose of the arms is transmitting the forces, exerted on the retaining walls while closed, to one single joint at the rear of each door. This ball joint gives the doors the opportunity to move freely in three degrees of freedom.

The first two compartments, number 1 and 2, are not used for the sinking/floating process of the barrier, therefore they do not contain any valves or pumps. The most outer of the filling compartments (number 3, 4, 14 and 15) are the 'trimming'-compartments, which are used for both the vertical positioning and to mitigate the pitch, therefore preventing the wall from sinking in a skewed position. Subsequently these compartments have a higher filling capacity than the rest of the compartments.

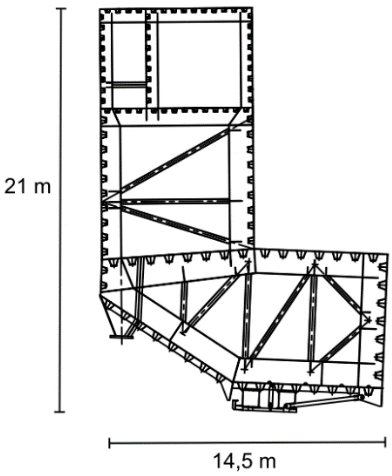


Figure 12: A cross section of the Maeslant barrier's retaining walls (source: Rijkswaterstaat)

To control the vertical movement and the pitch (a slight skewness, see Figure 13) of the wall, the retaining walls should be able to rotate around one central point in three degrees of freedom: horizontally, vertically and rotating. In order to do so, the barrier arm contains a ball-joint (see Figure 11 and Figure 13) at the point where it is connected to the mainland.

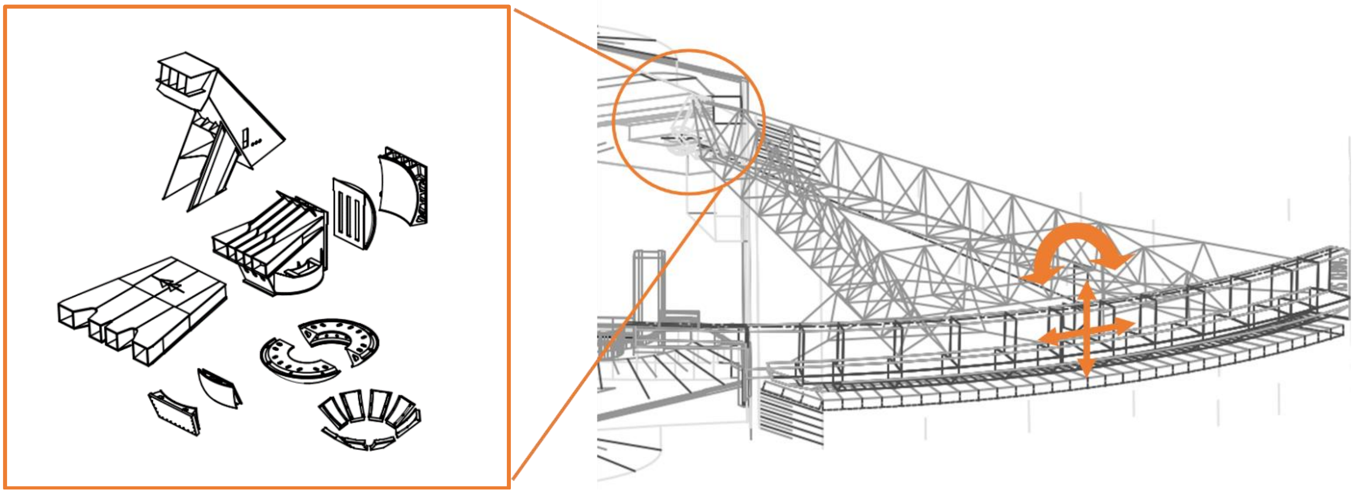


Figure 13: A decomposition of the ball-joint and indication of the sector gate movement, indicating horizontal and vertical movement as well as rotation (also known as the 'pitch-angle').

3.2.2 Key parameters

To monitor the performance of the Maeslant barrier, several key parameters are important. These key parameters are indicated below. Since the case study for this research focusses on the retaining walls of the barrier, only the parameters related to that component are mentioned.

Component	***Parameters***
Retaining walls	Horizontal position Vertical position Skewness (pitch angle)
Compartments	Water level
Pumps	Signal on/off Power Discharge
Valves	Signal open/closed
Ball joint	Horizontal rotation Vertical rotation Skewness rotation
River water	Water level on river side Water level on seaside

Table 2: The key parameters indicating the behaviour of the retaining walls.

3.3 Probability based maintenance.

The Maeslant barrier is part of a greater system of flood protection objects that protect the hinterland against floods according to a minimum flood risk level. This flood risk level is enshrined in the Dutch Water Act, that sets a minimum performance requirement for every element in the system, including the Maeslant barrier.

3.3.1 Risk Analysis methodologies used within Rijkswaterstaat.

All storm surge barriers are included in the Dutch Water Act [29], a law that prescribes a maximum probability of failure for the barrier. The performance requirements from this act are used to set up an *Object Risk Analysis (ORA).* Rijkswaterstaat uses different kinds of depth-levels to perform ORAs, depending on the importance of the object in the greater system. In daily practice, three different types of risk analyses are used by Rijkswaterstaat, which in the PRA guidelines [2] are described as:

- *Maintenance Plan*: Based on a semi-quantitative risk analysis in which the FMECA[5] tool is used to identify failure scenarios. It is applied primarily for permanent structures and line objects.
- *Performance-based Maintenance Plan*: Using a quantitative risk analysis based on the Reliability Centred Maintenance (RCM) method. This type of risk analysis is mostly used for management and maintenance of critical, movable objects and tunnels.
- *Maintenance Plan based on ProBO*: The most comprehensive form of quantitative risk analysis, used for storm surge barriers and construction of tunnels and water-retaining objects. This approach uses fault trees.

For a storm surge barrier, the most advanced level of ORA, the maintenance plan based on ProBO, is used. This is a risk analysis method where all the RAMSSHE€P (Reliability, Availability, Maintainability, Safety, Security, Health, Environment, economics (€) and Politics) aspects are included in the analysis. This ORA starts with a qualitative analysis that considers unexpected faults that have a significant effect on performance of the object and the measures required to keep it at the required performance level. When the qualitative ORA is completed, a quantitative ORA is made where the quantitative impact of events described in the qualitative ORA are calculated. For storm surge barriers, this results in a fault tree that indicates the probability of the barrier per closure (see also Appendix C).

3.3.2 Maintenance according to ProBO

To ensure each barrier meets the Dutch Water Act requirements, a strict form of asset management, called ProBO, is applied by Rijkswaterstaat[6]. Rijkswaterstaat defines ProBO as '*a Risk-based asset management methodology based on an expectation (calculated or estimated by expert judgement) that objects will satisfy set requirements in terms of performance. The risk-based methodology also enables the continuous demonstration of compliance with performance requirements in the different stages of the life cycle of infrastructure assets'* [2]. For storm surge barriers, the performance is expressed in a probability of not closing per request, calculated by means of a highly detailed, quantitative risk analysis. Usually fault trees or related methods (event trees, Bayesian networks) are used to determine the probability of failure of barriers. Given the complexity of the barriers, the many elements and failure modes involved, these fault trees tend to get complex and large.

Appendix C provides a further explanation of the ProBO concept and application on a storm surge barrier.

3.4 Knowledge and information challenges

3.4.1 General

Efficient and effective maintenance and operation of the storm surge barrier requires a wide spectrum of knowledge and information. Every step in the Plan-Do-Check-Act (PDCA) cycle requires its own set of specific experts providing the right knowledge and information to properly execute that step. Both domain knowledge and object specific knowledge is required for this execution. An example on how these different fields of knowledge work in the PDCA cycle is as follows (See also Figure 14): Risk management experts use their domain expertise to set up and maintain models for fault tree analyses (Act phase). They rely on technical experts (mechanical-, electrical-, civil-, ICT- engineers, etc.), who provide object specific information to feed their models. Asset managers then use the outcome of the models and their domain and object knowledge to formulate maintenance plans for the barrier (Plan phase). They ask technical experts to further formulate the technical details of these plans and make sure they are performed as intended (Do phase). Monitoring and data-analysis experts are then required to use their expertise in gathering data and

[5] FMECA is an acronym for Failure, Mode Effect & Criticality Analysis

[6] Rijkswaterstaat is the Dutch governmental organization responsible for operating and maintaining the storm surge barriers

information to verify if the plans are indeed performed as intended. They report back to the risk managers who update their probability of failure calculations using that information (Check phase).

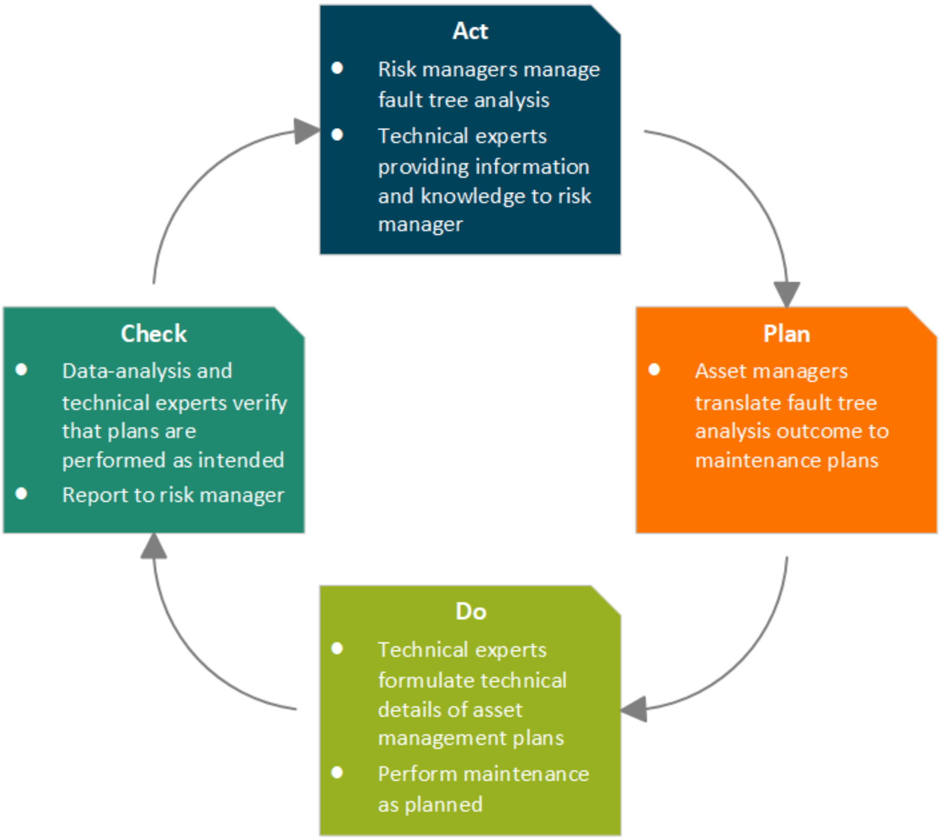


Figure 14: A schematic representation of the PDCA cycle. (For this illustration the order of steps has been adapted).

The asset management strategy, including the PDCA cycle, should be a method in which knowledge and information about the barrier is conserved. From an internal strategic document on storm surge barriers however, it becomes clear that Rijkswaterstaat has a broad knowledge and information challenge regarding storm surge barriers [1]. The knowledge and information that was build up during design, construction, operation, and maintenance of the barrier is limitedly transferred or is poorly traceably documented. This manifests itself in the fact that the Rijkswaterstaat teams responsible for asset management of storm surge barriers currently suffer from a decreasing level of barrier-specific knowledge [30]. This could be problematic since the asset management of storm surge barriers (see Section 213.3) strongly depends on this specific knowledge and traceable information. Two main reasons could be given for this problem: a decreasing number of internal experts and a limited availability of a generation to transfer knowledge to.

3.4.2 Decreasing number of internal experts and knowledge at Rijkswaterstaat

Preferably, all required expertise for the PDCA cycle is represented in the responsible asset management team, if possible, even in a redundant way. Currently, however, this is not the case. In fact, Rijkswaterstaat depends largely on the expertise of a small group of people that individually contain multiple fields of knowledge [1]. Due to national governmental policy of having small governmental organizations, Rijkswaterstaat's team of experts has shrunken drastically in the past twenty years (as mentioned by one of the interviewed employees, see Chapter 4). This has made Rijkswaterstaat dependent on the few remaining internal experts and depend on the expertise of external organizations (engineering consultancies, contractors, etc.) for maintaining the risk-based asset management methods at the Maeslant barrier. Internal knowledge on how to perform these methodologies is therefore decreasing and more and more dependent on (fragmented) external knowledge.

According to interviewed employees (see Chapter 4), transferring the knowledge of the small group of experts to newer generations within Rijkswaterstaat has not led to a broad conservation of knowledge so far.

The expertise remains sealed in the heads of the experts or, when documented, cannot be found back easily without help of the experts. The remaining Rijkswaterstaat experts not only have a large amount of knowledge about the barrier, but they also know where to find the information to support that knowledge. The complicated information storage systems make that experts spend much of their time on guiding people into finding the right information, instead of transferring their knowledge towards the new people. This delays the process drastically.

3.4.3 Limited availability of younger staff

The increase of young experts for the Maeslant barrier team has been limited in past decade and those who joined the team often left before they were fully trained (as indicated during the interviews). It means there are relatively few young people within Rijkswaterstaat to which the essential barrier knowledge can be transferred. An important reason for this is the slow education process.

One of the main challenges Rijkswaterstaat faces at the Maeslant barrier, is the long time it currently takes to transfer this knowledge to new people [30]. Due to the (sometimes illogical) object specific jargon for components and challenges, it appears to be complicated to find specific information and/or knowledge in the existing Rijkswaterstaat systems without the help of an experienced colleague, to tell in detail what search terms should be used. Therefore, the education process of new staff needs intensive guidance of experienced colleagues. To get new staff at the required knowledge level to independently perform their task for storm surge barriers currently takes, according to a Rijkswaterstaat report, 3 to 5 years [31]. Since the Maeslant barrier is the most complex barrier, with the most required object specific knowledge, it is assumed this period will be 5 years rather than 3 years. The knowledge transfer process is relatively independent of the amount of domain specific experience the new staff member has due to the uniqueness of the barrier. Subsequently, even new staff members with years of domain specific experience are told that nothing substantive was expected from them in the first three months, since they needed to find their way in the systems and specific problems of the barrier first[7]. This is a strong indicator that knowledge transfer is currently not well organized. Subsequently, people get demotivated due to the slow process and tend to leave the organization early. It has led to a more and more problematic situation when it comes to knowledge and information management. This has a negative impact on the effectivity of the maintenance process, the performance of the barrier and the technical life cycle of the barrier [32] [30].

To prevent the knowledge and information management from dominating the asset management of the barrier in a negative way, capturing and conservation of the knowledge is crucial. Essential knowledge needs to be captured and secured in an easily findable way, so future generations can keep on using the knowledge and know where to find the information.

[7] This 3 months was taken from individual conversation with one of the Rijkswaterstaat employees working on the Maeslant barrier

4 User requirements for the digital twin

To define the design requirements of a digital twin for the Maeslant barrier, its expected application is investigated by structurally interviewing the potential users. These applications form the basis for the design requirements of the digital twin. Using scientific literature and semi-structured conversations with employees within Rijkswaterstaat, an inventory of the possible values of a digital twin for the Maeslant barrier is made.

4.1 Approach: investigation of potential applications according to Zachman framework

The interviews to investigate the potential application of a digital twin were held with staff members with different roles in the Rijkswaterstaat organization, see Appendix N. These were selected according to the Zachman framework [13] (see Section 2.1). The total Zachman framework was filled based on the interviews, Table 4 provides a summation of the most important outcomes of filling in the framework. The full worked out framework is visible in Appendix E.

The interviews provided insight in the daily work processes the staff members are involved in. The theoretical background of digital twins (see Section 3.1) were then used to seek for the work processes a digital twin could help to improve. This led to a longlist of requirements for applications the digital twin prototype should fulfil to be successful. Table 3 provides an overview of the roles of the interviewed staff members, and how they relate to the Zachman framework. The goal was to interview staff members from every layer of the Zachman framework. Unfortunately, it has not been possible to interview anyone in the executive layer of the Rijkswaterstaat organization. Therefore, specific requirements from that layer of the organization could not be directly included.

Interviewed	**Department / company**	**Zachman role**
General maintenance manager storm surge barriers	Rijkswaterstaat WNZ	Business management
Program manager digital twins RWS	Rijkswaterstaat CIV	Business management
Asset manager of the Maeslant barrier	Rijkswaterstaat WNZ	Engineer
Data analyst for closure procedures Maeslant barrier	HVR Engineering	Engineer
Failure probability manager	Rijkswaterstaat GPO	Engineer
Principal expert Maeslant barrier	Rijkswaterstaat GPO	Technician
Cyber security expert	Rijkswaterstaat CIV	Technician
Technical expert storm surge barriers	Rijkswaterstaat PPO	Enterprise

Table 3: Summary of the interviewed people, these people were interviewed with the aim of giving substance to the five digital twin elements as described in Section 3.3

The interviews with staff members and external parties provided a filled Zachman framework (see Appendix E). A summary of the outcomes of this framework is given in Table 4, which laid the basis for the potential applications of the digital twin, further elaborated upon in Section 4.2 to 4.4.

Stakeholder	Stakes	Digital twin requirements
Executive (Estimated by author)	• Protecting Rotterdam delta area • Anticipating on climate change & new insights	• Timely information about required decisions • A warning sign if barrier becomes below standards • Conservation of knowledge
Business management	• Optimize Maintenance processes of the Maeslant barrier • Streamlined and reliable Risk management	• Live monitoring of the condition of the barrier • Possibility to determine the impact of scenarios • Quick and independent education of new staff members
System architect	• To gain a clear architecture that forms the basis for the construction of the Digital Twin	• Design a robust Architecture for the digital twin
Engineer	• To supply the digital twin with the engineering models and methods to calculate important parameters	• Monitor the status of the barrier • Make model calculations via Digital Twin • Predict the impact of observed developments • A clear visualization of data analysis
Technician	• To form the connection between the digital environment and the operational people in the field	• Warning signs when barrier components behave differently than expected • Clear insight in measured data • Monitor the performance of components
Enterprise	• Preserve knowledge • To improve asset management procedures • Save cost	• Train new staff • Gain insight in live condition of components • Adapt MTC procedures

Table 4: A summation of the most important outcomes of interviewing Rijkswaterstaat staff members and external parties that are involved with operation and maintenance of the Maeslant barrier.

In Section 4.2 to 4.4, the outcome of the interviews is further elaborated in a number of applications the digital twin should have for the organization. The applications are classified into four main categories, each containing several specific applications. These four main categories are:

- Increasing the efficiency in knowledge and information management
- Avoid unnecessary cost due to better monitoring of the barrier status.
- Better risk management due to models and the data-analysis platform
- Creating new insight in the barrier's behaviour

For each category, a description of the applications is given and related to (one of) the challenges the Maeslant barrier currently faces.

4.2 Increase in the efficiency in knowledge and information management.

As described in Section 3.3 and 3.4, one of the main challenges Rijkswaterstaat faces at the Maeslant barrier, is the long time it currently takes to transfer knowledge to new staff [30]. The unique (sometimes illogical) jargon for components and problems occurring at the barrier, make it difficult for people to get educated without intensive guidance of experienced colleagues. Since the experienced colleagues have a busy agenda due to shortage of staff, education of new people is often a long process [31]. A digital twin provides a structured digital environment that decreases the dependency of new people on experienced colleagues significantly, therefore decreasing the knowledge transfer time significantly. It supports in finding information more quickly, let new staff members independently learn the basic functionalities of the barrier and helps specialists at the barrier to transfer their knowledge.

A summation of the applications of a digital twin to contribute to more efficient knowledge and information management at the Maeslant barrier is given in Table 5. A further explanation of the application on the individual aspects is given in Appendix F.

Application of the digital twin	**Solution for problem**
Increase findability of information and knowledge	It is complicated to find specific information and/or knowledge in the existing Rijkswaterstaat systems without the help of an experienced colleague
Increase ability to independently obtain knowledge for new staff members	Unique (sometimes illogical) naming of components and the special kinds of problems occurring at the barrier, making people dependent on intensive guidance of experienced colleagues
Reduce knowledge transfer time	Specialists having a busy agenda, therefore there is a shortage of time to transfer the knowledge they have

Table 5: A summation of the applications of a digital twin related to more efficient knowledge and information management.

4.3 Avoid unnecessary cost due to better monitoring of the barrier status.

An often mentioned within the Maeslant barrier's staff is the findability/availability of data. Currently the data of the Maeslant barrier is not accessible to everybody that needs it, specialists often depend on technicians to provide data or on external companies to provide reports. This takes time and introduces risks of missing information, being too late to act or making unnecessary interventions.

The cost related to these issues are avoidable by having a central platform where the data can be automatically viewed, analysed, and linked to the models that specialists use to assess barrier or component performance. A digital twin contributes to a solution for this problem since it includes a data monitoring platform that visualizes the data in real-time and directly relates it to a 3D model of the barrier of the physical object. Parameters can be compared to each other according to the user's preferences and can be analysed with the tools in the platform. It makes it easier to provide insight in what the sensors in the barrier measure, and more importantly, the data is always available and up to date. This is important information for the asset manager of the barrier, since this data indicates how the components in the barrier perform.

A summation of the applications of a digital twin to contribute to data findability at the Maeslant barrier is given in Table 6. A further explanation of the individual applications is given in Appendix F

Application of the digital twin	***Solution for problem***
Direct availability of data	Findability and availability of data
Cost savings on external reports and advice	High spendings on external advisors and reports

Table 6: A summation of the applications of a digital twin related to avoiding unnecessary cost.

4.4 Better risk management based on model calculations and data-analysis platform.

To comply with the Dutch law, a periodic report needs to be sent towards the Dutch ministry for infrastructure and water regarding the state of failure probability of the Maeslant barrier. The calculation of this failure probability at a large object such as the Maeslant barrier is a time-consuming activity that depends on many assumptions. Rijkswaterstaat currently maintains the RAMSSHEEP method [33] for the failure probability calculations. This is a broadly accepted method with a high level of detail, but also requires many administrative activities (estimations are up to 2% of the foundation costs per year [34]). The digital twin provides an environment in which these activities can be streamlined, optimized, and simplified, leading to lower yearly costs.

A summation of the applications of a digital twin to contribute to data findability at the Maeslant barrier is given in Table 7. A further explanation of the individual applications is given in Appendix F.

Application of the digital twin	***Solution for problem***
Reduce time needed for reporting time and risk determination due to automated processes	Risk determination being a time-consuming activity
More accurate risk determination due to increasing insight in barrier's behaviour	Having to make assumptions for risk determinations

Table 7: A summation of the applications of a digital twin related to better risk control.

4.5 Summary of applications

The individual applications, that are discussed in Section 4.2 to 4.4 are summarized in Table 8. The most important areas where a digital twin for the Maeslant barrier could provide application are the efficiency increase in knowledge and information management, findability and analysis possibilities of data and the reduction of the costs for risk determination.

Application	Solution for problem
Increase in efficiency in knowledge and information management	
• *Increase of the findability of information and knowledge*	• It is complicated to find specific information and/or knowledge in the existing Rijkswaterstaat systems without the help of an experienced colleague
• *Increase ability to independently obtain knowledge for new staff members*	• Unique (sometimes illogical) naming of components and the special kinds of problems occurring at the barrier, making people dependent on intensive guidance of experienced colleagues
• *Reduce time required for knowledge transfer*	• Specialists having a busy agenda, therefore a shortage of time to transfer the knowledge they have
Avoid unnecessary cost due to better monitoring of the barrier status	
• *Direct availability of data*	• Findability and availability of data is not optimal
• *Cost savings on external reports and advice*	• High spendings on external advisors and reports
Better risk management based on model calculations and data-analysis	
• *Reduce time required for reporting and risk determination time due to automated processes*	• Risk determination is a time consuming activity
• *More accurate risk determination due to increasing insight in barrier's behaviour*	• Having to make assumptions for risk determinations
Providing insight into the barrier's behaviour	
• *Use the visualization and animation of the digital twin to provide (new) insight into the barrier's historic behaviour*	• Especially for new staff members, it is complicated to link data to actual movements/behaviour of the barrier.

Table 8: A summation of the total applications of a digital twin developed for the Maeslant barrier.

5 Design requirements

The first step in building the digital twin is to investigate the design requirements, which can be translated into a design architecture in a later phase. The design requirements are based on the user requirements of the digital twin, that were investigated in Chapter 4.

5.1 Design requirements

To fulfil the definition of a digital twin, the technical requirements were summarized into the same five categories as presented in the literature study of digital twins (Section 3.1.2):

- Service
- Data Interaction
- Accurate representation
- Simulation and Analysis
- Control of the object or system

In Section 5.1.1 to 5.1.5, these categories are further elaborated upon.

5.1.1 Service

The service the digital twin should provide is for the largest part discussed in Chapter 4, where the application of the digital twin is discussed. From the interviews with the individuals involved with asset management of the Maeslant barrier, several clear requirements the digital twin should fulfil to provide application to Rijkswaterstaat could be derived. These are summarized as:

- **Support in knowledge and information management**
    - The digital twin should be a platform for organizing and accessing knowledge and information in a structured manner. This platform should integrate with Rijkswaterstaat's current information system, yet the information should be accessible without needing knowledge of the exact coding within that system.
    - To increase the knowledge transfer process, the digital twin should provide a 3D user interface in which the behaviour of the barrier can be animated. This means the closing procedure of the barrier should be playable based on data, either measured or simulated data, to educate new staff members more quickly.
    - The digital twin should provide new staff members of the Maeslant barrier team a digital environment in which they can educate themselves the basic functions of the barrier.
- **Support in more accurate asset management**
    - To perform data analysis independently of external engineering consultants, the data platform within the user interface should provide the capability to compare various data sources (e.g., of a barrier closure process). It should allow adjusting the timeframe of the data to compare specific portions of the data and the platform should always provide access to the available data.
    - The platform should provide the capability to conduct risk analyses for specific situations. In doing so, it should expedite the processes related to risk management and enhance the accuracy of risk assessment.

5.1.2 Data Interaction

Data interaction refers to the dynamic process of exchanging, accessing, manipulating, or interpreting data between individuals, systems, or entities. The data interaction in the digital twin must happen on different kinds of levels. To fulfill the potential application, it should be able to view historical (or predicted) data in a data monitoring platform, it should be able to be animate processes with the 3D model based on data and it should be possible to find historical data such as documents, pictures, or videos. It indicates that data and information can be present in different forms. To further define which kinds of data is essential for storm surge barriers, a sub-division is made regarding the types of data:

Several categories for knowledge and information are defined:

- **Meta-data**
  Knowledge or Information describing the characteristics of an object, for example: design choices, typical object behaviour, data interpretation or model usage. The meta-data can be present in two forms:
  - *Implicit* - Knowledge stored in the heads of people without a traceable description.
  - *Explicit* - Knowledge translated into information and traceably stored in written files, images, audio fragments or videos.
- **Data**
  A form of information used as a basis for reasoning, discussion, or calculation. Two forms of data are distinguished:
  - *Static data* - The kind of data that does not change after being recorded, for example: design drawings or geographic information.
  - *Dynamic data* - The type of data that is periodically updated, meaning it changes asynchronously over time as new data becomes available, for example: sensor data, object inspections or environmental changes.
- **(Computer) models**
  A form of knowledge stored in a (computer) model which can be used to make new information from data.

Meta-data

The design and construction phase of the barrier has led to many object-specific knowledge, most of which was captured in design documents. These design documents primarily contain static data stored in drawings and written design descriptions. The meta-data from this phase is made explicit by writing it down in the design descriptions or in model test reports. Although not all meta-data is made explicit, many important choices and observations were documented. Finding these documents without the right instruction, however, can be challenging due to the quantity and traceability of the documents and slows down the knowledge transfer process. In Section 6.4, the meta-data is further described.

Static data

The Maeslant barrier's static data is present in the form of documents, drawings, pictures, and videos. This static data is currently stored in a system known as KMS (Knowledge Management System). This system is based on a Particle Breakdown Structure (PBS) established during the construction of the barrier. In the current scenario, information in the KMS is most easily located by searching for the coding of the PBS. However, without knowledge of this coding, finding files becomes a complex task. Therefore, the digital twin should enhance the accessibility of files, wherein a strong desire from current users is to use the same coding for components as the existing PBS. Section 6.1 describes how this data is processed in the digital twin prototype.

Dynamic data

For the dynamic data, many options exist that could be interesting to display in the digital twin. The Maeslant barrier generates vast amounts of data, and the challenge lies in designing the user interface in a way that maintains clarity and organization of this data. Therefore, to keep the overview, a list is made based on the most important parameters the digital twin should display. This is done based on the conversations with staff members of the barrier. Table 9 and Table 10 provide this first indication. The parameters shown in Table 9 indicate the parameters that were mentioned to be interesting for the Maeslant barrier in general.

Parameter	Unit	Measured or calculated?
Water level Seaside	NAP+…m	Measured
Water level River side	NAP+…m	Measured
Discharge river	m^3/s	Calculated
Temperature	C	Measured
Wind	m/s	Measured

Table 9: More general parameters that can be shown in the dashboarding of the entire retaining walls.

The parameters shown in Table 10 indicate the more specific required parameters per compartment in the retaining walls. For these parameters a particular requirement is to be able to make analysis of the data over multiple years, and to compare the data of similar components to each other. For instance, one would like to compare the data from one pump during a barrier test closure to the data of the same pump during test closures in earlier years. It could also be relevant to compare the data of multiple pumps during a test closure to each other, for instance to see if one pump performed significantly worse than the other ones.

Parameter	Unit	Measured or calculated?	Extra
Pump Power (filtered and unfiltered)	kW	Measured	
Pump(s) discharge (Δballast/Δt)	m^3/s	Calculated	Relate to pump curve
Head (water level in compartment)	m	Measured	Relate to pump curve
Energy usage	kWh	Calculated	
CO2 emission	kg/h	Calculated	
Electric Power MCCs	kW	Measured	
Pitch	mm/m	Measured	
Sinking angle	mRad	Measured	
Drive-up Speed and Rotational Speed	mRad/s	Calculated	
Valve position	Open/Closed	Measured	

Table 10 A first indication of the requirements for visualization of dynamic data in the dashboarding function of the digital twin. These parameters are visualized for every compartment in the retaining walls, meaning per barrier arm thirteen of these dashboards are created.

5.1.3 Accurate representation

A digital twin element that was marked to be important for the Maeslant barrier by all the interviewed experts, is the visualization part. In this case, both the visualization of data with graphs in a dashboard and the visualization of the movements of the barrier with a 3D animation were mentioned to be important.

3D animation

For the sake of knowledge transfer in education and training, the 3D animation of the barrier movement plays an important role. It can be used to explain the way the barrier works to new people, and to support the knowledge transfer of complicated physical phenomena. The phenomena can be shown by loading a dataset and let the digital twin play an animation based on the selected data. Since the prototype digital twin is developed focussed on the Maeslant barrier's retaining walls, the barrier movements that need to be processed in the 3D animation of the digital twin are:

- Raising + levelling water level in dock
- Dock door open
- Sailing towards position in river (including pitch, horizontal- and vertical position)
- Sinking process (incl. valve positions, retaining wall position and water level in the compartments)
- Water levels at both sides of the barrier
- Refloating process (incl. pump power, valve positions, water level in the compartments.)
- Sailing back into dock (including pitch, horizontal- and vertical position)
- Dock door closed,

Dashboarding

Data visualization, for instance via the data dashboards of the components in the digital twin, is a step that is very relevant for the sake of knowledge transfer support tools. The dashboards can be used to indicate trends in data and provide explanations for these trends. The way data is presented in the data dashboards and the possibilities for performing analyses on it have been investigated through discussions with specialists from the barrier. The primary user requirements that emerged from these discussions were:

- The capability to compare parameters with each other.
- The ability to analyse specific timeframes.
- The ability to toggle various data sources on and off to better analyse specific sources.

From the discussions, no specific requirements for the exact design of the data dashboards were mentioned. Therefore, this is further elaborated in Chapter 6, where the design of the digital twin prototype is described.

5.1.4 Connection to models

The data described in Section 5.1.2 can be processed by the digital twin and visualized in the digital twin user interface. It can also be used to run models that are connected to the digital twin, to gain new information from these datasets. A large variety of models has been developed in the past, for several components of the Maeslant barrier. Based on the interviews with Rijkswaterstaat individuals involved with asset management of the Maeslant barrier, a selection is made of the models that are relevant for the digital twin prototype of the Maeslant barrier. A brief description of the relevant models is given in this section, for a more elaborate description of the models and how they are connected to the digital twin, reference is made to Section 6.3.

Data simulation

The *A-omgeving* is an existing data simulation model that can simulate the water levels that could occur during heavy storms around the Maeslant barrier and simulate the barrier's reaction to these water levels. It means the data generated by the A-omgeving is like the data generated by a real closing procedure and can therefore be compared with each other. A logical technical requirement following from this possibility, is that the digital twin must have a direct connection with the A-omgeving, or at least be able to import the data simulated by the A-omgeving.

Pump performance

To perform asset management in accordance with ProBO, it is essential to accurately assess the likelihood of failure of components. In the case of the pumps in the retaining walls, this estimation can partly be based on the performance of the pumps. This performance can be determined by plotting the delivered power of the pump against the flow rate being pumped, which is then compared to the pump curve. This curve is a model indicating the theoretical performance (power versus flow rate) of the pump. By comparing this model with the measured values over time, potential degradation of the pump can be observed, enabling an estimation of the failure probability for the pump.

Forces acting on barrier

The forces exerted on the Maeslant barrier during the closing process can, due to the way the barrier moves, operate differently in certain cases than initially perceived. Hence, it's interesting to visualize the functioning of these forces in the digital twin user interface. This can be achieved by calculating forces using models based on observations (barrier position and water levels) as inputs. These can be both hydrostatic and hydrodynamic models, which calculate forces based on water levels in the Nieuwe Waterweg. There was a strong desire from specialists to integrate these models into the digital twin, so the forces would be visible in the user interface.

Failure probability

The failure probability of the barrier is calculated using a model called Fault tree. This model is integrated in special designed software, in which the failure probability manager is capable of simulating scenarios and see the effect on the total failure probability of the barrier. It is desirable to make a connection between the digital twin and this model to simulate the effect of scenarios directly from the digital twin.

5.1.5 Control

The "control" aspect is the most challenging part to address in the context of a digital twin for the Maeslant barrier. Direct control of the Maeslant barrier itself or the maintenance processes associated with it through a digital twin is not feasible, nor desired. Currently, the barrier is managed by an automated decision support system, which is not accessible externally due to cybersecurity measures. As a result, decision-making or influencing processes through the digital twin must occur indirectly. This means that "control" should take place through the Maeslant barrier staff based on outcomes from the digital twin. For instance, this might involve adjusting the failure probabilities of components based on data analyses or simulations performed via the digital twin. This represents an indirect influence of the digital twin on the ProBO maintenance process.

5.2 Summary of Design requirements

Based on the investigation towards the desired elements for the digital twin, as described in Section 5.1, the design requirements have been defined, which are presented in Table 11.

Category	Design requirements
Service	**Support in knowledge and information management** • Organize and access knowledge • Increase knowledge transfer process • Independent self-education for new staff members **Support in more accurate asset management** • Data analysis independent of external parties • Improve risk estimation process
Data interaction	**Meta-data** Include knowledge about a vision on the barrier, and why choices were made during the design, construct and maintenance phase **Dynamic data** A longlist of environmental and barrier parameters are required to be included and visualized (see next page for a complete description) **Static data to be included:** • Historic documentation & (design) drawings • Pictures & Video's • 3D models
Accurate representation	**3D animation:** the barrier movement and operation process is animated. A longlist of parameters are required to be animated (see next page for a complete description) **Dashboarding function** • The capability to compare parameters with each other. • The ability to analyse specific timeframes. • The ability to toggle various data sources on and off to better analyse specific sources.
Model connection	**Available models to be connected:** • Data simulation of the closing procedure (via the *A-omgeving*) • Pump performance • Forces acting on barrier • Failure probability
Control	**Digital twin suggesting actions or (process) changes towards the barrier staff, based on authomated data analysis or model calculations**

Table 11: A summary of the design requirements for the digital twin, as investigated in Section 5.1

6 Digital twin prototype design

This chapter describes the design and development following the first four steps of the 5-step approach, as described in section 2.2.1. It is mainly intended for the reader interested in the technical details and architecture of the digital twin. Section 6.1 describes the architecture of the prototype (step 1). Sections 6.2 to 6.4 then explain how this architecture was implemented to create a data monitoring environment (step 2), link models to it to simulate scenarios (step 3), and integrate acquired knowledge (step 4).

Developing in Unity, supported with Python scripts

The prototype of the digital twin is being built using Unity [35]. This is a game engine developed by the Danish-American company Unity Technologies for the development of (serious) computer games for PC, consoles, mobile devices, and websites. Unity includes the ability to connect 3D environments of an object with underlying models and datasets. In this regard, this software is certainly not unique; however, Unity has positioned itself as a reliable environment for building such models and has become one of the standards for developing digital twins. Rijkswaterstaat has also embraced this software and uses it for various digital twin projects.

To make connections between the Unity environment and existing models, Python [36] scripts are used. Python is a versatile, high-level programming language known for its readability and ease of use, making it a popular choice for a wide range of applications, from web development to data analysis and artificial intelligence. This makes it a perfect language for developing the calculation heart of the digital twin.

6.1 Step 1: Design architecture

In the first step of the digital twin prototype design, the types of available data for the Maeslant barrier are investigated, see Section 6.1.1. Based on the user requirements, described in Section 5.1, the datafiles that contain the relevant information are selected and linked to components of the barrier. The same process is followed for the available models for the barrier which is described in Section 6.1.2. This leads to a system architecture, that forms the design for the digital twin prototype, described in Section 6.1.3.

6.1.1 Data inventory

This section describes the different sorts of available data at the Maeslant barrier and which of these data sources are processed in the digital twin. A distinction is made between the data generated by sensors (dynamic data) and the data in documentation, drawings, etc (static data).

Static data

Rijkswaterstaat's archives of the Maeslant barrier contain large amounts documents. A significant amount of these documents originates from the design and construction phase of the barrier, which were supplemented with documents, drawings, pictures, and videos produced in the maintenance phase. Most of these documents are digitized and stored in a Rijkswaterstaat document management system, called Kennis Management Systeem (KMS) [37]. This system contains documents of the Maeslant barrier, Hartel barrier, Hollandsche IJssel barrier, Ramspol barrier and Eastern Scheld barrier, leading to a total of 350 thousand documents stored in KMS.

Although most of the documents are digitized and labelled, it can still be a challenge to find the right document without the original document guide. A search engine supports in finding documents however, due to the number of documents in KMS, and not always the same structured labelling method used, finding the right document can be challenging without knowing the right terms to search with. Besides its limitations, KMS still forms one of the most important sources for static data in the digital twin.

Dynamic data: Measured data files

For the digital twin prototype, as mentioned in Section 5.1.2, the data-files related to the retaining walls and water levels on the river are the most interesting files. Research into the data storage systems of

Rijkswaterstaat resulted in the conclusion that a single barrier closing produces ca 6.400 data files from sensors in the barrier. The outputs are all CSV-files in which the measurements are non-equidistant, with the time noted in milliseconds. Due to the enormous number of files, it is desirable to get an overview of the amount of data files that are interesting for the prototype. Figure 15 provides a schematization of the parameters, and the amount of data files generated per parameter during a barrier closing. In this case it means, given the fact that the entire barrier contains 2 retaining walls with each 13 fillable compartments, for the retaining walls and river water alone 534 data files are created. All of them need to be integrated in the digital twin prototype. A detailed description of the measured parameters is given in Appendix G.

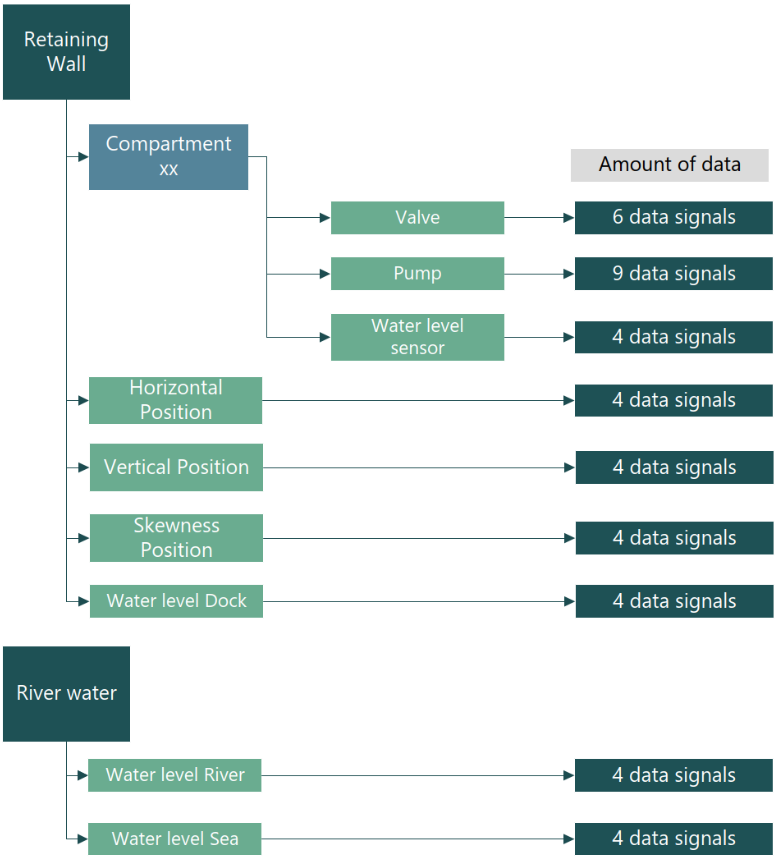


Figure 15: An overview of the types of datafiles produced in the retaining walls during a closing procedure of the Maeslant barrier. The retaining walls exist out of 15 compartments, of which compartment 3 to 15 can be filled and emptied with water. Therefore, they contain several Valves, Pumps and Water Level sensors. Appendix G provides a more detailed data overview.

6.1.2 Model inventory

Based on the design requirements, as defined in Section 5.1, models are identified that can meet these requirements. In Section 6.3, these models are further described and is explained how the models are connected to the digital twin prototype. Therefore, these models are not described in this section however, it is relevant to indicate which models are connected to this prototype, to feed the design architecture of Section 6.1.3, these models are presented in Table 12.

Model name	***Type of model***	***Output parameter***
A-omgeving	Data simulation	Simulated barrier closure
FaultTree+	Failure probability calculation	Simulated failure probability
Hydrostatic force	Physical based calculation	Calculated force
Tangential force on locomobile	Physical based calculation	Calculated force
Pump curve	Theoretical pump curve	Performance

Table 12: The available models that are connected to the digital twin prototype.

6.1.3 Design architecture of the digital twin

The design architecture was developed using ArchiMate, this language provides different predefined layers to support a well-structured and organized architecture. The design architecture of the digital twin prototype distinguishes three layers. The business layer consists of the stakeholders and describes their stakes. The application layer consists of the components of the digital twin, such as data, models, and information. And the technology layer consists of the supporting hardware, servers, communication software, etc.

In this section, only the application layer is elaborated upon. This is the layer that describes how the software of the digital twin is designed, which is the most important aspect for this chapter. Appendix H provides a complete description of the digital twin architecture.

Application layer

The digital twin application layer is the conceptualization of software implementations and the relations between them. Therefore, the applications described in this layer are linked to the business processes that must be fulfilled. These links are further described in Appendix H. To further describe the details of the elements in the application layer, it is split into two sub-layers: the *digital twin user interface* in which all visualization processes and clickables are indicated, and the *digital twin model* layer where all data, modelling and calculation processes are indicated. A simplified version of these architecture layers are presented in Figure 16, a more elaborate version of these architecture layers is presented in Appendix H.

Digital twin user interface layer

The central element in the digital twin application layer is the Unity model, which acts as the digital twin *user interface*. This provides the environment in which the users of the digital twin give all commands to do analyses, run simulations or make animations. The Unity interface contains a Knowledge sector, a Data dashboard sector and a 3D simulation sector. Figure 16 indicates how these processes are part of the Unity environment. All components that need to be included in the digital twin prototype are listed in the Knowledge, Data, and 3D Visualization sections of this architectural layer. Each component represents a function in the Unity environment. For example, if the data of the retaining walls is selected, the data of the positions of the retaining walls should be visualized. There should also be an option to zoom in further and select data for each compartment. When this is done, the data of the pumps and valves for the specific compartment should be displayed, and there should also be an option to zoom in further and open the data for a specific pump or valve.

Digital twin model layer

For the digital twin model layer, the primary sources are the data, and how this data is connected to the models. Especially for the data holds that this could be something dynamic, a source that is constantly updated, from different kinds of sources. As indicated in the bottom part of Figure 16, the data is gathered in one central point. From that point it could either be sent directly to the servers of the digital twin application or sent to connected models via a script that can be called for, when necessary, after which it is also sent towards the server. This happens via an API connection, a connection making it possible to send data secured to the server.

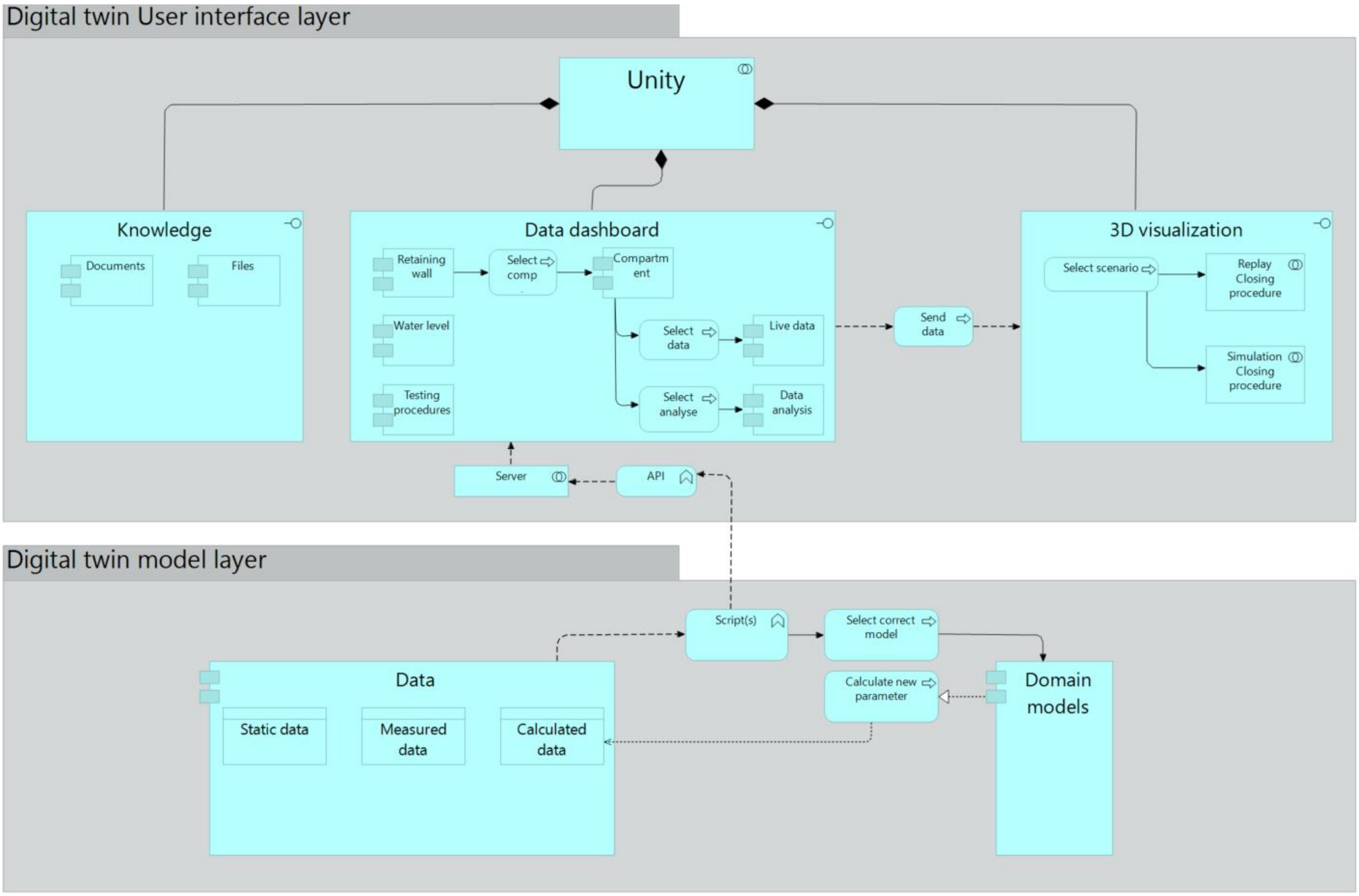


Figure 16: A simplified representation of the application layer of the digital twin architecture. a more elaborate version of these architecture layers is presented in Appendix H

6.2 Step 2: Data monitoring platform

In step 2, a data monitoring platform is linked to the 3D visualization. Section 6.2.1 discusses how the data is prepared to enable the visualization. Then, sections 6.2.2 and 6.2.3 describe how the data is visualized in data panels and through 3D animation respectively.

6.2.1 Data preparation

The data from Rijkswaterstaat measurement system is not directly usable in for instance a Python script or Excel model. This has to do with the fact that the collected data during a closing procedure is not recorded on a fixed time step. A notification of a measurement value is made when it is relevant to measure it. This means the time step is not constant, it could be 1 second between data point A and B, while it is 3 seconds between data point B and C. The result of this type of data collecting, is that the amount of datapoints per dataset differs. Before the data can be used, it needs treatment to make all datasets uniform.

Interpolation of missing data

The data from the retaining walls is noted with an accuracy of one thousand of a second. This is quite accurate, and not necessarily needed to be noted that accurate, since the time step between to data points is hardly less than a second and the closing procedure takes more than one hour to be fulfilled. Therefore, the first step in treating the data, is to round the time measurement of the data to whole seconds.

Once the time steps in the data set are rounded to whole seconds, the data set is laid next to a timeline with constant time steps of 1 second. These two datasets are merged, meaning a matrix is created, with the fixed time steps in the first column. When the time in the measurement data equals a time point in the first column, the actual measured datapoint is given a position in that line in the matrix. This is done for every used dataset, creating one big matrix of datapoints with equal time steps.

The above-mentioned method of comparing the data means not all points in the matrix are filled with data. These NaN's (Not a Numbers) are in the case of pump signal data filled with a method called 'linear interpolation', where all NaN's are filled linearly between two values value. In some cases, a method called 'forward filling' is used, meaning NaN's are filled identically to the last value until a new value is registered.

6.2.2 Data visualized via the monitoring platform.

The data monitoring platform visually displays the data as described in Section 6.1.1. This is done in the form of various data panels, which are linked in the user interface of the digital twin to components of the 3D model. Which data panel is linked to which component is described in the system architecture.

Unity

In the Unity environment, there is the possibility to open data linked to a component of the barrier via clickables. For example, by placing a digital button near the retaining walls in the 3D environment, clicking on it allows you to retrieve and display the data of the retaining walls from the server. The data initially displayed in panels consists of the position (horizontal, vertical, and skew), but this also opens an option to view the data for each compartment individually. At that moment, new buttons appear at each compartment in the retaining walls, offering the possibility to retrieve more data and open new panels. The same principle holds for other components in the Unity environment. Figure 17 schematically illustrates how the various components in the Unity environment can lead to the retrieval of different types of data.

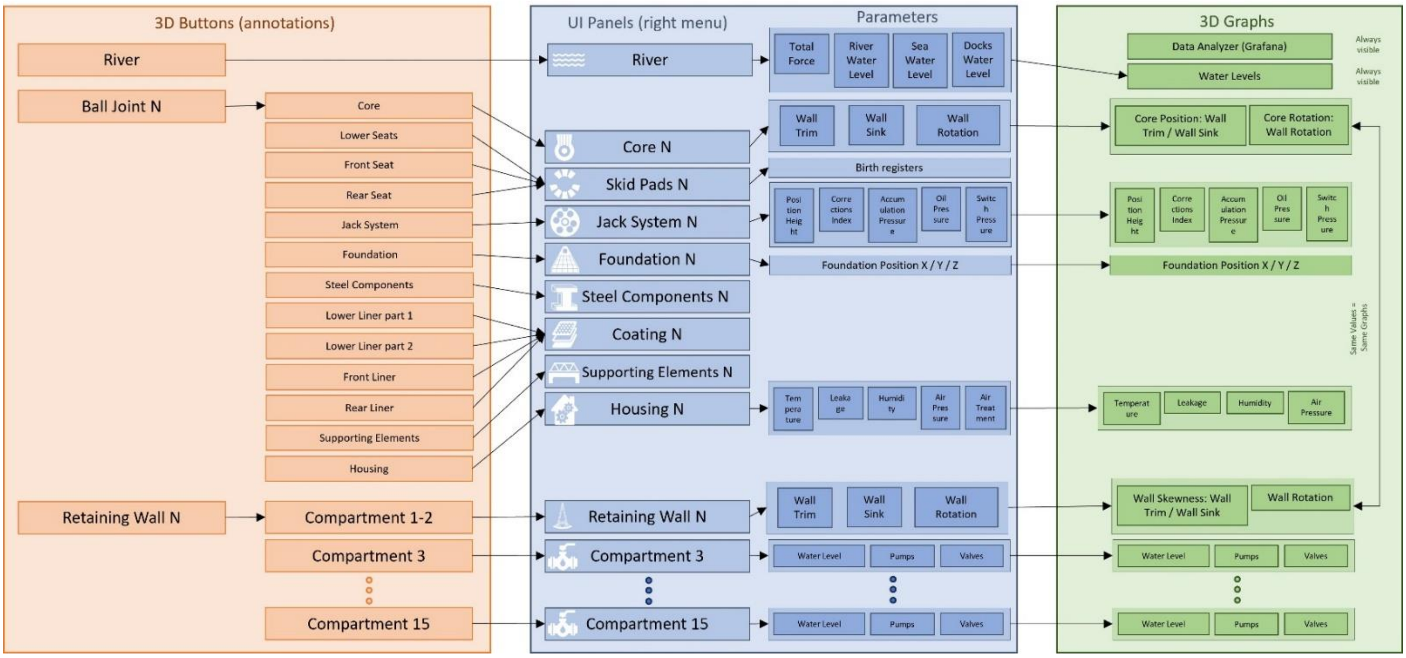


Figure 17: A schematic representation of the clickable buttons to call for data visualization in the Unity environment.

Grafana

Grafana is used to provide a more advanced data analysis platform. Grafana is an open-source application for analytics and interactive visualization. This application can be directly linked with Unity and used to perform more complex data analyses. The possibility to analyse data via Grafana can be seen as a plugin for the Unity environment, to extend the possibilities of the digital twin prototype.

6.2.3 3D Visualization and animation

The Maeslant barrier is in the digital twin visualized using a 3D model. This model is created based on the original Maeslant barrier's design drawings, as part of one of the elective courses in the EngD program. The models are created using 3D visualization software programs, in this case Maya and Blender. When finished, the 3D models are imported in Unity together with measured or simulated data. This data is used in Unity to animate the movement of the barrier based on this data. Unity also provides an opportunity to visualize the data by panels on the background of the 3D model.

3D model structure

The 3D model is built in two parts: the terrain and the barrier wall. The terrain is a non-moving part of the model in which materials can be appointed to different parts of the model to indicate how it is built up. Figure 18 indicates an example of the terrain, in this case by means of a screenshot of the model in the 3D visualization software.

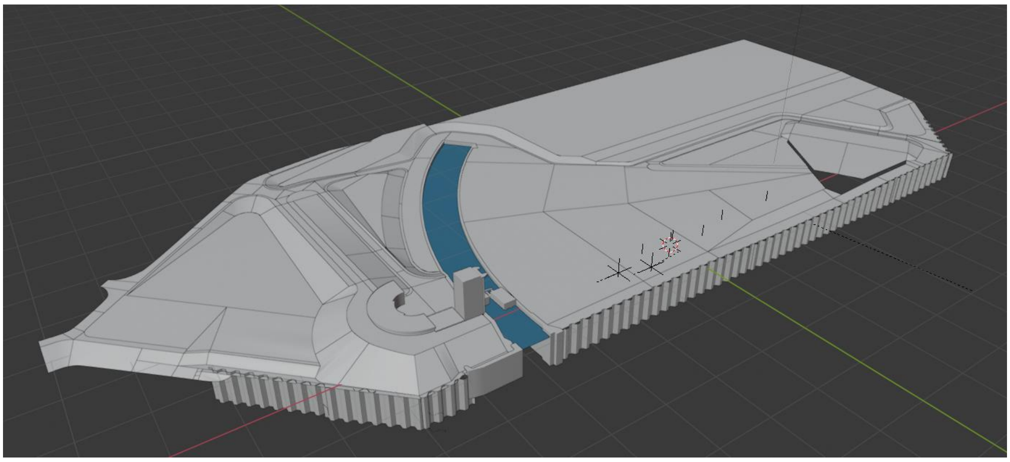


Figure 18: A screenshot of the terrain model of the Northern side of the Maeslant barrier. This is the non-moving part of the 3D model.

The 3D model of the barrier's door, including its sector gate and ball joint, is the part of the 3D model that forms the moving particle of the digital twin prototype (see Figure 19). The retaining walls should be able to move in three degrees of freedom (vertically, horizontally and rotating) to realistically represent the movement of its real-world counterpart. The part of the barrier that realizes the three degrees of freedom movement of the retaining walls is the ball joint. Since this is a unique part of the barrier that does not exist in any other structure in the world, it is a complicated part to imagine. It can therefore be useful, in the context of knowledge transfer, to decompose this part for explanation of its structure. Figure 19 (the right side) provides an example of how this is realized with the 3D model. In this case the screenshot is made from the 3D visualization software to indicate the possibilities of 3D visualization.

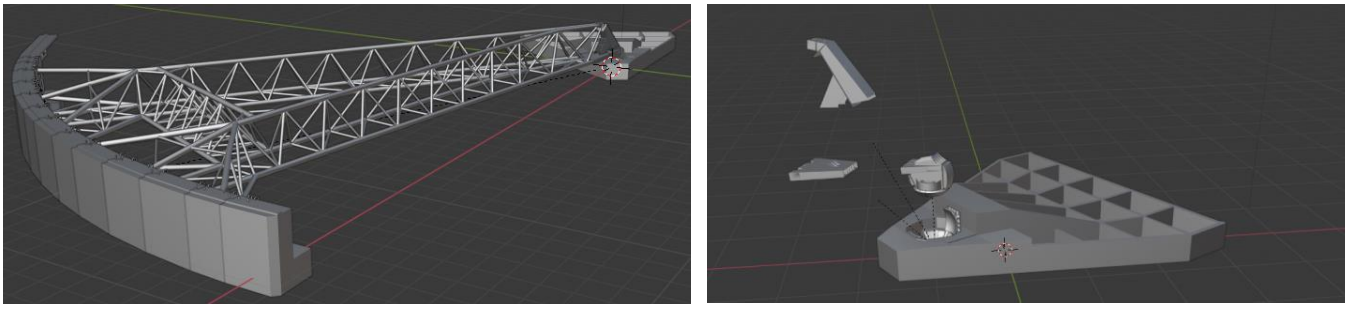


Figure 19: A screenshot of the 3D model of the barrier wall, the part that can move in the Unity animation model. The left panel indicates the barrier wall, the right panel indicates the components of the ball joint.

3D model animation

The animated movements of the barrier are based on the user requirements defined in Section 5.1. Each movement of the barrier is controlled by data (measured or simulated). For example, the horizontal and vertical position and skewness of the retaining walls that is visible during an animation are determined per time step (one minute by default but adaptable via the user interface) by the selected dataset. If the dataset from the 2020 operational closure is chosen, the retaining walls will move based on that data. This means the movement the retaining walls made during that specific closure is animated similarly. This also applies to the movements of the ball joint and the water levels in the river and in the compartments of the retaining walls.

Level of detail in animation

The 3D animation possibilities are extensive, it is possible to create highly detailed scenes or scenarios. An example is visible in Figure 20, in which a scene is created where the Maeslant barrier is not maintained for years, and corrosion and sprawl is visible on the barrier and the terrain around it.

These are visual possibilities the digital twin could provide; however, this also demands high capacities of the visual card of the computer, which most laptops at Rijkswaterstaat cannot fulfil. Therefore, to keep the digital twin prototype available for the average laptop of the Rijkswaterstaat employees, a choice was made to downgrade the level of detail of the visualization.

Figure 20: An indication of the visualization possibilities of the digital twin user interface. To keep the digital twin available for all laptops within Rijkswaterstaat, this level of detail is downgraded and not included in the current digital twin prototype.

6.3 Step 3: Integration of domain models

This Section describes the implementation of the models that will be used in the digital twin prototype and the use cases (see Chapter 7).

6.3.1 Hydrostatic force on retaining walls

Section 5.1.4 describes the desire to visualize parameters such as the forces acting on the barrier. These forces are not directly measured, so they need to be determined using a model. This can involve advanced models that consider all the details, such as dynamic wave action, material bending, and dynamic flow beneath and alongside the retaining walls. Finite Element Method, a computational technique for approximating partial and integral equations that describe physics, can be used, for example. There is an ongoing project within Rijkswaterstaat to develop such a model for the retaining walls. However, this project has not yet been completed, so it cannot be utilized here. For this prototype, it has been decided to use a simplified version that calculates only the static forces on the retaining walls.

Hydrostatic force theory

The hydrostatic force on a standing wall, such as a dam or retaining walls, can be calculated using the principles of fluid mechanics. The hydrostatic force arises due to the pressure exerted by a fluid (like water) on the surface of the wall. This force is calculated by the following formula:

$$F = P * A$$

Where:
- F is the hydrostatic force in Newtons (N).
- P is the hydrostatic pressure in Pascals (Pa) at a specific depth.
- A is the area of the wall in square meters (m^2) that is exposed to the fluid.

To calculate the hydrostatic pressure P at a specific depth in a fluid, the following formula is used:

$$P = \rho g h$$

Where:

- ρ (rho) is the density of the fluid in kilograms per cubic meter (kg/m³). For fresh water, it's typically around 1000 kg/m³, salt water is typically around 1025 kg/m³.
- g is the acceleration due to gravity, which is approximately 9.81 m/s² on Earth.
- h is the depth of the fluid above the point of interest, measured in meters (m).

Model calculation

These formulas are used to calculate the hydrostatic force on every compartment of the retaining walls, at every second. In the case of the retaining walls, the hydrostatic force per compartment has been calculated. This was done because each compartment has an (approximate) flat surface and is not curved. By calculating the force per compartment, an estimate can be made of the transfer of the hydrostatic force on the entire retaining walls towards the ball joint. It also means that the surface area where the water presses against (A) is equal to the water height (h) times the width (B) of the compartment. The hydrostatic force is then equal to:

$$F = \rho g h^2 B$$

Since the hydrostatic force is working from two sides of the retaining walls, the river side and the seaside, the net force (F_{net}) that is transferred towards the ball joint is the force on the seaside (F_s) minus the force on the river side (F_r). This is visualized in Figure 21.

$$F_{net} = F_s - F_r = \rho g h_s^2 B_s - \rho g h_r^2 B_r$$

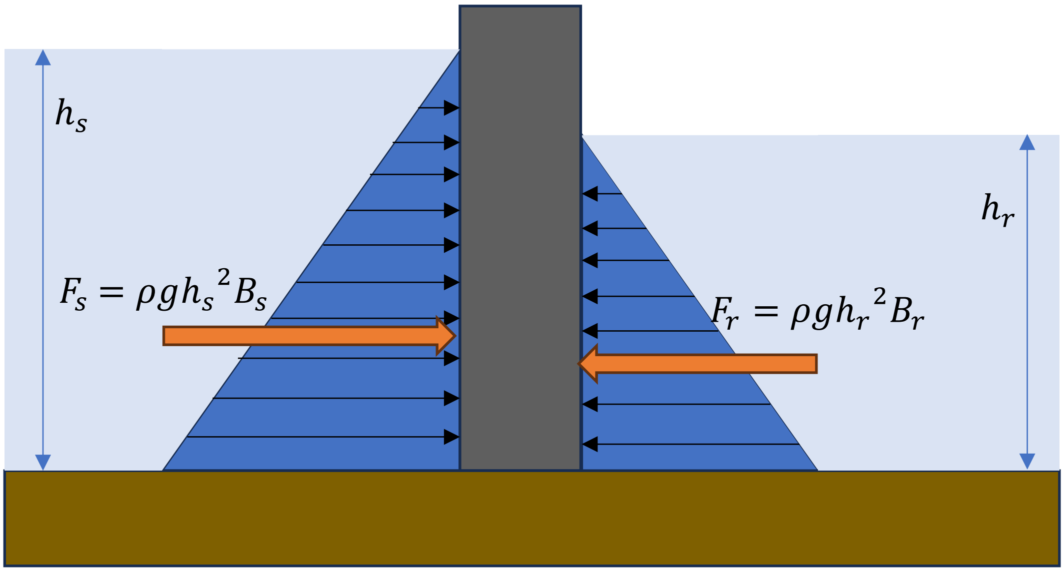


Figure 21: A schematic representation of the hydrostatic forces from the seaside (F_s) and from the river side (F_r) acting on the retaining walls.

For every timestep, the measured water levels on the river, and the position of the retaining walls are used to calculate the hydrostatic force. Per compartment it is determined what the water head is, by subtracting the difference between river bottom and the retaining wall's bottom from the measured water height. The skewness of the retaining walls is considered using the horizontal distance of the compartment from the wall's centre point, combined with the skewness angle (see Figure 22).

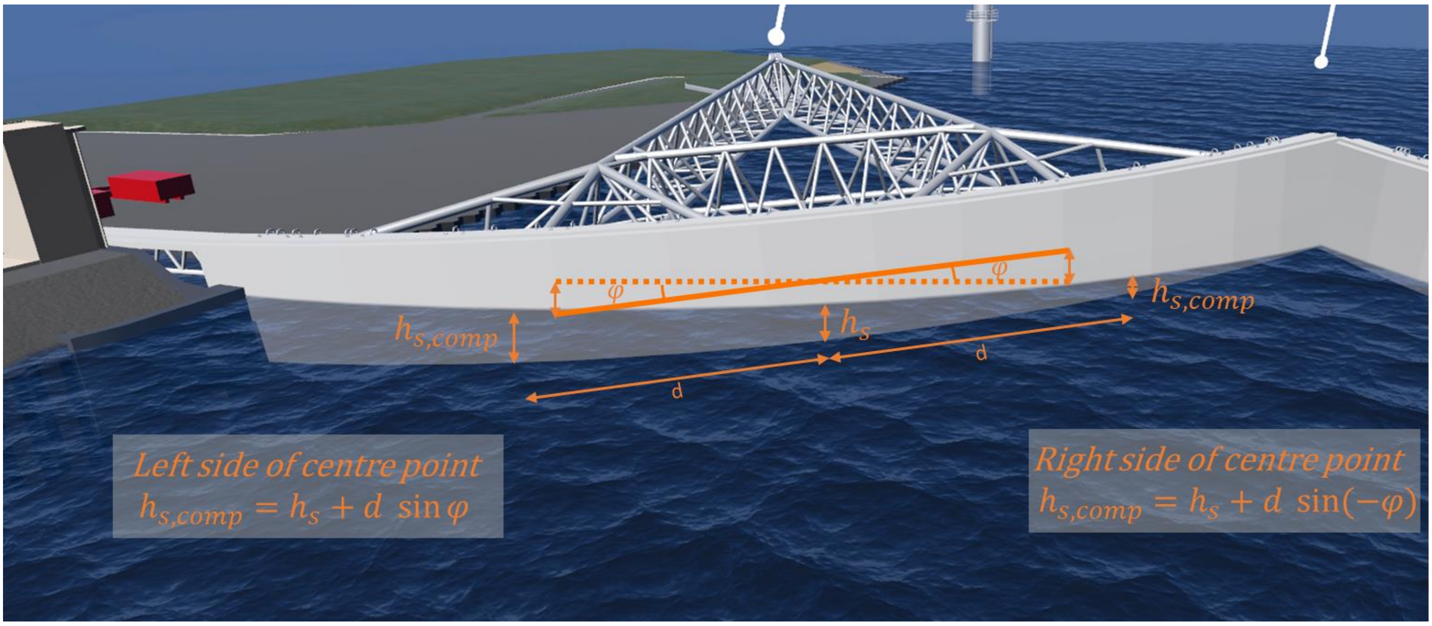


Figure 22: An illustration of the skewness effect on the water head causing the hydrostatic force at the retaining wall. In this figure h_s is the water head at the centre point of the retaining wall, $h_{s,comp}$ is the water head per compartment, ϕ is the skewness angle and d the distance from the centre point of the wall to the centre point of the compartment.

The skewness effect can be determined using Pythagoras' law for every compartment. It means the force per compartment ($F_{net,comp}$) can be calculated by:

$$F_{net,comp} = \rho g(h_s + d_{comp} \sin \varphi)^2 B_s - \rho g(h_s + d_{comp} \sin \varphi)^2 B_r$$

Camber effect

The retaining wall sinks to the riverbed by rotating (in the vertical sense) around the ball-joint, meaning it doesn't descend exactly vertically. This means its bottom is not horizontal when the wall is in a floating state. The bottom must be horizontal when it rests on the riverbed. This results in what is called a "camber" (see Figure 23) in the retaining wall, a curvature on the underside of the barrier, causing the central part of the retaining wall to be approximately 1 meter higher than the sides. This curvature affects the hydrostatic forces acting on the wall, therefore, this effect has also been considered in the model.

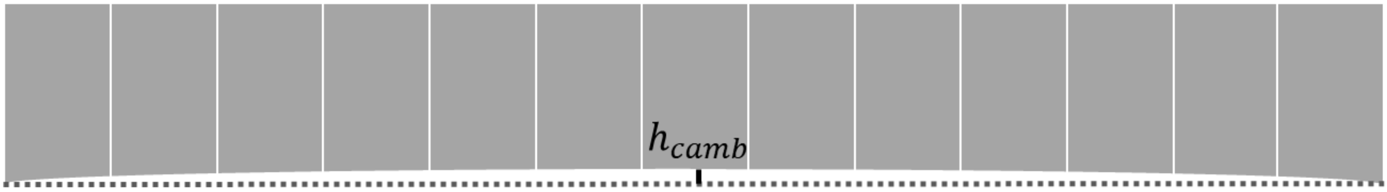


Figure 23: A schematization of the camber effect of the retaining wall. In this figure, h_{camb} represents the camber effect per compartment.

The camber, which varies during the sinking process of the barrier, is known for every compartment at every wall vertical position. The range varies from 0 m at the most outer compartments (nr. 3 and 13) and 1 m at the most centre compartment (nr. 9) in floating position, to 0 m for every compartment in complete sunken position. The camber effect can be included in the force calculation by subtracting the effect per compartment ($h_{camb, comp}$) from the water head. This leads to:

$$F_{net,comp} = \rho g(h_s + d_{comp} \sin \varphi - h_{camb,comp})^2 B_s - \rho g(h_s + d_{comp} \sin \varphi - h_{camb,comp})^2 B_r$$

Total force on ball joint and locomobile

The next step is to determine how these forces are transferred towards the ball joint and the locomobile. Each compartment has its own position relative to the ball joint, which means that they each contribute separately to the total force in both the tangential (perpendicular direction) and radial (longitudinal direction) component to the ball joint and locomobile. Therefore, each hydrostatic force acting on the ball joint must be resolved into a radial and a tangential component. This component depends on the angle of the compartment relative to the centre of the barrier arm, denoted in this case as theta (θ). Figure 24 provides a schematic representation of the forces on the retaining walls and how the forces are transferred towards the ball joint and locomobile.

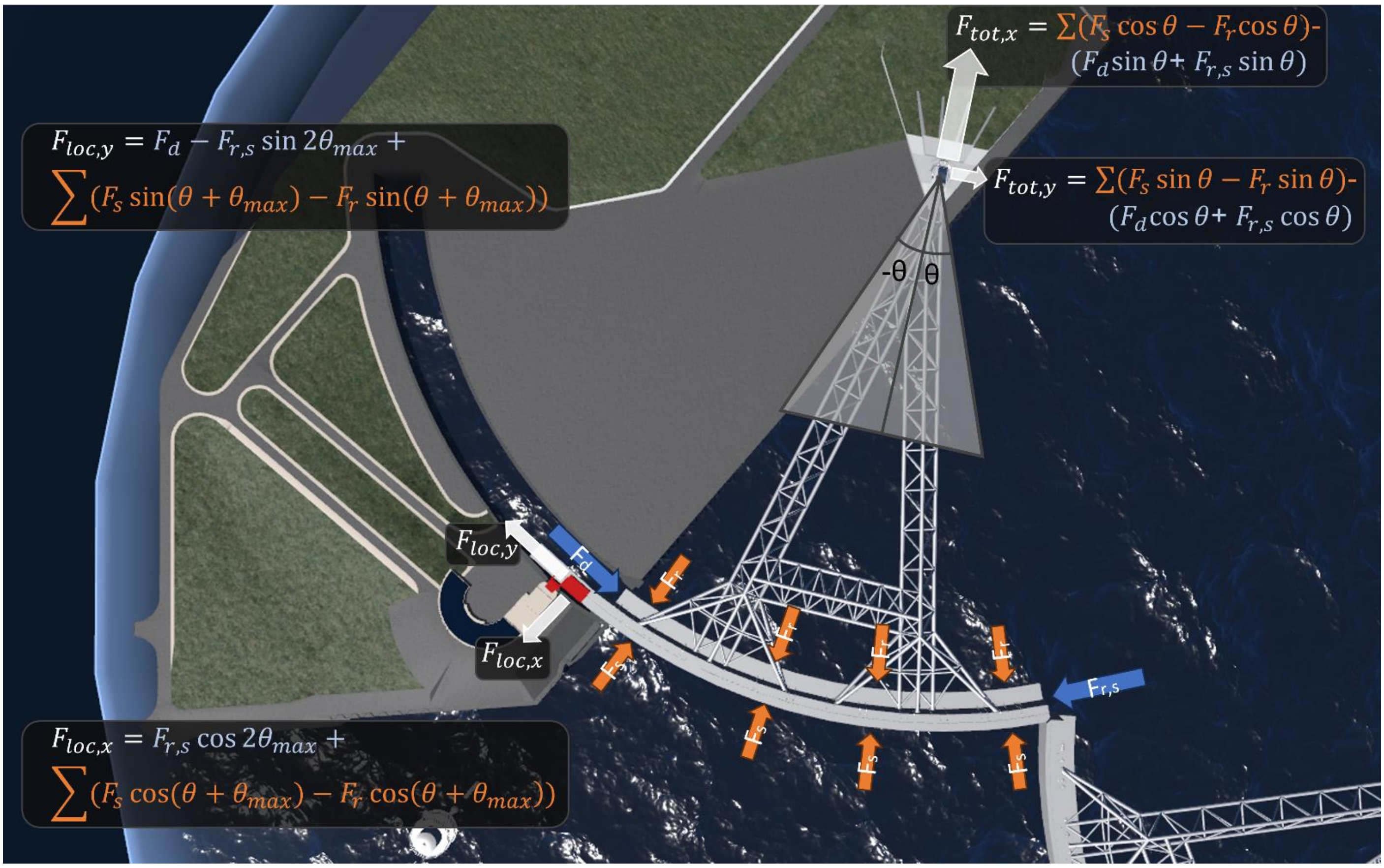


Figure 24: A schematization of the hydrostatic forces working on the retaining walls and the formulas for how these forces are transferred towards the ball joint and locomobile. In this schematization, Fs represents the hydrostatic force from the sea side, Fr from the river side, Fd from the dock on the side and Fr,s from the river on the side.

In Figure 24 the blue arrows represent the hydrostatic force the water is acting on the sides of the barrier's retaining wall, the force from the dock-side is indicated by F_d and the force from the river side by $F_{r,s}$. The orange arrows represent the hydrostatic forces on the front- and backside of the wall, F_s indicates the force from the seaside, F_r the force from the river side. Each force contributes to the total force on the ball joint (radial: $F_{tot,x}$ and tangential: $F_{tot,y}$) and on the locomobile (radial: $F_{loc,x}$ and tangential: $F_{loc,y}$). To calculate that contribution, hydrostatic forces (in total: both sides of the wall and the river- and seaside of each compartment) are calculated according to Figure 21 and resolved in a radial and tangential component.

Resolving the force is done using Pythagoras' law (indicated by the formula's in Figure 24), where the angle (θ) required to make this calculation is different for each compartment or side of the wall. In the formula's the contribution of the forces on the front- and backside of the wall are indicated in orange text, the contribution of the forces on the sides of the wall is indicated in blue text.

6.3.2 Probability of failure model

As explained in Section 3.3, the maintenance of the Maeslant barrier is based on detailed fault trees that estimate the operational reliability of the barrier, i.e. the probability of non-closure (see appendix I for a more detailed description). The fault tree of the Maeslant barrier consists of more than 7000 basic events and is used to estimate the impact of a modification to the probability of non-closure. However, the applied fault tree software (FaultTree+ [38]) is not easily externally controlled, and therefore hard to directly link to the digital twin.

Rather than linking the fault tree directly, the 'minimal cutsets' are provided to the digital twin. A minimal cutset is a combination of basic events that lead the undesired top event, i.e., not closing of the barrier. A minimal cutset could, for example, be: 1) Valves in compartments x&y fail, 2) Pump x1 doesn't start, 3) Pump x2 doesn't start. Only if all three events in this cutset occur simultaneously one speaks of barrier failure.

Each minimal cutset in the list has its own failure probability contribution, determined by multiplying the failure probability of each individual event in that cutset. This is under the assumption that the individual events are independent. Ultimately, the failure probability contributions of each cutset are summed up, resulting in the failure probability of the entire barrier. This process is visualized in Figure 25.

To simulate the impact of a specific scenario on the failure probability, an algorithm has been built that can search in the list of cutsets for all individual cutsets containing a specific event, for example, all cutsets containing the event 'failure of pump xx'. The algorithm is then capable of changing the failure probability associated with that specific event. This is done by multiplying the failure probability by a factor 'c'. The factor can be determined by the person controlling the algorithm. A factor greater than 1 result in a scenario of lower reliability (because of a higher failure probability), while a factor less than 1 results in a scenario of higher reliability (because of a lower failure probability). By adjusting these specific values in the cutsets, the overall failure probability of the barrier is ultimately influenced. This is illustrated in Figure 25, in this case a scenario is simulated where one specific event in the cutset is adapted, which is marked in yellow.

For the digital twin prototype, five types of multiplication factors (the factor 'c') were defined, see Table 13.

Name	***multiplication***	***Meaning***
Perfect	0.00001	Maintenance is performed so intensively that the component approaches a failure probability of 0
30 times better	0.03333	Very good maintenance
10 times better	0.1	Good maintenance
10 times worse	10	Bad maintenance
30 times worse	30	Very bad maintenance
Malfunction	Replace by 1	Component has failed

Table 13: The multiplication factors for the failure probability calculation of the simulation model connected to the digital twin prototype.

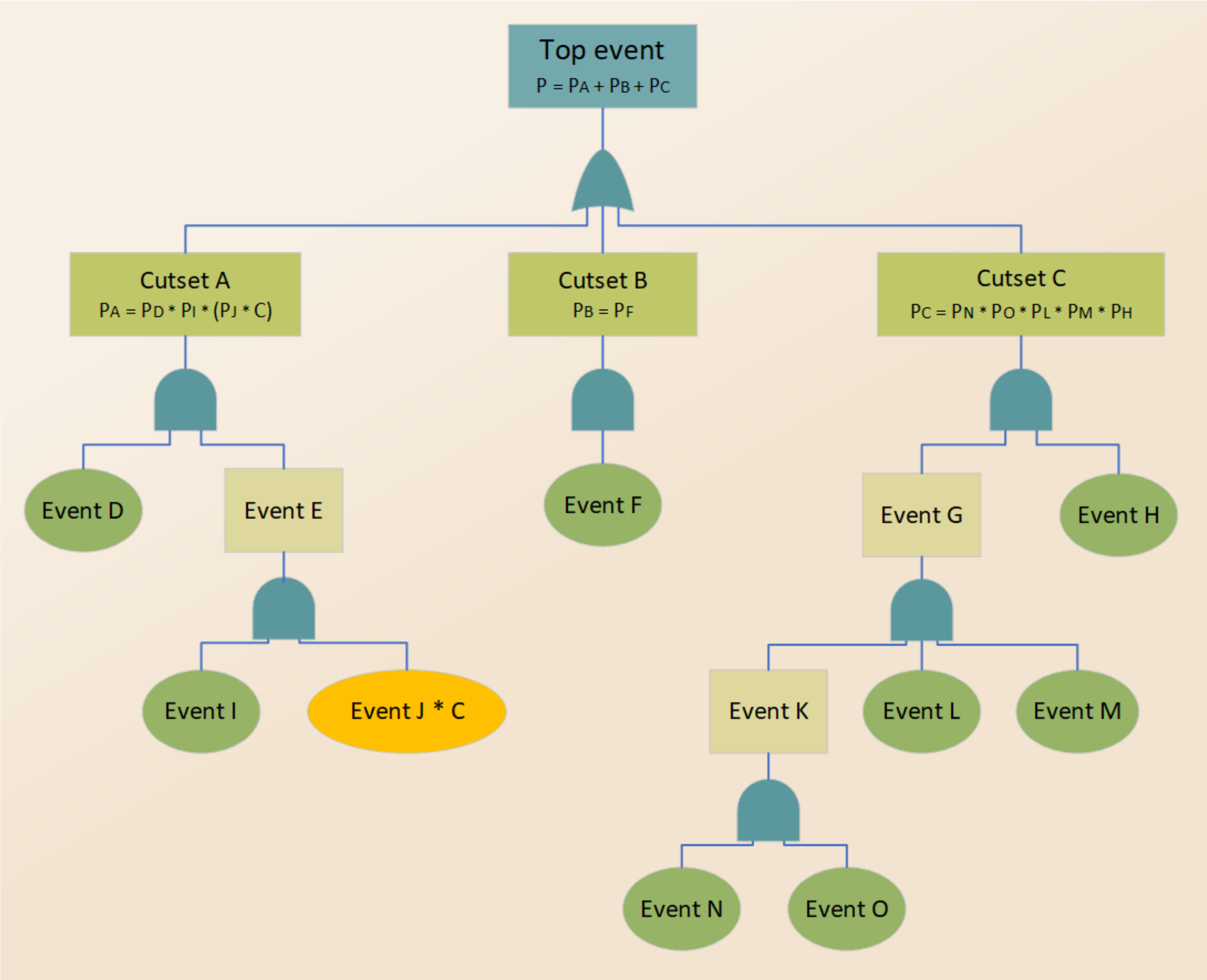


Figure 25: A schematization of the process of calculating the failure probability of the barrier, where 'P' stands for the probability of an event. Each green ball in the scheme represents an individual event. A cutset is the other end of the line (in this case A, B or C), that is calculated by multiplying each previous event together. To demonstrate how scenarios can be calculated, Event J is multiplied by a factor 'c' to calculate the impact of that action. All events are assumed to be independent and probability values of P_A, P_B and P_C to be small.

6.3.3 Pump discharge calculation and pump curve

For asset managers, it is interesting to see if the components installed in the barrier perform as they are theoretically supposed to. An example of this is the performance of a pump, such as those installed in the retaining wall. They are used to control the water level in the retaining wall when the barrier is becoming floatable to open the gates. These pumps are supposed to achieve a certain flow rate in relation to the head, to which a specific power is also linked. This theoretical value is determined in a so-called pump curve.

A pump curve (see Figure 26) is a graphical representation of a pump's performance. It displays the relationship between flow rate (volume per unit time) and total head or pressure generated by the pump. Starting at the shut-off head, where there is zero flow, the curve shows how the pump's head decreases as flow rate increases. The point where the curve intersects the flow rate axis represents the pump's best efficiency point (BEP), indicating its optimal operating conditions. The slope of the curve signifies how the pump handles varying flow rates and pressures. Engineers use pump curves to select the most suitable pump for specific applications, ensuring efficient and effective performance.

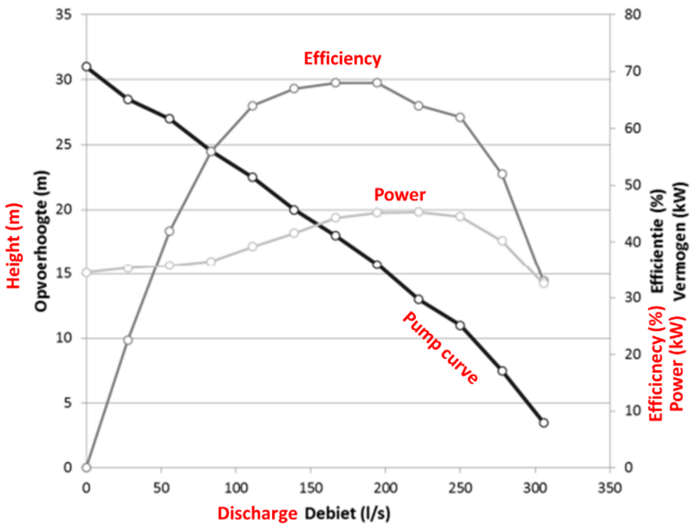


Figure 26: An example of a pump curve (base figure from Deltares). The original pump curve was written in Dutch, the English translations are included in red.

For the digital twin prototype, the principle of the pump curve was used by comparing it with two measured parameters: pump power and water levels in the compartment. From the water levels measured over time, a flow rate can be derived that is being pumped at that moment. This is done by multiplying the water level difference per time step by the surface area of the water in the compartment. Since the dimensions of the compartments are known, a flow rate can be derived in this way. This flow rate can then be compared to the pump curve, either by plotting it against the measured pump power or by plotting it against the measured water levels. This process is visualized in Appendix F.

6.3.4 Data simulation of barrier closings

Rijkswaterstaat has developed its own data simulation environment, called the *A-omgeving* (see Figure 27 and Figure 28 for an example), in which closings of the barrier can be simulated. The *A-omgeving* is a data simulation model that can simulate the water levels that could occur during heavy storms around the Maeslant barrier and simulate the barrier's reaction to these water levels. This is done by feeding the water levels, simulated by a model called SOBEK-WANDA, to a copy of the barrier's decision system (called BOS). When the copied version of BOS decides to 'close the barrier', it switches on a copied version of the barrier's operating system (called BesW). The operating system controls the barrier as if it is the real barrier, on which the SOBEK-WANDA model reacts by simulating the response of the water levels to the closing process of the barrier. The interaction between these systems simulates the behaviour of the barrier as if it was a real closing procedure. It means the data generated by the A-omgeving is like the data generated by a real closing procedure and can therefore be compared with each other. A logical technical requirement following from this possibility, is that the digital twin must have a direct connection with the A-omgeving, or at least be able to import the data simulated by the A-omgeving.

The intention for this prototype was to generate a series of datasets using the A-omgeving. These datasets would represent different scenarios that could then be loaded into and visualized/animated with the digital twin prototype. However, due to complications, the A-omgeving was unfortunately not available during the construction of the prototype, which also made it impossible to generate the datasets. Therefore, this is a recommendation for future work.

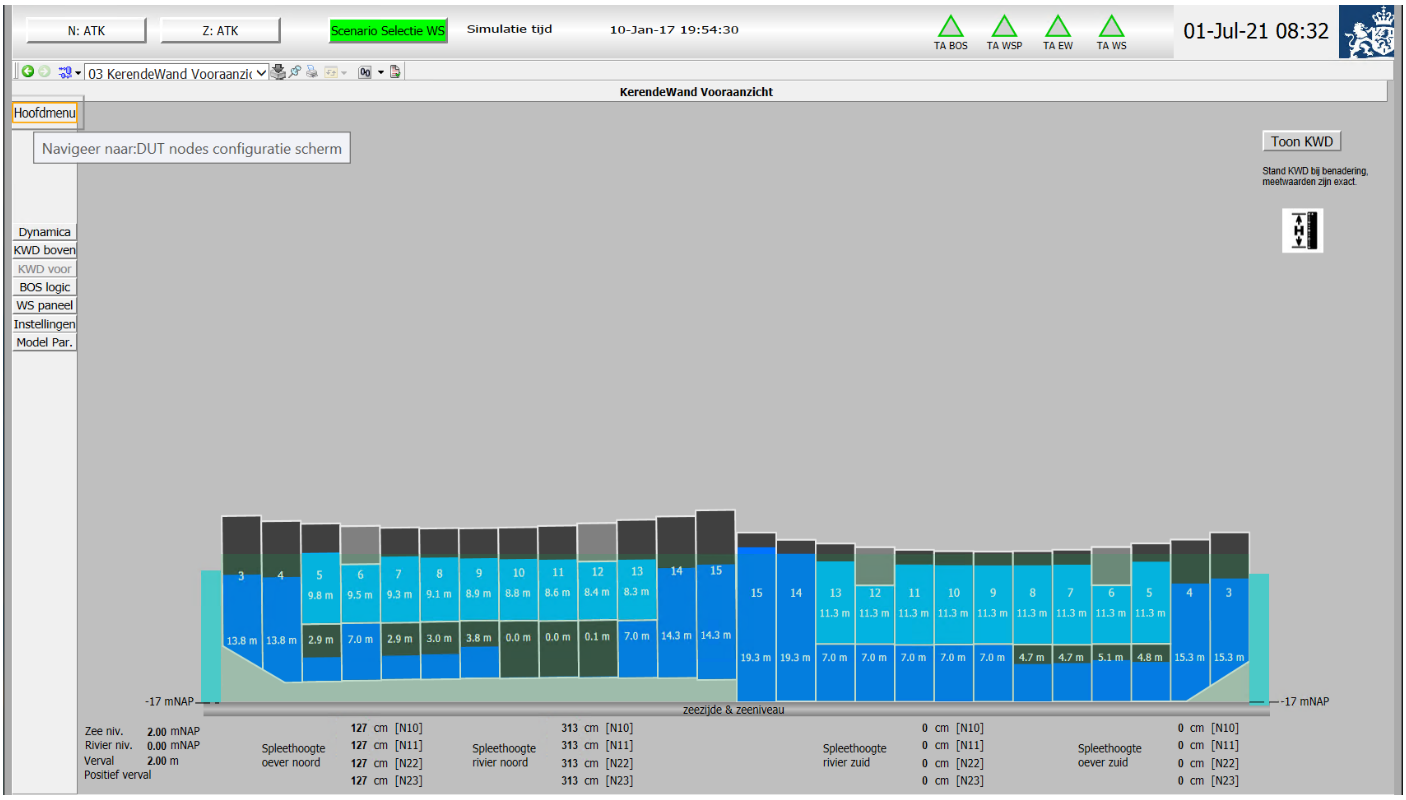


Figure 27: A screenshot of how the A-omgeving visualizes the simulated data. In this case it visualises the filling process of the compartments in the retaining wall and the horizontal position of the wall itself.

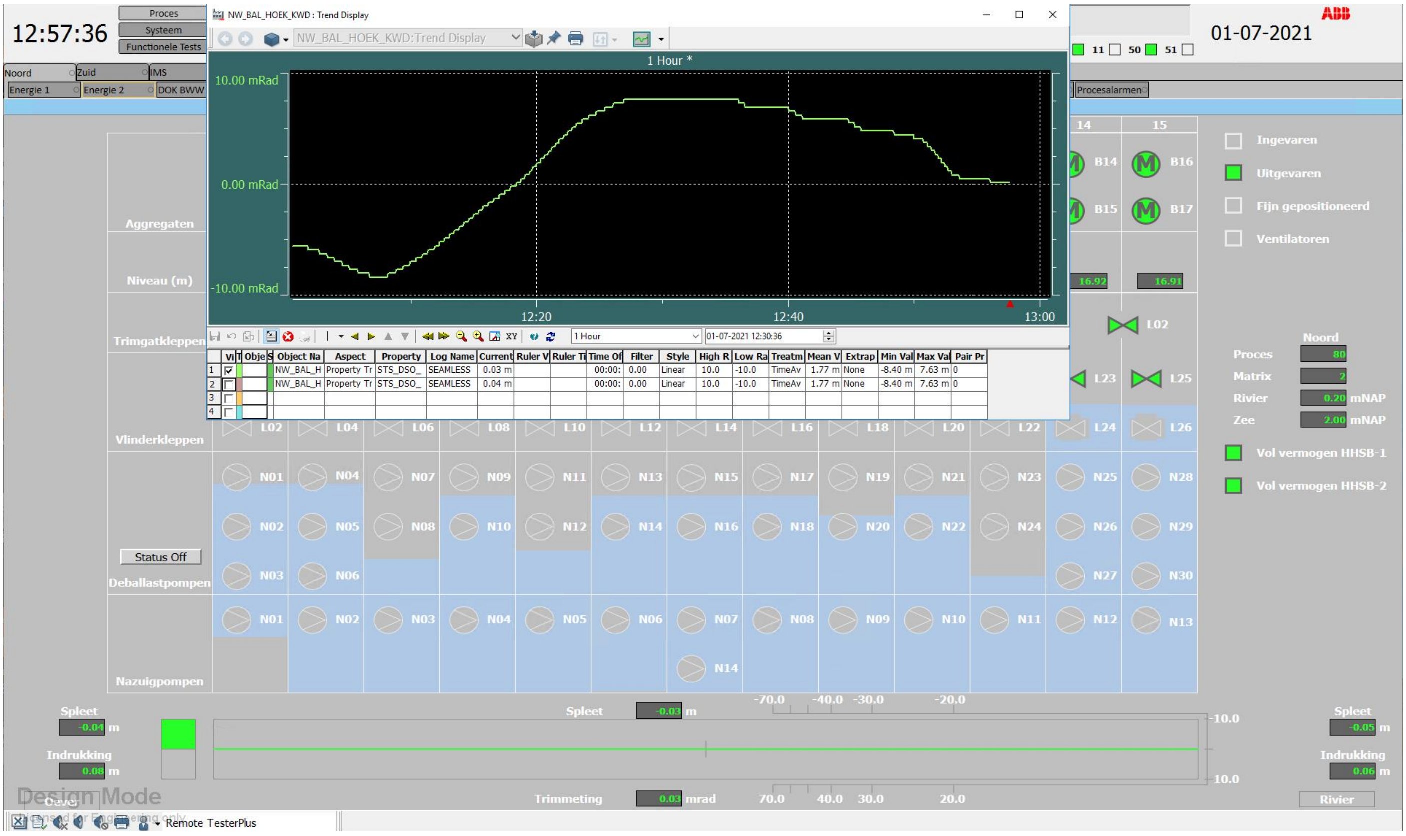


Figure 28: A screenshot of the data analysis possibilities in the A-omgeving. In this case, the water levels in the compartments are visualized on the background, The data visualization panel demonstrates the water level in one of the compartments over time.

6.4 Step 4: Capturing expert knowledge.

The knowledge components implemented in the digital twin prototype are included in two different ways: in the visualization through animated movements, data limits, or warning signals, and in the form of essential knowledge documentation directly linked to components in the 3D model.

6.4.1 Visualization through animation, data limits and warning signals

Knowledge is captured in the digital twin prototype by selecting parameters that are included in the animation of the barrier's movement, sometimes by making them stand out more clearly.

Closing process in animation

An example of this is the skewness of the retaining wall. This is an essential part of the barrier's closing process, but it is not immediately visible to the untrained eye, as the effect is relatively small. By building an option in the prototype that can enhance this effect, it can be presented more clearly. The same applies to the filling of the compartments during the sinking process, which becomes more visible because the barrier gates can be made transparent. Another example is visualizing the forces acting on the barrier wall and the ball joint. The hydrostatic forces calculated by the model described in Section 6.3.1 are represented on the screen by arrows indicating the direction of the force and growing or shrinking based on the magnitude of the force. These are both examples of knowledge that is normally in people's minds and is now captured and transferable to future generations in this way. Table 14 provides more examples of animations that contribute to knowledge capture.

Data limits and warning signs

In the data dashboard of the prototype, where data is visualized using graphs, it is possible to set limits. This can be done by Maeslant barrier specialists themselves, without the need for a modeler. It is also possible to attach a message to this limit, which appears when the data exceeds a certain threshold. This message can indicate the effect of exceeding that limit and suggest possible means to address it. In this way, specialists can document their knowledge based on their experience. This is also included in Table 14.

Animation or simulation possibility	***Unique knowledge that is visualized***
Ball joint movement	Awareness of the movements of the joint and relation to the retaining walls
Amplified sector gate skewness	Insight in the movements of the gates during sinking process, amplified for more awareness of the skewness
Hydrostatic force visualization	Awareness of the direction and magnitude of forces acting on the retaining walls and the ball joint
Transparency of gates	Insight into the filling process of the compartments in the retaining walls
Failure probability change	Awareness of the influence of possible actions in the maintenance process
Data limits	Indications from specialists that data is exceeding a value that could cause harm to the barrier
Warning signs	Messages from specialists to indicate why the exceedance of certain data values is potentially harmful and providing possible solutions for it.

Table 14: A summation of the animation or data visualisation components that contribute to knowledge transfer or assurance.

6.4.2 Documentation of essential knowledge

Several (confidential) documents exist in which several phenomena that did or could occur are described. For every phenomenon a description is given of its characteristics and the possible measures to prevent or control it [39] [40]. The documents focus on recognition of the phenomena, analyzing the data to judge the situation and describe measures to control the situation. The way these documents are written however, already requires specific domain knowledge or even deeper understanding of the Maeslant barrier itself. The terminology is specific, short, and concise, which means it is difficult to understand without extensive background knowledge.

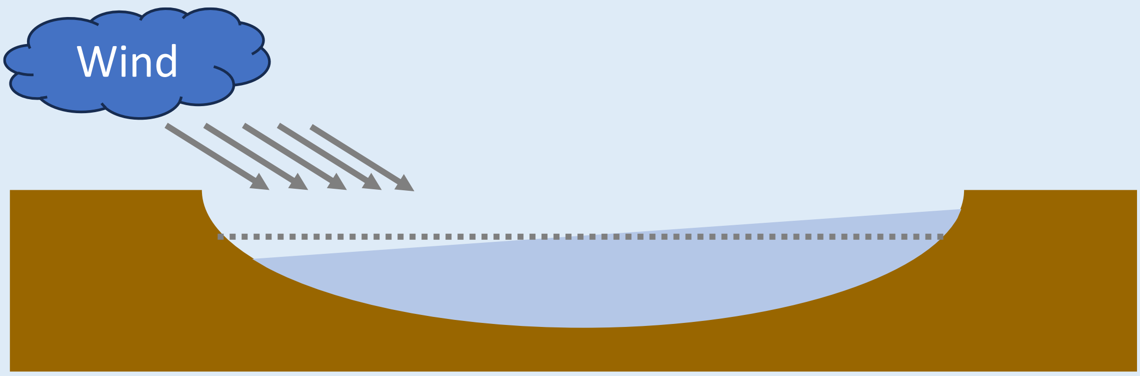
Some examples of situations in which specific barrier knowledge or domain knowledge is required in order to understand which measures could be taken are captured in the textbox.

Ball joint

The ball joint is a component that is specifically designed for the Maeslant barrier to give the retaining walls three degrees of freedom in movement (vertically, horizontally and rotating). This component is one of a kind and has had several re-design iterations based on observations during the maintenance phase. It requires knowledge of these re-designs as well as domain knowledge of mechanical and material engineering to understand the functioning of the ball joint as it currently is, therefore, how to maintain the ball joint in good condition.

Seiches

Seiches, standing wave oscillations in bodies of water caused by atmospheric pressure variations or seismic activities, might happen during the barrier's closure (see figure), potentially causing rhythmic water level fluctuations. If these occur on the seaside of the Maeslant barrier, the sea side's water level could briefly become lower, exerting seaward force on the barrier's ball joint. Preventing damage to the ball joint requires expertise in hydraulic engineering to detect seiches and understanding the barrier's operation to take appropriate measures, such as bringing the barrier into floating mode. Even though seiches could occur damage to the barrier, the probability of causing damage is very low.



Data simulation

When using the A-omgeving (see Section 6.3.4) for testing the barrier, the simulation once showed a high fender deflection during dynamic preloading of the retaining walls. This caused a large pitch and automated control actions that were completely contrary to what was expected. If the control system (BesW2012) could react like this, it would be a very serious problem (causing partial failure of retaining water, possibly leaking tanks and non-availability for a subsequent closure). Human intervention in the automated control is required in such a case. It requires specific knowledge about the barrier’s control system, functioning of the barrier and domain knowledge on several forms of engineering to be able to understand what should be done in such a situation.

CTR system naming

To search for documents in the database, the Maeslant barrier follows a structured naming convention for documents, which has been maintained since the design phase of the barrier. This naming convention, known as the CTR naming, is documented in a list that allows for various levels of detail. For the northern barrier, the naming convention starts with MN, while for the southern barrier, it is MZ. Each component of the barrier has its own number, for example, MN61 for the retaining walls. As more detail is needed in the designation, a number and a period are added. This can lead to designations such as MN61-01.01.1.1, which, in this case, stands for the Access Hatch Walkway Landside. This detailed naming convention results in a list of approximately 1600 different names for components or parts. It is beyond the scope of this report to discuss all these designations, so a selection has been made of the components relevant to the prototype, as shown in Table 15.

Link to digital twin user interface

The documents collected during the research are categorized under the names according to the CTR list. Then, a folder has been created for each component, where all those documents can be found, and this folder is accessible in the digital twin prototype. This can be done through the 3D model in the user interface, whereby clicking on the buttons, users have the option to open information. When the user selects this option, the selected file is retrieved from the database, and there is the possibility to download or view it directly. Table 15 indicates which component in the 3D model is linked to which folder according to the CTR naming convention.

CTR name	***Component***	***Link to component in 3D model***
M00	Maeslant barrier general	Control office
MN52	Locomobile guidance tower	Not included
MN54	Site facility	Not included
MN55	Ball joint	Button near ball joint
MN61	Retaining walls	Button near dock
MN62	Half-timbered construction	Button connected to Half-timbered construction
MN65	Movement construction	Not included
MN85	Electrical installation	Not included
MN89	BesW (operating system)	Control office

Table 15: A selection of the naming of component according to the CTR system and how these are connected to the 3D model in the user interface.

7 Use cases for the digital twin

The applications the digital twin could provide are elaborated into three cases, that describe scenarios in which the digital twin can be used. The use cases are based on the prototype developed within this EngD research and supplemented with possibilities for future digital twins. In Table 16 an overview of the use cases is given and also what their link is to the applications that were researched in Chapter 4. For each use the following aspects are described: current situation, application of digital twin prototype, results and new insights, and future possibilities. All three cases are shown based on actual data, either of a test closure of the Maeslant barrier or of individual component tests.

Use case	**Link to application (see Table 10)**
Case 1: Analysis of closures based on observations	• Direct availability of data • Cost savings on external reports and advice
Case 2: Knowledge conservation and transfer: hydrostatic forces example	• Increase of the findability of information and knowledge • Increase ability to independently obtain knowledge for new staff members • Reduce time required for knowledge transfer
Case 3: Observing abnormal behaviour and Inclusion in risk assessment	• Reduce time required for reporting and risk calculation due to automated processes • More accurate risk determination due to increasing insight in barrier's behaviour

Table 16: A summation of the use cases and the links to the required applications, that were researched in Chapter 4

7.1 Case 1: Analysis of closing procedures based on observations.

Use case 1 explores the potential of digital twins to analyse past closures and data. The relevant datasets in this use case are:

- Position of the retaining wall (horizontal, vertical and skewness)
- Water levels, valve positions and pump power in the retaining wall's compartments.

Current situation

Part of the ProBO (see Section 3.3) method is to evaluate every closure after the mission is ended. Therefore, after each closing mission, the closure data are analysed by specialists. Based on this analysis, the status and functioning of the barrier is reported towards the asset management department. This analysis is currently for the most part carried out by an external engineering consultancy firm. This process, however, takes several months to be completed, is expensive and makes Rijkswaterstaat dependent on a single party to analyse the closing procedure. As soon as the company has been commissioned to do the analyses, it is difficult for Rijkswaterstaat to adjust in this commission. It is desirable for Rijkswaterstaat to be more in control of this process and less dependent on external sources.

Application using digital twin

The digital twin provides a platform in which the specialists at Rijkswaterstaat can analyze closing missions of the barrier themselves and can compare them to other historical closing procedures. To do so, measured data from multiple sensors installed across the barrier (e.g., water levels, pump power, barrier position, valve positions, etc.) are visualized in the digital twin. Based on these measured data, the digital twin animates the barrier's closing mission, allowing technical experts to visualize the barrier's response to environmental conditions. This gains experts valuable insights into the barrier's performance under different scenarios.

Animation of closure

The Maeslant barrier experts can select a range of measured data they would like to analyze in the user interface of the digital twin. This could for instance be the data measured during a closing procedure, which can be imported by entering this closing procedure's time range (see Figure 29). The experts analyse the closing of the barrier by watching the animation and try to notify any deviations (from the expected behaviour) in the movement of the barrier. For the retaining wall, they focus on the key parameters (as described in Section 3.2.2) to monitor the behaviour of the barrier. It sometimes helps them to use the possibilities to slow-down or speed-up the animation, or to amplify a certain effect (e.g. the pitch of the wall, the light skewness of the retaining wall that is explained in Section 3.2.1), to notify differences that are not visible by the naked eye. When deviations are notified by the experts, the animation can be paused, and specific data can be opened for more detailed analysis. This process is schematically visualized in Figure 29.

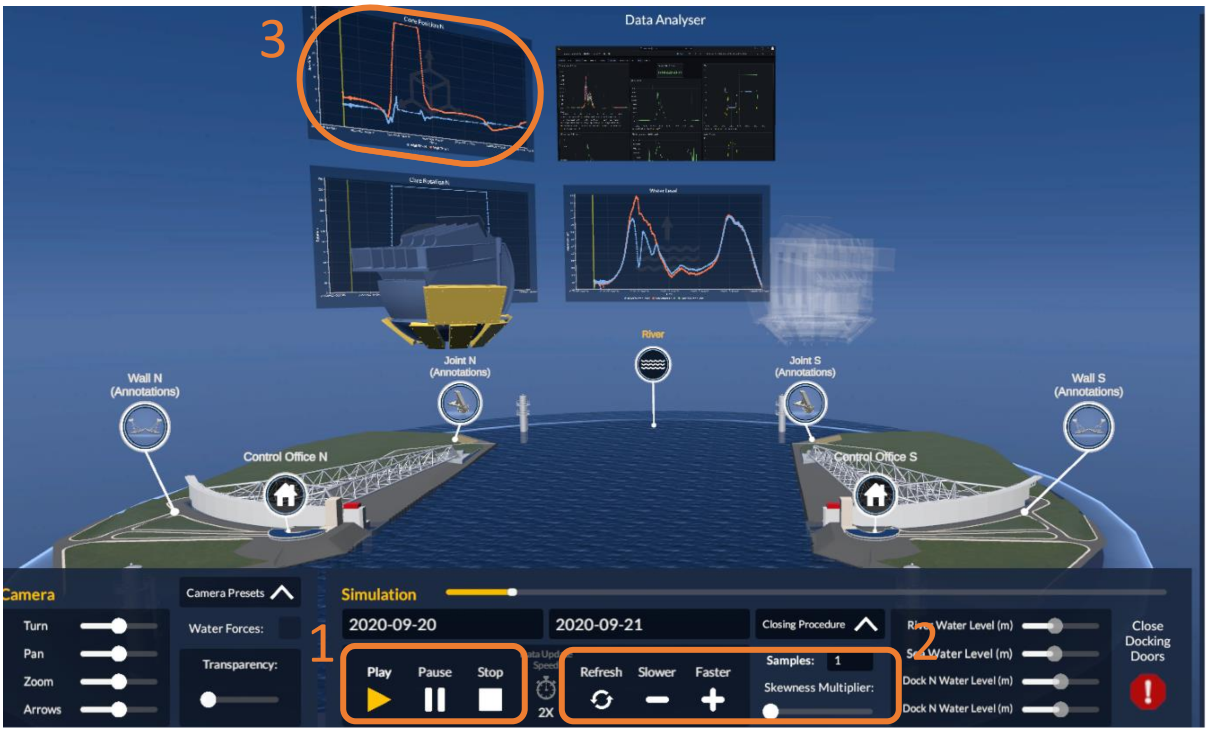


Figure 29: The digital twin is used for the test closure of the year 2020 to 1) animate a closing procedure, 2) accelerate or slow down the procedure and amplify the pitch effect of the wall and 3) open specific data for further analysis. In this case the following information is shown in the third panel: the vertical position (red line) and skewness (blue line) of the retaining wall.

Results and new insights

The digital twin provides insights that are directly valuable for improving (knowledge about) the closing procedure. For instance, the experts observe the retaining wall displaying strange behaviour for the pitch during refloating phase (see Section 3.2.1). In this phase pumps are used to lower the water level in the compartments. The experts replay this phase in a higher velocity and note the water level in one of the compartments in the retaining wall tends to lower more slowly compared to the other compartments. They open the data analysis functionality and select the data of the valves, pumps, and water levels of that specific compartment, call one of the connected models to calculate the discharge per pump and compare the data. When comparing this data, it is noticeable that one of the pumps is pumping only half the discharge compared to the other pumps in the compartment, while still using the same power. This is an indication this specific pump is not performing well. Therefore, the asset manager is given a sign that this pump probably needs maintenance and must be inspected. The process is schematically visualized in Figure 30.

Future possibilities

The experts are of course not capable of capturing every small deviant behavior of the barrier. Therefore, on the background, different models are constantly running that support the experts in the analysis process. For instance, Artificial Intelligence models that automize the data analysis process. Although this is something that is not included in the prototype yet, it is something that is a valuable addition in future digital twin models. These models run automatically together with the animation of the closing procedure and give warning signs when deviant behavior is noticeable in the data. When the models are trained with expert knowledge or historical experience, it provides warning signs to the experts, who are therefore capable of analyzing the closing procedure more quickly and more accurately, saving them time to focus on other cases.

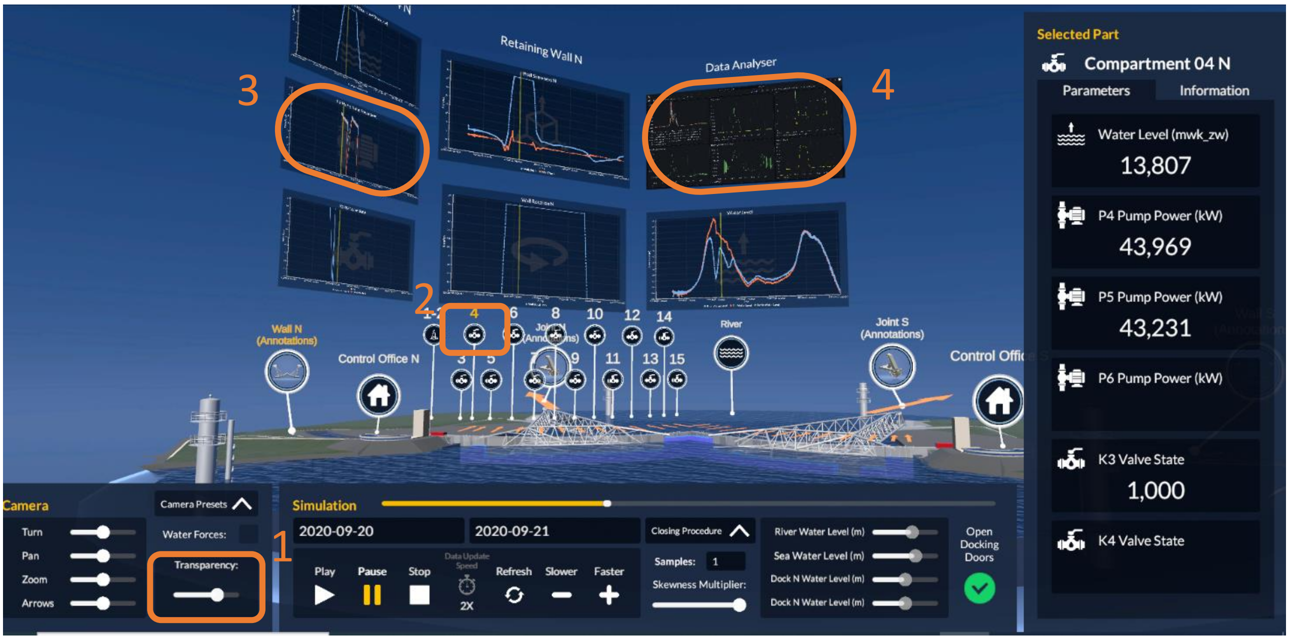


Figure 30: The digital twin is used to 1) visualize the amplified pitch position of the retaining wall, 2) make the wall transparent and notice deviations in compartment 4 in the water levels, 3) open the data of that compartment and 4) further analyse the data. The data in this example is based on measured data during the 2020 test closure.

7.2 Case 2: Knowledge conservation and transfer: hydrostatic forces

This case study describes an application scenario for a digital twin as a knowledge conservation and transfer platform for the Maeslant barrier. The relevant datasets in this use case are:

- Hydrostatic forces acting on the retaining wall (calculated by a model)
- Water levels on the sea- and riverside, and in the dock
- Position of the retaining wall (horizontal, vertical and skewness)

Current situation

Knowledge transfer at the Maeslant barrier currently relies on (training) documents supplemented with explanations from specialists. For new employees at Rijkswaterstaat, it is quite challenging to locate the correct documentation without the assistance of specialists. Acquiring in-depth knowledge about the functioning of specific components or occurring phenomena is therefore difficult to achieve independently. Additionally, it is crucial to experience the closing process in practice, which is possible once a year during the operational closure of the barrier. It is desirable for Rijkswaterstaat to visualize the closing process, especially the scenarios that can occur during that process, without solely relying on these practical experiences and documentation only. This applies to many topics; in this use case, the example of the hydrostatic force on the barrier is taken as an illustration.

Application using digital twin

The animation and visualization capabilities of the digital twin are used to support in the education process for new staff members of the barrier. Users can animate scenario's (measured or simulated) in the digital twin and get visualized how, in this example, the hydrostatic force acts on the retaining wall, therefore influencing other components. Subsequently, staff members can partly educate themselves the basics of the barrier using the digital twin. For the more complicated cases, like explaining the *tangential force on the locomobile* (see Appendix B), specialists can use it in collaborative workshops and interactive training sessions, to facilitate cross-functional learning and knowledge sharing.

Hydrostatic force analysis

By running animations of historic or simulated closings of the barrier, a model connected to the digital twin is enabled to calculate the hydrostatic forces, which are visualized indicating their magnitude and direction. This is done using arrows in the direction of the force indicating the magnitude of the force by enlarging or reducing in size (see Figure 31). The model also calculates how the forces are dissolved on the ball-joint, which is again visualized using arrows (see Figure 31).

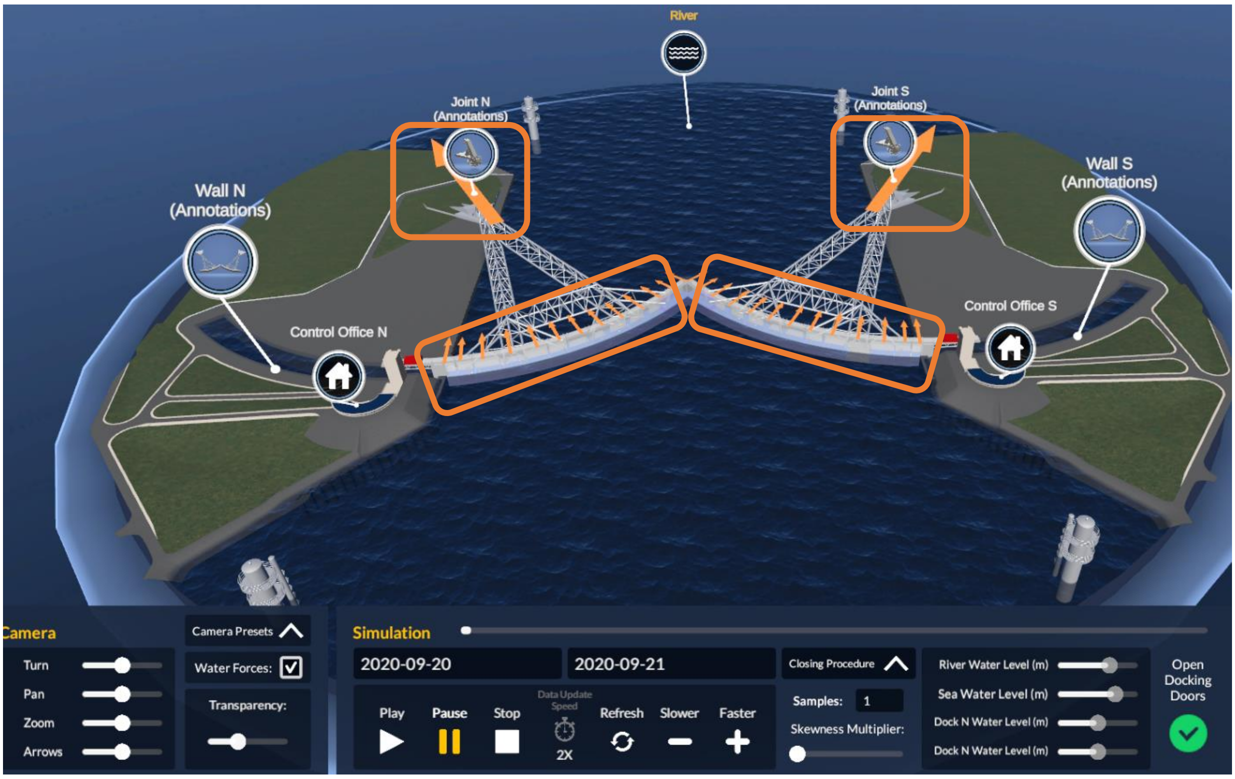


Figure 31: A representation of the way the hydrostatic forces are visualized in the digital twin user interface. It is done using orange arrows (in the panels) that enlarge or reduce in size depending on the magnitude of the hydrostatic forces. The data itself can be opened by clicking on the buttons connected to the components in the retaining wall.

To analyze the development of these hydrostatic forces during a closing, different data panels can be opened that show graphs of the data. This provides the opportunity to compare the calculated data of the hydrostatic forces to measured data like: river- and seawater level or horizontal-, vertical- and pitch-positions of the retaining walls, water levels in the retaining wall compartments or valve positions (Figure 32).

Results and new insights

The visualization of the hydrostatic forces provides especially new staff members a quick(er) insight into the way forces work on the barrier. It also helps specialists to explain step by step where in the timeline the interesting developments are, and which parameters influence them. The specialists can use the data panels to indicate the relations between parameters or zoom in to indicate details that could be important. For instance, it demonstrates that the hydrostatic forces acting on the retaining wall not only cause a force in the radial direction, but also cause a light tangential force on the ball joint. This effect is caused by non-uniform loading of the retaining wall because of the skewness during the sinking process and becomes visible when both datasets are compared to each other (see Figure 33). Although this effect is only small compared to the force in the radial direction of the ball joint, it is still an effect one should be aware off. Since the new staff member already has the basic knowledge of the forces due to self-education, the expert can focus on these kinds of details instead of having to spend valuable time on the basics as well.

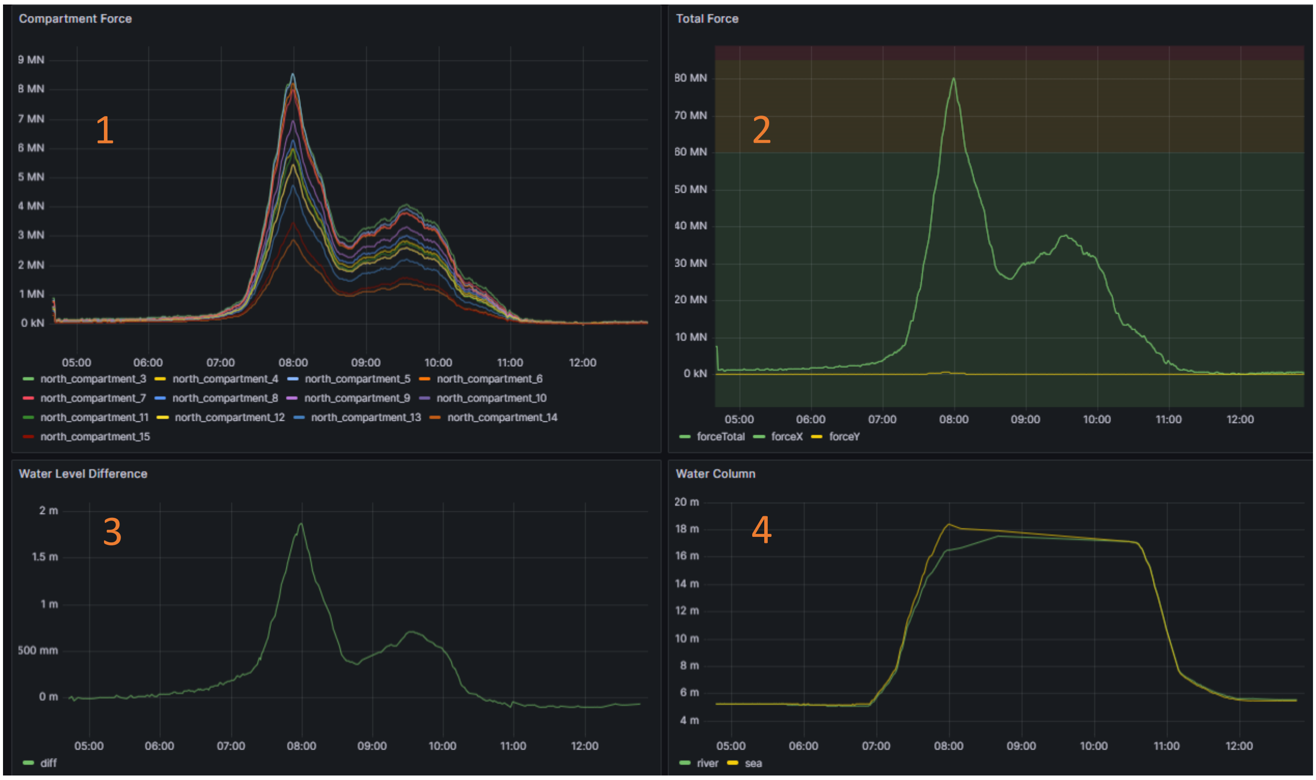


Figure 32: An example of a data analysis panel to show/explain how forces work and which parameters are involved. In this figure 1) represents the hydrostatic force of each compartment in the retaining wall, 2) represents the total radial and tangential force, 3) is the water level difference between the seaside and river side of the barrier and 4) represents the water head on the sea- and river side of the retaining wall.

Figure 33: When the tangential force (left panel) is compared to the skewness of the retaining wall during sinking (right panel), one notifies a same pattern in the data.

Future possibilities

In more advanced versions of the digital twin, more advanced models can be included that also calculate the hydro-dynamic forces acting on the retaining wall. These forces are caused by waves and dynamic flows under and around the barrier. These models should provide more insight in the details around phenomena like the mystery forces. Using the already existing visualization possibilities of the digital twin, this helps staff members of the barrier to better understand which parameters influence this phenomenon.

7.3 Case 3: Observing abnormal behaviour and including risk assessment.

This use case demonstrates the possibility of using the digital twin for observing abnormal behavior (based on data analysis) and assessing its impact on the probability of non-closure. Additionally, the digital twin is used to explore the efficacy of mitigating measures. The relevant datasets in this use case are:

- Water levels, valve positions, pump power and discharge (calculated) in the retaining walls' compartments.
- Failure probability (calculated)

Current situation

ProBO (Probabilistic Based maintenance, see Section 3.3) is one of the core processes of the Maeslant barrier, all changes and actions (e.g., changes in maintenance) have to be assessed for their potential effect on the failure probability. In the current situation, the failure probability manager within the Maeslant barrier team is the person with complete knowledge of the (current) barrier's failure probabilities. Team members at the barrier depend on the failure probability manager's expertise (and time) to assess the failure probabilities of components. If employees want to assess the impact of certain actions or changes, they rely on the failure probability manager for an assessment. This process is inefficient as the failure probability manager is often busy and lacks time to assist everyone quickly. It would be more efficient if, for example, asset managers or technical specialists can make an own initial assessment of the impact of failure probability changes.

Application using digital twin

The digital twin includes a model to calculate the failure probability of the barrier. This model, based on the minimal cutsets derived from the fault tree analysis (see Section 3.3), can be used to determine the effect of actions. The user can simulate components of the barrier to be more reliable, less reliable, or to let them malfunction. The impact on the overall failure probability of the barrier is then calculated by the model (see also Section 6.3.2). For this use case, an example is chosen of an asset manager investigating the impact of a different form of maintenance to pumps, which he/she thinks is possible based on data analysis, but its effect on the failure probability needs to be assessed.

Using analysis of pump tests for adapted maintenance.

The asset manager opens the data analysis panel in the digital twin and selects the data of all pump tests from the past 5 years. In the panel, a dataset appears showing all measured signals, pump powers and compartment water levels of the past 5 years (see Figure 34 for an example of 1 pump test). The data analysis panel provides the possibility to calculate the discharge the pumps delivered, which can be compared to the amount of measured power (see part 2 of Figure 34). The discharge is calculated by a model that uses the geometry of the compartment, in combination with the water level data, to determine how much water per timestep flows out of the compartment. The asset manager now wants to know if one of the pumps delivered a lower discharge (with respect to the measured power) than the other pumps. And if so, how urgent it is to replace or maintain the pump. Therefore, a quick calculation can be made using the failure probability model (see Figure 35), to estimate the risk of not urgently fixing the pump.

Figure 34: The pump data (1) can be analysed via the data analysis platform in the digital twin, this also provides the possibility to calculate the pump discharge (2).

Results and new insights

If the data indicates that one of the pumps is performing significantly less than the other pumps, for instance because it delivers only half the discharge using the same amount of power as the other ones, this pump needs maintenance or replacement. The asset manager needs to know if this maintenance is urgent, or the situation can be investigated first. This is quickly answered using the failure probability model. First a standard situation with no differences, i.e., a perfectly working pump, is calculated (see part 1 in Figure 35). Secondly the situation with the failed pumps is simulated (see part 2 in Figure 35). In this case it indicates that the overall barrier failure probability increases with 0.1%, indicating that it is not an urgent task. This provides the asset manager the opportunity to seek for another, potentially cheaper, solution for this problem.

Future possibilities

The data analysis that is performed by the asset manager in this use case is a task that can be automated in the future. In the current approach, the model depends on the cutsets of the fault tree, which could change in time. In the future, the digital twin and the original fault tree can be coupled.

Artificial intelligence models can analyse the data and pick discrepancies from the data automatically. The model gives the asset manager a signal when components perform less, in which immediately an indication if given for the risk of not intervening. When the situation turns out to be urgent, the asset manager can immediately contact the operational technicians to start investigating the pump. If the technicians are not familiar with the pump itself, the asset manager can use the 3D environment of the digital twin user interface to brief them about the situation.

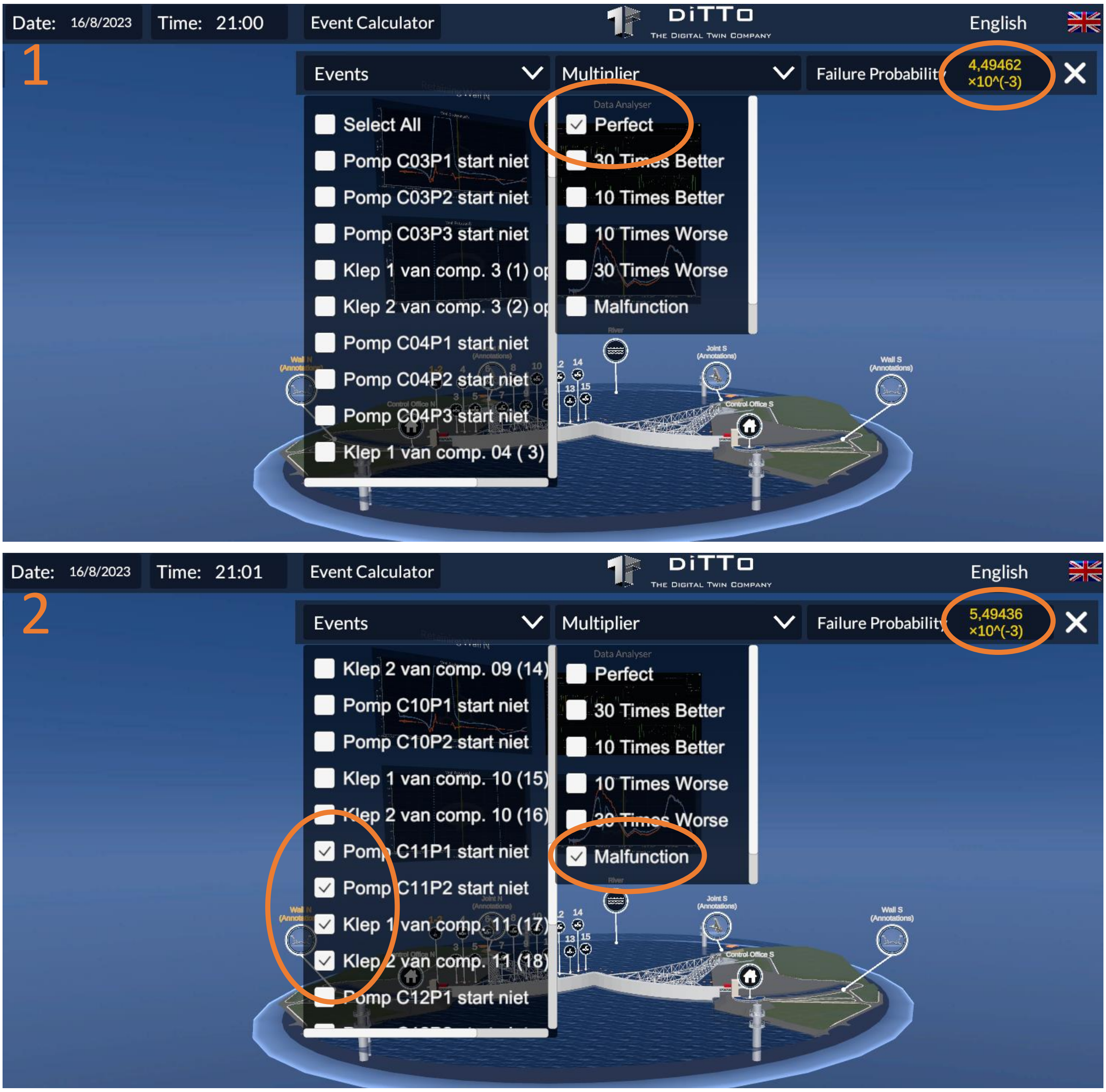


Figure 35: An example of using the failure probability calculator to simulate an event and calculate the impact. In this figure the failure probability is calculated for 1) the situation without any deviations and 2) a scenario where the pumps of compartment 11 have failed.

8 Testing and results

With the digital twin designed, the use cases defined, and the prototype developed, the last phase is to test whether the digital twin meets the potential applications, as defined in Chapter 4. To dive deeper into this subject, the user experience of potential users of the digital twin becomes relevant. Therefore, a testing procedure is set up to measure the user experience of individuals when working with the digital twin prototype. This is done by asking individuals that have jobs related to the Maeslant barrier (in any form) for their opinion about the prototype. Amongst other by asking them to use the prototype themselves.

8.1 Testing protocol

To test the digital twin prototype, a test panel has been assembled. During the interviews that were held to determine the potential application of the digital twin (see Section 4.1), the Zachman framework formed the basis for the composition of this test panel. For the prototype tests, the intention is to invite several individuals from each layer of the same framework to participate. These individuals were approached based on their roles within Rijkswaterstaat and their involvement with the Maeslant barrier, and they were asked to participate in the test. A selection is made in which also the panel members from the interviews of Section 4.1 were invited. The Executive role is left out of the testing panel since he/she will be no active user of the digital twin, the Architect is also left out since this is in this case the role of the researcher. For all other roles in the framework, a minimum of two persons are selected that can (given their function and experience within Rijkswaterstaat) critically judge the prototype.

Zachman role	*Number invited*	*Number of respondents*
Executive	Not involved	-
Business management	5	4
Architect	Own role	-
Engineer	6	4
Technician	4	2
Enterprise perspective	4	1

Table 17: The Zachman framework and the number of individuals invited to participate in the tests.

Subsequently, the testing procedure is done according to the following protocol.

1. The test panel participant is first instructed on the functioning of the digital twin prototype.
2. The use cases of the digital twin prototype are shared with the participant to indicate the capabilities of the prototype.
3. Every panel member is asked to perform several actions in the prototype. The type of actions the panel member is asked to do depends on the role he/she has within Rijkswaterstaat.
4. After executing the asked actions, the panel member is asked to try to use the digital twin for a purpose he/she wants to use it for.
5. After both actions, the panel member is asked to answer several questions regarding the testing of the prototype. This is done via an online questionnaire (see Appendix J for the questions asked).

8.1.1 Questionnaire

For this testing procedure several aspects are important to check to provide a complete image of the testing results. It means the prototype is tested on the following aspects:

- **Digital twin prototype functional verification and performance** This test is done to test if the digital twin prototype's virtual model accurately represents the real world. It is done to identify and address any discrepancies between the virtual model and real world. To identify any potential issues or limitations in the digital twin, the model's performance is tested extensively. This helps to improve the overall performance of the digital product.
- **Compliance** The digital twin must be checked on whether it meets the requirements that were set by the potential users in the pre research, as described in Section 5.1.

- **Scalability** Since the tested product is in this case a prototype of an element of the Maeslant barrier, scalability is an important factor to test. This indicates whether the prototype model is robust enough to be implemented over the entire barrier.

The types of questions that were asked to the panel members after testing the prototype are meant to measure their opinion on different purposes of the digital twin. To set up these questions, first several factors are determined that need to be answered in order to receive a complete vision of the test panel's opinion of the digital twin. The factors of importance, including the testable aspect, for these questions are:

- Representation of reality (*functional performance*)
- User comfort (*functional performance*)
- Ability to find information (*compliance*)
- Ability to analyse data (*compliance*)
- Knowledge transfer ability (*compliance*)
- Usability of models to make new information (*compliance*)
- Simulation / animation possibilities (*compliance*)
- Ability to gather new knowledge (*compliance*)
- Potential efficiency in asset management (*scalability*)
- Potentially improvement and insight into probability of failure (*scalability*)
- Potentially better insight into the current state of the object (*scalability*)

The complete questionnaire is available in Appendix J.

8.2 Test results

8.2.1 Overview and summary

The answers to the questionnaire form the input to verify whether the digital twin prototype meets the user requirements of Chapter 4. The results from the testing panels are presented into three different categories:

- Digital twin prototype user interface experience (questions 5-8, further information in Section 8.2.2)
- Digital twin prototype application (questions 9-14, further information in Section 8.2.3)
- Digital twin potential and scalability (questions 15-22, further information in Section 8.2.4)

In Section 8.2.2 to 8.2.4, the response of the respondents is presented. The questions in which was asked to provide a rated answer (on a 1 to 5 scale) are presented in a table. In these tables, the rated scores are presented for each relevant question in this category and for each respondent. In Table 18, a summary is presented of the test results, in this case sorted by category and Zachman role of the respondents. The respondents are anonymized and sorted based on the Zachman role (see Section 4.1) they have. The answers to open questions are described in the text. Questions 1 to 4 are related to the role and experience the respondents have within Rijkswaterstaat; therefore, these are not included in Section 8.2.2 to 8.2.4.

Zachman role	***Respondents***	***User experience score (on a 1 to 5 scale)***		
		Prototype user interface	Prototype application	Scalability
Executive	-	-	-	-
Business management	5	3.4	4.1	4.3
Architect	-	-	-	-
Engineer	3	3.9	3.9	3.8
Technician	2	3.3	3.0	2.7
Enterprise perspective	1	3.3	-	3.0

Table 18: Aggregation table of the total result of the prototype tests, sorted per category and Zachman role.

8.2.2 Digital twin prototype user interface and experience

The participants of the test were asked to take the controls of the digital twin prototype themselves and experience the user interface. Afterwards they were asked for their opinions about this user interface, of which the results are presented in Table 19. The questions presented in this table are:

- **Question 5 (Q5)**: How did you experience the navigation and interaction with the digital twin prototype? (On a scale of 1 to 5, with 1 being 'very difficult' and 5 being 'very easy')
- **Question 6 (Q6)**: How would you rate the overall design and layout of the user interface of the digital twin prototype? (Options: scale of 1 to 5, with 1 being 'Not representative at all' and 5 being 'very representative)
- **Question 7 (Q7)**: How self-explanatory (or intuitive) do you find the prototype to be? (Options: scale of 1 to 5, with 1 being 'Not intuitive at all' and 5 being 'very intuitive)
- **Question 8**: Any additional comments, feedback, or suggestions you would like to provide? (open answer)

The respondents' assessment of the user interface of the digital twin is reasonably consistent. They average rate from the users was 3.6 (on a scale of 1 to 5), and as shown in Table 19, there is not much variation int the ratings. Some respondents did provide feedback that the initial navigation was counterintuitive. They expected the controls of the prototype to work in the opposite way in terms of movement.

	Score		
Zachman role	**Q5**	**Q6**	**Q7**
Technician	3	3	3
Technician	4	4	3
Engineer	4	4	4
Engineer	4	4	4
Engineer	3	4	4
Business management	4	4	4
Business management	-	4	4
Business management	4	4	3
Business management	4	5	3
Business management	1	3	2
Enterprise	3	4	3

Table 19: The numerical results of the respondents of the tests, in this table related to the user experience of the user interface of the digital twin prototype.

8.2.3 Digital twin prototype application

For the second part of the questionnaire, we delved further into the application of the digital twin. The emphasis was placed on the specific features that the prototype already possesses and how they could be applicable in the current work of the Maeslant barrier team. The questions related to this subject are:

- **Question 9 (Q9)**: How accurately did you feel the digital twin prototype represented the actual storm surge barrier?
  (Options: scale of 1 to 5, with 1 being 'Not accurate at all' and 5 being 'very accurate)
- **Question 10 (Q10)**: How useful did you find the visualizations and graphical representations in the digital twin prototype for understanding the behaviour of the storm surge barrier?
  (Options: scale of 1 to 5, with 1 being 'not useful at all' and 5 being 'very useful)
- **Question 11 (Q11)**: To what extent does the digital twin improve the findability of information?
  (Options: scale of 1 to 5, with 1 being 'no improvement' and 5 being 'significant improvement)

- **Question 12 (Q12)**: How would you evaluate the overall performance of the digital twin prototype? (Options: scale of 1 to 5, with 1 being ‘not useful’ and 5 being ‘very useful’)
- **Question 13:** Which features do you find most valuable? Please describe. (open answer)
- **Question 14:** Which features do you feel are missing or could be developed to bring additional value? Please describe. (open answer)

When examining the results of this part of the questionnaire (Table 20), it's noticeable that there is greater variation in the given answers compared to the assessment of the user interface. Although the average rating is slightly higher at 3.81 (on a scale of 1 to 5), it's apparent that opinions differ, especially in terms of information findability and data visualization.

When looking at the written responses however, this pattern is less pronounced. In response to the question about which aspect they found most valuable, all respondents answered that visualization of the measured or calculated data, or creating an animation of it, was the most important feature of the prototype.

	Score			
Zachman role	**Q9**	**Q10**	**Q11**	**Q12**
Technician	2	2	2	4
Technician	2	3	5	4
Engineer	4	4	5	4
Engineer	4	4	4	3
Engineer	4	4	4	3
Business management	3	4	5	5
Business management	3	4	4	4
Business management	-	-	4	-
Business management	4	5	5	5
Business management	4	3	3	4
External	-	-	-	-

Table 20: The numerical results of the respondents of the tests, in this table related to the user experience of the application of the digital twin prototype.

8.2.4 Digital twin potential scalability

The final part of the questionnaire focuses on the potential of a digital twin when it is fully developed. The results from this part of the questionnaire are presented in Table 21. The questions presented in this table are:

- **Question 15 (Q15)**: To what extent do you consider yourself capable of independently learning the basic principles of the operation of the Maeslant barrier using the digital twin, without the assistance of a specialist? (Options: scale of 1 to 5, with 1 being ‘Not possible without a specialist’ and 5 being ‘completely independent’)

To what extent do you agree/disagree with the following statement (Options: scale of 1 to 5, with 1 being ‘completely disagree’ and 5 being ‘completely agree’):

- **Question 16 (Q16)**: A fully developed digital twin of the entire Maeslant barrier could contribute to accelerating knowledge transfer processes

- **Question 17 (Q17)**: A fully developed digital twin could help reduce costs for external parties, such as consulting firms or engineering firms.
- **Question 18 (Q18)**: A digital twin could help reduce costs for external parties, such as consulting firms or engineering firms.
- **Question 19 (Q19)**: A digital twin is valuable in supporting decision-making for maintenance and emergency planning of storm surge barriers.
- **Question 20 (Q20)**: How likely are you to recommend the digital twin to others for monitoring and management of storm surge barriers?
- **Question 21 (Q21)**: How well did the digital twin prototype meet your expectations?

When examining the results of this part of the questionnaire, it's noticeable that there is even greater variation in the answers compared to the prototype application (Section 8.2.3). This is most evident in question 15, where respondents were asked whether they envision people being able to educate themselves by using the digital twin. In general, the response to this question is negative, but there are still some respondents who see added value in it. It's also notable that a digital twin is considered a valuable tool when a specialist is involved in the knowledge transfer process, using it to visualize knowledge in the digital twin (question 16). From the respondents the digital twin is not a replacement for specialists in the context of knowledge transfer. It is a valuable tool though for the specialists to transfer their knowledge.

	Score						
Zachman role	**Q15**	**Q16**	**Q17**	**Q18**	**Q19**	**Q20**	**Q22**
Technician	1	3	2	3	2	3	2
Technician	2	4	2	4	2	4	4
Engineer	5	5	4	4	3	3	4
Engineer	4	5	4	3	3	4	4
Engineer	3	4	3	5	4	3	3
Business management	5	5	5	5	4	4	5
Business management	3	4	-	4	4	-	4
Business management	1	4	5	5	-	-	4
Business management	2	5	5	5	5	4	5
Business management	2	5	3	5	4	3	4
External	1	4	-	-	-	4	-

Table 21: The numerical results of the respondents of the tests, in this table related to the user experience of the application of the digital twin potential.

8.3 Additional user feedback

In addition to the scores, users could give written feedback on the digital twin prototype. Some additional comments from respondents with different Zachman roles are presented in Section 8.3.1. In Section 8.3.2 some suggestions for improvement from the respondents are presented.

8.3.1 Written comments

The test panel members had the opportunity to provide written comments on the digital twin prototype. All written comments are included in the following section. In summary, it can be concluded from the comments that there are concerns about implementing a full-scale digital twin. There is doubt about whether the organization is ready for it and whether Rijkswaterstaat can maintain control over the digital twin. This valuable input pertains to the organizational feasibility, as discussed in Section 9.3.

Comments

Business management: "The prototype is an important step towards the development of digital twins. If I focus on the gates, I would like to see the prototype further developed by adding better models for forces, establishing a connection with fault tree analyses (to support reliability-centered maintenance), and linking it with the A-omgeving (to enable other scenarios and automatic use of better models). Additionally, I am in favor of expanding the scope to include other structural components and spatial modeling to bring other functionalities into view: a testing environment for software reliability, force analysis during closure (locomobile, mystery force), etc. In parallel with this expansion, internally at RWS, we will have to think about the architecture of DTs and their management. If we place DTs so centrally, then their approach should receive (almost) as much attention as the construction and maintenance of the actual object."

Engineer: "Question 15: "The basic principles of how the Maeslant barrier operates" – the definition will differ for everyone. It would be nice if standard storm scenarios could be simulated. For training purposes, it would be useful to include an operator and learner option."

Engineer: "The more the model can do, the greater the risk of 'nonsense' due to increased complexity. Verification of digital behavior based on measured behavior is essential. Additionally, the question is, 'who is the manager of the digital twin'? Who determines what, when is good enough to connect, who is responsible for input validation and output verification, which data is real-time only, which needs to be stored, where and for whom, who provides training for use, who is allowed to use it? Who can propose, implement, and accept model improvements?"

Business management: "It is difficult to see the added value of the twin in a business case. Depending on maintainability and availability, more is possible, but if Rijkswaterstaat is not able to control this model independently, I fear that this initiative could fade away. It should be the primary tool for analyzing maintenance, usage, and fault data. Data representation can certainly help predict maintenance, but it also requires a different approach at Rijkswaterstaat."

Engineer: "I would first further develop the concept of deploying and managing the digital twin before proceeding with further construction (via a growth path). This way, we can build a more uniform foundation so that the Digital Twin remains usable and maintainable in 10 years. Keep up the good work! And I am curious about what comes next."

8.3.2 Suggestions and wishes for improvement.

In general, the written responses from the respondents can be summarized into several positive and negative points. They consider the ability to visualize and easily locate data as a highly positive aspect. Additionally, they view animating the dynamic behavior of the barrier, including visualizing the forces at play, as a valuable tool for explaining how the barrier operates. On the negative side, they found the use of the user interface somewhat challenging to understand without prior explanation. The navigational aspect is counterintuitive, leading to confusion. Additional to the positive and negative point, the respondents also indicated which elements could be added to the prototype. In Table 22 the suggestions, which could also be interpreted as a wish list, from respondents for extension of the digital twin prototype towards a full digital twin are summarized.

Stakeholder	Suggestions for improvement
Service	Widening scope to create an environment for reliability of software operation and control
Data interaction	Add to digital twin: • On/off moment of pumps and valves • Real-time information of continues parameters (e.g. water levels in canal) • Error and maintenance information
Accurate representation	A more detailed 3D model, for instance opening a more detailed 3D model of a specific component by selecting it
Model connection	Make connection from digital twin to: • More detailed water force models and expand models to visualize force on locomobile (mystery force) • Fault tree software • A-omgeving (data simulation) • FEM model of the retaining wall and/or arms with hydrodynamic wave loading to assess forces, from experienced loads, on design-identified critical cross-sections • FEM model of the locomobile to also identify forces due to the dynamic behavior of the retaining wall. • SOBEK model

Table 22: A wish list with suggestions from respondents for extension of the digital twin prototype into a full digital twin

9 Feasibility of a full-scale digital twin

The feasibility of a complete digital twin for the Maeslant barrier is evaluated for three categories: Technical, Economic and Organizational. The technical feasibility is investigated by checking the technical possibilities the market currently offers and relate this to the state of the soft- and hardware of Rijkswaterstaat. Next, the economic feasibility is evaluated in a business case study. In the organizational feasibility, a test phase of the digital twin prototype is described to provide insight into the readiness of the Rijkswaterstaat organization to extend and implement a digital twin.

9.1 Technical feasibility

The technical feasibility of the digital twin assesses the practicality of constructing a digital twin using the technology currently available in the market. To discover what the technical needs for successful implementation are, the different elements that have led to a successful implementation in other industries are further researched. This leads to several required components that need to be on a decent level for successful implementation. From a high-level perspective, these are categorized into: hardware- and software maturity.

This section is limited to a description of the state of the hard- and software at Rijkswaterstaat. Appendix 0 provides a detailed description of the required hard- and software equipment for a digital twin. A summary of this detailed description is given in Table 23.

Required	***State at Rijkswaterstaat***	***Sufficient for digital twin usage?***
Hardware		
Data collecting devices such as sensors, actuators, and cameras, also known as the Internet of Things (IoT) devices	Most of the data collecting devices are old but in a reasonable well-functioning state.	The quality of the measured data is good enough to import in the digital twin
Computing power	Most devices for computing power are more than 5 years old.	Needs to be upgraded
Networking infrastructure and connectivity between data source and digital twin	Cyber security prevents direct accessibility to data sources	Needs te be improved
Software		
Modelling and simulation tools	Present but only accessible via a stand-alone computer	Very useful, if the software is accessible from an external computer
Data integration and analytics software	Not or very poorly present. Data analytics is outsourced	Not usable
Visualization and user interface software	In a limited form present for the *A-omgeving*	Not very useful due to inaccessibility from outside
Connectivity and communication software	Not investigated	-
Security and data privacy software	Not extensively investigated	The current policy on cyber security prevents (to a certain extend) the development of a full-scale digital twin

Table 23: A summary of the current state of hardware and software within the Maeslant barrier operations and maintenance team

9.1.1 State of hardware at Rijkswaterstaat

At the Maeslant barrier, hardware technology is not as advanced as the market currently provides. The data collecting devices (sensors, camera's), are quite advanced and deliver large sets of usable data. These data, however, still need to be collected locally and can't be reached via a network connection due to Rijkswaterstaat's policy on cyber security. Although the technical facilities (network infrastructure) to automatically collect the data are present at location, the policy obstructs this development. This means that, to develop a state-of-the-art digital twin with live data updates, policy on cyber security needs to be changed within Rijkswaterstaat. This may complicate a full implementation.

When this state-of-the-art and detailed digital twin of the entire Maeslant barrier is built and runs at a Rijkswaterstaat location, the current availability of computing power is probably not sufficient. It means new devices need to be bought that can support the models that are connected to the digital twin. It goes too far for this report to go into detail about which types of devices need to be bought however, one should think of a range of new routers, edge servers, IoT gateways, etc.

9.1.2 State of software at Rijkswaterstaat

The software at Rijkswaterstaat is in a relatively poor state in certain aspects, see also Table 23. The software is either outdated or not developed in a user-friendly manner for the people who need to work with it. This was also revealed in a recently published report by the Ministry of Infrastructure and Water Management [41]. Therefore, establishing a connection between highly advanced digital twin software and the existing operating system at the Maeslant barrier could pose a challenge. For instance, the existing operating and control system (BesW) dates back to 2012, which, in software terms, is considered very old [32]. History has also proven that software development or implementation projects within Rijkswaterstaat are not always succesful [41], indicating that this could be a risk factor when developing a digital twin for the Maeslant barrier.

9.1.3 Technical feasibility

The state of software and hardware at Rijkswaterstaat is not particularly good. Many software systems are outdated, and there appears to be significant room for improvement in internal networks and cybersecurity. However, when looking at the market, it's evident that there is more than enough technology available to build a full-scale digital twin. There are plenty of examples, as seen in Appendix A. Consequently, it will be technically possible to develop a digital twin within Rijkswaterstaat. However, this will require a serious upgrade of existing software and hardware.

9.2 Economic feasibility

A business case study has been performed to investigate if a digital twin for the Maeslantbarrier could be cost effective. The business case study is done by estimating the expected investment costs (Section 9.2.1) and benefits (Section 9.2.2), from which a Return on Investment (ROI) expectation is derived. This section is a summary, Appendix L evaluates further on this business case study.

9.2.1 Expected investment costs

To get an indication of what the cost reduction should be to make a full-scale digital twin financially feasible, an estimation is made of the expected development costs and benefits. In this case, the cost estimate is linked to the 5-step approach for a digital twin development (see Section 2.2) and based on the experience of developing the prototype digital twin. The benefits are estimated based expected time savings.

Expected investment cost.

The estimated amount of hours and extra cost for developing a full-scale digital twin are summarized and presented in Table 24 and Table 25. The hours are in this case estimated by extrapolating the hours spent to develop the prototype (see also Appendix L), to which the additional development costs are added. To get an indication of the expected costs for labour, an hourly rate of €120, - per hour is used, which is an average rate for the type of engineering consultancy firms involved with developing this product. This creates an estimate of the investment cost (CAPital EXpenditure, or CAPEX) and the maintenance cost (OPerational EXpenditure, or OPEX), which are presented in Table 24 and Table 25. For a more detailed explanation of the costs, reference is made to Appendix L.

CAPEX Cost aspect	***hours***	***CAPEX (€)***
Labour for software		
Step 1: Architecture		€ 150.000
Step 2: Data monitoring & Architecture	*2640*	€ 316.800
Step 3: Integration live data & Models	*5200*	€ 624.000
Step 4: Integration knowledge	*3120*	€ 374.400
Step 5: Sub system integration	*2000*	€ 240.000
Visualization		€ 100.000
Hardware		€ 2.000.000
Total		**€ 3.805.200**

Table 24: An estimation of the initial investment costs (CAPEX) for developing a full-scale digital twin

OPEX Cost aspect	***hours***	***OPEX (€)***	**Comment**
Assets			
Infrastructure		€ 20.000	Assumed relatively low in OPEX due to high CAPEX
Data management	250	€ 12.500	Assumed to be internally organized
Software maintenance	520	€ 60.000	Commercial hour rate used (€120 per hour)
Integration and connectivity	100	€ 5.000	Assumed to be internally organized
Analytics and simulation updates	250	€ 30.000	Commercial hour rate used (€120 per hour)
User support and training	500	€ 25.000	Assumed to be internally organized
Security and compliance	250	€ 12.500	Executed in cooperation with RWS CIV
Lifecycle updates	100	€ 12.000	Commercial hour rate used (€120 per hour)
Total		**€ 177.000**	

Table 25: An estimation of the operation and maintenance costs (OPEX) of the digital twin

Using the CAPEX and OPEX estimate presented in Table 24 and Table 25, combined with a Net Present Value (NPV) [42] and an Equivalent Annual Annuity (EAA) [42] calculation, the required profitability of the digital twin is determined for multiple payback periods, using an interest rate of 6%. This provides insight in what the project's profitability should be, given a certain payback period. The results are presented in Table 26, in which both the investment (CAPEX) and annual maintenance cost (OPEX) are taken into account. Appendix 3 provides a table in which also the NPV of the investment times is incorporated.

The results from Table 26 indicate that, for a digital twin to be beneficial within 5 years, the annual benefits should be in the order of €1.000.000,-. This number decreases when a longer investment time is taken, however, since a digital twin is a digital product, the lifespan of soft- and hardware is expected to be in the order of 5 years. Therefore, from now on, it is assumed the digital twin should provide **€1.000.000,-** in benefits each year in order to be a worthy investment for Rijkswaterstaat.

Cost aspect	1	2	3	4	5
Step 1: Feasibility					
Sub-Total EAA	€ 169.000	€ 91.524	€ 65.540	€ 52.432	€ 44.479
Step 2: Data monitoring & Architecture					
Sub-Total EAA	€ 385.808	€ 221.338	€ 165.634	€ 137.144	€ 119.556
Step 3: Integration live data & Models					
Sub-Total EAA	€ 711.440	€ 388.896	€ 280.561	€ 225.799	€ 192.484
Step 4: Integration knowledge					
Sub-Total EAA	€ 446.864	€ 252.755	€ 187.183	€ 153.767	€ 133.230
Step 5: Sub system integration					
Sub-Total EAA	€ 304.400	€ 179.449	€ 136.903	€ 114.980	€ 101.324
Visualization					
Sub-Total EAA	€ 106.000	€ 54.544	€ 37.411	€ 28.859	€ 23.740
Hardware					
Sub-Total EAA	€ 2.120.000	€ 1.090.874	€ 748.220	€ 577.183	€ 474.793
Total EAA	**€ 4.210.512**	**€ 2.247.341**	**€ 1.590.355**	**€ 1.259.991**	**€ 1.060.337**

Table 26: Equivalent Annual Annuity Cost (EAA) of the investment and maintenance cost, given a certain payback period of the project. For each step in the development phase a range is given for the expected CAPEX (a lowest and highest estimation), therefore also

9.2.2 Expected benefits

To estimate the benefits of the digital twin, the added value of each development step of the 5-step approach is estimated. This is done by making an estimation of the amount of time the Rijkswaterstaat staff could save using the digital twin. The use cases, as defined in Chapter 7, formed the basis to make this estimation. In Appendix L a full description of the motivation for the expected benefits is given, this section only contains a summary of these findings.

The most vital added value elements of a digital twin applied on the Maeslant barrier are: the efficiency increase in knowledge and information management, findability/analysis possibilities of data and the reduction on risk determination cost. The individual added values are summarized in Table 27.

All assumptions considered, a digital twin is considered to be cost efficient for Rijkswaterstaat. The total yearly benefits (€1.125.000,-) the digital twin could generate transcend the expected yearly investment costs (€1.000.000,-), when an investment period of five years is considered.

Application	***Estimated savings***	***Quantification***
Increasing the efficiency in knowledge and information management	40% in savings of the barrier's knowledge and information management budget	€ 275.000,-
Avoid unnecessary cost due to better monitoring of the barrier status	5% in savings of the barrier's total maintenance budget	€ 550.000,-
Better risk management due to models and the data-analysis platform	2 FTE per year in savings for the staff	€ 200.000,-
Creating new insight in the barrier's behaviour	1 FTE per year in savings for the staff	€ 100.000,-
Total savings per year		**€ 1.125.000,-**

Table 27: A summary of the benefits a digital twin could generate for Rijkswaterstaat

9.2.3 Sensitivity analysis

The assumptions that were made in Section 9.2.1 and 9.2.2 to estimate the cost and benefits of the digital twin are not always free of risk, since the assumptions were made with relatively low information. Therefore, to get an idea of the financial risks that are related to these assumptions, a sensitivity analysis is made. For this analysis, the benefits are considered to be overestimated or underestimated by 25%. These scenarios are indicated in Figure 36, where a negative scenario means an over-estimation of the benefits and a positive scenario means an underestimation of the benefits. This provides a spread of the Return On Investments (ROI) of the digital twin.

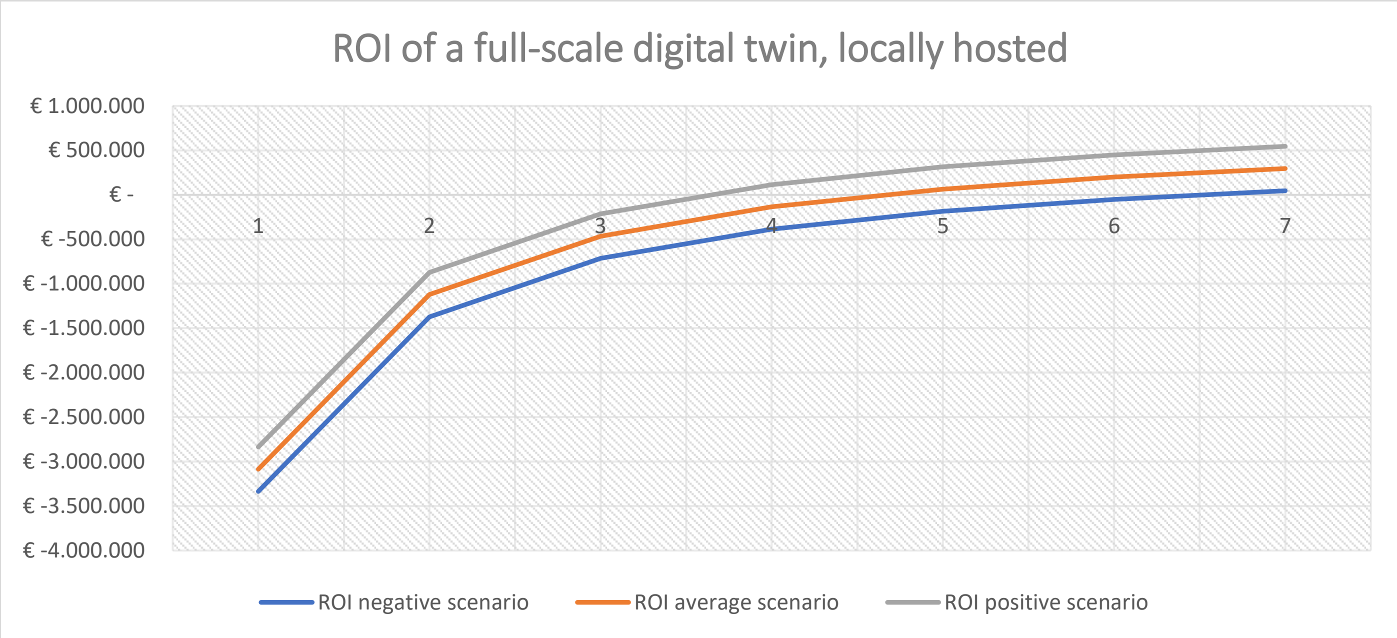


Figure 36: An indication of the spread of the financial risk when the benefits appear to be overestimated (ROI negative scenario), correctly estimated (ROI average scenario) or underestimated (ROI positive scenario). This is for the case where the digital twin is locally hosted.

Figure 36 indicates that the return on investment time differs when the different scenarios are considered. For a negative scenario, the digital twin becomes cost effective after 3 years, while for a negative scenario this is after 7 years. It indicates that the investment could be risky, meaning the benefits need to be evaluated in more detail in a next study.

Since the sensitivity of the full scale digital twin appears to be high, a second scenario is considered. In this scenario the benefits of the digital twin are considered equal, however, in this case the digital twin is not hosted locally, but at an external server. In that case the procurement of hardware is not present, therefore saving €2.000.000,- on investment cost. It does however mean that the hosting cost and cyber security cost are higher (in this case assumed to be €200.000,- per year). When this situation is considered however, see Figure 37, one notices that the financial risk is significantly lower, as well is the ROI time (2 to 4 years).

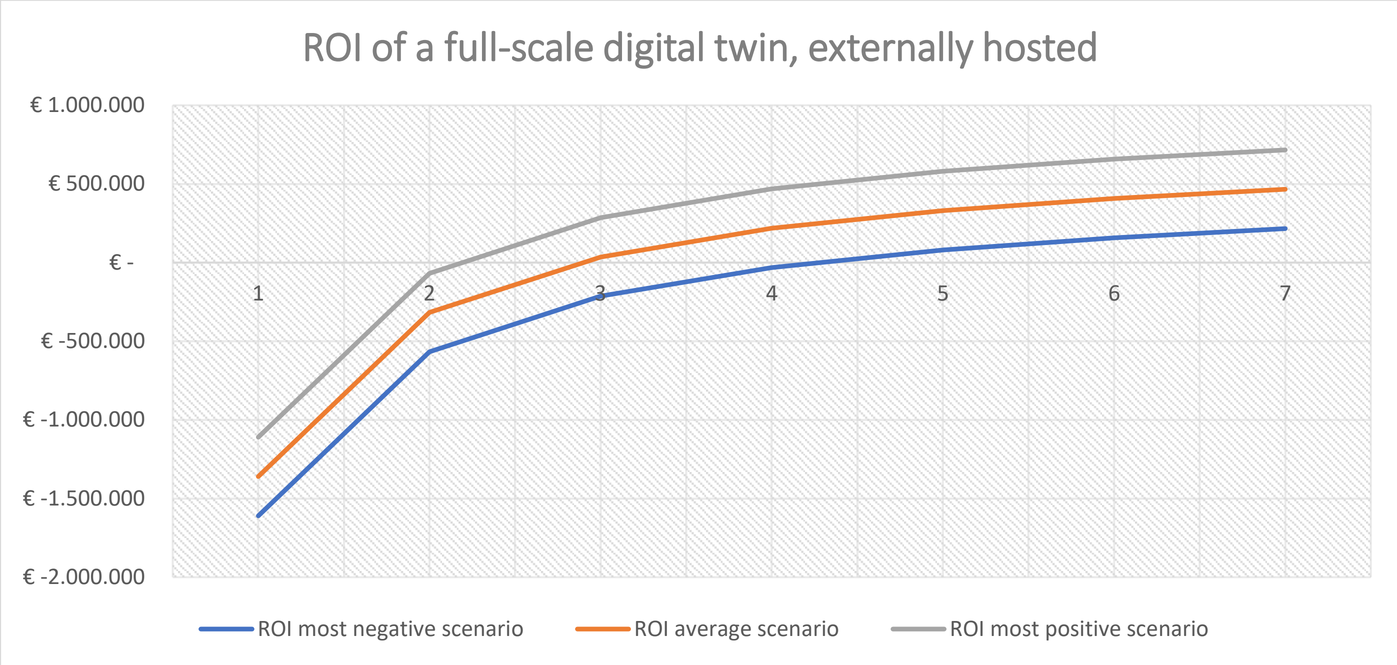


Figure 37: An indication of the spread of the financial risk when the benefits appear to be overestimated (ROI negative scenario), correctly estimated (ROI average scenario) or underestimated (ROI positive scenario). This is for the case where the digital twin is

9.2.4 Summary of economic feasibility

Considering all arguments and considerations as described in this report, the conclusion is drawn that application of a digital twin on the Maeslant barrier is cost effective. The investment costs (CAPEX) are estimated to be around €3.800.000,- and the maintenance costs (OPEX) to be €177.000,- per year. This makes that the digital twin would need to make €1.000.000,- in benefits per year (considering a 5 year investment period) to be cost effective. The benefits of the digital twin do (under reasonable assumption) add enough value to the organization to justify the investment costs. This is primarily realised by optimizing maintenance processes of the barrier and to offer a platform in which knowledge can be transferred or saved more easily for future generations. The following savings are expected to be made by the investigated user requirements of the digital twin.

1. **Increasing the efficiency in knowledge and information management**
   An estimated 40% are saved on knowledge and information budgets every year, due to more efficient education of new people and more efficient (re-)finding information around the barrier. It leads to an expected saving of €275.000,- per year.
2. **Avoid unnecessary cost due to better monitoring of the barrier status**
   An estimated 5% is expected to be saved by making the maintenance processes more efficient. With an expected saving of €550.000,- per year.
3. **Better risk management due to models and the data-analysis platform**
   2 FTE per year are expected to be saved since staff members can find information more easily and are able to make first risk assessments themselves, without having to consult the failure probability manager.
4. **Creating (new) insight in the barrier's behaviour**
   1 FTE per year is expected to be saved as the understanding of the barrier's behaviour

The financial sensitivity of implementing a full-scale digital twin, however, is high when the digital twin is hosted locally and hardware needs to be purchased. When the cyber security issues could be solved, and the digital twin is hosted on an external server, the investment costs and sensitivity decrease significantly.

This sensitivity could be reduced even more when a small step implementation approach is chosen. By doing so, the project is divided into several sub-projects, each with its own budget. The project starts with implementing the first sub-project. As soon as this is successfully finished, the next budget for a sub-project is released. This makes the budget more controllable and large financial missteps are prevented.

9.3 Organizational feasibility

For the implementation of a digital twin, it is crucial to investigate whether the organization (the potential users of the digital twin) is ready to adapt the technology. To evaluate this organizational feasibility, first, the Maeslant barrier team has been assessed through research following the method of Chemweno et al. [43]. The method considers ten evaluation classes or indexes and rates these according to predetermined levels. The classes or indexes are: (1) organizational culture, (2) maintenance policy, (3) performance management, (4) failure analysis, (5) planning and programming of preventive maintenance activities, (6) CMMS[8], (7) spare parts inventory management, (8) standardization and document control, (9) human resource management and (10) results management (maintenance costs and quality). This research tells something about the potential readiness of the organization. Next, it is tested how the organization experiences the use of a digital twin by asking them to use the prototype and fill in a questionnaire based on it.

9.3.1 Theoretical organizational readiness

For the matter of Rijkswaterstaat, the first steps have been taken to implement the phenomenon digital twin broadly in the organization. There are several initiatives for building digital twins in different kinds of departments of Rijkswaterstaat, and a team of experts is formed to coordinate these initiatives. The team has written a vision document and set up a roadmap for further development of the digital twins [7]. It mentions internal digital twin and data management developments and suggests three focus points for further development:

- Organizational: Strengthening the organization (sharing knowledge, training) so that Digital Twin applications can become a standard in the work processes
- Operational: Focus on essential, object related fields of knowledge
- Technical: Step by step developing building blocks for Digital Twins based on use cases

Organizational readiness

Although Rijkswaterstaat's vision document [7] gives reason to believe the organization is ready to adapt digital twin technology, to double-check if this is the case, also own research towards this organizational readiness is performed. For this research, the Rijkswaterstaat document [7] is combined with an own inventory on organizational readiness of implementation of new digital technology. In this inventory, information gathered from conversations with Rijkswaterstaat employees is used in a combination of the Zachman framework [14] and a maturity framework developed by Chemweno et al. [43] to investigate the organizational readiness. The investigation resulted in a table in which a score from 1-5 (where 1 is the lowest score and 5 is the highest score) is given regarding the maturity of the organization on certain subjects. The description of the score is from the score table from the Chemweno method (see Figure 55 in Appendix K), this is not coming from the writer. A summary of these scores is given in Table 28.

Briefly concluded, one can state that there is an intention within Rijkswaterstaat to further develop digital twins for large objects. Some pilots for developing a digital twin have been carried out (e.g., the locomobile of the Maeslant barrier), of which several were successful. The organization itself, however, is still in an early stage of development when it comes to implementing digital twin like technique in the daily work. Knowledge about items is often scattered and many processes and tools are deprecated or take longer than necessary. A digital twin therefore shows high potential added value by forming a solution for these kinds of challenges. A successful implementation of a digital twin, however, also asks for a state of maturity of processes, which are at some points still below the required level. This paradox might cause the implementation of a digital twin to take longer than necessary.

[8] Computerized maintenance management system

	Level	Description
Organizational culture	2	Changes are accepted reluctantly. The need for continuous improvement was identified, but not yet adopted. Limited teamwork
Maintenance policy	2-3	Maintenance is considered important in achieving the organization's objectives. Preventive maintenance in order to increase productivity and reduce costs
Performance management	3	Performance indicators calculated periodically, with a focus on technical and economic indicators, determined for the whole object, at the line and equipment level
Failure analysis	1	Failure analysis without a defined method, performed when failures with significant impact occur
Planning and scheduling of preventive maintenance activities	3	Planning carried out based on the manufacturer's manuals covering all equipment. Delays and programmed actions not completed.
Computerized maintenance management system (CMMS)	3	Computerised system for planning and control of maintenance, with some unused functions, not integrated with other computer systems of the company
Spare parts inventory management	2	Classification of spare parts based on only one criterion (e.g. price or consumption pattern). Demand forecasts based on historical consumption
Standardization and document control	2	Documentation of equipment and processes are organized. Some processes and activities are standardized, but not revised
Human resource management	2	Skills development plan for maintenance employees nonaligned with area's needs. competence
Result management (Maintenance cost and quality)	2-3	Implementation of actions to control costs, with level of waste and recurrence of failures measured but not investigated

Table 28: Index level score for the 10 different categories of the maturity model summarized.

9.3.2 Evaluation of applications

The theoretical readiness research from Section 9.3.1 neither provides a convincing reason to assume the organization is completely ready to adopt a digital twin, nor that it's not ready. The results of the research presented in Table 28 are mostly middle rated scores, which are not convincingly positive or negative. The user experience tests of the digital twin (see Chapter 8) therefore becomes extra relevant.

To investigate how the organization experienced the usage of the digital twin. The test results from Chapter 8 are summarized and linked to earlier defined potential applications of the digital twin (see Chapter 4). Based on the answers from the respondents, an average score is given to each application including a short reflection based on the answers. The score indicates the extent to which the test respondents (see Chapter 8) perceive added value in the application presented by the digital twin prototype. For each application it is also indicated which questions are related to this application (see Section 8.2).

1. **Increasing the efficiency in knowledge and information management (Q10, 11, 15 & 16)**
   Score: 3.8 / 5.0
   According to respondents a digital twin will increase knowledge and information management, however not without the specialist's guidance. This is clearly visibly in the answer to question 15, where the average score is low.

2. **Avoid unnecessary cost due to better monitoring of the barrier status (Q17)**
   Score: 3.7 / 5.0
   Data visualization will increase awareness of the barrier's status, therefore avoiding potentially high cost for maintenance. The fact that data is more clearly findable and visible supports this, according to the respondents.

3. **Better risk management due to models and the data-analysis platform (Q19)**
   Score: 3.4 / 5.0
   Respondents are mildly enthusiastic about the improvement of risk calculation accuracy. In the written they did not reply specifically to this subject and gave relatively low scores. One does only limitedly see an added value of the digital twin compared to the current risk management system, which is why the scores were lower.

4. **Creating new insight in the barrier's behaviour (Q10, 11, 18 & 20)**
   Score: 4.0 / 5.0
   According to the respondents a digital twin primarily provides insight into the barrier's current behaviour and will improve decision making (Q10, 11, 18). There is mild trust that it will provide new insights (Q20). Nevertheless, the highest score was given to this subject.

The scores that were given to the applications indicate that the respondents see added value in the implementation of a digital twin in the organization. The most added value is seen in creating insight via the visualization capabilities of the digital twin and use it for knowledge transfer and education. For risk quantification, there was less enthusiasm, but still a cautious positive response. It should be noted that (see Section 8.2) there is some division among the respondents regarding the added value of certain digital twin functions. This division also appears to be related to the Zachman role of the respondents. The respondents from the business management layer appear to be more positive about digital twin implementation compared to the technician layer.

9.4 Summary

The results of this chapter indicate that a fully developed digital twin for the Maeslant barrier is expected to be feasible when it comes to technology. The available technology in the market, both at hardware and software level is sufficient to develop a digital twin for the entire Maeslant barrier. Although the state of hard- and software is not at a sufficient level within Rijkswaterstaat yet, it is possible to solve this with available technology in the market.

A fully developed digital twin is financially feasible, an indicative business case study indicated that a digital twin could be cost effective within a few years. The anticipated development cost of the digital twin would be 3,800,000 (CAPEX) and € 177,000 (OPEX), with the benefits estimated to be € 1,125,000 per year. This means the benefits should outweigh the cost within 5 years.

From an organisational readiness study towards adopting digital twin technology in the Maeslant barrier team organization, no clear positive or negative conclusion could be drawn. Therefore, the digital twin prototype tests were included in evaluating that aspect. In a survey, employees of the organization have responded positively to the development of a complete digital twin. Responses were particularly positive in terms of knowledge transfer and information findability. For risk quantification, there was less enthusiasm, but still a cautious positive response. It is also noticeable that there is some division among the respondents regarding the added value of certain digital twin functions. This division also appears to be related to the Zachman role of the respondents. The respondents from the business management layer appear to be more positive about digital twin implementation compared to the technician layer.

10 Discussion

10.1 Reflection on design

To reflect on the design of the digital twin prototype, the methodology to design the prototype as well as the prototype design itself are discussed. Finally, a reflection is given on the extent to which the prototype could be further developed towards a fully functioning digital twin.

10.1.1 Methodology: 5 step approach

The design of the digital twin necessitates expertise in a) user preferences and organizational insight; b) civil and mechanical engineering (tailored for the Maeslant barrier); c) ICT and digital twin software development. The design process unfolds iteratively, interweaving explorations and developments across these domains. This interplay underscores the complexity of the process, necessitating a structured approach. In response to this challenge, a solution was found in the form of a five-step methodology.

Reflecting on the application of this prototype-building approach, it can be concluded, based on firsthand experience, that it proved effective for the overall process. The requirement to systematically navigate through the steps compelled the author to contemplate the application's intricacies and thoroughly investigate the user needs first. Interviews with potential users yielded interesting new insights into these applications. This led to a shift in the focus of the digital twin, which initially aimed to improve the efficiency of asset management but now places greater emphasis on knowledge and information management. The interviews revealed that there is a greater need for a platform to store knowledge and make it more easily transferable than there is for making asset management more efficient. Although the desire for improved asset management efficiency is still present, it does have a lower priority. This also became clear from the interviews conducted with the user panel (see Chapter 8)

10.1.2 Prototype design

In the design and construction process of the digital twin, various choices were made that have influenced the final product. Some choices were made based on the information that was available at that time, of which the impact could now always be foreseen. This section therefore reflects on the choices that were made, and how these decisions are expected to turn out for possible future versions of the digital twin.

Level of detail of the user interface

The user interface of the digital twin prototype is currently a relatively small software application that can run on a standard laptop. This choice was made to make it easy to provide the prototype to colleagues at Rijkswaterstaat for testing. However, to achieve this, the detail level of the 3D model in the user interface had to be significantly reduced. Otherwise, an average laptop would freeze because the graphics card is not powerful enough. This results in the current 3D environment lacking sufficient detail to, for example, convey technical details to engineers at a very high level of detail (for example the details of an individual valve or pump). If Rijkswaterstaat wishes to use the digital twin for detailed asset management and operations, consideration should be given to the appropriate hardware support.

Data sources

The data used in this digital twin prototype is mostly from the data measurement system of the barrier itself. It exists of data files from sensor measurements during test procedures for components or the closing procedure of the barrier. This provides valuable information about the functioning of the barrier; however, it does not tell anything about its environment. For example: live visualization of water- and air temperature, river water levels, ground water levels, weather conditions, etc. There are several (open) data sources that could provide this kind of information. For instance, Rijkswaterstaat’s GeoWeb portal [44] or Dataregister [45] that could provide valuable (often live) information about water heights, soil structure, flora & fauna, environmental aspects, vessel movements, and many more. A direct connection between these data sources could add value to the digital twin. However, it requires further research to investigate which data sources would be useful to the potential users.

Accessibility of data

The data imported into the digital twin prototype is currently stored on a secure server. This data was imported to the server by exporting it from the barrier's data-system and burning it onto a DVD. The data is downloaded from this DVD on a computer and imported onto the server. A similar process must be carried out to export simulated data from the *A-omgeving* (Rijkswaterstaat's data simulator for the Maeslant barrier) to the digital twin. This is a cumbersome process, but it is currently necessary because a direct connection to an external source cannot be made from the barrier's data-system or the A- omgeving, because of security requirements. It is desirable to find a solution for providing such direct and "live connection" if a digital twin of the entire Maeslant barrier would be developed.

Cyber security in general

The digital twin prototype is currently a software application that can run solely on a laptop. To run an animation, import data or use the connected model, a connection with the server needs to be made. This server is a secure server where several datasets are stored that were exported from the Maeslant barrier data system. However, it is not tested whether this server meets the standards of cyber security within Rijkswaterstaat. Therefore, a choice was made not to include sensitive information such as the actual failure probability numbers. When the digital twin is further developed, this is something that needs to be investigated in detail, to make sure the digital twin needs the standards of Rijkswaterstaat cyber security. If, for instance, the cyber security rules and regulations prevent the digital twin to be able to connect to a server via internet, the data must be stored locally. This results in a significantly less flexible digital twin user interface since it needs to be wired to connect to the server and run animations or models.

Data simulation

If a simulation of a barrier closing process is desired from the A-omgeving, this simulation happens in real-time. A closing procedure of, for example, 12 hours also takes 12 hours to simulate. This makes it firmly unusable for quick educational purposes, also because the digital twin includes an option for "fast playback of closures" (see Section 6.3.4).

To use simulated data in the digital twin, a large set of different closures must be simulated with the A-omgeving and stored in a database, from which the data can then be imported into the digital twin when needed. However, this results in less flexibility for the digital twin, which is in that case always dependent on the availability of data files. It would be preferable to be able to simulate a closing process 'live' from the digital twin via the A- omgeving without it taking hours. For this to happen, the A- omgeving would need to be modified, and it would need to be possible to establish a direct connection between the digital twin and the A-environment.

For this research, it was planned to create a series of datasets with the A-omgeving for use in the current prototype. However, the A-omgeving was not available during the last 8 months of the research period due to maintenance, and therefore this information could not be used. It is therefore recommended that for further development of the digital twin, the creation of this dataset of simulated barrier closures is prioritized.

Types of models used.

The models to which the digital twin prototype is connected, are relatively easy models to run. They don't require many calculations capacity from the computer. The downside is that they form a less accurate representation of reality. The calculated forces on the retaining walls for instance, are based on a hydrostatic calculation. This is a relatively easy calculation to make since it is based on one formula. However, it only represents reality to a certain extent. To make a more accurate assessment of the forces acting on the retaining walls, things like hydro-dynamic flows and wave impact should be included as well. For these kinds of calculations, more advanced models already exist that were developed by Deltares [46]. There is a possibility to make a connection between the models and the digital twin however, the required calculation capacity would increase drastically. In the future also other advanced models, e.g., Finite Element Models (FEM) for barrier strength could be linked to the digital twin. For this prototype, a choice was made not to include these models yet, if it is desired to make a connection, it requires a reconsideration of the supporting hardware.

10.2 Reflection on testing

10.2.1 Testing of representations of reality

During the building of the prototype, it appeared to be complicated to determine to what extent the prototype represents the reality of the barrier's movements. Especially for the detailed movements of the barrier (e.g., the ball joint movement or detailed filling of compartments in the retaining wall), hardly any comparison material was available. Therefore, the testing of the representability of the animations in the prototype was done based on documentation (the so-called *handbooks* [47][9]), video material of the barrier closing, and on the reactions of experienced Maeslant barrier employees. For the basic movements of the barrier this methodology was sufficient however, more detailed movements of the barrier were not tested extensively. It is therefore recommended to search for more methods to verify that the animations represent the reality of the barrier movement sufficiently.

10.2.2 Test panel members testing the Application and user interface

To mitigate potential issues in the testing phase of the digital twin prototype, it was essential to carefully plan user testing, provide clear instructions to participants, use a diverse group of users if possible, and combine questionnaire feedback with other evaluation methods such as usability testing, interviews, and direct observation. These measures were taken during the individual tests. Additionally, the questionnaire was structured in a way to make the respondents' opinions quantifiable. In this case, by having the questions answered on a scale from 1 to 5, where the numbers represented 1 as the most negative and 5 as the most positive. This led to the responses of the respondents being easily comparable.

One factor that does influence the reliability of the results is the number of respondents. The number of people with sufficient knowledge of the Maeslant barrier to reliably complete the questionnaire is limited, which is why the expected number of respondents was limited from the onset. Of the 18 Rijkswaterstaat employees contacted, 14 completed the test and filled out the questionnaire. This is a limited quantity but still provides a relatively good indication of the prevailing opinion on digital twins within the organization. However, the number of respondents per Zachman role (see Section 4.1) is relatively small (2 to 5) which limits the reliability of the results by role. For some roles (Executive management) no one participated in the evaluation and testing. If it is decided to proceed with the digital twin a further and more extended user investigation would have to be performed.

10.3 Discussion of Feasibility

10.3.1 Technical feasibility

As described in Appendix A, there are highly advanced digital twin models for civil infrastructure and other systems worldwide. These models are capable of monitoring e.g., entire factories, involving a vast amount of data. Visualizing that data, combined with the connected models, requires significant computing power. The software used for this purpose (often Unity) has proven itself capable of handling the visualizations and animations in such cases. Additionally, there are AI models capable of quickly analysing data and deriving

[9] There are 12 handbooks, created in the design phase of the barrier, that describe in detail how components of the barrier work. Each handbook focusses on one or two components of the barrier. For this research, Handbook 2: 'Retaining walls and half-timbered construction arms' was used mostly.

conclusions and recommendations from it. In summary, it can be concluded that the technology for building digital twins has proven itself in many areas. Although the soft- and hardware at Rijkswaterstaat is not in a state-of-the-art condition (see Section 9.1), this is solvable by purchasing these components, as the market offers sufficient options.

The successful technical implementation of a digital twin for a critical object like the Maeslant barrier also highly depends on cybersecurity. Within Rijkswaterstaat, addressing this aspect can be a complex process, of which limited attention has been paid to in this research due to time constraints.

Due to factors such as potential cybersecurity measures, a detailed investigation has not been conducted on how various existing models can be integrated into the digital twin. For example, the *A-omgeving*; this data simulation model cannot be accessed from the outside because cybersecurity prohibits internet access to the model. This is a significant limitation, making it impossible to establish a direct connection between the A-environment and the digital twin.

10.3.2 Economic feasibility

To create a business case for the digital twin, assumptions were made regarding the costs and benefits. For these assumptions, a reference point was needed, which in this case could only be the own prototype development research, as other reference projects were not present. Thes assumptions were therefore made including a relatively wide cost range. Despite this wide range, there may still be discrepancies in the estimated costs. This means that the economic feasibility presented in this research should be considered with less certainty.

The development costs for the digital twin prototype were a known factor, therefore it gave a good reference point to estimate the development costs for a full-scale digital twin. This was not the case for all parameters. The cost parameters that could be estimated with less certainty are the following:

- Required hardware to run the digital twin. However, this research did not focus on determining the costs for this hardware, which is why the cost estimate for these expenses is uncertain.
- Server costs. These costs strongly depend on the choice of storing all data locally or using external servers. Since this choice has not yet been made, the costs cannot be estimated.
- Maintenance costs. These costs depend on the size of the digital twin, the models used, and the level of detail in the integrated 3D model. Currently, the detail level is low because the decision was made to focus on knowledge transfer regarding the general operation of the barrier. When this detail level increases significantly, maintenance costs will also rise because this model will require constant updates.

The quantification of the added value of the digital twin has been conservatively chosen. Feedback from individuals involved with the Maeslant barrier suggests that these values could potentially be much higher. E.g., one respondent indicated that it could significantly accelerate the education process, meaning several FTE per year could be saved extra. However, these assumptions could not be based on any practical reference, which is why they were not included in the assumptions.

10.3.3 Organizational feasibility

Risk of top-down implementation

The test results (see Section 8.2) revealed that the reactions to the application of the digital twin prototype were divided. The divided reactions from the respondents might lead to a risk for the implementation of a complete digital twin in the organization (see Section 8.2). From the respondents to the test, it appears that the people with a more practical role in the barrier asset management (the Technicians in the Zachman framework) responded less enthusiastically to the prototype. The most positive respondents were the Business management group. This is a risk since IT projects in the Dutch government (also at the Maeslant barrier) have shown a trend of becoming extensively more expensive than budgeted, particularly because they were implemented top-down [41]. The management of the organization developed/implemented the IT systems without consulting the needs of the colleagues that need to work with the systems. This tends to become the case for the development and implementation of a complete digital twin for the Maeslant barrier.

Critical note: Number of respondents

The prototype testing within this research was done by asking 14 individuals to participate in the test. Although this provides a valuable insight into the experience of the potential users of the digital twin, did it not cover the entire Maeslant barrier team. The potential participants from Rijkswaterstaat could have been up to 30 when all Rijkswaterstaat colleagues involved with the Maeslant barrier were asked to participate. It was chosen not to include all potential participants in the tests due to time issues. This provides a less widespread insight into the experience of the potential digital twin users.

10.4 Implementation for other storm surge barriers

From conversations with Rijkswaterstaat employees it appeared that the knowledge and information management problems occurring at the Maeslant barrier also occur at other storm surge barriers. This gives reason to assume a digital twin could be a valuable tool for other barriers as well. When asked in the questionnaire, most respondents replied that they indeed expected it to be valuable. The challenges that need to be overcome to succeed in implementing a digital twin for the Maeslant barrier, however, are also expected to play a role for other barriers. Cyber security, for instance, is a subject that needs attention for all barriers.

At the Ramspol barrier (see Appendix B), also a prototype digital twin was developed. This was done independently of the Maeslant barrier digital twin prototype in this research. It would be very useful to compare the experience of developing the Ramspol prototype to the Maeslant barrier prototype and learn from each other's experience before starting to implement the digital twin on a full-scale.

11 Conclusion

11.1 Main conclusions

In this Engineering Doctorate (EngD) research, the development and application of a digital twin for a storm surge barrier was investigated, with the Maeslant barrier serving as the case study. Therefore, as a first step, the user needs were investigated by conducting interviews with Rijkswaterstaat employees. This was done using the Zachman framework, to ensure a comprehensive view of the organization was employed. The user needs were translated into four applications for which the digital twin should fulfil to provide added value for the organization (see below). Based on the insights gathered, a prototype of a digital twin for the Maeslant barrier was constructed, with a particular focus on its retaining walls. For the design of this prototype, knowledge from three fields had to be integrated: 1) organizational & user needs; 2) functioning of the barrier (civil and mechanical engineering); 3) ICT architecture design. The result of the prototype is presented in Figure 38.

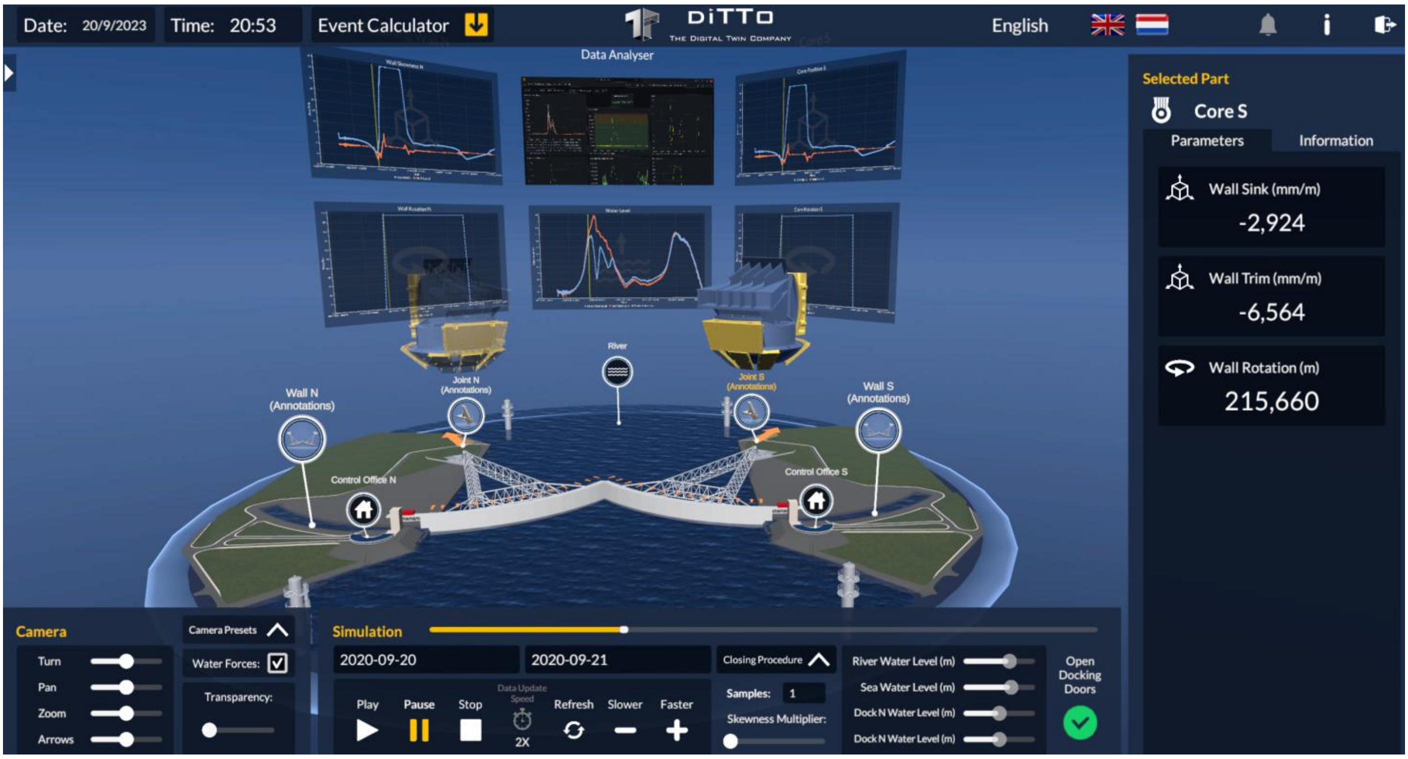


Figure 38: A visualization of the digital twin prototype. It shows the animation of the barrier closing (center), control panels for the simulation or replay of an actual closure (lower panel), clickable panels for data visualization and further data analysis (top panels) and 'live' values of the animated parameters including the option to search for more information (right side)

The prototype is tested among 14 potential users within Rijkswaterstaat to investigate the organizational feasibility. The test panel members, who received a personalized demonstration of the digital twin prototype based on three use cases and were given a questionnaire, responded positively on the potential implementation of a full-scale digital twin for the Maeslant barrier. The presented use cases were:

- Case 1 - Analysis of closing procedures based on observations.
- Case 2 - Knowledge conservation and transfer: hydrostatic forces example.
- Case 3 - Observing abnormal behaviour and including risk management.

The testing panel members responded positively on the potential implementation of a full-scale digital twin for the Maeslant barrier. The average ratings from the respondents are used for evaluating the earlier investigated digital twin's application for the Maeslant barrier organization, of which the results are summarized below.

A digital twin for the Maeslant barrier will contribute to:

1. **Enhancing efficiency in knowledge and information management (research question II)**
   Respondents score: 3.8 / 5.0
   Respondents expect that a digital twin can significantly improve knowledge and information management but acknowledge that specialist guidance is essential. The specialists use the digital twin as a platform to explain the behaviour of the barrier using the animation and data visualization possibilities. Self-education though, without specialists' guidance, is not a feature the respondents found realistic.
   The use case that describes this best is: Case 2 - Knowledge conservation and transfer: hydrostatic forces.
2. **Avoiding unnecessary costs through better barrier status monitoring (research question III)**
   Respondents score: 3.7 / 5.0
   Data visualization enhances awareness of the barrier's status, therefore potentially preventing costly maintenance issues. The respondents saw an added value in the more organized form of (re)finding data of test procedures or barriers closings. The same holds for the findability of historical information of specific barrier components.
   The use case that describes this best is: Case 1 - Analysis of closure procedures based on observations.
3. **Improving risk management with models and data analysis (research question IV)**
   Respondents score: 3.4 / 5.0
   Respondents showed moderate enthusiasm for enhanced risk calculation accuracy. They provided relatively low scores, also from the open questions did they not elaborate on this aspect. The digital twin's probability of failure calculator, to perform quick failure probability calculations of changes to the asset management, was not rated to be directly useful in its current form.
   The use case that describes this best is: Case 3 - Observing abnormal behaviour and including risk assessment.
4. **Providing insights into barrier behaviour (research question V)**
   Respondents score: 4.0 / 5.0
   According to respondents, a digital twin primarily offers insight into the barrier's current behaviour, and this can enhance decision-making. The animation and data visualisation possibilities again form an important added value for this application. Although this application received the highest score, respondents indicated that the level of detail of data visualization and animation needs to improve significantly to able to gain new insights in barrier behaviour.
   The use case that describes this best is: Case 3 - Observing abnormal behaviour and including risk assessment.

The results of the questionnaire demonstrate that digital twin users recognize clear value to enhance knowledge and information management. Even the current prototype exhibits potential in this regard, especially for the sake of information sharing and education, suggesting significant possibilities for a full-scale digital twin. In the long term, it is expected that the digital twin could add value in increasing the barrier's asset management. An important notification, however, is that the reactions of respondents was diverse. The respondents with a more technical role at the barrier (e.g., the engineers and operational technical specialists) were less enthusiastic about the prototype for direct use for asset management than the higher management. The prototype would have to increase significantly in level of detail, as well as the models that are connected, to provide an added value for the technically oriented staff members.

The development of the prototype demonstrated the feasibility of a small-scale digital twin of the barrier. However, it does not guarantee a successful implementation of a full-scale digital twin within the Rijkswaterstaat organization. Therefore, the challenges and obstacles in implementation have been further investigated through a technical, economic, and organizational feasibility study. The outcomes of these investigations are given below, subsequently answering research question I & VI.

The prototype development indicated that the available technology in the market, both at hardware and software level is sufficient to develop and implement a full-scale digital twin for the Maeslant barrier. However, the current state of hard- and software within Rijkswaterstaat is insufficient for full-scale implementation. Especially on cyber security, challenges need to be overcome to be able to use the maximum capacity of a full-scale digital twin.

A fully developed digital twin is expected to be financially feasible, an indicative business case study indicates that a digital twin could be cost effective within two to four years. To calculate this, the economic added value of the digital twin is estimated to be € 1,125,000 per year, based on expected savings in time and maintenance cost for Rijkswaterstaat. The development costs are estimated to be ca € 3,800,000 (CAPEX) and € 177,000 (OPEX) and are found by extrapolating the hours spent on development of the prototype and the additional cost. This means the benefits should outweigh the cost within 5 years.

The Maeslant barrier organization is, resulting from the questionnaire, enthusiastic about implementation of a full-scale digital twin. However, achieving a digital twin with added value to the entire organization necessitates further development of the existing prototype, and a better connection to the user needs of the respondents that rated the prototype less positive.

All points considered it is concluded that a full-scale digital twin is, under reasonable assumption of overcomming several challenges, feasible to implement for the Maeslant barrier.

11.2 Future outlook

The digital twin prototype provides an insightful initial assessment of digital twin feasibility for the Maeslant barrier. Although certain discrepancies exist within the prototype or its design, it serves as a foundational starting point for future endeavours. Expanding upon this prototype to create a full-scale digital twin is contingent on addressing several prerequisites:

- **Cybersecurity**: Presently, cybersecurity measures restrict direct access to measured or simulated data. Consequently, the digital twin cannot operate in tandem with the barrier itself, limiting its functionality. Investigating cybersecurity solutions is a top priority.
- **Organizational Support**: Within the organization, enthusiasm for digital twin usage among operational-level asset management staff, including technicians and engineers closely involved with the barrier, appeared to be relatively limited. It is essential is to investigate how the digital twin could support the needs of this organizational layer.

Conversations with members of the management team revealed their enthusiasm for the concept and recognition of its potential benefits. To translate this enthusiasm into action, they need to inspire operational team members, but a common challenge is the lack of available time of operational team members. Considering the current structure within the Maeslant barrier organization, the most promising approach for implementation is likely to be a bottom-up strategy, sufficiently facilitated by the management team.

Therefore, next steps in the digital twin development, would be the involvement of a broader group of potential users to explore their detailed needs. A decision must be made on the way the digital twin is ‘hosted’: at local Rijkswaterstaat servers or via online servers. In case of the first, it requires upgrading the current hardware. In case of the second, possibly extra measures must be taken to address cyber security, requiring investigation with Rijkswaterstaat CIV. This also holds for the accessibility of data. If a direct link with the data sources or A-omgeving (for data simulation) is desired, this requires deep research for cyber security measures. If these choices are made and challenges overcome, the digital twin software can be further developed. Parallel, an operations and management team for the digital twin must be set up, that are tasked with maintaining the digital twin and keeping the data streams up to date.

With these steps taken, a full-scale digital twin for the Maeslant barrier is expected to be feasible!

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A. Digital twin implementation phases and market

Implementation of Digital Twins

Digital Twin is a relatively new but highly emerging concept that is becoming a common way of working in sectors such as Aircraft, Aerospace, High-tech, Energy or Manufacturing industry [4] [5] [6] [15] [16] [17] [18], see also Figure 39 and Figure 40 for an example. They are successfully implemented to reduce cost, for instance by optimizing design procedures or by simulating systems and components. It enables predictive maintenance, operation efficiency, and enhancing safety through real-time performance monitoring. *Digital twinning* has proven itself on relatively small objects, but data processing capabilities of computers keep improving, which makes digital twins more and more applicable on large (movable) objects such as offshore platforms, bridges, sea-locks and storm surge barriers [5] [48].

Figure 39: An example of a digital twin application for a windfarm built in Unity (source: Unity & 4Subsea)

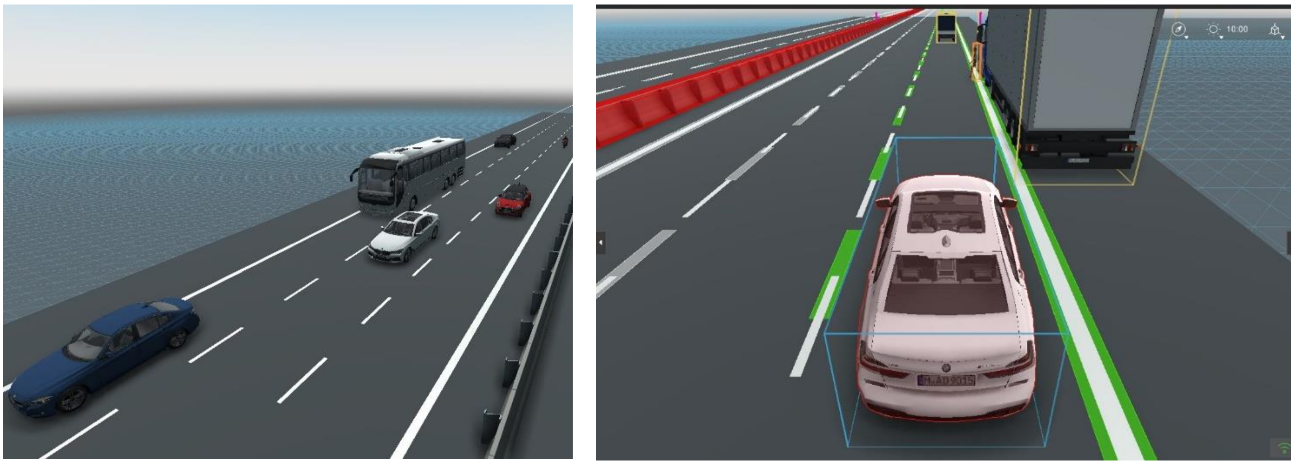


Figure 40: An example of BMW's Unity-based scenario editor, which lets its AD developers test with precise control. These images show a simulated test parameterized across different times of day and weather conditions (source BMW & Unity [49])

The first examples are published where digital twins have been applied on a larger scale, for instance in the concept of 'smart cities' [50]. A smart city is basically a digital twin in which geospatial data is combined with many kinds of measured data and artificial intelligence to gain new insights into the many systems and objects a city has. For instance, to monitor the performance of infrastructural systems, to investigate where energy could be saved or to find out if the garbage collection system is as efficient as it could be.

Figure 41: An example of a digital twin of Vancouver airport (source Unity & Fracture Reality [51])

In 2021 the subject has become of such importance in many different industries that the national government of Great Britain has set up a National Digital Twin program [48] and a Centre for Digital Build Brittan (CDBB)[10] in order to bring technology to a next level. In the Dutch national government the digital twin is starting to get common as well and has led to a Digital Twin Roadmap with a vision towards 2030 [52] [30].

Digital twins are implemented in all phases (design-, manufacturing-, operational- and retire-phase) of an object or system [6] [15]. Many kinds of techniques are available or becoming available to make digital twins' part of all these phases. The way it is implemented however, changes with the phase. In Appendix A an example is given on how digital twins and digital twin applications could support all these phases.

Implementation phases

Digital twins are implemented in all phases (design-, manufacturing-, operational- and retire-phase) of an object or system [6] [15]. Many kinds of techniques are available or becoming available to make digital twins' part of all these phases. The way it is implemented however, changes with the phase. In the next paragraph an example is given on how digital twins and digital twin applications could support all these phases.

During the design and engineering phase of the object the digital twin is used to optimize the design time. A visualization environment, for instance a (3D)BIM [53] [54] or GIS model, is used as a basis and calculation models are connected to elements in this visual environment. The impact of every adaptation in the visual model is automatically (re-)calculated by these calculation models. This allows the designers to optimize the design of their object faster and with less risks of missing crucial elements. In the meantime, the model is used to link all historical documentation, engineering decisions and information to the component it applies to in the visualization environment. This forms the basis for the digital twin in the next phases.

During the manufacturing (or building) phase, the digital twin contains all information the builders need to do their work. This could be construction drawings, work instructions, compliancy documents, etc. The digital twin 'grows' together with the construction of the object itself. Every aspect that is added to the physical object, is digitally added to (or marked as finished in) the digital twin. In the meantime, the digital twin helps monitoring the construction process [16] using data that is gathered from the construction site. This data is translated into information using calculation models. During this process, all kinds of relevant

[10] https://www.cdbb.cam.ac.uk/

information is created that needs to be found back in the future as well. This is automatically connected to the right component of the object by the digital twin. At the end of the building phase, the digital twin application includes all relevant information the operational organization of the object needs.

For the operational phase the digital twin uses models combined with data to support the maintenance and operation of the object, while continuously changing with the physical object. The digital twin can now for instance be used to find and visualize relevant historical information, or to simulate scenarios to determine the impact of measures that can be taken on the physical object. The *digital twin* continues to use the data to detect errors or faults in the system, or to advise (or decide) on measures that can be taken to prevent errors [55]. When the object is considered to have reached the end of its life or 'out of life', the digital twin application contains a full dossier about the object, which can be used to decide on how the object can be removed or demolished.

Digital twin market

The market for digital twins is witnessing significant growth and is poised for further expansion. This is also visible in the global digital twin market, which was valued at USD $3.8bn in 2019, and it is expected to rise to USD $35.8bn by 2025 [56] [3]. Two-thirds of large industrial companies are expected to be working with digital twins within the next decade, with an average expected 10% improvement in effectiveness [3] [57]. Growing at a compound annual growth rate (CAGR) of over 30%. This exponential growth is fueled by the increasing adoption of IoT devices, advancements in data analytics and AI, and the demand for improved asset management and predictive maintenance practices. These numbers indicate that the market development for digital twins will most likely not be the bottleneck for the implementation of digital twins in an organization such as Rijkswaterstaat.

In the Architecture, Engineering and Construction (AEC) sector, digital twins are still mostly at the prototype stage [8]. For a more specific domain such as the Hydraulic Engineering industry the reported application is still limited. Publications regarding Hydraulic Engineering are for instance focussed on port developments [9], drainage systems [10], offshore pipelines [11] or dams [12]. Definitions for digital twins in these publications can be ambiguous or inconsistent, and processes for developing a digital twin are not set straight yet. Furthermore, a lack of established protocols and standards to develop a common narrative and guidance delays the development of digital twins in the AEC sector [58]. Therefore, the AEC industry is still significantly behind other industries in the use of digital twins, although the first signs of development start to appear and digital twin application is beginning to take off, however, fully realised examples are still hard to find [57]. Digital twins are often still seen as something futuristic, complex, and difficult to realise [3]. Recently however, different governmental organizations and companies have mentioned the subject to be of great importance for the common years, especially to apply the technique on existing vital objects [52].

Recently the Centre for Digital Built Britain (CDBB) has started a collaboration with multiple industry partners and institutions, to determine the state of development of digital twins in the AEC sector. Among the collaborating partners were: Bentley systems, Cambridge University Institute for Manufacturing (IfM), ICE's digital transformation group, BSI and key civil engineering consultancies (e.g. Arup, Mott MacDonald) [56] [20] [59]. This collaboration led to four metrics (autonomy, intelligence, learning, and fidelity) that were evaluated and rated from 1 to 5[11] [3]. Among the nine case studies presented in the report, none were up to Level 4 or 5, one was judged at Level 3 only, proving that many objects face the same problems, hence the need for further applied studies.

[11] Level 1 is when the virtual-real connection is present, however, the twinning has limited functionality, e.g. a basic model or a map; Level 2 is when there is some capacity for feedback and control, however, the DT is limited to small-scale systems, e.g. house temperature sensors which inform a human operator; Level 3 is when the DT allows for predictive maintenance and analytics, e.g. early-warning system of failure for rail infrastructure; Level 4 is when a DT is able to learn about the surrounding environment through various data sources and has autonomous decision-making for a specific task. E.g., real-time route recommendations for drivers; Level 5 is when the DT ultimately approaches the ability of autonomous reasoning and acting on behalf of the users using AI, with the capacity to react to unpredicted scenarios and interconnect with other systems (or DTs), e.g., multiple infrastructure networks providing feedback to a city-level decision-making hub.

These digital twin techniques have proven themselves to provide positive results in gaining new insights in (and predict) the behaviour of large, technically complicated structures or systems. In the Netherlands this information is becoming relevant for the different storm surge barriers the national government owns and controls. The earlier mentioned knowledge and information challenges of Rijkswaterstaat for instance (see also section 3.4), are examples to which a digital twin could provide a solution, or at least contribute to finding a solution.

Digital twin boundary conditions for successful implementation

To discover what the needs for successful implementation of a digital twin are, the different elements that have led to a successful implementation in other industries are further researched. This leads to several required components that need to be on a decent level for successful implementation. From a high perspective, these are categorized into three boundary conditions: hardware-, software- and organizational maturity. The basic required elements for hardware and software are described in this paragraph. The organizational maturity is further researched in Section 9.3.1.

Hardware

The current state of hardware to support digital twins is rapidly evolving in the industry, with advancements in technology leading to more robust and efficient implementations. Digital twins rely on a combination of hardware components to capture real-time data, process information, and enable seamless connectivity between the physical world and the virtual replica.

Required hardware components.

Based on literature research on publications of digital twins in technical industries (see also references in the earlier sections of this chapter), a list of vital software components indicating successful implementation of a digital twin is distracted. These components are:

- **Data collecting devices such as sensors, actuators, and cameras, also known as the Internet of Things (IoT) devices**
  These devices play a crucial role in collecting data from the physical environment. IoT devices have become increasingly sophisticated, offering higher precision, better data accuracy, and improved connectivity options. They enable the seamless integration of real-time sensor data into the digital twin, providing a comprehensive understanding of the physical counterpart.
- **Computing power**
  As digital twins generate vast amounts of data and require complex computational capabilities, powerful hardware infrastructure is essential. High-performance servers, cloud computing resources, and edge computing devices are used to process, store, and analyse the data collected using the IoT devices. This allows for real-time monitoring, simulation, and predictive analytics, enhancing the functionality and effectiveness of digital twins.
- **Networking infrastructure and connectivity**
  Reliable and high-bandwidth networks, such as 5G, enable fast and smooth data transmission between the physical and digital elements. This facilitates real-time monitoring and control, ensuring that the digital twin accurately reflects the behaviour of its physical counterpart.

The industry provides high level quality hardware and is also rapidly evolving their products. The digital twins that were successfully developed in high-tech sectors (Aerospace, Aircraft, Manufacturing, etc.), as mentioned in the introduction of this chapter, prove that the available hardware in the market is not the limiting factor for successful development of a digital twin.

Software

Software plays a vital role in the creation of digital twins. Especially when it comes to modelling, simulation, analyzation, and visualization of the digital replicas. The current worldwide state of software to support digital twins is highly dynamic and continuously evolving as well. Advancements in various areas enable the creation, management, and utilization of digital twins across industries.

Required software components.

Based on literature research on publications of digital twins in technical industries (see also references in the earlier sections of this chapter), a list of vital software components indicating successful implementation of a digital twin is distracted. These components are:

- **Modelling and simulation tools**
  These tools allow engineers and designers to create virtual representations of physical assets, capturing their geometry, behaviour, and attributes. Advanced modelling software offers rich libraries of components and parameters to accurately replicate the physical system. Simulation capabilities enable the testing and analysis of the digital twin's performance under different scenarios, providing insights into its behaviour or optimizing its design.
- **Data integration and analytics software**
  These tools facilitate the integration of data from various sources, such as sensors, IoT devices, and historical records. They enable real-time data ingestion, processing, and analysis, extracting valuable insights and patterns. Advanced analytics techniques, including machine learning and AI algorithms, are employed to detect anomalies, predict failures, optimize performance, and support data-driven decision-making based on the digital twin's data.
- **Visualization and user interface software**
  Enhance the user experience and enable intuitive interaction with digital twins. These tools provide graphical representations of the digital twin, allowing operators, engineers, and stakeholders to visualize and navigate the virtual environment. User-friendly interfaces enable users to monitor the system, analyze data, and make informed decisions.
- **Connectivity and communication software**
  This is vital for establishing seamless interactions between the physical system and its digital replica. Application programming interfaces (APIs), protocols, and middleware enable the integration of different software systems and ensure the smooth exchange of data between the physical environment and the digital twin. These software components enable real-time monitoring, control, and synchronization, ensuring that the digital twin accurately reflects the state of the physical counterpart.
- **Security and data privacy software**
  Critical components of digital twin solutions. They ensure the protection of confidential data, safeguard against cyber threats, and maintain the integrity and confidentiality of the digital twin. Security measures include encryption, access controls, authentication mechanisms, and monitoring tools to detect and respond to potential security breaches.

The industry currently offers a wide variety of software (in the categories described above) to support digital twins. It encompasses a range of tools and technologies, that work in tandem to enable the creation, operation, and utilization of digital twins. The software developers often provide new kinds of software quicker than potential users can adapt it within their organization. A software developer like Unity has proven to be successful in setting up digital twins in the high tech, engineering, construction, energy, automotive and manufactering industry [60].

As technology advances, digital twin software is expected to become even more sophisticated, offering enhanced modeling capabilities, advanced analytics, and seamless integration with emerging technologies like AI and IoT. In some sectors this technology is already a common way of working, in other sectors it is still upcoming. In general however, it is safe to state that the software to set up the digital twins has proven itself to be in a developed state in the market.

B. Storm surge barriers in the Netherlands

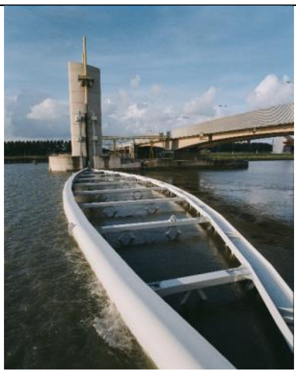
A storm surge barrier is a moveable barrier. It can be temporarily closed during extreme storms to control water levels in the basin behind the barrier, whereby prevent flooding of the area surrounding this basin. The barrier is opened during normal conditions to allow tidal exchange and facilitate navigation [61]. There are ca 20 storm surge barriers in the world, and these are all unique objects. The Netherlands hosts seven storm surge barriers [62], see also Figure 42 and Table 29, all managed, operated and maintained by Rijkswaterstaat.

Afsluitdijk / Closure Dam (source: Wikipedia)

Hollandse IJssel barrier

Eastern Scheldt barrier

Maeslant barrier



Hartel barrier

Ramspol barrier

Figure 42: Images of the Dutch storm surge barriers. All images from Beeldbank (Photo Archive) Rijkswaterstaat. Source: https://beeldbank.rws.nl

Barrier	Construction period	Type	Length# (m)	Main design and multifunctional considerations
Afsluitdijk (Closure Dam)	1927 - 1933	Closed dam with sluices	32,500	Freshwater supply by new lake behind barrier, land reclamation
Hollandse Ijssel barrier	1954 – 1958	Double vertical lift gates	200	Better alternative for flood protection than dike reinforcement, allow shipping and tidal flow
Haringvliet sluices	1958 - 1970	17 Openable sluices	5,000	Initially a closure dam with sluices, got a storm surge barrier status since 2018
Eastern Scheldt barrier	1976 - 1986	64 Vertical lift gates and island in the middle	9,000	Initial plan for closed dam was changed to open dam during construction for fisheries & environment
Maeslant barrier	1989 - 1997	Floating retaining walls	360	Barrier considered a better alternative than dike reinforcement, needed to account for shipping in Rotterdam port area
Hartel barrier	1993 - 1997	2 vertical lift gates	147	Combined system with Maeslant barrier; navigation
Ramspol barrier	1996 - 2002	3 Inflatable gates	450	Flood protection against storm surge on Lake IJssel, open to discharge river flow in normal conditions.

 # includes both the gated as well as permanent sections of the barrier.

Table 29: Overview of storm surge barriers in the Netherlands (supplemental data from Mooyaart and Jonkman, 2017)

C. Performance-based Risk Analysis (ProBO)

Maintenance according to Performance-based Risk Analysis

Storm surge barriers in the Netherlands need to comply with the Dutch Water Act [29]. In the act the term 'duty of care' (in Dutch 'zorgplicht') forms an important aspect. It means an organization has a responsibility towards society and does everything within its power to keep the structure they control at the required safety level and protect people against flooding. For the Maeslant barrier, it means the probability of failure per closure should be demonstrable 1/100 or lower. In 2013, the Executive Board of Rijkswaterstaat therefore decided to implement *risk-based asset management* (in Dutch called *Probabilistisch Beheer en Onderhoud*, or *ProBO*) as a basis for construction and maintenance activities to stay in control over their assets. To do so, a risk analysis method called *performance-based risk analyses* must be used during construction and/or maintenance work, e.g., on storm surge barriers [2].

In the Guidelines on Performance-based Risk Analyses (PRA) [2], the definition for ProBO is given as follows:

> "Risk-based asset management entails a methodology based on an expectation (calculated or estimated by expert judgement) that objects will satisfy set requirements in terms of performance. The risk-based methodology also enables the continuous demonstration of compliance with performance requirements in the different stages of the life cycle of infrastructure assets. (…) The risk-based approach thus ensures that performance (or potential performance) can be charted coherently and be recorded in such way that it remains fully traceable. Furthermore, it allows mitigation of risks in terms of performance, identification of weak spots in an object, implementation of targeted measures and comparison of alternatives, with the possibility of cost optimization emerging as a result."

The performance requirements from the Dutch Water Act are used to set up an *Object Risk Analysis (ORA),* which forms the basis for the ProBO method. Rijkswaterstaat uses different kinds of depth-levels to perform ORAs, depending on the importance of the object in the greater system. For a storm surge barrier, the most advanced level of ORA is used. This is a risk analysis method where all the RAMSSHE€P[12] aspects are included in the analysis. This ORA starts with a qualitative analysis that considers both unexpected faults that have a significant effect on performance of the object and the measures required to keep it at the required performance level. When the qualitative ORA is completed, a quantitative ORA is made where the quantitative impact of events described in the qualitative ORA are calculated. For storm surge barriers, this results in a fault tree.

The Plan Do Check Act cycle.

Within Rijkswaterstaat, risk-based asset management is performed in line with the PDCA cycle (Plan, Do, Check, Act) [2]. With the ProBO method, risks are defined based on possible events. To control these risks, actions are formulated that are included in a maintenance plan (Plan). The actions formulated in these plans need to be executed (Do), which will ensure that the object meets the required level of performance. When the object is in operation, the actual performance of both the object and the measures taken need to be measured and demonstrated periodically (Check). The results of the check -action are then used in the ORA to see if the object still fulfils the requirements (Act), after which the maintenance plan can be adjusted and the PDCA cycle is repeated. This process is illustrated in Figure 43.

Documentation of all the actions taken in the PDCA steps are essential to keep the process running. The information about how and why certain actions were taken can be of great value in the future. The determination of failure probability of components for instance, can become more accurate when more

[12] RAMSSHE€P is an acronym for Reliability, Availability, Maintainability, Safety, Security, Health, Environment, economics (€) and Politics.

information about components is available. One can also learn from mistakes that have been made in the past, to have information for preventing similar events in the future. Examples like this underline the importance of proper storage of al information gathered during the asset management process of the barrier.

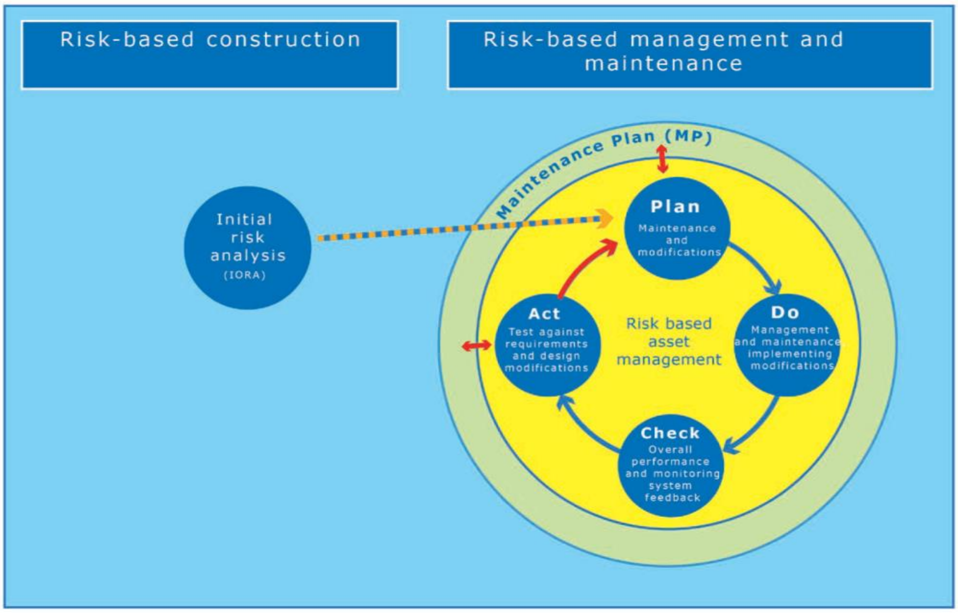


Figure 43: The PDCA cycle according to the Guidelines on Performance-based Risk Analyses (PRA) [2]

D. Five step design approach

Five step approach

In this approach, step 1 starts with an investigation towards the service the digital twin should provide, subsequently what the design requirement to fulfil this service are. Each next step represents the addition of one of the elements defined in Section 0. After all elements have been added, when step 5 is reached, a full digital twin is built and ready to be tested. The five steps are summarized in Table 30, a more extended explanation of each of the five steps is given in the rest of this paragraph. A schematization of the five steps is given in Figure 44

Step	*Description*	*Added element (see 0 for definition)*
1. Design requirements & Architecture	Investigate the required service the digital twin must provide and determine the design requirements. Then convert this into an Architecture.	Define the *service* the digital twin should provide
2. Data monitoring platform	Set up the first version of the digital twin application is set up with a 3D visualization of the real-world counterpart. This includes a data visualization aspect that is directly linked to the components in the 3D model.	Determine the *data & visualization* the digital twin will use
3. Integration of existing models	The digital twin is built by making a digital environment that connects the incoming data to existing models. Users can analyse and replay scenarios that have occurred or simulate scenarios that could occur.	Determine how the digital twin makes a *connection to models* & *controls* the real-world object
4. Capture and conserve knowledge	Essential knowledge elements are added to the digital twin and connected to the corresponding component in the digital twin application.	Define which static *data* is included in the digital twin
5. Sub-system integration	More advanced data analytics functions are added to the digital twin, including Artificial Intelligence and Machine Learning.	Determine how the digital twin can *control* the real-world object better

Table 30: A summation of the 5 steps that are developed to lead to a full-scale digital twin.

Step 1: Design requirements and architecture

A digital twin must provide a kind of *service*, in other words, it must provide a solution for an existing problem or need within an organization. The desired service must first be researched, and design requirements must be derived from this research.

This makes step 1: an investigation towards the design requirements of the digital twin. First, the organizational readiness for a digital innovation such as a digital twin is tested, which is done according to a set of predefined frameworks. When these studies towards lead to a positive result, the desires and/or boundary conditions for the digital twin are formulated based on interviews with all possible levels of stakeholders of the digital twin. This eventually leads to a design for the digital twin, which is set up according to a reference architecture and supporting design document in which the structure of digital twin and digital twin application is extensively described.

Step 2: Creation of a Data Monitoring Platform to form the basis for a digital twin application.

The second step is to start building the digital twin application, which starts with including the *data* and *visualization* elements. These are two basic elements of the digital twin and combining both elements reinforce each other. Visualization of data make the data easier to interpret and analyse. The other way around, does a visualization require a reliable source of data to provide a realistic visualization.

This defines step 2 of the process, in which the digital twin applications needs to be built and fed with data from the object. The object is visualized using a movable 3D-model of the barrier, with data panels linked to specific components of the barrier. These data panels are visible on the background of the 3D model and can be opened/changed by clicking on individual components in the 3D-model. In the panels, different kinds of data time series can be opened and analysed, for instance measured data from earlier (test) closing procedures or testing of individual components.

In this phase, this is not yet done in real time, but from a standalone computer or laptop. At this stage, what needs to become a digital twin is much more of a visualization platform with a dashboarding function than a real-time digital twin.

Step 3: Integration of measurements and domain specific models

When the data monitoring platform is functioning well, extra information can be gathered from the data by making a *connection* with models. The platform that realizes these connections, the digital twin, makes it possible to make extensive analyses of the functioning of the barrier. The result of these analyses can be used to better *control* maintenance processes of the barrier.

In this step 3, it means more and more intelligence is added to the digital twin in the form of specific calculation models and automated data analysis models. In this phase of development, measured data from (test) closing procedures feed specific calculation models that increase the analytical and predictive power of the digital twin. In the meantime, the dashboards in the digital twin are included with warning levels that provide insight into the current functioning of parts of the barrier.

Step 4: Integration of expert knowledge

Currently present specific knowledge about the barrier needs to be processed and included in the form of (meta-)*data* to conserve the knowledge and make transferring this knowledge more efficient. This is a process that runs continuously and parallel to the development of the other steps, to give it a place in the development process it is included in step 4.

In this step, specific knowledge and information elements are added to the digital twin environment. This means specific knowledge from domain experts is added on different levels of detail of the digital twin. For instance, by making a link between specific components and related static-data like documents, instruction videos, pictures, etc. Dynamic data, for instance in the form of scenarios that can be (re)played, also forms a valuable source to conserve and transfer specific knowledge. By using the existing system breakdown structure of the barrier, these links can be structurally organized in the digital twin.

For the Maeslant barrier, several instruction videos are already present, and the knowledge strategy program has led to the documentation of some unique knowledge of people currently involved with maintaining and operating the barrier [1]. However, there is probably many more knowledge that could be documented in some way and included in the digital twin.

Step 5: Gain new insight by sub-system integration, including Artificial Intelligence and Machine Learning

Making connections with artificial intelligence (AI) models, for instance machine learning models, is the next step in making a connection between data and model. The models can be used to automatically analyse the data and support in providing new insights from the data, therefore providing better *control* over the barrier. Adding AI to the digital twin is considered a separate step in developing the digital twin as these models do not exist yet for the Maeslant barrier and need to be developed separately.

The technical calculation models to which the digital twin is connected in step 3 are existing models that already function individually. In step 5, new models are added to the digital twin to try to extract more information/insight from the provided data. There is a possibility to include AI models that have proven their application in other industries, or to develop such models from scratch. The goal of these models is to 'see' relations between datasets or to notice oddities in datasets that are not directly noticed with the human eye. Therefore, these kinds of models need to connect data to all relevant systems within Rijkswaterstaat to gain these new insights.

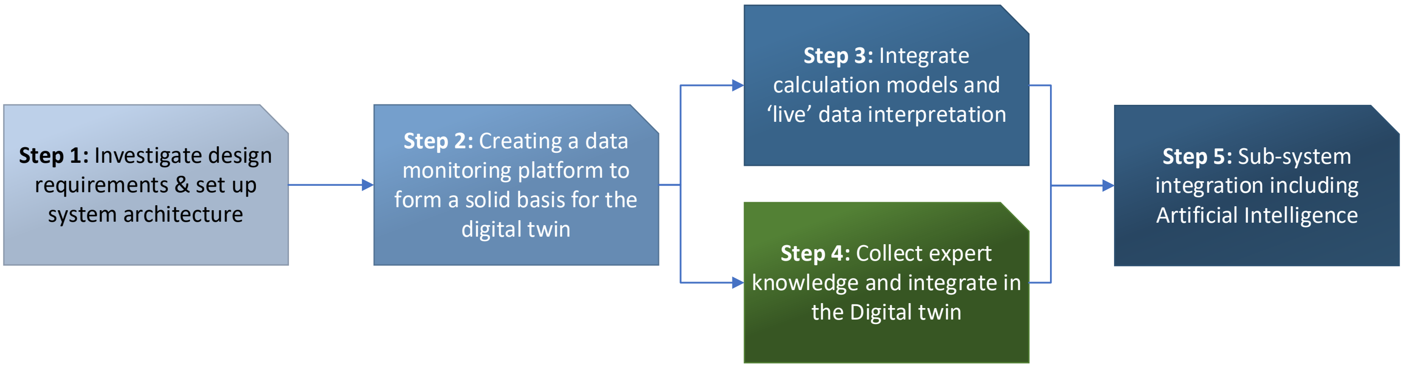


Figure 44: A 5 step approach for the development of a digital twin applied on the Measlant barrier's retaining walls

Cyber security

Although the proof of concept of the digital twin does not contain any confidential data, the 3D model itself provide useful information for potential malicious people and organizations. Therefore, the security level used for the proof of concept should always be considered and in principle be the same as that of confidential documents within the asset owners' organization (in this case Rijkswaterstaat). This also holds for the design documents, which could contain confidential Rijkswaterstaat information.

This makes it necessary for the digital twin to be located within a secure environment so that the transfer of data takes place "in house". For example, because the constellation could provide cyber criminals with insight into the design or access to related data. It is also possible to obtain information about the state of the Maeslant barrier. The Cybersecurity level must therefore be at least that of a regular Rijkswaterstaat account.

As cybercriminals could potentially cause massive damage if they had access to this type of data, it becomes more and more important that data traffic must be able to take place Cyber securely. More generally, this aspect concerns the question of who should have access to which part of the Digital Twin and how this is secured. In addition, the Verification (Authentication) protocols are included to ensure that only legitimate users can log in to the Digital Twin system.

As logical as this integration may be, it is of course accompanied by new and not inconsiderable risks. In such a case, they no longer only concern the Maeslant barrier, but also possibly other parts of Rijkswaterstaat. This means that the Cybersecurity level must also be geared to this. Encryption is for instance a method to keep the risks under control, in which information is put into a form that hides its real meaning. In these phases of the digital twin approach, all data exchange within the Digital Twin will therefore have to take place encrypted.

E. Zachman framework worked out

(a) Framework explanation

The Zachman Framework is an enterprise architecture model focussing on IT companies that finds it origin in 1987, when John Zachman published the article "A Framework for Information Systems Architecture" [13]. The basic idea of the Zachman framework is that one thing can be described with different purposes and from different perspectives of roles within the organization. The most recent Zachman framework (version 3.0) has six different roles (Executive, Business management, Architect, Engineer, Technician and Enterprise) and six different purposes (What, How, When, Who, Where, and Why) [14]. Putting these aspects together as a matrix leads to a total of 36 different viewpoints. Figure 45 gives an overview to provide insight in the order of the roles and purposes of the Zachman framework [14].

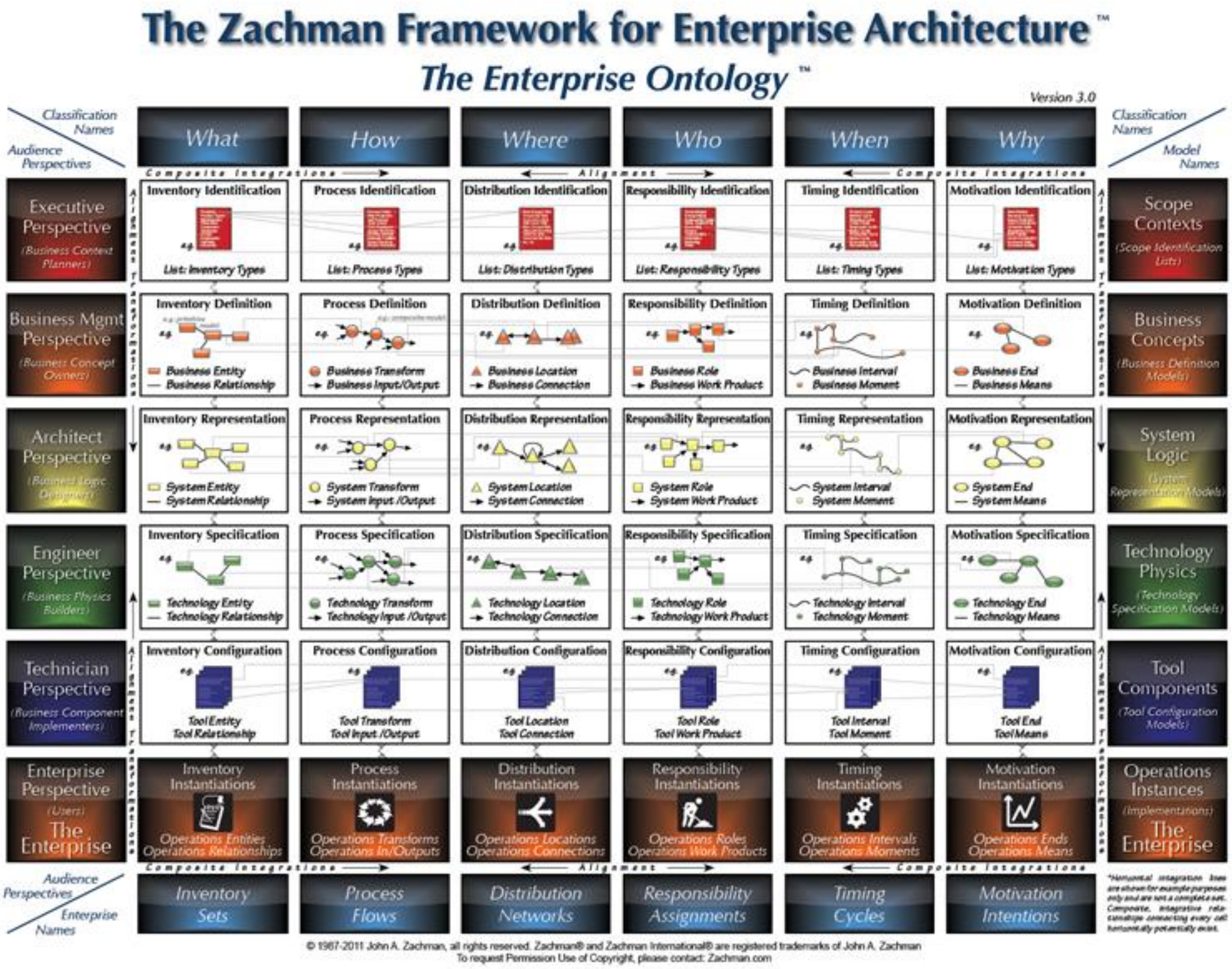


Figure 45: An overview of the Zachman framework with 36 different viewpoints on enterprise architecture, as presented on the website of Zachman International [14]

The Zachman framework is applied on the development of a digital twin of the Maeslantbarrier's retaining wall. Each cell in the framework stands for a certain aspect of the digital twin's enterprise architecture that should be present to have a perfect base to build it on. The framework is filled in based on interviews with different people within the organization and an elaboration of the available data, to determine which of these enterprise architecture aspects are already present. The result of this investigation says something about the maturity or readiness of the organization to further build the digital twin.

The Zachman framework is used to investigate how the digital twin could add value to the organisation around the Maeslantbarrier. This is done by viewing the digitization process of Storm Surge Barriers from different perspectives. Within the Zachman framework, these perspectives are prescribed in the framework, namely: Executive, Business management, System Architect, Engineer, Technician, Enterprise. Each perspective is further described in this chapter.

The Zachman framework is filled in based on conversations with multiple persons within Rijkswaterstaat. During the conversations the Zachman framework was not filled in together with the conversation partner but was used to give direction to the conversation to try to find out the desires and necessities for every role in the framework. The remains of this appendix provides further explanation of each conversation and indicates how the framework is filled for that specific Zachman role.

(b) Executive

The executive perspective in this case is the view from the Director Network Management within Rijkswaterstaat. The purpose of the director is (amongst others) to make sure the Rotterdam delta area is protected against water in accordance with the standards the Dutch law prescribes. To see whether these standards are met, she wants to be informed about the condition of the storm surge barriers in the Netherlands. More specific does she wants to know in detail whether the barrier still meets the standards it is designed for, meaning the probability of failure should be below the limit of 10^{-2} per year. When the barrier does not meet the standards or is about to exceed the limit, she wants to know this as quickly as possible to take actions.

This probability of failure depends on many factors and parameters, of which data is collected during closing procedures of the barrier and maintenance activities. This data can be translated to information regarding the condition of the barrier, preferably in an automated process to reduce delay. The focus from an executive perspective should therefore lie on the asset management phase of the barrier, in which the yearly test closing procedure plays a vital role.

(i) Executive view on digital twin according to Zachman framework

For the Director Network Management, the most important aspect regarding the Maeslantbarrier is to get the confirmation that the barrier still fulfils the requirements that are laid down in the Dutch law. When the requirements are met, this can be reported towards the Dutch ministry of Traffic and Water management. For that case it is important to have the decisions that are made regarding the determination of complying the law clearly traceable.

The technical details about how the probability of failure is determined are not so important daily from an executive point of view. However, when problems around the barrier occur or when questions are asked about the determination of probability of failure the traceability of decisions becomes important. The technical details about how decisions are made and why they are made can be a decisive factor. Therefore, the administration on these decisions should be well organized, to give the executive level of the organization the right ammunition to defend the decisions that were made against critical questions from higher levels.

Looking at the application of digital twin technique, the most important aspect that should be involved in the digital twin itself is a decent administration of data, dataflows and models. It should always be possible to trace decisions, to which the administration forms the basis.

	What	How	Where	Who	When	Why
Executive	- Clearly traceable conformation that barrier meets standards - On time information about required decisions - Keeping Maeslantbarrier's prob. of failure below limits - (uniform way of working)	- Live information insight about MB's condition - Translation from (live) data to useful information	Applied on: - Maeslantbarrier (- Europoort barrier)	Director netwerkmanagement	- In Asset management phase Maeslantbarrier - During Closing procedures of Maeslantbarrier	- Protecting Rotterdam delta area - Anticipating on climate change & new insights

(c) Business management

When looking from a business management point of view, some nuances in the terminology is required. Since Rijkswaterstaat is a governmental organization, there is a different perspective of looking at the 'business' compared to a commercial organization. In this case the business is not to make profit, but to keep the Maeslantbarrier in the right condition to fulfil its function. It is the business manager's job to keep the barrier in the right condition and, since it is tax money that is spent on this job, to make sure no unnecessary high cost are involved with this task. Within Rijkswaterstaat the staff of the WNZ department are responsible for keeping the barrier in condition, meaning this will be the perspective to fill in the Zachman framework.

(i) Business management view on digital twin according to Zachman framework

From a business management perspective, the most important aspect is to monitor the condition of the barrier and determine the impact of possible scenarios. The barrier is equipped with many sensors that measure all kinds of parameters that could influence the many particles of the barrier. The data from these sensors tell something about the performance of the particles, which can be translated to the condition of those particles. With that information, calculations can be made to determine the probability of failure of the barrier, which can be given to the Director Network Management. This affects the way maintenance is performed on and around the barrier.

Monitoring the barrier is opted to be done in the future via a digital twin, which automates many digital processes and upgrades the process of gathering information from data in and around the barrier. The data from the barrier is automatically linked to domain models to calculate the impact of what is measured. This is used by the staff around the barrier to set a strategy on how to perform their tasks of keeping the barrier in the right condition. In a further developed stage of the digital twin this can also be translated into direct actions or advices towards the barrier's manager to improve performance of particles or to reduce maintenance costs.

	What	How	Where	Who	When	Why
Business management	- Live monitoring of the condition of the barrier - Determine the imapct of possible scenarios	Building a Digital Twin of the Maeslantbarrier based on: - RWS processes - Closing procedure MB - Probability of failure model MB	Within the RWS IT systems	Staff WNZ (senior asset manager)	- Closing procedure - MTC activities	- Optimize MTC processes - Optimize Risk management

(d) System architect

The system architect's task is to draw the basis for a digital product and determine how the different components of the system should interact and are responsible for implementing, maintaining, and operating these systems. The System Architect is usually a trained IT professional involved in the development and implementation strategy of the computer system along with the network. Systems architecture is typically recognized as computer systems analysis that leads to the creation of hardware, software, and network systems. This also involves the design of backup procedures, troubleshoot problems, provide resolution, and ensure that systems development follows the guidelines.

(i) System architect's view on digital twin according to Zachman framework

When looking at the development of a digital twin, the System Architect's perspective is to design a system or schedule that forms the basis for building the digital twin itself. The system architect, in this case the EngD student, wants to map all processes to form the digital twin and indicate how these processes interact with each other. This means vital processes like Data management, Data analysis, Model integration, Visualization, Data flow models need to be worked out and described in detail. Some of these processes are already worked out in earlier stages of development. These procedures might form a basis to work the system architecture further out.

	What	How	Where	Who	When	Why
System Archtitect	- Set up Digital Twin architecture	- Data management - Data analysis - Model integration - Visualization - Data flow models (data models from John Hessels are good)	Digital Twin Design documents	- EngD Trainee TU Delft	Upcomming 2 years	- To gain a clear architecture that forms the basis for the construction of the Digital Twin

(e) Engineer

The engineer is the person in the organization to design the technical details that were described by the system architect. This involves data models, domain models, visualization, etc. The engineer determines into detail how different elements of the digital product interact and how they communicate with each other. Where the system architect for instance determines that certain datasets should be combined in order the gain new insights, does the engineer determine how they should be combined.

(i) Engineer's view on digital twin according to Zachman framework

For the development of a digital twin within this EngD research the focus lies primarily in connecting data to domain models in order to gain new insight. Although visualization is a very important aspect in the digital twin, does the focus of the engineer in this case lie on the data models. The visualization part is outsourced towards a specialized party that uses Unity to visualize the data models and make a connection to relevant particles of a 3D model of the Maeslantbarrier.

The engineer will mostly use Python as a programming language to make sure the data is connected to the domain models. This language is chosen because it is a relatively accessible language that is familiar by many engineers and is widely applied on data models, making it relatively easy to adjust in the models. To make the models work properly within the Rijkswaterstaat organization, it is important to use the local Rijkswaterstaat servers and data collection systems (PGIM, PMI, BOS) as a basis for all models.

	What	How	Where	Who	When	Why
Engineer	- Construct overall data connection model - Connect models via Digital Twin - Develop models to calculate and predict the impact of developments - Connect existing models - Asset management models	- Python data connection models - Unity visualization environment	- Online Testing environment for PoC - Local RWS servers, related to all data aquisition models - PGIM - PMI - Peilmetingen - BOS	- EngD Trainee TU Delft - IT experts	Upcomming 3-5 years	- To give substantive interpertation to the architecture

(f) Technician

The role technician can be interpreted in different ways, varying from the person doing the maintenance work on the physical object to the person maintaining the IT logistic systems to the IT specialists building new digital tools for the organization. For the sake of this EngD research, the Technician is considered the IT specialist that collects data and forms.

(i) Technician's view on digital twin according to Zachman framework

For the case of building the digital twin, the technician is interpreted as the IT specialist that builds new tools. This means he/she brings the designs that were set up by the system architect and the data connection models set up by the engineer towards a usable product. In the case of a digital twin this means the collection of the data, coding specific data models and creating 3D models of parts of the barrier. It means a very tight interaction between the system architect, engineer and technician is required to create a product that corresponds with the original idea and design of the product. When the technician is finished with the job, the digital twin is ready to be used.

	What	How	Where	Who	When	Why
Technician	- Collect data - Use models to make information from data - Water level pred. - Closing program calc. - Mistery force	- Individual Python data models - Unity model - Domain models	Data collected from PGIM - Water level comp. - Water level riv. - Wall pitch - Wall position - Pump power - Pump/Valve signals - Comp. Surface vs height Other data sources: - Ultimo - A-omgeving - BesW - BOS - PMI - Groundwater measurements - Geometric position - Wind measurements	- IT experts	Upcomming 3-5 years	- To form the connection between the digital environment and the operational people using the Digital Twin

(g) Enterprise

The enterprise organization is interpreted as the team of people that will be using the digital product daily. This team of users have their own desires and preferences for the design of the product, meaning they are an important party to include in the design and operate process of the digital twin. Basically, they should be involved on every level of the Zachman framework.

(i) Enterprise view on digital twin according to Zachman framework

The users of the Maeslantbarrier digital twin have to main purposes for using the model. From the interviews with Rijkswaterstaat staff followed that the highest concern lies currently in preserving knowledge of the barrier. Since it is such a unique object with very specific elements and interaction between elements, there is no reference material to learn from. This complicates conservation and transmission of knowledge, meaning the knowledge is in some cases only stored in the minds of people instead of documented well. The digital twin is a useful tool for knowledge conservation and training new staff. Because of the visualization of data, the digital twin could act as a kind of ‘flight simulator’ to play scenarios to which staff can be trained.

Looking a bit further into the future, the digital twin could help staff to simulate new scenarios around the barrier and see what the impact of such a scenario is on the barrier itself. The first step into creating this simulator is to bring insight into the current state of the barrier using data from sensors placed at the barrier. This data is visualized in the digital twin, which simplifies the insight in the meaning of the data and is on itself an added value for the staff.

	What	How	Where	Who	When	Why
Enterprise	- Train new staff - Gain insight in live condition of particles - Adapt MTC procedures	- Closing procedure analysis workflow - Translate MTC plans to good workflows	- On and around the barrier - Digital operating environment	- Operational staff	As soon as the digital twin is ready to be used	- Preserve knowledge - Improve asset management procedures - Save cost

F. Schematization of pump discharge calculations compared to pump curves

Figure 46 represents a flowchart of the way data is used to calculate the pump discharge and compare this data to the pump curve.

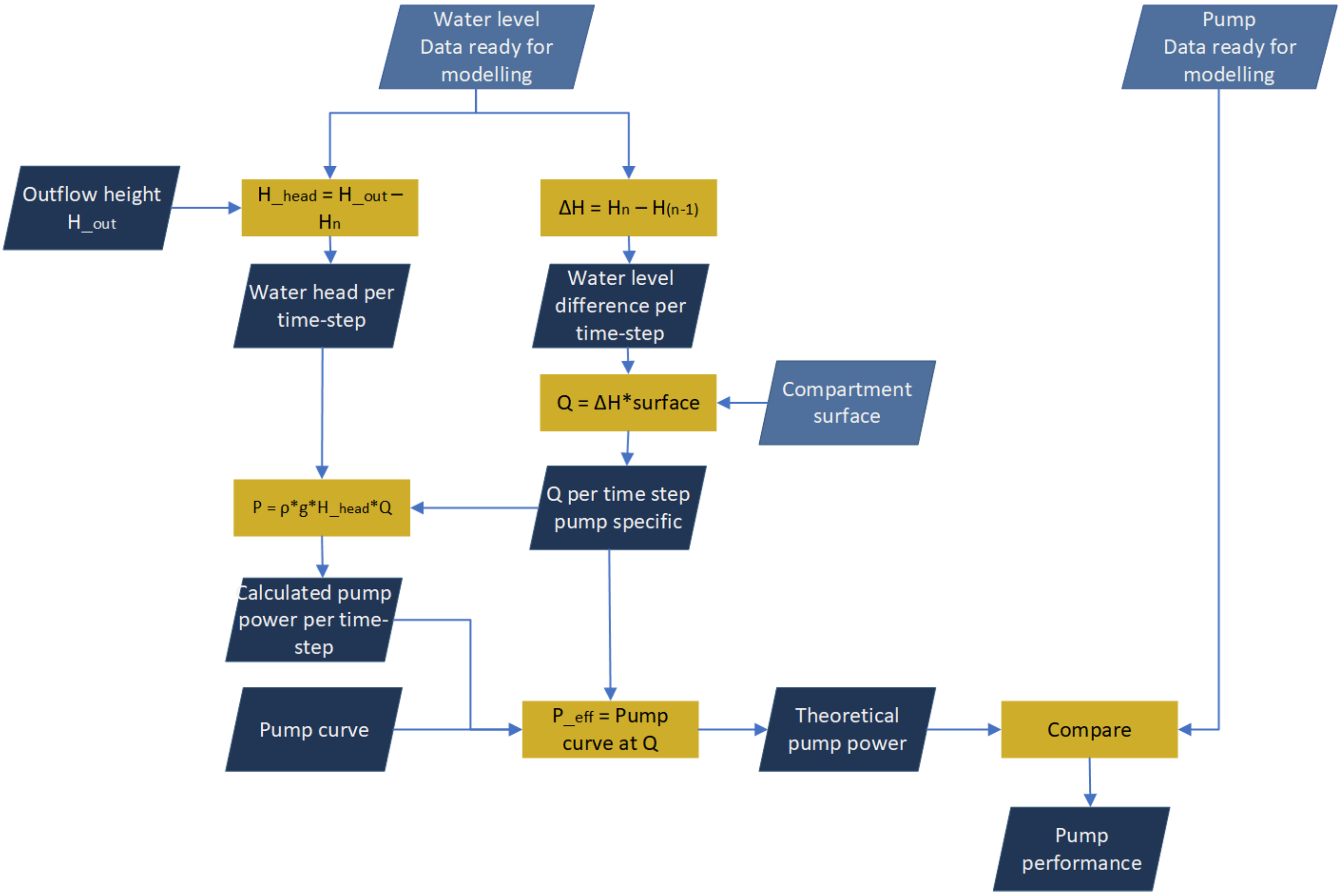


Figure 46: A schematization of the calculation of pump discharges and the comparison to the pump curve

G. Types of data

Retaining walls

The retaining walls exist out of 15 individual compartments, each with its own set of pumps, sensors, aggregates, and butterfly valves. A schematization of these compartments is shown in Figure 47. This figure demonstrates how each compartment exists out of 2 or 3 direct pumps (P), 1 or 2 after pumps (NP), 2 butterfly vales (K) and 2 aggregates (A). Compartments 1 and 2 do not contain any pumps, valves, or aggregates, therefore they are not presented in this figure. In each compartment of the retaining walls the water level is measured at 3 locations. These locations are not all at the same height in the compartment, therefore it is important to compensate the data for this difference in height, to prevent false measurements. Figure 15 provides an example of the decomposition of the data measured in the retaining walls.

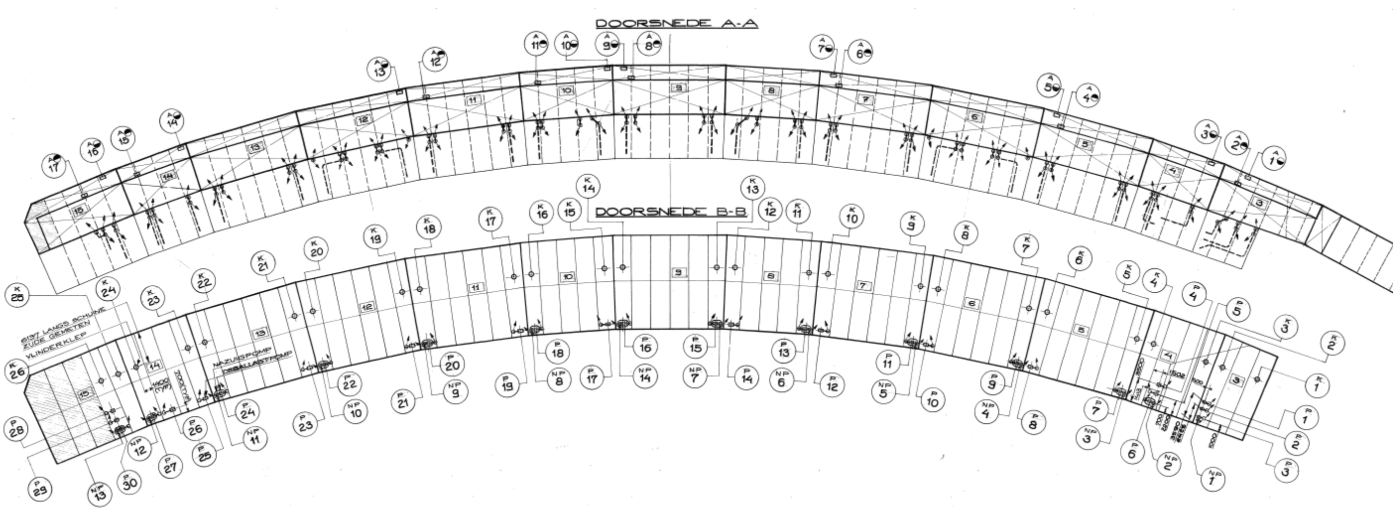


Figure 47: A top view and intersection of the retaining walls. In this drawing the division of the wall into multiple compartments is clearly visible

In each pump, after pump and valve a sensor is placed to measure its 'condition'. In the case of a pump or after pump this means the power of the pump is measured, whether it is turned on or off, the return-signal (on/off) it receives and whether the pump has an error. Per pump this leads for example to 12 sets of data, per dataset varying from a couple of data points to many thousands of data points. In the case of a valve the position of the valve (open or closed) is measured.

River water levels

The water level is measured at several points around the barrier. Measurement stations installed at the seaside and river side of each barrier arm constantly measure the water level at four different locations. Two of these locations are downstream, at the seaside of the barrier (see Figure 48), two more are installed upstream from the barrier, at the river side. Each measurement station has two sensors installed, to make the measurement redundant. The same holds for both docks, where the water level is measured as well, also in a redundant form.

Figure 48: The Maeslant barrier with the water level measurement locations on the seaside of the barrier indicated in orange. These measurement stations are located downstream of the barrier. There are two more locations where the water level is measured, these are more upstream of the barrier, not visible in this figure.

Documentation

The digital twin has a (real-time) connection with its physical counterpart and the world around it. This connection constantly feeds the digital twin with data, either automatically or via a human action. This section describes the different kinds of data sources the Maeslant barrier contains, and the way they feed the digital twin with data. The types of data and their sources are described in Table 31.

Data	***Type of data***	***Update frequency***	***Source***
Design drawings & documents	Static		KMS
Manufacturer data	Static		KMS
Pictures	Static		KMS
Videos	Static		KMS
Current object decomposition	Static		??
Current object 3D model	Static		??
Measurements closing procedures	Dynamic	Yearly	Historian/PGIM
Measurements environment	Dynamic	Every Day/Hour/Minute	
Maintenance history	Dynamic	Weekly	Ultimo
Failure probability information	Dynamic	Half yearly	
Environmental information	Dynamic		
Meta-data	Static/Dynamic		

Table 31: All available data sources to feed the Maeslant barrier's digital twin.

Static data

Rijkswaterstaat’s archives of the Maeslant barrier contain large amounts documents. A significant amount of these documents remains from the design and construct phase of the barrier, which were supplemented with documents, drawings, pictures and videos produced in the maintenance phase. Most of these documents are digitized and stored in a Rijkswaterstaat document management system, called Kennis Management Systeem (KMS). This system contains documents of the Maeslant barrier, Hartel barrier, Hollandse Ijssel barrier, Ramspol barrier and Eastern Scheld barrier, leading to a total of 30-40 million documents stored in KMS.

The detailed design drawings, supplemented with the design reports, describe into detail how the Maeslant barrier is designed and what the important design choices were. These documents relate back to the period between 1992 and 1997, when the barrier was designed and constructed. Although most of the documents are digitized and labelled, it can still be a challenge to find the right document without the original document guide. A search engine supports in finding documents however, due to the number of documents in KMS, finding the right document can be challenging without knowing the right terms to search with.

During the maintenance phase the focus of the produced documents was/is more on inspection- and testing reports with photos and videos of the tested object. These documents are also stored in KMS. Unfortunately, storage of the documents is not done as accurate as during the design and construct phase, meaning documents are not always traceably stored, or might even be deleted.

Besides its limitations, KMS still forms one of the most important sources for static data in the digital twin [37]. The information in this system must be processed in the digital twin in some form. For instance, by making a detailed 3D model based on the most up to date drawings of the barrier. By doing so, information about the barrier's dimensions, materials, structures, etc. should be found directly in this model. For other types of documents, a direct link from the digital twin to KMS should provide a solution. A technical requirement for the digital twin is therefore to use the same system breakdown structure for the information management part as the KMS.

Dynamic data: Sensor data from closing procedures

Dynamic data on and around the Maeslant barrier can be found in different forms. On the barrier itself, there are many sensors that measure a large variety of parameters when the barrier closes. The data files are stored in the data management system called Historian [37]. Before 2020 this system was called PGIM and before 2007 it was called DAS. In 2012, a new way of naming the data-files was introduced, meaning a name-transformation table is required to compare data-files before 2012 to data-files after 2012. The data from before 2007 (so the DAS-data) are currently not reachable for Rijkswaterstaat anymore.

Based on research among the asset management team of the Maeslant barrier, the (test-)closing procedure of the Maeslant barrier are currently its most valuable source of data. Unfortunately, however, the closing procedures of the barrier have not been executed more than twice a year in the Maeslant barrier's lifetime, meaning there is no frequent update of the entire sensor-dataset. Some components of the retaining walls, for instance the pumps, are tested on a monthly base and provide more data. However, a highly frequent (for instance hourly) update of the sensor-data of the barrier is not possible.

Besides the low frequency of data updates from the sensors, it is still highly desirable to process this data in the digital twin. It provides valuable information about the status of the barrier's components and could even lead to more insights when measurements are combined. Currently, the team depends on the analysis done by an external party to gain insight from the measured data. A strong desire exists to be able to do some of these analysis in an own environment [63].

Figure 49: An example of measured values during a closure of the barrier. In this case the horizontal movement (top graph), sink angle (middle graph) and skewness (bottom graph) of the retain wall is visualized

Dynamic data: Environmental data

The closing procedures of the Maeslant barrier are not the only source of dynamic data with potential valuable information. In the area around the barrier multiple sensor systems are installed or frequent measurements are done by external organizations. Permanent systems for gathering environmental data are for instance the ground water level, wind, temperature, or the wave-height and -frequency measurements on the Nieuwe Waterweg channel and North Sea. These measurements are done by Rijkswaterstaat; however the results of the measurements are not included in the Historian (or previously PGIM or DAS) data management. A separate data system exists to store this data.

On a frequent base (not known in detail how frequent) measurements are done on the anodes that are placed on the sheet piles for cathodic protection, and on the preservation layer on the steel elements of the barrier. These measurements indicate the degradation process of the anodes or preservation layer and are done by an organization that specializes in these kinds of measurements. The same holds for measurements of the bottom of the channel, a specialized party executes the measurements and provides the data to Rijkswaterstaat [37].

Not all the mentioned environmental data does directly affect the retaining walls of the Maeslant barrier. Only the data involved with preservation of the steel elements provides extra information about the status of the retaining walls. Therefore, these datasets are desirable to include in the digital twin prototype. The other datasets are important to include when a digital twin of the entire barrier is made, for now however, it is only a ‘nice to have’.

Technical Requirement for the digital twin connection to the real world can be summarized as:

- Make a clear connection with KMS, so documents can be found directly via de digital twin application.
- Make a connection with the historical data bases of closing procedures (when available)

- Provide the availability to import new data from closing procedures.
- Make a connection with relevant environmental data.

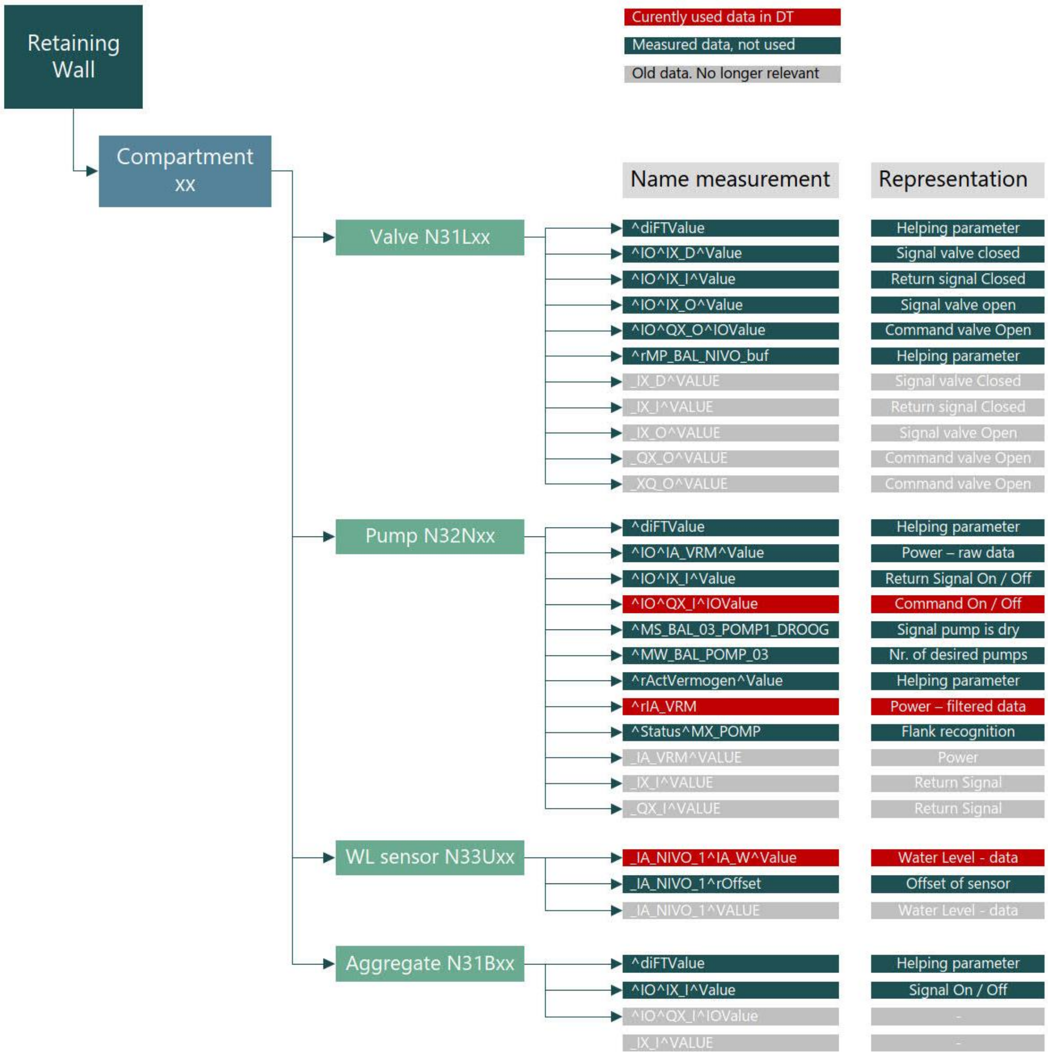


Figure 50: An overview of the types of datafiles produced in the retaining walls during a closing procedure of the Maeslant barrier. The retaining walls exist out of 15 compartments, of which compartment 3 to 15 can be filled and emptied with water. Therefore, they contain several Valves (N31Lxx), Pumps (N32Nxx), Water Level sensors (N33Uxx) and Aggregates (N31Bxx). The 'xx' behind every coding can be replaced by a number when a specific signal needs to be found. Each valve, pump, wl sensor or aggregate produces a series of signals, that can be found in the database by combining the code, number and extension mentioned in the column 'Name Measurement'.

Figure 51: An example of measured water levels in the compartments of the retaining walls during closure of the Maeslant barrier (top graph set). The in- and outflow discharge (bottom graph set) in the compartments is a calculated parameter based on the measured water levels in the time and the dimensions of the compartments.

H. Design architecture

The chosen design method for the digital twin architecture is a process and service-oriented approach. To translate this method into a clear reference architecture, a software language is desired in which these models are already (partly) included in the system. The ArchiMate language fulfills these desires and provides a good environment for drawing up the architecture. This language uses different layers to provide structure and organization in the architecture. The goal is to use these predefined types of layers and integrate them into one clear architecture. This leads to a systematic approach and forms a guideline to make sure the relations between these different layers are described in one design and observed from different viewpoints. The three types of layers that were used for this digital twin are:

- Business layer (in this case supplemented with the external party to which Rijkswaterstaat reports)
- Application layer (in this case split into Digital twin application and Digital twin)
- Technology layer

Business layer

The first layer of the architecture is the business layer. The term 'business' stands in this case for the tasks Rijkswaterstaat has when it comes to operating and maintaining the Maeslant barrier. This layer exists out of the involved stakeholders, the processes involved and the interactions between the processes and stakeholders. In this case, the stakeholders are related to the roles as described in the Zachman framework. For each stakeholder is determined which tasks he or she has for which the digital twin provides a useful tool. These tasks, marked with an arrow in the business layer of the architecture, are connected to a functionality the digital twin has. This is schematized in Figure 52.

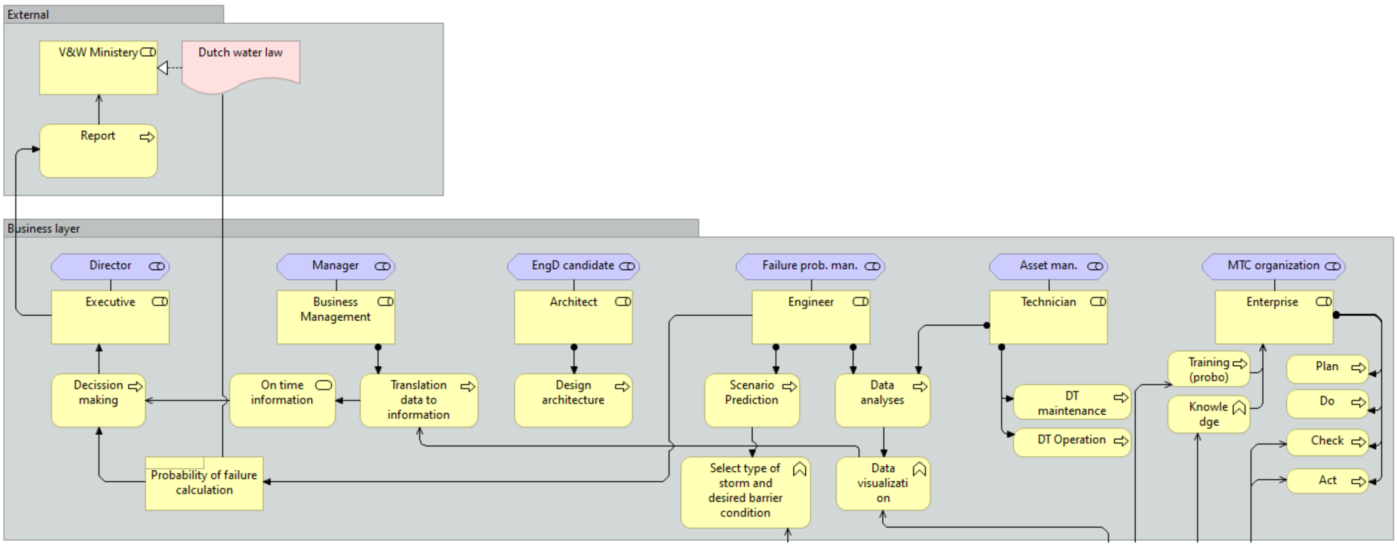


Figure 52: The business layer, supplemented with an external party, of the Maeslant barrier's digital twin architecture.

Application layer

The digital twin application layer and the digital twin model layer are the conceptualization of software implementations and the relations between them. Therefore, these applications are linked to the business processes that must be fulfilled, these processes are indicated in the Business layer (see Figure 52). The Application layer is split into the *digital twin user interface* layer and the *digital twin model* layer. In the *digital twin user interface* layer, all visualization processes are indicated, in the *digital twin model* layer all data and modelling processes are indicated.

Digital twin user interface layer

The central element in the digital twin application layer is the Unity model, which acts as the digital twin *user interface*. This provides the environment in which the users of the digital twin give all commands to do analyses, run simulations or make animations. The Unity interface contains a Knowledge sector, a Data dashboard sector and a 3D simulation sector, which are all indicated in the digital twin application layer, as visualized in Figure 53. In the data dashboard sector and the 3D visualization sector of this layer (Figure 53) is briefly indicated which processes could be followed to open new dashboards or a specific 3D visualization or animation. In Section 6.2 is explained how these processes work.

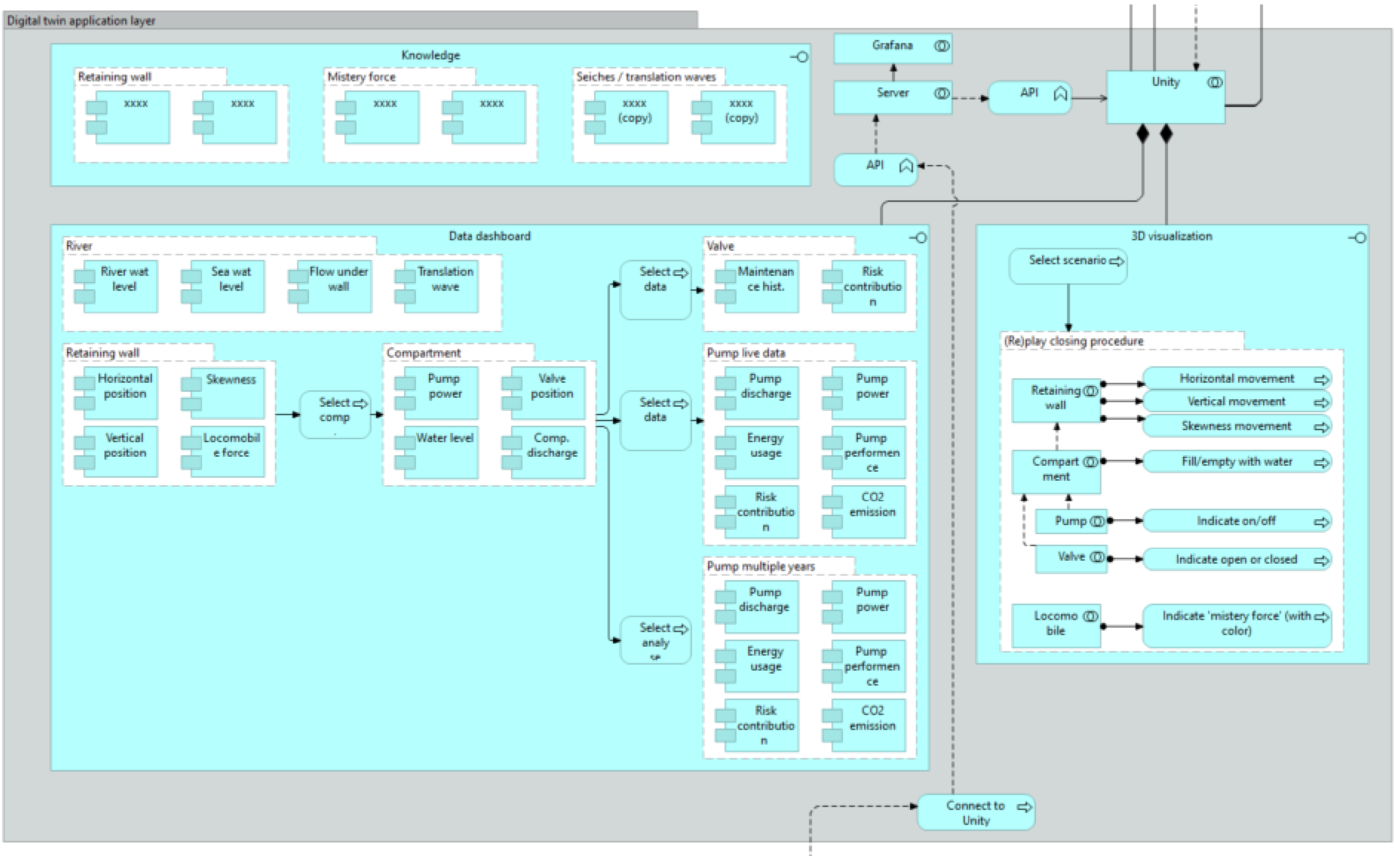


Figure 53: The top side of the Application layer, for the digital twin prototype called the Digital twin application layer.

Digital twin model layer

Data and models are the most important elements in the digital twin layer. Especially for the data holds that this is something that is constantly updated, from different kinds of sources. As indicated in Figure 16, the data is gathered in one central point. From that point it could either be sent directly to the servers of the digital twin application or sent to connected models via a script that can be called for, when necessary, after which it is also sent towards the server. This happens via an API connection, a connection making it possible to send data secured to the server.

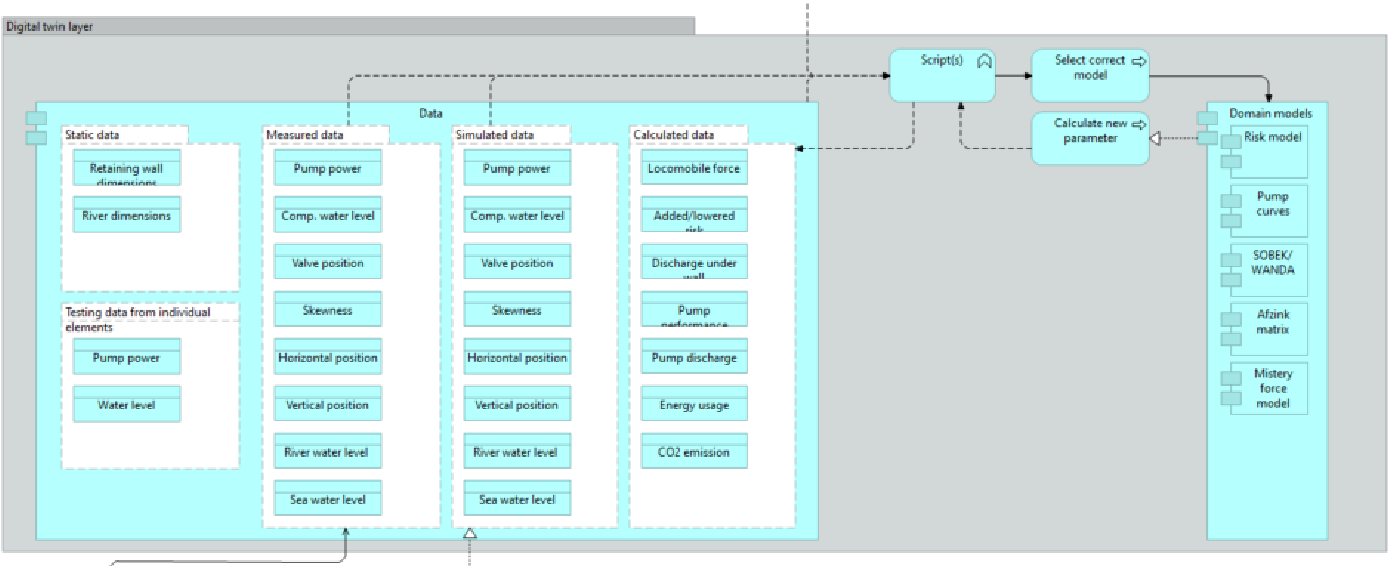
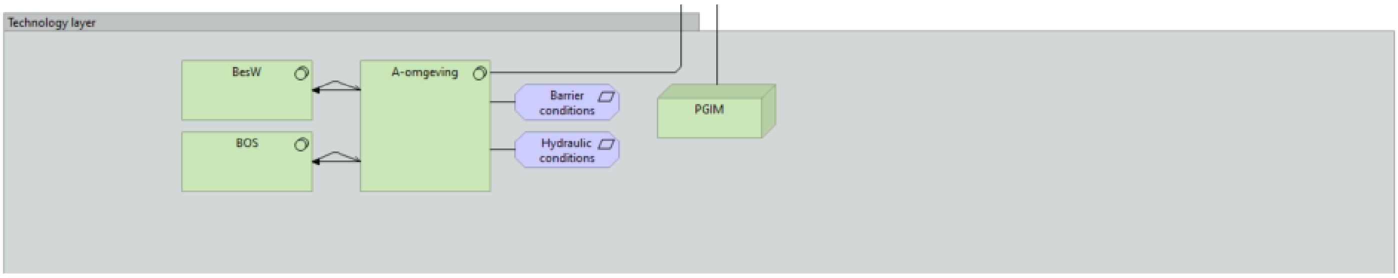


Figure 54: The bottom side of the Application layer, for the digital twin prototype called the Digital twin layer.

11.2.1 Technology layer



I. Failure probability calculation method

Risk Analysis methodologies

The Maeslant barrier is part of a greater system of flood protection objects that protect the hinterland against floods according to a minimum flood risk level. This flood risk level is enshrined in the Dutch Water Act, that sets a minimum performance requirement for every element in the system, including the Maeslant barrier.

These performance requirements are used to set up a *Object Risk Analysis (ORA).* Rijkswaterstaat uses different kinds of depth-levels to perform ORAs, depending on the importance of the object in the greater system. In daily practice, three different types of risk analyses are used by Rijkswaterstaat, which in the PRA guidelines [2] are described as:

- *Maintenance Plan*: Based on a semi-quantitative risk analysis in which the FMECA[13] tool is used. It is applied primarily for permanent structures and line objects.
- *Performance-based Maintenance Plan*: Using a quantitative risk analysis based on the RCM[14] method. This type of risk analysis is mostly used for management and maintenance of critical, movable objects and tunnels.
- *Maintenance Plan based on ProBo*: The most comprehensive form of quantitative risk analysis, used for storm surge barriers and construction of tunnels and water-retaining objects. This approach uses fault trees.

For a storm surge barrier, the most advanced level of ORA is used, a risk analysis method where all the RAMSSHE€P[15] aspects are included in the analysis. This ORA starts with a qualitative analysis that considers both unexpected faults that have a significant effect on performance of the object and the measures required to keep it at the required performance level. When the qualitative ORA is completed, a quantitative ORA is made where the quantitative impact of events described in the qualitative ORA are calculated. For storm surge barriers, this results in a fault tree.

[13] FMECA is an acronym for Failure, Mode Effect & Criticality Analysis

[14] RCM is an acronym for Reliability Centred Maintenance

[15] RAMSSHE€P is an acronym for Reliability, Availability, Maintainability, Safety, Security, Health, Environment, economics (€) and Politics.

In the Guidelines on Performance-based Risk Analyses (PRA) [2], fault tree analysis is described as follows:

"A fault tree analysis (FTA) is an analysis calculating a system's probability of failure (the probability of the top event) by combining the probabilities of failure of the individual system elements in a model. The difference with the method 'addition' (the simplest way of combining the characteristics of the system elements to produce the system's reliability and availability aspects), is that the FTA correctly uses probability calculation and correctly regards redundancy and dependency. This produces a less conservative result than addition of the system elements' data alone. The FTA also provides better insight into a system's weak spots than is possible with the 'addition' method.

An FTA is characterized by the 'fault tree', a graphic representation showing the correspondence between the failure of the different system elements which could result in the top event.

A fault tree consists of a single 'top' event located above various basic events. Basic events describe the failure of system elements. This could be the failure of a physical system element, but it could also be that of a software module, a fault in terms of human actions, or an external event. A basic event or combination of basic events necessary and sufficient to cause the top event is called a 'cut set'. A cut set with a single basic event is termed a 'single point of failure'. A cut set in which two basic events have to occur in order to cause the top event is termed a 2nd-order cut set, etc.

Calculating and adding the probability of each cut set produces a value for the probability of the top event. Depending on the type of analysis, this results in a probability or frequency of failure. If the recovery times are included, the analysis will result in the unplanned non-availability of the system, which is also the probability of failure per demand."

Risk quantification

To manage the events that follow from the fault tree, a *failure probability manager* is included in the Maeslant barrier's team who continuously monitors the total probability of failure of the barrier. Therefore, the components that lead to failure events in the fault tree must be continuously monitored. To quantify the contribution of each component, the failure probability manager or makes a calculation or asks for input from colleagues with expertise about the component.

Four different kinds of components that can contribute to failure are distinguished, namely: hardware components, software components, human actions, or external events. For every type of component that can contribute to probability of failure of the barrier, a methodology or number of methodologies is described in the PRA guidelines [2]. The failure probability manager is expected to use (one of) these methodologies for the quantification of risks in the analysis. These methodologies are not extensively elaborated in this report, only a short description is given. For a more elaborate description of the methodologies, reference is made to Guidelines on Performance-based Risk Analyses (PRA) [2].

When it comes to hardware components in the barrier, there are several ways to quantify its contribution to the probability of failure of the barrier:

- *Statistics*: By registering the failure of hardware components (physical elements such as a pump or an electromotor), a probability of failure can be derived based on the statistics of the data. For many hardware components, generic databases exist that can be used to extract average failure frequencies and convert them into probabilities of failure.
- *Expert opinion*: The opinion of experts can be sought if there are no statistics available, for example because an entirely new component is being used or the generic data available does not apply to that situation. An expert can make an estimate on the probability or frequency of failure by using experience with similar components in similar situations.

- *Calculation*: It is sometimes possible to calculate a component's probability of failure by modelling the component's functioning, often with random input data. This structural analysis is primarily used for components that collapse due to degradation or (excessive) loads.

For software components, the probability of failure is estimated using the TOPAAS[16] method. The method is carried out by independent experts who determine the scores based on information provided by the supplier. This method looks at the development process, the product, the degree of traceability and verification, the extent of product testing, and the environment in which the product operates. The method broadly consists of specifying the various software modules and calculating their probability of failure.

To calculate failure probabilities resulting from human actions, the OPSCHEP[17] [64] model has been developed by Rijkswaterstaat. In the title of the model a reference is made to the Europort Barrier (Europoortkering), of which the Maeslant barrier is part as well. The model was developed within this project that started in 1992, after the finishing of the project in 1997 the model was applied in other large projects as well. The OPSCHEP model is geared towards the quantification of human errors, or the contribution made by people to the non-availability of a system or sub-system.

For the determination of the impact of external events[18], a separate analysis is required [65]. With this analysis an overview is made of the events or threats that have a direct or indirect impact on the performance of the object. Examples of external events include fire, lightning strike, collision and flooding. These external events are usually defined using a standard list of potentially threatening external events. By screening this list and compare it to the situation the object is in, one can determine which specific events form a threat to the object's functioning. Several sub-methods have been developed for analysis of the impact of a number of external events, for instance: risk of lightning, fire or collision. These sub-methods are not further treated in this report.

[16] TOPAAS is an acronym for Task-Oriented Probability of Abnormalities Analysis for Software.

[17] OPSCHEP is an acronym for Ontwikkeling keringen europoort Project Software for the Calculation of Human Error Probabilities

[18] A definition given by the PRA guidelines for an external event is an undesired event that occurs beyond compass of the normal functioning of the system under consideration, but which could still result in failure of the system.

J. Questionnaire

The questions for this user test study are divided into two categories:
- The use of the digital twin user interface
- The potential added value for work on the Maeslantkering, or storm surge barriers in general.

In this case, it concerns a prototype, which is why limited functionality that could be incorporated into a digital twin are included here. When answering the questions, you are therefore asked to imagine certain features.

General

1. What is your current job function?
2. Are you an employee at Rijkswaterstaat and/or how many years of experience do you have within Rijkswaterstaat?
3. Do you have experience with the use of digital twins in the past?
   (Options: Yes, Somewhat, No)

Use of the digital twin user interface

4. What actions or tasks have you performed using the digital twin prototype?
   (Dropdown with several specific actions to check)
5. How did you experience the navigation and interaction with the digital twin prototype?
   (On a scale of 1 to 5, with 1 being 'very difficult' and 10 being 'very easy')
6. How would you rate the overall design and layout of the user interface of the digital twin prototype?
   (Options: scale of 1 to 5, with 1 being 'Not representative at all' and 10 being 'very representative)
7. How self-explanatory (or intuitive) do you find the prototype to be?
   (Options: scale of 1 to 5, with 1 being 'Not intuitive at all' and 10 being 'very intuitive)
8. Any additional comments, feedback, or suggestions you would like to provide?
   (open answer)

Possible added value for the work

9. How accurately did you feel the digital twin prototype represented the actual storm surge barrier?
   (Options: scale of 1 to 5, with 1 being 'Not accurate at all' and 10 being 'very accurate)
10. How useful did you find the visualizations and graphical representations in the digital twin prototype for understanding the behaviour of the storm surge barrier?
    (Options: scale of 1 to 5, with 1 being 'not useful at all' and 10 being 'very useful)
11. To what extent does the digital twin improve the findability of information?
    (Options: scale of 1 to 5, with 1 being 'no improvement' and 10 being 'significant improvement)
12. How would you evaluate the overall performance of the digital twin prototype?
    (Options: scale of 1 to 5, with 1 being 'not useful' and 10 being 'very useful')
13. Which features do you find most valuable? Please describe.
    (open answer)

14. Which features do you feel are missing or could be developed to bring additional value? Please describe.
    (open answer)

The following questions address the potential added value of a fully developed digital twin of the Maeslant barrier. It is assumed that the principle of the developed prototype remains the same, but the functionalities will be greatly expanded.

15. To what extent do you consider yourself capable of independently learning the basic principles of the operation of the Maeslant barrier using the digital twin, without the assistance of a specialist?
    (Options: scale of 1 to 5, with 1 being 'very difficult' and 10 being 'very easy')

    To what extent do you agree/disagree with the following statement:

16. A fully developed digital twin of the entire Maeslant barrier could contribute to accelerating knowledge transfer processes
    (Options: scale of 1 to 5, with 1 being 'completely disagree' and 10 being 'completely agree')
17. A fully developed digital twin could help reduce costs for external parties, such as consulting firms or engineering firms
    (Options: scale of 1 to 5, with 1 being 'completely disagree' and 10 being 'completely agree')
18. A digital twin could help reduce costs for external parties, such as consulting firms or engineering firms?
    (Options: scale of 1 to 5, with 1 being 'completely disagree' and 10 being 'completely agree')
19. A digital twin is valuable in supporting decision-making for maintenance and emergency planning of storm surge barriers?
    (Options: scale of 1 to 5, with 1 being 'completely disagree' and 10 being 'completely agree')
20. How likely are you to recommend the digital twin to others for monitoring and management of storm surge barriers?
    (Options: scale of 1 to 5, with 1 being 'completely disagree' and 10 being 'completely agree')
21. How well did the digital twin prototype meet your expectations?
    (Options: scale of 1 to 5, with 1 being 'completely disagree' and 10 being 'completely agree')
22. Which other storm surge barriers do you see in using a digital twin for actual decision making?
    (Open answer)

K. Organizational feasibility

To determine the maturity of an organization, a large variety of models and methods is available. For the EngD course CEE5003 Asset management, extended research was done towards the maturity of the Rijkswaterstaat storm surge barrier asset management organization for the sake of implementation of new digital technology. The methods applied in this research are a combination of different widely applied models and frameworks to determine the level of digital maturity of the Maeslant barrier's asset management organization. Firstly, an inventory is made of the requirements for the enterprise architecture of a digital twin, which is based on the Zachman method [13]. The Zachman method provides a framework in which the organization is tested on the What, How, When, Who, Where, and Why of the business the organization is involved in, on different kinds of levels in the organization. In this case the term 'business' is a bit difficult to apply since the Maeslant barrier is operated by a governmental organization, therefore in this case it stands for the task the organization is involved with. The subject the framework is applied on is the enterprise architecture of a digital twin of the retaining walls.

When filled in, the Zachman framework provides insight into which parts of the enterprise architecture for the digital twin are not (enough) developed within the organization. The result of this framework provides input for the second model, which is the Asset maintenance maturity model developed by amongst others Chemweno et al. [43]. This model forms a structured guide to determine the asset management process maturity based on index level scores. The model aims at inventorying the maintenance decision making capabilities within the organizations, which leads to a weighted maintenance performance assessment score that facilitates performance measurement and benchmarking [43].

The index level scores from the organizational Asset maintenance maturity model are summarized in Table 32. To visualise the results, a radar figure was made, which is presented in Figure 56. Based on the results from the maturity index investigation a more specific application of the digital twin is opted to be found. This will form the base for a specific plan of action to develop the digital twin, therefore finding a more specific business case.

Theoretical framework for the Maturity of the organization

For this maturity check, a model is used that has been developed step by step in several research programs. The first maturity model was introduced in the quality management area by Crosby in 1979 [66]. This knowledge was used to develop a model that was introduced by P. Antil in 1991 [67] and was further developed by T. Wireman [68], C. Cholasuke et al [69], Campbell and Reyes-Picknell [70]. The final version of the model was presented in 2015 by P. Chemweno et al [43], which was also mentioned by Albuquerque Oliviera and Lopes [71] to develop an interpretation of the model.
The model considers ten evaluation classes or indexes that were defined as: (1) organizational culture, (2) maintenance policy, (3) performance management, (4) failure analysis, (5) planning and programming of preventive maintenance activities, (6) CMMS, (7) spare parts inventory management, (8) standardization and document control, (9) human resource management and (10) results management (maintenance costs and quality). See Figure 55 for a short explanation of the indexes, for a more elaborate explanation of this model a reference is made to the article by Albuquerque Oliviera and Lopes [71].
The model is used to check the level the organization currently holds. The index is determined from the digital twin development point of view, emphatically not from other points of view since this could lead to a totally different index score. This means not all parameters in the index are equally important.

Measurement class	Level 1	Level 2	Level 3	Level 4	Level 5
Organizational culture	Changes are not well accepted. There is no guidance for continuous improvement and teamwork	Changes are accepted reluctantly. The need for continuous improvement was Identified, but not yet adopted. Limited teamwork	Changes are accepted and considered important. Implementation of actions for continuous improvement. Teamwork	Changes are accepted and considered important. Actions for continuous improvement with defined methodologies. Teamwork. Team spirit	There is commitment to the change, adapting to the new strategic priorities. Actions for continuous improvement with defined methodologies. Teamwork. Team spirit
Maintenance policy	Maintenance is considered a necessary evil, being focused on the resolution of faults in the shortest possible time	Maintenance is considered a necessary evil, but the need to act preventively is recognized	Maintenance is considered important in achieving the organization's objectives. Preventive maintenance in order to increase productivity and reduce costs	Maintenance is considered important in achieving the organization's objectives. Acting proactively (including improving equipment) in order to increase productivity, reduce costs and improve quality	Maintenance is considered a strategic function. Acting proactively (including improving equipment) and efficiently in order to increase productivity, reduce costs, improve quality and reduce accidents and environmental impact
Performance management	There are no defined indicators	Performance indicators calculated sporadically, with a focus on technical indicators determined for the all factory and/or at the production line level	Performance indicators calculated periodically, with a focus on technical and economic indicators, determined for the all factory, at the line and equipment level	Technical, economic and organizational indicators calculated and analyzed periodically, supporting decision making and giving rise sporadically to improvement projects; reliable data	Technical, economic and organizational indicators aligned with the strategic objectives of the organization, calculated and analyzed periodically, supporting decision making and giving rise to improvement projects; reliable data
Failure analysis	Failures analysis without a defined method, performed when failures with significant impact occur	Failures analysis without a defined method, performed sporadically and when failures with significant impact occur	Periodic failures analysis based on a defined method	Identification of critical equipment and critical failures sporadically and implementation of measures based on a methodical analysis of failures that causes a low recurrence of failures	Updated information of critical equipment and critical failures, and implementation of measures based on a methodical analysis of failures, which leads to the absence of fault recurrence
Planning and scheduling of preventive maintenance activities	Preventive activities defined following the occurrence of critical events	Planning carried out based on the manufacturer's manuals covering some equipment. Delays and programmed actions not completed	Planning carried out based on the manufacturer's manuals covering all equipment. Delays and programmed actions not completed	Revised activity planning based on failure rate and equipment monitoring. Occasional deviations in plans fulfillment	Revised activity planning based on failure rate and equipment monitoring. Programming defined based on planned production
CMMS	No electronic records of maintenance data	Use of computer applications for maintenance management, not integrated with other computer systems of the company	Computerized system for planning and control of maintenance, with some unused functions, not integrated with other computer systems of the company	CMMS where not all functions available are widely and properly used, not integrated with other systems of the company	CMMS to support all functions of maintenance management, with a high degree of automation, whose functions available are effectively used, integrated with other systems of the company
Spare parts inventory management	Spare parts are not classified. There is no forecast of future demand	Classification of spare parts based on only one criterion (e. g. price or consumption pattern). Demand forecasts based on historical consumption	Classification of spare parts based on only one criterion (e.g. price or consumption pattern). Demand forecasts defined empirically and based on historical consumption	Classification of spare parts based on more than one criterion related to spare parts supply characteristics (e.g. lead time, suppliers) and/or inventory characteristics (e.g. price, obsolescence). Demand forecasts based on historical consumption, spare parts lifetime and maintenance strategy	Classification of spare parts based on their functionalities (impact of stock out), supply characteristics and inventory characteristics. Inventory management strategy defined for each group of the classification. Inventory levels regularly reviewed based on forecast demand, defined based on spare parts lifetime and maintenance strategy
Standardization and document control	Documentation of equipment unavailable or outdated. Non-standardized processes and activities	Documentation of equipment and processes are unorganized. Some processes and activities are standardized, but not revised	Documentation of equipment and processes are organized. Most processes and activities are standardized, but not revised	Documentation of equipment and processes are organized, with quick and easy access. Processes and activities are standardized and revised	Documentation of equipment and processes are systematically updated with quick and easy access. Processes and activities are standardized and systematically revised
Human resource management	Punctual training motivated by high-impact problems. Employees have low competence	Skills development plan for maintenance employees nonaligned with the area's needs	Skills development plan aligned with the area's needs	Skills development plan aligned with the area's needs. Polyvalent maintenance employees, with involvement of production employees in certain activities	Skills development plan aligned with the objectives of the area. Polyvalent maintenance employees, involved in improvement activities. Involvement of production employees in certain activities. Plans for recognition and reward
Results management (maintenance costs and quality)	High and uncontrolled cost; high waste of materials and high recurrence of failures	High and uncontrolled cost, with some actions performed sporadically to reduce waste and recurrence of failures	Implementation of actions to control costs, with level of waste and recurrence of failures measured but not investigated	Controlled costs, with level of waste and recurrence of failures measured and investigated	Controlled costs, low waste and low recurrence of failures

Figure 55: The maturity level index developed by Antil in 1991 [67] and was further developed by Wireman [68], Cholasuke et al [69], Campbell and Reyes-Picknell [70]. The final version of the model was presented in 2015 by Chemweno et al [43]

Theoretical maturity framework worked out.

The theoretical framework for the maturity model as described earlier is used and futher filled in based on the knowledge from filling in the Zachman framework and a theoretical model, combined with interviews and conversations with Rijkswaterstaat employees.

Organizational culture

The organizational culture was rated 2 for this case. Although the team spirit is present in the teams, there is resistance notable against changes in the organization. Especially in the field of digitization appears to be a large interest in new technology, however this technology is not implemented or adopted because one somehow fears to bring changes to the current state of being. This is partly explainable by a shortage of qualified staff with a specialization in digital technology development and causes a relatively low level of knowledge about this subject within the organization. This makes it hard to make decisions about which kind of technology should be adopted and which shouldn't. When this moves on for several years a somewhat conservative culture regarding digitization develops, which is not positive for implementation of new digital technology like digital twins.

Maintenance policy

Rijkswaterstaat's maintenance policy on storm surge barriers is quite well developed. The ProBO model (Probabilistisch Beheer en Onderhoud) determines the maintenance activities on the barriers based of probability of failure of all these particles. The fact that this advanced maintenance method is applied is already an indication of a developed maintenance organization. The team has clearly thought the way maintenance should be performed through and has brought this system to practise.

Considering the maintenance of digital products within Rijkswaterstaat, the current state is unfortunately not so developed compared to the physical objects. Maintenance of digital products is often outsourced, leading to a low level of knowledge about these products within the organization itself. This is a sensitive point when it comes to developing the digital twin, Rijkswaterstaat should be able to maintain this product (at least to a certain extend) itself to keep control over the way the digital twin is used. Otherwise, knowledge about the product will disappear from the organization and the product itself is doomed to be useless in a short amount of time. Because of the low level of knowledge about digital products and how to maintain these products, the index score for this part is rated 2-3.

Performance management

The driving force behind performance management around the Maeslantbarrier is the probability of failure of the barrier. Since the Dutch law prescribes a minimum performance level for probability of failure this automatically how the performance is anchored in the organization. It affects the way of working of almost everybody involved with operation and maintenance of the barrier, therefore also the way the digital twin should be set up.

The probability of failure of the barrier is reported once a year towards the ministry of traffic and water management. A dedicated team of engineers is involved in constantly determining this probability of failure, so the indicators are calculated and analysed periodically to support decision making on multiple levels in the organization. This indicates that the performance indicators are calculated systematically, where the focus lies on technical indicators. The economic parameters are considered but are not the leading factor because of the importance of the barrier in the Dutch water defence system.

Adding up the arguments as described above, an index level of 4 could be given to the organization. However, conversations with different people within Rijkswaterstaat showed that there is quite some discussion about how these parameters are calculated. Since there is no consensus on the determination of these parameters, an index level of 3 is scored.

Failure analysis

Failure analyses are not performed systematically within the organization when focussed on digital products. There is no clear method on how failures in digital product developments are evaluated and how the learnings from these failures are translated into better processes or products. Therefore, an index level of 1 is scored for this part. To prevent confusion: failure analysis is performed on the physical parts of the barrier and on the closing procedures. When these procedures are rated, probably an index level of 3 or 4 is scored. However, in this section only the digital products are evaluated which means an index level of 2 is scored.

Planning and scheduling of preventive maintenance activities

Maintenance activities on the barrier itself are based on the ProBO method and are planned up to years in advance. Activities can deviate from the planning when inspection of the particles gives reason to do so.

There are no data-based maintenance activities on particles of the barrier. Therefore, for this part an index level of 4 is scored when looking at all activities around the barrier. This score becomes lower when only digital products are considered, maintenance on digital products is not always related to the ProBO method, only when it concerns the direct control systems of the Maeslantbarrier. Therefore, the index level score should be adapted a bit when it concerns digital products like a digital twin. Subsequently a fairer index level score is 3.

Computerized maintenance management system (CMMS)

Rijkswaterstaat uses a CMMS called Ultimo to plan the maintenance management. This system is not integrated with other computerised systems and is primarily used for planning and control of maintenance activities. Not all functions of Ultimo are used, however the system also offers functionalities that are not needed to be used. This leads to an index level score of 3 for this subject.

Spare parts inventory management

Spare parts are not a large issue when it comes to maintenance of digital products. Therefore, this subject is not treated in the most literal sense of the word. Spare parts are in this case interpreted as the way physical digital products like servers, hard drives, etc are maintained. During the interviews this subject was difficult to discuss as a separate department within Rijkwaterstaat exists to maintain these parts. This department could not be reached in time to interview; therefore, this is a subject that could not be answered.

Standardization and document control

Rijkswaterstaat has produced many kinds of procedures within their organization which have led to many standardizations as well. Maintaining these procedures, for instance document control, is not always kept to the right level. Therefore, it is not always crystal where documents are saved, under which name and which version. Official documents are usually well organized, but internal reports, memo’s, etc. are often not well documented and hard to find back. This is a structural problem within the organization and does not only hold for documents, it is also applicable on datasets, 3D models, drawings, etc. Therefore, the index level is scored a 2 for this case.

Human resource management

HRM within Rijkswaterstaat is determined by the policy of the ministry. The policy for a long time was to not directly hire specialists within governmental organization, but to outsource this to specializing parties. The reason behind this policy was to save money since people with knowledge were only hired from specialized companies when required. This has led to a significant reduction in knowledge about specialized subjects, which makes the maintenance organization very vulnerable and dependent on external parties. The policy has changed recently, and more and more specialized people are hired directly within Rijkswaterstaat again, however it will take a long time to recover the current ‘damage’. Therefore, an index level of 2 is scored in this case.

Result management (Maintenance cost and quality)

Maintenance on the Maeslantbarrier is only partly cost driven. The ProBO maintenance policy determines when particles need maintenance, cost officially don’t play any role in these decisions but are starting to become more and more important. Since it is tax money that is spent on the barrier maintenance, unnecessary high cost should not be accepted. Therefore, more and more attention is given to methods that could reduce the cost of maintenance in a responsible manner. This means an index level of 2-3 can be scored, since most of the methods are still in development.

Summation of the maturity model

The index level score as described in section the earlier sections are summarized in Table 32. To visualise the results, a radar figure was made, which is presented in Figure 56.

	Level	Description
Organizational culture	2	Changes are accepted reluctantly. The need for continuous improvement was identified, but not yet adopted. Limited teamwork
Maintenance policy	2-3	Maintenance is considered important in achieving the organization's objectives. Peventive maintenance to increase productivity and reduce costs
Performance management	3	Performance indicators calculated periodically, with a focus on technical and economic indicators, determined for the all factory, at the line and equipment level
Failure analysis	2	Failure analysis (on software models) without a defined method, performed sporadically, and when failures with significant impact occur
Planning and scheduling of preventive maintenance activities	3	Planning carried out based on the manufacturer's manuals covering all equipment. Delays and programmed actions not completed.
Computerized maintenance management system (CMMS)	3	Computerised system for planning and control of maintenance, with some unused functions, not integrated with other computer systems of the company
Spare parts inventory management	-	This index was complicated to determine, therefore no further clarification.
Standardization and document control	2	Documentation of equipment and processes are organized. Some processes and activities are standardized, but not revised
Human resource management	2	Skills development plan for maintenance employees nonaligned with the area's need
Result management (Maintenance cost and quality)	2-3	Implementation of actions to control costs, with level of waste and recurrence of failures measured but not investigaded

Table 32: Index level score for the 10 different categories of the maturity model summarized.

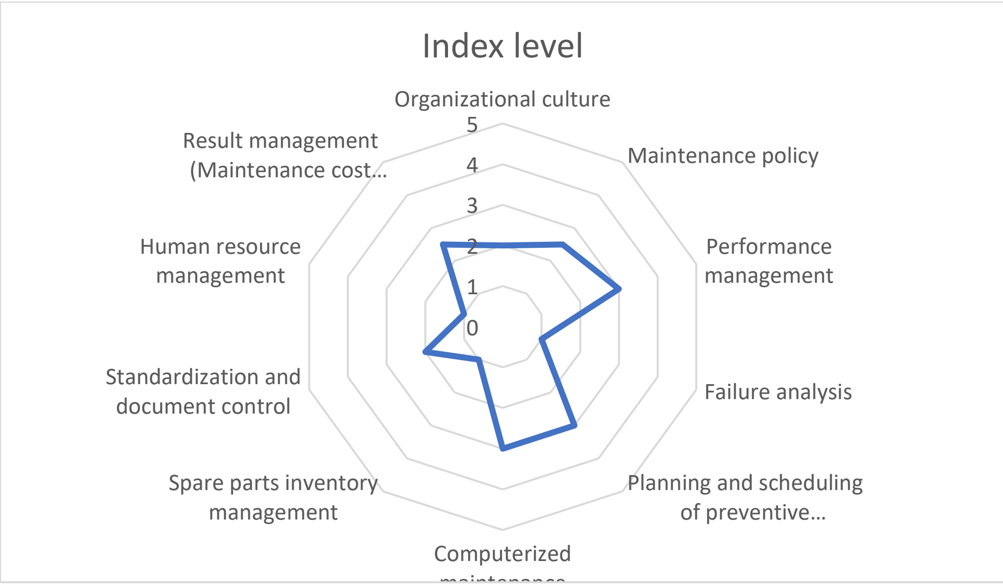


Figure 56: The index level scores of the maturity model presented in a radar figure.

L. Economic feasibility

Within this chapter the design requirements (Chapter 5) were used to estimate the investment cost (CAPital EXpenditure, or CAPEX) and the operational and maintenance cost (OPerational EXpenditure, or OPEX).

CAPEX analysis

Developing a digital twin for the Maeslant barrier can be classified as a 'greenfield' project, meaning there has been done only limited amount of development for this kind of digital twins so far. New developments are not dependent on earlier paved roads, which leads to a wide range of opportunities for the developers. It also means many work needs to be done to set a decent base for the digital twin, as there are no previous projects to use as an example or base-line.

Cost estimate

For the digital twin development, the cost estimate is based on the 5 step approach for a digital twin development (see Section 2.2) and the experience of developing a prototype digital twin for the Maeslant barrier's retaining wall within the EngD program. An indication of the entire development cost can be made based on this prototype, which contains the following elements:

- Medium detailed level 3D model of the Maeslant barrier including terrain around the barrier
- A dashboard function for showing:
  - Historical retaining wall data of closing procedures
  - Retaining wall data of simulated closing procedures ('what if'-scenarios)
  - Calculated retaining wall data from connected domain models
- Several connected domain models using measured data for calculating:
  - The 'live' probability of failure of the barrier (focussing on the retaining wall)
  - Visualization of the hydrostatic forces on the retaining wall and ball joint
  - The "mystery force" on the locomobile
- Data analysis models for:
  - Indicating deviant behaviour of components in the retaining wall

Prototype software cost

One of the main costs of a digital twin are driven by the hours spend by different companies to (digitally) create the product, the amount of physical assets required to make the product is also a significant cost aspect. The hours need to be estimated based on the time (and result following from this available time) and other cost it took to develop a prototype digital twin of the Maeslant barrier's retaining wall. The hours for this prototype are mostly spent by the EngD candidate, who is in charge of developing the prototype. Within the EngD program of the TU Delft, 60 of the 120 ECTS need to be spend on developing the product itself, which comes down to 1 FTE (2080 hours). Relating this to the 5 step approach presented in section 3.1, an estimation of deviation of the hours would be:

- Step 1 – Already partly done in earlier project in Rijkswaterstaat (cost: €30.000,-)
- Step 2 – Estimated to have cost ¼ FTE, or 520 hours
- Step 3 – Estimated to have cost ½ FTE, or 1040 hours
- Step 4 – Estimated to have cost ¼ FTE, or 520 hours (will probably not be completely finished)
- Step 5 – Not included in the prototype due to lack of time and relevance

Extra cost for the prototype were made for visualization purposes of the digital twin. For this, a professional company was hired to set up a Unity model of the barrier and include an animation of the barrier movement. These cost came down to €25.000,-. No hardware was purchased for the prototype, as the software app could be operated from a standard laptop and data was stored on an external server.

Estimation of a full scale digital twin cost

An indication is made on the costs for developing a full-scale digital twin (of the entire Maeslant barrier) based on the prototype costs. The prototype was developed for the *retaining wall*, one of the barrier's four main components. Other main compartments are the *ball-joint, half-timbered system* and *'locomobile'* (the driving mechanism). When a digital twin of the entire Maeslant barrier is constructed, all four components should be included. To estimate the cost for the full-scale digital twin, an estimation should be made for all four components. For this estimation, the full-scale digital twin is assumed to be hosted locally (meaning hardware needs to be purchased), all available data can be visualized and the level of detail of the 3D model is sufficient for technicians to do their work.

Labour cost

No reference exists on making a digital twin of each of the four main components of the barrier. Therefore, for this business case, it is estimated for each of the components to take roughly as much labour as developing the retaining wall's digital twin, meaning a full digital twin costs around four times the development cost of the prototype. Since these costs are a rough estimate, and many aspects are still unknown, an extra margin of 25% is added to cover these potential risks. For step 4, a 50% margin is taken, as this is a step with greater uncertainty when it comes to expected time to implement. This would mean:

- Step 1
    - €30.000,- * 4 = €120.000,-
    - Including extra 25% margin: €150.000,-
- Step 2
    - 520 hours * 4 = 2080 hours
    - Including extra 25% margin: 2640 hours
- Step 3
    - 1040 hours * 4 = 4160 hours
    - Including extra 25% margin: 5200 hours
- Step 4
    - 520 hours * 4 = 2080 hours
    - Including extra 50% margin: 3120 hours
- Step 5
    - Not included in the prototype. Estimation is 2000 hours (ca 1 FTE).

Looking at the amount spent on visualization, and following the same theory as for labour, the cost for visualization are estimated to lay around €100.000,-.

Hardware cost

To make an estimation of the cost for required hardware, comparison is made to a former project within Rijkwaterstaat. Within this project, the *A-omgeving* (a data simulation environment for the Maeslant barrier) was developed and built. The precise finances of this project are not known, however, the hardware cost were estimated €2 mln to €3 mln by one of the project participants, which was ca 1/3 of the project budget.

The hardware costs for a full-scale digital twin are estimated to be of the same order as for the *A-omgeving* development. This is because the data simulations that can be ran with the *A-omgeving* are an important source for the digital twin as well. This also means that a part of the current calculation capacity of the *A-omgeving* can probably be used for the digital twin as well. Therefore, not all equipment needs to be completely renewed, however, considering the short life time of computer hardware, a significant part of the hardware still needs to be purchased. This makes that procurement of new computer hardware is estimated to be in the order of €2.000.000,-

CAPEX estimation

The estimated amount of hours and extra cost for developing a full digital twin are summarized and presented in Table 33. To get an indication of the expected costs for labour, an hourly rate of €120,- per hour is used, which is an average rate for the type of engineering consultancy or software firms involved with developing this product.

Cost aspect	*hours*		*CAPEX (€)*
Labour for software			
Step 1: Architecture		€	150.000
Step 2: Data monitoring & Architecture	*2640*	€	316.800
Step 3: Integration live data & Models	*5200*	€	624.000
Step 4: Integration knowledge	*3120*	€	374.400
Step 5: Sub system integration	*2000*	€	240.000
Visualization		€	100.000
Hardware		€	2.000.000
Total		**€**	**3.805.200**

Table 33: An estimation of the initial investment costs (CAPEX) for developing a full-scale digital twin

OPEX analysis

The cost to maintain a software system like a digital twin can vary significantly based on several factors, including the complexity of the system, the size of the digital twin, the technology stack used, the level of integration, and the specific requirements of the organization. Some cost influencing considerations are:

- **Infrastructure**: Costs for hosting the digital twin on dedicated infrastructure, including server maintenance, storage, and data transfer, contribute to ongoing expenses.
- **Data Management**: The cost of collecting, processing, storing, and managing the real-time data exchanged between the digital twin and its physical counterpart is a substantial ongoing expense.
- **Software Maintenance**: Regular updates, bug fixes, and improvements to the software system are necessary to ensure optimal performance, security, and compatibility with evolving technologies.
- **Integration and Connectivity**: Integrating the digital twin with various systems, devices, and data sources can involve ongoing costs for maintaining connections, APIs, and ensuring interoperability.
- **Analytics and Simulation**: The digital twin employs advanced analytics, simulation, or machine learning algorithms, meaning there are costs associated with algorithm refinement, model updates, and computational resources.
- **User Support and Training**: Providing user support, training, and documentation to ensure efficient usage of the digital twin can incur ongoing costs.
- **Security and Compliance**: Implementing and maintaining robust security measures, encryption, and compliance with data protection regulations are critical ongoing expenses.
- **Lifecycle Updates**: Over time, the physical entity being represented by the digital twin may undergo changes, upgrades, or replacements, necessitating updates to the digital twin to reflect these modifications.

No references were found that gave an indication of the maintenance cost of a digital twin. When looking at Rijkswaterstaat's cost of ownership report of storm surge barriers [34] no cost for digital maintenance could be found either. Therefore, a very rough estimate needs te be made, which in this case is done based on the expected time Rijkswaterstaat employees (or external companies) need to spend on the operation and maintenance of the digital twin. For each of the above mentioned operational and maintenance points, an estimation is made for the required time. The cost of ownership report [34] mentions the average costs for Rijkswaterstaat for one FTE to be €100.000,- per year (or ca €50,- per hour), which is used as a starting point for the cost estimation.

Cost aspect	hours	OPEX (€)	Comment
Assets			
Infrastructure		€ 20.000	Assumed relatively low in OPEX due to high CAPEX
Data management	250	€ 12.500	Assumed to be internally organized
Software maintenance	520	€ 60.000	Commercial hour rate used (€120 per hour)
Integration and connectivity	100	€ 5.000	Assumed to be internally organized
Analytics and simulation updates	250	€ 30.000	Commercial hour rate used (€120 per hour)
User support and training	500	€ 25.000	Assumed to be internally organized
Security and compliance	250	€ 12.500	Executed in cooperation with RWS CIV
Lifecycle updates	100	€ 12.000	Commercial hour rate used (€120 per hour)
Total		**€ 177.000**	

Table 34: An estimation of the operation and maintenance costs (OPEX) of the digital twin

Net Present Value and Equivalent Annual Annuity

Using the CAPEX and OPEX estimate presented in Table 33 and Table 34, combined with a Net Present Value (NPV) [42] and an Equivalent Annual Annuity (EAA) [42] calculation, the required profitability of the digital twin is determined for multiple payback periods, using an interest rate of 6%. This provides insight in what the project's profitability should be, given a certain payback period. The results are presented in Table 35, in which both the investment (CAPEX) and annual maintenance cost (OPEX) are taken into account. Appendix 3 provides a table in which also the NPV of the investment times is incorporated.

Cost aspect	*1*	*2*	*3*	*4*	*5*
Step 1: Feasibility					
Sub-Total EAA	€ 169.000	€ 91.524	€ 65.540	€ 52.432	€ 44.479
Step 2: Data monitoring & Architecture					
Sub-Total EAA	€ 385.808	€ 221.338	€ 165.634	€ 137.144	€ 119.556
Step 3: Integration live data & Models					
Sub-Total EAA	€ 711.440	€ 388.896	€ 280.561	€ 225.799	€ 192.484
Step 4: Integration knowledge					
Sub-Total EAA	€ 446.864	€ 252.755	€ 187.183	€ 153.767	€ 133.230
Step 5: Sub system integration					
Sub-Total EAA	€ 304.400	€ 179.449	€ 136.903	€ 114.980	€ 101.324
Visualization					
Sub-Total EAA	€ 106.000	€ 54.544	€ 37.411	€ 28.859	€ 23.740
Hardware					
Sub-Total EAA	€ 2.120.000	€ 1.090.874	€ 748.220	€ 577.183	€ 474.793
Total EAA	**€ 4.210.512**	**€ 2.247.341**	**€ 1.590.355**	**€ 1.259.991**	**€ 1.060.337**

Table 35: Equivalent Annual Annuity Cost (EAA) of the investment and maintenance cost, given a certain payback period of the project. For each step in the development phase a range is given for the expected CAPEX (a lowest and highest estimation), therefore also

The results from Table 35 indicate that, for a digital twin to be beneficial within 5 years, the annual benefits should be in the order of €1.000.000,-. This number decreases when a longer investment time is taken, however, since a digital twin is a digital product, the lifespan of soft- and hardware is expected to be in the order of 5 years. Therefore, from now on, it is assumed the digital twin should provide **€1.000.000,-** in benefits each year in order to be a worthy investment for Rijkswaterstaat.

In the next paragraph is further investigated whether the digital twin could provide this benefits by generating added value or reduces costs. Or what reasonable assumptions are to justify this benefit.

Benefits analysis

The added value of a digital twin within the organization around the Maeslant barrier is in many cases not directly measurable. The value lies in aspects that contribute to improving the organization in an indirect manner, which leads to savings in budgets. This chapter further reflects on these added values, related to implementing a digital twin in the organization of Rijkswaterstaat. An attempt is made to quantify the added value per digital twin application (as mentioned in Section 4.5). For this investigation, the digital twin prototype tests were used as a starting point.

Digital twin prototype test results

To investigate how the organization experienced the usage of the digital twin. The test results are summarized and linked to earlier defined potential applications of the digital twin (see Chapter 8). Based on the answers from the respondents, an average score is given to each application including a short reflection based on the answers. The score indicates the extent to which the test respondents perceive added value in the application presented by the digital twin prototype.

The scores that were given to the applications indicate that the respondents see added value in the implementation of a digital twin in the organization. The most added value is seen in creating insight via the visualization capabilities of the digital twin and use it for knowledge transfer and education. For risk quantification, there was less enthusiasm, but still a cautious positive response. It should be noted that there is some division among the respondents regarding the added value of certain digital twin functions. This division also appears to be related to the Zachman role of the respondents. The respondents from the business management layer appear to be more positive about digital twin implementation compared to the technician layer.

The added value of all four applications of the digital twin are elaborated in next four sections, for which the results of the digital twin prototype tests form the basis.

Increase efficiency in knowledge and information management

The test results of the digital twin prototype indicate that the potential added value for increasing knowledge and information management is high. Currently it takes almost 5 years to educate new people for the barrier [30], which could, according to reactions of Rijkswaterstaat employees, be significantly shorter when more efficient methods (such as a digital twin) are used.

No scientific publications could be found about efficiency increase in knowledge management due to digital twins. In an article published by McKinsey [72] however, it was noted that in a knowledge intensive sector such as product development, implementations of digital twins have shown an increase in efficiency of 20 to 50%. This was mostly due to the fact that knowledge could be transferred more efficiently, which is also confirmed during the tests of the digital twin prototype.

To translate this to the potential the digital twin has for the Maeslant barrier's knowledge and information management, an estimation is made for the way barrier specific knowledge develops for new staff members. The required knowledge level of new staff to fully function at the barrier is therefore set to be a 100% and it is assumed the knowledge level starts at 0%. An estimation is then made about how the knowledge transfer develops over the years, which is represented by the blue line in Figure 57. Next, the numbers in the McKinsey report [72] are used, and a calculation is made on what the decrease in knowledge transfer time would be if the efficiency increased by 20% (represented by the orange line in Figure 57) and increased by 50% (represented by the grey line in Figure 57). The moment the line touches the 100% value, means the knowledge is fully transferred to the new staff member. Subsequently, one finds that an increase in efficiency of 20%, means a reduction in knowledge transfer time of 1 year. For an efficiency increase of 50%, the time reduces with 2 years.

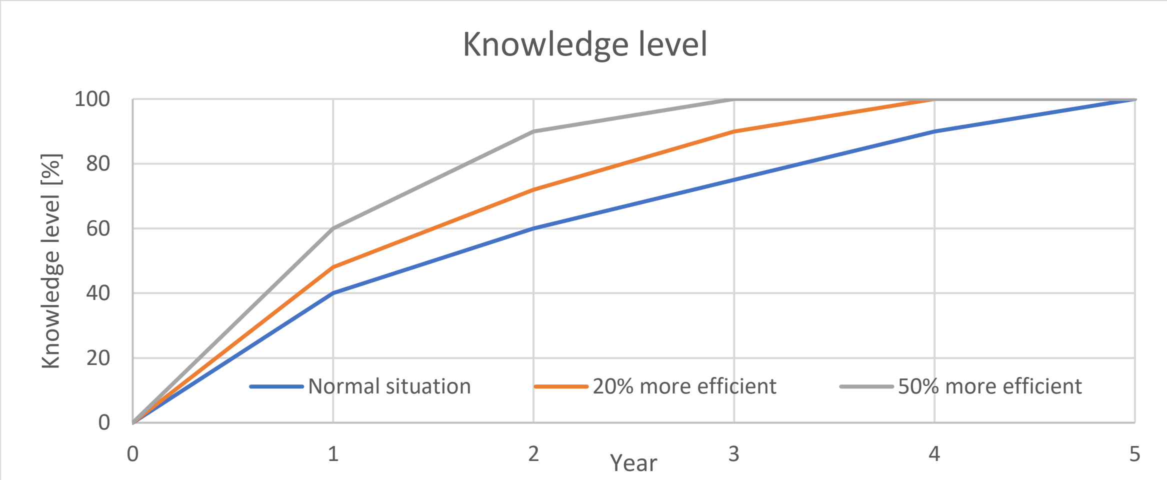


Figure 57: A thought experiment on the knowledge development of new staff around the Maeslant barrier

With the above reasoning, it is estimated that when a digital twin is used, the knowledge transfer period for new staff members reduces with 1 to 2 years (so 20 to 40%). It means, in case a digital twin is used, the budgets for knowledge transfer at the Maeslant barrier are reduced by 20 to 40%. Since the application for knowledge and information management was rated high (see Section 8.2), it is expected that the budget savings are more likely to be 40%.

In the Rijkswaterstaat and I-STORM.NL report [34] the cost for knowledge maintenance were estimated for the Ramspolbarrier to be €137.600,- per year. Unfortunately these costs are not known for the Maeslant barrier, however taking into account that the realisation costs for the Maeslant barrier are about 5x the realisation cost of the Ramspol barrier and assuming these extrapolation also holds for the knowledge management cost, the estimated cost are €688.000,- (or ca 8 FTE) per year. Increasing this process by 40% means a saving of €275.200,- per year.

Avoid unnecessary cost due to better monitoring barrier status

The costs that could become avoidable due to digital twin usage are estimated based on the current maintenance budgets for the barrier. Currently, according to a (confident) report by Rijkswaterstaat and I-STORM.NL [34] on cost of ownership of the Ramspol barrier, ca 20% of the total budget is spent on external staff and advice. A similar report of the Maeslant barrier does not exist, however, these cost deviations are expected to be of an equal order of magnitude for the Maeslant barrier. A digital twin takes over or simplifies certain data analysis tasks, therefore reducing the cost on external staff and advice. It is roughly estimated, based on conversations with Rijkswaterstaat staff, that ca 5 to 15% of the current external reports become unnecessary when the analysis can be made in the digital twin. Therefore leading to 5 to 15% of savings of these costs. Given that 20% of the total budget is spent on external advice and staff, it means 1 to 3% of the total maintenance budget could be saved.

Since the digital twin brings the maintenance specialists more in control of the status of the barrier, the costs for the so called “firefighting” maintenance tasks are expected to decrease. It is difficult to make an accurate estimate for the amount of tasks that could be saved however, it is reasonable to assume that the amount of savings is not extensive. Most of the maintenance tasks still need to be achieved, meaning the savings are relatively small. A savings of 5 to 10% are therefore assumed to be a reasonable estimate. Since the current cost for general small maintenance jobs are currently ca 25% of the total maintenance budget [34] it leads to a total savings of 1,5 to 2,5% of the total maintenance budget.

This brings the total of estimated savings to be 2,5 to 5,5% of the total maintenance budget. Since the respondents of the prototype tests rated this application relatively high, it is estimated that the savings are more likely to be 5,5% than 2,5%, therefore it is rounded to an estimated 5% in savings of the barrier's maintenance budget.

Following the same logic as in Section 4.2, the maintenance budget for the Maeslant barrier is expected to be around €11.000.000,- per year. Saving 5% of this budget means €550.000,- in savings per year.

Better risk control due to models and data-analysis platform

Based on conversations with Rijkswaterstaat staff members, it is assumed reasonable to state that at least one hour per week could be saved on finding information more quickly and accurately when a digital twin is used, which relates to half a day per month. An estimated second hour per week could be saved when staff members can make a risk assumption for possible actions themselves, therefore saving a meeting with the failure probability manager, meaning another half day per month is saved.

With 60 people involved with operating and maintaining the barrier (including the PPO department, excluding contractors), a saving of 1 day per person per month brings the total to 2 FTE[19] per year in savings. This relates to €200.000,- in savings per year.

Create (new) inside in barrier's behaviour

As mentioned, the creation of insides in the barrier's behaviour by the digital twin was rated the highest added value by the test respondents. The data visualisation and animation aspects of the digital twin are considered valuable in understanding the behaviour of the barrier. Quantification of this value lies again in time savings for the Maeslant barrier staff. Although a concrete estimation is complicated to make, one could state that instructing and educating people becomes easier and quicker due to the animation and simulation aspect of the digital twin. If another hour per week could be saved (with the similar reasoning as the previous section) it means half a day per month is saved, meaning another 1 FTE per year, which relates to €100.000,- in savings per year.

The Maeslant barrier has unique problems. A digital twin helps, for instance due to connection of data models or artificial intelligence techniques, to clarify certain unique phenomena. This could provide new insight in what is currently unknown, leading to new actions to reduce risks and prevent serious damage to the barrier. It reduces the costs for emergency measures since measures can be taken upfront instead of afterwards, when the status of components indicate that risks are becoming unacceptably high. The added value of new insight is not further worked out due to the lack of information. However, when serious damage to the Maeslant barrier can be prevented, one quickly talks about hundreds of thousands of euros, maybe even millions. Therefore a small contribution to providing more timely knowledge about the current unknown could already be valuable for the operating organization of the barrier.

Summary

The most vital added value elements of a digital twin applied on the Maeslant barrier are: the efficiency increase in knowledge and information management, findability/analysis possibilities of data and the reduction on risk determination cost. The individual added values are summarized in Table 36.

[19] Full Time Equivalent unit

Application	Estimated savings	Quantification
Increasing the efficiency in knowledge and information management	40% in savings of the barrier's knowledge and information management budget	€ 275.000,-
Avoid unnecessary cost due to better monitoring of the barrier status	5% in savings of the barrier's total maintenance budget	€ 550.000,-
Better risk management due to models and the data-analysis platform	2 FTE per year in savings for the staff	€ 200.000,-
Creating new insight in the barrier's behaviour	1 FTE per year in savings for the staff	€ 100.000,-
Total savings per year		**€ 1.125.000,-**

Table 36: A summary of the benefits a digital twin could generate for Rijkswaterstaat

All assumptions considered, a digital twin is considered to be cost efficient for Rijkswaterstaat. The total yearly benefits (€1.125.000,-) the digital twin could generate transcend the expected yearly investment costs (€1.000.000,-), when an investment period of five years is considered. In the next paragraph, these assumptions are exposed to a brief sensitivity analysis, where also a scenario of external hosting is considered.

Sensitivity analysis

The assumptions that were made in the previous section, to estimate the benefits of the digital twin are not always free of risk, since the assumptions were made with relatively low information. Therefore, to get an idea of the financial risks that are related to these assumptions, a sensitivity analysis is made. For this analysis, the benefits are considered to be overestimated or underestimated by 25%. These scenarios are indicated in Figure 58, where a negative scenario means an over-estimation of the benefits and a positive scenario means an underestimation of the benefits. This provides a spread of the Return On Investments (ROI) of the digital twin.

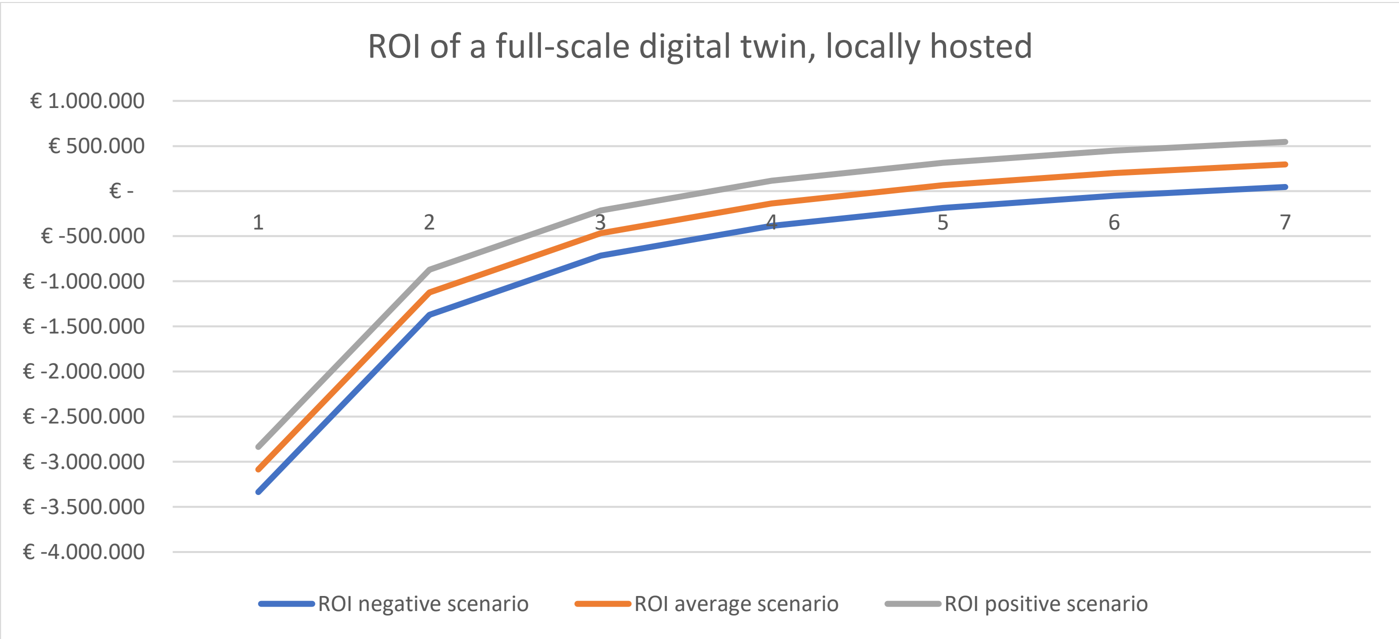


Figure 58: An indication of the spread of the financial risk when the benefits appear to be overestimated (ROI negative scenario), correctly estimated (ROI average scenario) or underestimated (ROI positive scenario). This is for the case where the digital twin is locally hosted.

Figure 58 indicates that the return on investment time differs when the different scenarios are considered. For a negative scenario, the digital twin becomes cost effective after 3 years, while for a negative scenario this is after 7 years. It indicates that the investment could be risky, meaning the benefits need to be evaluated in more detail in a next study.

Since the sensitivity of the full scale digital twin appears to be high, a second scenario is considered. In this scenario the benefits of the digital twin are considered equal, however, in this case the digital twin is not hosted locally, but at an external server. In that case the procurement of hardware is not present, therefore saving €2.000.000,- on investment cost. It does however mean that the hosting cost and cyber security cost are higher (in this case assumed to be €200.000,- per year). When this situation is considered however, see Figure 59, one notices that the financial risk is significantly lower, as well is the ROI time (2 to 4 years).

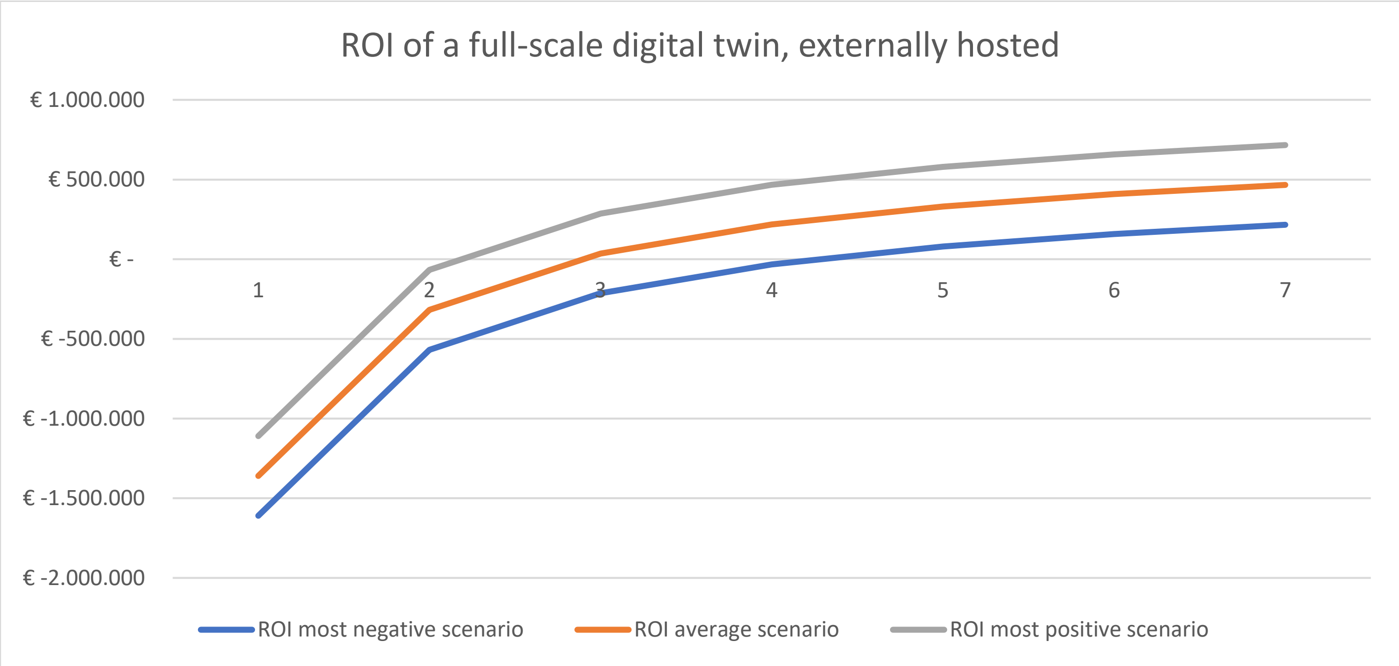


Figure 59: An indication of the spread of the financial risk when the benefits appear to be overestimated (ROI negative scenario), correctly estimated (ROI average scenario) or underestimated (ROI positive scenario). This is for the case where the digital twin is externally hosted.

M. Technical feasibility

To discover what the needs for successful implementation are, the different elements that have led to a successful implementation in other industries are further researched. This leads to several required components that need to be on a decent level for successful implementation. From a high perspective, these are categorized into three elements: hardware-, software- and organizational maturity.

Hardware

The current state of hardware to support digital twins is rapidly evolving in the industry, with advancements in technology leading to more robust and efficient implementations. Digital twins rely on a combination of hardware components to capture real-time data, process information, and enable seamless connectivity between the physical world and the virtual replica.

Required hardware components.

Based on literature research on publications of digital twins in technical industries (see also references in the introduction of this chapter), a list of vital software components indicating successful implementation of a digital twin is distracted. These components are:

- **Data collecting devices such as sensors, actuators, and cameras, also known as the Internet of Things (IoT) devices**
  These devices play a crucial role in collecting data from the physical environment. IoT devices have become increasingly sophisticated, offering higher precision, better data accuracy, and improved connectivity options. They enable the seamless integration of real-time sensor data into the digital twin, providing a comprehensive understanding of the physical counterpart.
- **Computing power**
  As digital twins generate vast amounts of data and require complex computational capabilities, powerful hardware infrastructure is essential. High-performance servers, cloud computing resources, and edge computing devices are used to process, store, and analyze the data collected using the IoT devices. This allows for real-time monitoring, simulation, and predictive analytics, enhancing the functionality and effectiveness of digital twins.
- **Networking infrastructure and connectivity**
  Reliable and high-bandwidth networks, such as 5G, enable fast and smooth data transmission between the physical and digital elements. This facilitates real-time monitoring and control, ensuring that the digital twin accurately reflects the behavior of its physical counterpart.

The industry provides high level quality hardware and is also rapidly evolving their products. The digital twins that were successfully developed in high-tech sectors (Aerospace, Aircraft, Manufacturing, etc.), as mentioned in the introduction of this chapter, prove that the available hardware in the market is not the limiting factor for successful development of a digital twin.

State of hardware at Rijkswaterstaat

At the Maeslant barrier, hardware technology is not as advanced as the market currently provides. The data collecting devices (sensors, camera's), are quite developed and deliver large sets of usable data. These data, however, still needs to be collected locally and can't be reached via a network connection due to Rijkswaterstaat's policy on cyber security. Although the technical facilities (network infrastructure) to automatically collect the data are present at location, the policy obstructs this development. This means that, to develop a state-of-the-art digital twin with live data updates, policy on cyber security needs to be changed within Rijkswaterstaat. This forms a risk of delaying the project.

When this state-of-the-art and detailed digital twin of the entire Maeslant barrier is built and ran at a Rijkswaterstaat location, the current availability of computing power is probably not sufficient. It means new devices need to be bought that can support the models that are connected to the digital twin. It goes too far for this report to go into detail about which types of devices need to be bought however, one should think of a range of new routers, edge servers, IoT gateways, etc.

Software

The current worldwide state of software to support digital twins is highly dynamic and continuously evolving as well. Advancements in various areas enable the creation, management, and utilization of digital twins across industries. Software plays a vital role in the creation of digital twins. Especially when it comes to modelling, simulation, analyzation, and visualization of the digital replicas.

Required software components.

Based on literature research on publications of digital twins in technical industries (see also references in the introduction of this chapter), a list of vital software components indicating successful implementation of a digital twin is distracted. These components are:

- **Modelling and simulation tools**
  These tools allow engineers and designers to create virtual representations of physical assets, capturing their geometry, behaviour, and attributes. Advanced modelling software offers rich libraries of components and parameters to accurately replicate the physical system. Simulation capabilities enable the testing and analysis of the digital twin's performance under different scenarios, providing insights into its behavior or optimizing its design.
- **Data integration and analytics software**
  These tools facilitate the integration of data from various sources, such as sensors, IoT devices, and historical records. They enable real-time data ingestion, processing, and analysis, extracting valuable insights and patterns. Advanced analytics techniques, including machine learning and AI algorithms, are employed to detect anomalies, predict failures, optimize performance, and support data-driven decision-making based on the digital twin's data.
- **Visualization and user interface software**
  Enhance the user experience and enable intuitive interaction with digital twins. These tools provide graphical representations of the digital twin, allowing operators, engineers, and stakeholders to visualize and navigate the virtual environment. User-friendly interfaces enable users to monitor the system, analyze data, and make informed decisions.
- **Connectivity and communication software**
  This is vital for establishing seamless interactions between the physical system and its digital replica. Application programming interfaces (APIs), protocols, and middleware enable the integration of different software systems and ensure the smooth exchange of data between the physical environment and the digital twin. These software components enable real-time monitoring, control, and synchronization, ensuring that the digital twin accurately reflects the state of the physical counterpart.
- **Security and data privacy software**
  Critical components of digital twin solutions. They ensure the protection of confidential data, safeguard against cyber threats, and maintain the integrity and confidentiality of the digital twin. Security measures include encryption, access controls, authentication mechanisms, and monitoring tools to detect and respond to potential security breaches.

The industry currently offers a wide variety of software (in the categories described above) to support digital twins. It encompasses a range of tools and technologies, that work in tandem to enable the creation, operation, and utilization of digital twins. The software developers often provide new kinds of software quicker than potential users can adapt it within their organization. A software developer like Unity has proven to be successful in setting up digital twins in the high tech, engineering, construction, energy, automotive and manufactering industry [60].

As technology advances, digital twin software is expected to become even more sophisticated, offering enhanced modeling capabilities, advanced analytics, and seamless integration with emerging technologies like AI and IoT. In some sectors this technology is already a common way of working, in other sectors it is still upcoming. In general however, it is safe to state that the software to set up the digital twins has proven itself to be in a developed state in the market.

State of software at Rijkswaterstaat

At the Maeslant barrier, finding the connection between highly modern digital twin software and the existing operating system could be a challenge. The existing systems are from 2012, which in software terms is extremely old [32]. History has also proven that software development or implementation projects within Rijkswaterstaat are not always succesful, indicating that this could be a risk factor when developing a digital twin for the Maeslant barrier.

N. Interviews

Interview Rijkswaterstaat Digital Twin platform CIV

Introduction round. What do you do in everyday working life? What is the relationship with the Maeslantbarrier (MB) or Digital Twin (DT)?
Person A: Within RWS I am team leader within CIV department for topographical matters and geo developments. In addition, I take part in the strategic team of CDO (Chief Data Officer), among other things to get the development of Digital Twins to a higher level. For this purpose, a roadmap has been drawn up that should shape the development path up to 2030.

Person B: I am coordinator in the field of Data integration within the Asset Management of Rijkswaterstaat. I have been involved in drawing up the roadmap and vision for using Digital Twins. We thought about all aspects of the Digital Twin concept, and how this can be implemented within the organization. A few dozen initiatives have currently come forward in this area, 5 of which have been identified as promising to develop further.
Introduction of PDEng project.
Brief introduction of the project and what the interests of the organizations involved are.

That being said, let's take a step back and take a closer look at the Digital Twin. What is your view on the Digital Twin phenomenon? Does it have added value?
The added value of a Digital Twin depends on its application, which is why there is no clear answer to this question. In the first place, we are therefore also interested in the application of the model or technique. There is a big difference between the application of a Digital Twin for the construction phase, the maintenance phase, or the operational phase. Each element requires a different approach to the Digital Twin and how it is designed and constructed. However, for many applications there seems to be an added value, which is why we are very interested in the concept of Digital Twin as a whole. In addition, a Digital Twin is also characterized by combining applications, as an example: Measuring or calculating aging on an object is a part of DT, not a specific purpose. In this sense, a Digital Twin can perhaps best be seen as a 4D (3D + factor time) visualization of an object.
Now, a platform is being built where different geo-files can be linked to each other, leading to a living platform where live data can be viewed. This could also be seen as a Digital Twin, but on a larger scale.
At this point in the interview, an Introduction has been given to the current Proof of Concept model of the Digital Twin of the ball joint of the Maeslantbarrier. This is no more than a Proof of Concept that is limited to a 3D representation of the spherical hinge in an environment in which fictitious data has been used to represent the 'live state' of the object. However, this does provide insight into how the Digital Twin could work. Based on this demonstration and the explanation given therein, the interview will be conducted further.

Can AI (Artificial Intelligence) extract more information from the current data? Can it also be seen as a threat?
AI can be an important building block of the DT, but only when it is applied in the right way. A phenomenon such as Machine Learning can for instance lead to an apparent accuracy when information is incorrectly extracted from data. However, for us it can also offer ease of work, for example via an AI model that establishes a link with an external environment and automatically extracts and assesses /processes data from it.

How does this fit **into the platform that is currently being built?**
On this platform, everything can be linked together geographically. All kinds of different forms of data can be linked and displayed in many ways. The building blocks for various Digital Twin applications have also been cast here, including forms of artificial intelligence. This is brought together on the platform and

visualized. The information request we must extract from the platform always depends on the application, as well as the way in which it is visualized.

What is the current policy in the field of Digital Twins within RWS?
We are currently working on the transition of different phases of Digital Twin developments. We are currently working from a pilot phase to a uniformity phase. This means: no new pilots for Digital Twin are being developed anymore, new projects use building blocks that are already being developed when creating a roadmap for Digital Twins. It also means that new developments that do not match the building blocks are not accepted.

That's an interesting statement, if my project doesn't fit in with it, it would mean that I wouldn't be able to get support from you. Where can I find the building blocks for Digital Twins, to check whether my project fits in with them?
One problem is that the architecture of those building blocks has not yet been completed, which is why we cannot give you this yet. However, it seems that your project does fit in with the main lines of these building blocks and is still in a phase where adjustments can be made to make it fit in well with the policy. A central point to register your projects is also not yet set up, this means that no projects can be approved or rejected yet. There is software architecture within RWS, which is an RWS-wide policy and must be adhered to, I can send this to you. For frequently used software packages, the policy is written out here, but there is also room for movement, which means a strict policy is not yet used for all types of software. For example, no choice has yet been made for a digitization engine such as Unity.

Are there collaborations with other government organizations?
We participate in the national initiative of geologists and the national initiative for Digital Twin. Geonoven organizes the Digital Twin physical living environment. Almost all governments and research institutions are affiliated with this.

What is the potential role of the National Cyber Security Centre in this project? Is this a party to be reckoned with?
The policy of this institution is a nationally wide policy, which we follow.

Additional comments:
There has been a preliminary investigation into the application of different forms of Digital Twins in and around Rijkswaterstaat. In the preliminary investigation it was found that more than 30 pilot projects have been started that have been developed from the market, but these initiatives cannot run within the RWS environment. They cannot be managed because they run on developer environments. This probably leads to the fact that these kinds of initiatives are not intoxicated for a long time within Rijkswaterstaat.
On a large scale, the storage of data is not yet well organized. Another investment is needed to be able to store all data for the future. There are several small initiatives for this, but it has not yet been widely taken up. The best thing would be to store everything in a cloud-based environment, but RWS is not yet so far that that is possible.

Twynstra en Gudde has made an advisory report for the 5 leading and promising DTs within Rijkswaterstaat. I can send you this report for your information.

Interview Cyber security CIV

Introduction round. What do you do in everyday life? What is the relationship with the MK?
Within Rijkswaterstaat I work in the Security by Design team. This means that we as a department want to be involved from the start of an IT-related initiative, so that all components of cyber security are considered. As a department, we provide training in this, and we provide both internal and external information on the

matters that need to be taken into account. As a result, I do not have a direct relationship with the Maeslant barrier, but I have been indirectly involved in digitization initiatives.

Introduction of PDEng project.
Brief introduction of the project and what the interests of the organizations involved are.

How do you view the Digital Twin phenomenon? Does it have added value?
Digital Twin, to a greater or lesser extent of development, is a must in current design methodology. With complex systems, you cannot avoid applying a form of Digital Twin if you want to meet the intended end of life date of an object. The 'old-fashioned' design and construction method is no longer sufficient for this due to the rapid developments in many areas. I'm a proponent of building the electronics of an object before the object itself. Often you see that this part built in afterwards, which often means that the ideal equipment does not fit. However, the development of electronic products is also going so quick that by the time you want to deliver something, there is already a newer version on the market, making the current one old-fashioned. This makes the finding and application of the right equipment difficult.

Besides this, construction and design are becoming a more and more integrated process, the classic forms of this can therefore no longer be maintained and must be supported digitally. This also has its consequences for the type of equipment that can be applied in an object.

Can AI extract more information from current data? Or do you see it as a threat?
Based on ISO 27001, a conscious choice was made between separating the test environment from the physical environment. Different forms of artificial intelligence can provide good support for this. Which AI model fits this situation best depends strongly on the situation.

How do you see the possibility of processing your work in the Digital Twin environment?
We are advisors, so we do not have an active role in building digital twins, but we do have an opinion / advice. Security design itself lies with the architects of the system, the framework for this design is given by our department, the architect must conform to it. If this cannot be adhered to, a deviation to the rules and regulations must be made, we can support with making the risk analysis for this deviation. There are then multiple ways to assess the architect's plans. Security maturity is an important component that we consider in this process.

What international standards do you use to extract, process and secure data?
We initially adhere to the general standards and legislation of Information Security that have been drawn up by our national government.

In the CCer there are 5 levels of security defined that must be complied with. For certain objects, such as the Maeslant barrier, additional requirements or standards can be added. This is done based on a risk assessment.

From the aspect of looking at a computer, it is therefore unwise, for example, to have the entire process automated. A computer can't make those decisions.

Introduction given to the current Proof of Concept model of the Digital Twin of the ball joint. This provides insight into how the Digital Twin could work. Based on this demonstration and the explanation given therein, the interview will be conducted further.

To what extent should we comply with the Network and Information Systems Security Act (in Dutch: WBNI)?
This legislation ensures that suppliers of vital digital objects adhere to standard rules, which are based on European directives. So, in the end you will have to stick to that when a product is going to be delivered to

Rijkswaterstaat. It is up to the CIV (Central Information Provision) of Rijkswaterstaat to lay down these types of regulations in a contract with my department.

As an additional note: It is sometimes difficult to determine whether the requirements are met because you 'do not see what you do not see'. For example, how are security incidents reported? And to whom? There is insufficient overview, therefore it is not possible to keep track of which incidents are not reported. This also means that the requirements and wishes are not met.

What should a Digital Twin consider in terms of cyber security?
Every year a check must be done on the current situation and whether the standards of rules and regulations as imposed by RWS are still met.

For this, the VSP requirements are especially important. The more realistic the Digital Twin becomes, the heavier the requirements are that must be met. So, this is a dynamic control system.

What is the potential role of the National Cyber Security Centre in this project? Is this a big stakeholder in this case?
The NCSC is mainly concerned with sharing of knowledge and the search for vulnerabilities in the system (national and local). If there are weaknesses found in the system, they can decide to act on this. It is therefore definitely a party to consider, you must meet their guidelines.

As a final note: Take a good look at page 44 of the cser, here is clearly explained what the guidelines are that you must adhere to. And maybe it is useful to contact the Datalabs of the CIV, because interesting things are done here that fit well with your project.

Interview HVR Engineering (16-12-2021)

Introduction round. What do you do in everyday working life? What is the relationship with the Maeslantbarrier (MB)?

As a lead engineer I am involved in the analysis of the measurement data on the locomobile, this is our own measuring station where information is collected throughout the year. The data is analyzed every 3 months. However, data processing of the closure procedures of the barrier is the main work we are involved in.

I have been involved with the object since the design phase of the Maeslantbarrier. I've had many different positions at the barrier, and I've been involved in many kinds of parts of the barrier. Lately, the focus has mainly been on developing new measuring stations and making a FEM model of the retaining walls.

Introduction of PDEng project.

Brief introduction of the project and what the interests of the involved organizations are.

What is your opinion on the Digital Twin phenomenon? Does it have added value? Can, for instance, AI extract more information from current data?

Generally, we are both positive towards Digital Twin as a concept. We see a lot of added value in other industries, such as in factories where many of the same machines are running constantly. Application in hydraulic engineering is more difficult because the amount of (usable) data is generally less. Models that describe the parameters must be trained with very specific data for a specific machine. This differs to situations in, for instance, a factory with many similar machines. In such a situation many versions of the same machine are in circulation, meaning the model that simulate that machine can be tuned to the behavior of all machines. However, there is only one Maeslantbarrier, so you can't compare the behavior to anything else or tune models to it.

Question HVR: What is your (or RWS) objective of deploying a Digital Twin?

Answer Luc: That depends on who you ask within RWS, one person finds asset management important, a second person is more into data / information processing, and another person is more into simulations and trend analyses. In any case, my aim is to create an environment where the operation of the barrier under changing conditions (climate change) can be simulated.

How do you see the possibility of processing your work in a DT of the Maeslantbarrier?

The calculations that the controlling system of the MB uses (BesW) are not always correct, this is also demonstrable through analysis of data. There are inaccuracies in the assumptions and a Digital Twin can help to bring them to the surface. Our possible role is to include this kind of knowledge in a digital twin environment and check whether the model simulates this correctly.

Example: The inverting wall is not rigid; displacement calculations lead to confusion in the reading of the data (margins in floating and submerged state) and should first be put in order before a conclusion can be drawn from this. This is now being done using the FEM model and strength calculations will soon also be done with this. Ultimately, this can also be translated into loads on, for example, the spherical hinge and can be translated in how well the barrier functions.

What international standards do you use for collecting and processing data?

HVR has its own method of data processing in Matlab. These models are widely applicable and are also used for analyzing the data of the closure procedure. We further stick to the rules and regulations of Rijkswaterstaat.

How reliable are the data sources? Given that something seems to be missing sometimes.

Not treated in interview

What would be interesting (data) relationships to explore?

The amount of data that is extracted with the closure procedure is not sufficient to make a decent trend analysis for all parts of the barrier. In total, the barrier has been closed 27 times, the vast majority of which are not during storm conditions. When performing a trend analysis, a deviation will therefore always be found. Interpretation of the data is therefore extremely important. To know whether this is a deviation from the normal, mechanical, or hydraulic engineering insight is required about the specific part. This knowledge has been developed over the years and cannot be seen in isolation from the data analysis itself.

What is currently being measured (extra) compared to what was installed in 1997?
An additional project has been started in which structural measurements are carried out on the Locomobile. This attempts to extend the lifespan of the hydraulic installation.

What tests are performed on the barrier, and how often does this happen?
Once a month a test series on the pumps. Once every three months a test on the locomotive. For the rest, the barrier is closed once a year for testing.

FEM modeling and condition monitoring, to what extent does this currently provide new insights?
FEM model is not yet fully operational, so can only be answered later.
Interesting additional notes:

- The design philosophy of the MB was that BMK does not have to measure anything, because there was a very good quality design system. That system should be sufficient to ensure that the barrier works.
- Variable forces in the y-direction ensure that the ball-joint of the barrier never remains in the same spot. There is always a little bit of movement on the jack system, which means the system wears out quite quickly.
- RWS does not make trend analysis themselves. They don't have the in-house skills and they don't know what to look at.

Interview Maeslant barrier asset manager

Introduction round. What do you do in everyday working life? What is the relationship with the MB?
Within Rijkswaterstaat I currently fulfill the role of maintenance manager at the 4 storm surge barriers in southwest Netherlands. I am also a senior advisor in asset management at Rijkswaterstaat, so I basically have 2 roles, which can occasionally cause a confusing situation. 20 years ago, I started on the barrier, where I have now fulfilled various roles. I therefore think have a lot of knowledge about the content of the Maeslantbarrier, which mainly concerns the functioning of the barrier itself. When it comes to, for example, the dynamic behavior of the retaining walls, there are other specialists who know more about it.

Introduction of PDEng project.
Brief introduction of the project and what the interests of the organizations involved are.

How do you view the Digital Twin phenomenon? Does it have added value? Can AI extract more information from current data? Is it a threat?
A digital twin can certainly offer added value. Provided, of course, that it is applied in the right way. And that makes it so difficult now because I have already seen digital twin initiatives that approach the project from 5 different angles. There is not one best way of applying a digital twin, which makes it understandable that there are initiatives from different perspectives. However, this must all be done in a structured and controlled manner, otherwise it will be chaos.

In the case of the retaining walls, for example, it is important to first determine its function properly, and also how the individual compartments function in that manner. That should be the starting point for the digital twin.

In addition, I see great added value in the visualization of the data from the measurement stations. This is an important part of the digital twin and can offer great added value for training and simulation purposes.

How do you see the possibility of processing your work in that DT?
There are currently several issues that play a role within the maintenance team. A digital twin could at least be a supportive tool to provide solutions for this. The 'struggles' within the team include:

- There is currently still uncertainty about the ideal standing in which the butterfly valves must be placed in the reversing wall to function optimally. With the digital twin model, various parameters can be connected to each other, and it can be determined how the valves in the compartments should be used. This could include optimizing in, for example, the angle at which the valves are used.
- Many aspects are measured on the barrier, but we do not always know 'live' when a parameter indicates a value that goes beyond the limits of what is acceptable. This is often determined afterwards when the data is analyzed. We would like to automate this process so we can get a warning signal earlier. However, the question that is very relevant (and we don’t have an answer to yet) for this would be: How can we determine a boundary of the things that are being measured at the barrier? There is a lot to win if we could determine this
- We try to approach our maintenance probabilistically. This means that based on the condition of an object, we determine what the probability of failure is and whether it needs maintenance. However, it is not yet possible for all elements in the barrier to carry out the maintenance in a probabilistic manner. Various parts are still replaced based on age and not on performance. For example, a pump in a compartment is now replaced after xx years because we have no other methodology. We could possibly relate the maintenance of this pump to the performance of the pump, for example the flow rate related to the water lever. However, here again the question is: But what is the rejection limit if this value changes and when do we determine when the pump will perform below par?
- Some sensors have a measurement error and therefore must be adjusted monthly. If this is not known, a model in a digital can indicate an incorrect crossing of a border. For example, there are still many small things that make it difficult to determine the state of the object based on data alone. Many objects also require prior knowledge.

If we zoom in on the focus of this PDEng research, namely a compartment of the retaining walls, what are relevant matters to include in the data analyses?

The pumps in the compartments of the retaining walls have a security system. When there is too little back pressure in the pump it cannot deliver power, therefore it automatically shuts down. This is based on the power of the pumps, not on the water level in the compartment.

The switching on and off moment of the pumps causes confusion in the data because they have a start-up and shutdown mode. To properly analyze the performance of the pumps, these moments should be cut from the dataset. How this can be done properly can best be discussed with Hans Nederend. The datasets from the monthly tests of the pumps can provide valuable information about their functioning.