MASTER THESIS

Towards construction 4.0: An assessment on the potential of Digital Twins in the infrastructure sector

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PREFACE

This report presents the result of the master thesis ''Towards construction 4.0: An assessment on the potential of Digital Twins in the infrastructure sector''. This thesis is the final part of my master's program Construction Management & Engineering at the University of Twente and has been performed in collaboration with Heijmans.

My thesis is intended to offer a perspective on the increasingly popular Digital Twin concept in the context of the construction industry. Over the past months, I studied what the concept entails for the construction industry and how it can support the operations of infrastructure contractors. It was a great challenge in which I have greatly appreciated the guidance from both my Heijmans and University supervisors.

In the first place, I would like to thank Arjen Adriaanse and Andreas Hartmann for their constructive feedback and recommendations during our meetings. Our conversations helped me to structure the research and stay on the right track. In addition, I would like to thank Sjoerd Mangnus and Willem Michielsen for the possibility to perform my thesis at Heijmans and for their continuous support throughout the whole project. In particular the numerous brainstorms we have had helped me a lot. Furthermore, I would like to thank all other colleagues at Heijmans that supported me during my thesis. Finally, I would like to thank my family and friends for their encouragement during the whole project and the moments of distraction from my thesis that helped me to relax.

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ABSTRACT

The fourth industrial revolution (i.e. Industry 4.0) reflects a growing trend towards increasingly digitising and automating production environments where communication between physical products, their environment and business partners becomes enabled. A key concept of Industry 4.0 concerns the Digital Twin (DT), whose vision relates to the seamless convergence between the physical and virtual world. In the light of Industry 4.0, DTs have been extensively reported over the past years and proven to offer business benefits in various industries. Yet, the equivalent for the construction industry, referred to as Construction 4.0, has only received limited attention to date. Since Construction 4.0 principles have the potential to strongly impact the industry, Heijmans has set the ambition to have a DT for every project by 2023, which formed the motivation for conducting this research.

Although much literature is available on the DT concept, a uniform definition and reference model are absent. Combining the need for consolidation on the concept in the light of existing research and construction applications, the goal of this research was to contribute to the integration of DTs in the operations of infrastructure contractors by studying what the concept entails for construction and developing a functional design for DTs to assess the potential value that their applications can offer. This research focused on the initial phases of the asset lifecycle, from the start of the design till the end of the construction phase. To conduct this research, the design science methodology has been followed. Using this method, knowledge questions and design problems were treated. Knowledge questions served to frame the DT in the context of the construction industry and to identify potential application areas. The design problem focused on the development of a functional design for two DT use-cases in construction, which were used to validate potential benefits at construction practitioners.

In order to classify the DT in construction, a literature study was conducted that revealed that the interpretation of a DT is affected by four variables: the simulation aspect, lifecycle phase, content, and the physical twin. This yielded that a DT is the virtual equivalent of a physical system that evolves along its lifecycle in a synchronous manner. Furthermore, it was found that DTs can be classified in multiple types and that several authors have taken initiatives to classify DTs in typologies based on different dimensions. In this research, a framework was developed that merges three existing DT typologies and enables to frame a DT based on three dimensions:

- Attribute (Asset, Process, Fleet);
- Lifecycle phase (Beginning of Life [BOL], Middle of Life [MOL], End of Life [EOL]);
- Extent of data integration (Digital Model, Digital Shadow, Digital Twin).

Using this framework, six interrelated types of DTs for application in the construction industry were differentiated. These were distinguished based on whether they are applied during the BOL phase (design & construction planning) or MOL phase (construction), and whether they provide the virtual representation of an asset, process, or fleet of similar assets or process steps. For each of the six types, application areas were found in the construction industry based on interviews at Heijmans, document analysis, and literature regarding DT applications in other industries. DTs can thereby be regarded as a means to monitor, analyse, simulate and predict the performance of a physical system. The identified applications centre around virtual commissioning, evaluation of design and process configurations, (real-time) monitoring, what-if scenarios, and information continuity along the asset lifecycle.

To explore the practical applicability of DTs in construction and assess the potential added value, a functional design was developed for two use-cases. Since literature lacks a general accepted reference model, a literature study regarding DT building blocks was conducted to provide guidance on the functional design. The literature study found that reference frameworks are context dependent and influenced by the classification used for DT. For application in the construction industry, a DT reference framework has been developed that consists of six building blocks that are semantically linked:

- Physical layer;
- Model layer;
- Data layer;
- Connection;
- Service layer;
- Enterprise layer.

The six building blocks in the DT reference framework provided the baseline for the functional designs of two use-cases, respectively:

- Simulation based optimisation of asphalt paving operations;
- Progress monitoring using field data capturing technologies for groundwork activities.

Simulation based optimisation of asphalt paving operations provides a practical example on how DTs can be used during the BOL phase with the emphasis on the process domain. This application enables to virtually evaluate multiple process configurations in a data-driven simulation environment. Based on the simulation outcomes, the most cost-effective alternative can be selected. Validation of this use-case demonstrated that it could lead to improved predictability of the process, cost reductions and improved communication.

Progress monitoring using field data capturing technologies for groundwork activities provides a practical example of a monitoring service that can be offered by the DT during the MOL phase. Based on geometric comparisons between the as-planned model and point-clouds of the as-built status on a reference moment, this application enables to keep track of the progress made on the construction site and highlight progress discrepancies. Furthermore, monitoring data can be analysed to detect activities that regularly cause delays or cost overruns. Validation of this use-case demonstrated that the implementation of this use-case could lead to earlier identification of deviations with regard to schedule, better financial control, and better traceability of deviations from the design.

Overall, this research found that DTs can be expected to offer added value in the primary business process of infrastructure contractors. DTs thereby mainly affect the way how stakeholders interact with information throughout the asset lifecycle. The main transformation areas can be expected on the control and feedback loops, where stakeholders can benefit from better informed decision making due to the availability of quantified progress data and simulation capabilities.

Recommendations based on the results of this research concern that in the light of Heijmans' ambition for 2023, for relatively simple projects where no Operations & Maintenance is included in the scope, the two types of DT process applications can most likely offer most added value. Furthermore, it is recommended to conduct a Proof of Concept for both use-cases to validate the actual added value instead of relying on predictions. In addition, it is recommended to start with monitoring services because they facilitate to collect data in a structured manner that can be used for both, controlling the process as well as input for simulations for future operations.

SAMENVATTING

De vierde industriële revolutie (Industry 4.0) beschrijft het in toenemende mate digitaliseren en automatiseren van productieomgevingen waarbij communicatie tussen fysieke producten, hun omgeving en ketenpartners mogelijk wordt. Een sleutelbegrip binnen Industry 4.0 betreft de Digital Twin (DT), welke gebaseerd is op een visie waarbij een naadloze overgang tussen de fysieke en virtuele wereld gerealiseerd wordt. In het kader van Industry 4.0 is de afgelopen jaren uitvoerig geschreven over DT’s vanuit verschillende sectoren. Ze worden daarbij geassocieerd met verschillende bewezen voordelen voor bedrijven. Desondanks heeft de evenknie voor de bouwsector, Construction 4.0, tot nu toe slechts beperkte aandacht gekregen. Echter, aangezien Construction 4.0 principes de potentie hebben om de bouwsector sterk te beïnvloeden, heeft Heijmans de ambitie gesteld om in 2023 voor elk project een DT te hebben, hetgeen de aanleiding vormde voor dit onderzoek.

Hoewel veel literatuur omtrent DT’s beschikbaar is ontbreekt een uniforme definitie en referentiemodel. De behoefte voor een synthese van bestaande literatuur gecombineerd met de beperkte beschreven DT-toepassingen in de bouw hebben ertoe geleid dat het doel van dit onderzoek geformuleerd is als: het bijdragen aan de integratie van DT’s in de bedrijfsvoering van aannemers in de infra sector door te bestuderen wat het concept inhoudt voor de bouw en het ontwikkelen van een functioneel ontwerp voor DT's om de potentiële waarde te beoordelen. Dit onderzoek richtte zich enkel op de beginfasen van de levenscyclus, van ontwerp tot en met realisatie. Om dit onderzoek uit te voeren is de Design Science methode gevolgd waarmee kennisvragen en ontwerpproblemen beantwoord werden. Kennisvragen dienden om de DT in de context van de bouwsector te classificeren en potentiële toepassingsgebieden te identificeren. Het ontwerpprobleem was gericht op de ontwikkeling van een functioneel ontwerp voor twee DT use-cases in de bouw, die gebruikt zijn om potentiële voordelen bij vakmensen te valideren.

Om de DT in de bouw te classificeren werd een literatuurstudie uitgevoerd waaruit bleek dat de interpretatie van een DT wordt beïnvloed door vier variabelen: het simulatie-aspect, de levenscyclusfase, de inhoud en de fysieke tweeling. Hieruit kon worden opgemaakt dat een DT het virtuele equivalent is van een fysiek systeem dat synchroon langs zijn levenscyclus mee evolueert. Daarnaast werd vastgesteld dat DT's in meerdere typen kunnen worden geclassificeerd. Meerdere onderzoeken hebben DT’s geclassificeerd in typologieën op basis van verschillende dimensies. In dit onderzoek is een raamwerk ontwikkeld dat drie bestaande DT-typologieën combineert en het mogelijk maakt om een DT te positioneren op basis van drie dimensies:
• Attribuut (Asset, Proces, Vloot);
• Levenscyclusfase (Beginning of Life [BOL], Middle of Life [MOL], End of Life [EOL]);
• Mate van data-integratie (Digital Model, Digital Shadow, Digital Twin).

Aan de hand van dit raamwerk werden zes onderling gerelateerde typen DT's voor toepassing in de bouw onderscheiden. Deze werden onderscheiden naargelang ze worden toegepast tijdens de BOL-fase (ontwerp en werkvoorbereiding) of MOL-fase (realisatie), en of ze de virtuele weergave bieden van een asset, proces of vloot van vergelijkbare assets of processtappen. Voor elk van de zes typen zijn toepassingsgebieden in de bouw gevonden op basis van interviews binnen Heijmans, documentanalyse en literatuur over DT-toepassingen in andere sectoren. DT's kunnen daarbij worden gebruikt als een middel om de prestaties van een fysiek systeem te bewaken, analyseren, simuleren en voorspellen. De geïdentificeerde applicaties voor de bouw staan in het teken van virtuele inbedrijfstelling, evaluatie van ontwerp- en procesconfiguraties, (real-time) monitoring, wat-als scenario’s en informatiecontinuïteit langs de levenscyclus.

Om de praktische toepasbaarheid van DT's in de bouw te beoordelen en de potentiële toegevoegde waarde in kaart te brengen werd een functioneel ontwerp ontwikkeld voor twee use-cases. Aangezien er vanuit literatuur geen algemeen geaccepteerd referentiemodel bestaat werd een literatuurstudie naar DT-bouwblokken uitgevoerd. Deze bouwblokken dienden als uitgangspunt voor het functionele ontwerp. Uit de literatuurstudie bleek dat referentiemodellen contextafhankelijk zijn en worden beïnvloed door de classificatie die voor DT’s wordt gebruikt. Voor toepassing in de bouw is een DT-referentiemodel ontwikkeld dat bestaat uit zes bouwblokken die semantisch met elkaar zijn gekoppeld:

- Fysieke laag;
- Modellen laag;
- Data laag;
- Connecties;

- Service laag;
- Enterprise laag.

Het DT-referentiemodel vormde de basis voor het functionele ontwerp van twee use-cases:
- Optimalisatie van het asfalt verwerkingsproces doormiddel van simulatiemodellen;
- Voortgangsbewaking met behulp van scan- en meettechnologieën voor grondverzet.

Optimalisatie van het asfalt verwerkingsproces doormiddel van simulatiemodellen biedt een praktisch voorbeeld van hoe DT's kunnen worden gebruikt tijdens de BOL-fase, met de nadruk op het procesdomein. Deze toepassing maakt het mogelijk om virtueel meerdere procesconfiguraties te evalueren in een data-gestuurde simulatieomgeving. Op basis van de simulatieresultaten kan het meest kosteneffectieve alternatief worden gekozen. Validatie van deze use-case toonde aan dat het gebruik kan leiden tot een betere voorspelbaarheid van het proces, kostenbesparingen en verbeterde communicatie.

Voortgangsbewaking met behulp van scan- en meettechnologieën voor grondverzet is een praktisch voorbeeld van een monitoringsdienst die door de DT kan worden aangeboden tijdens de MOL-fase. Op basis van een geometrische vergelijkingen tussen de geplande voortgang en een puntenwolk van de werkelijke voortgang op een referentiemoment, maakt deze toepassing het mogelijk om de voortgang accuraat inzichtelijk te maken en voortgangsverschillen te visualiseren. Bovendien kunnen monitoringgegevens worden geanalyseerd om activiteiten te detecteren die regelmatig vertragingen of kostenoverschrijdingen veroorzaken. Validatie toonde aan dat de implementatie van deze use-case zou kunnen leiden tot een eerdere identificatie van afwijkingen met betrekking tot planning, betere financiële controle over het project en betere traceerbaarheid van afwijkingen van het ontwerp.

Uit dit onderzoek is gebleken dat het aannemelijk is dat DT’s toegevoegde waarde kunnen bieden in het primaire bedrijfsproces van infrastructuuraannemers. DT's hebben vooral invloed op wijze van interactie met informatie gedurende de levenscyclus. De belangrijkste transformatiegebieden kunnen worden verwacht op de controle- en feedbackloops, waar gebruikers kunnen profiteren van beter geïnformeerde besluitvorming vanwege de beschikbaarheid van onder andere gekwantificeerde voortgangsgegevens en simulatiemogelijkheden.

Aanbevelingen op basis van de resultaten van dit onderzoek betreffen dat in het kader van de ambitie van Heijmans voor 2023, voor relatief eenvoudige projecten waarbij geen beheer of onderhoudscomponent in de projectscope is opgenomen, de twee typen DT-procestoepassingen waarschijnlijk de meeste toegevoegde waarde kunnen bieden. Verder wordt aanbevolen om voor beide use-cases een Proof of Concept uit te voeren om de werkelijke waarde te valideren in plaats van uit te gaan van verwachtingen. Bovendien wordt het aanbevolen om te beginnen met monitoring toepassingen omdat deze kunnen worden gebruikt om gegevens te verzamelen op een gestructureerde wijze die zowel gebruikt kunnen worden voor bewaking van het proces, evenals input voor simulaties voor toekomstige werkzaamheden.

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1 INTRODUCTION

This chapter clarifies the motivation for conducting the research and provides background on the topic. Furthermore, the problem of the guest organisation and the research goal and questions are presented.

1.1 Background

In the recent years, Industry 4.0 has been proposed as a popular term to reflect a trend towards increasingly digitising and automating production environments in the manufacturing industry (Schmidt et al., 2015). Supported by underlying technologies such Internet of Things, Big Data Analytics, and Machine learning, Industry 4.0 enables the creation of a digital value chain where communication between physical products, their environment and business partners becomes possible (Schmidt et al., 2015). Closely related to the concept of Industry 4.0 is the notion of Digital Twin (DT), whose vision relates to the seamless integration between the physical and virtual world (Tao, 2019). DT as core concept of Industry 4.0 has been extensively reported over the past years and has proven to offer many business benefits in various industries (Negri, Fumagalli, & Macchi, 2017; Tao, 2019).

Despite the potential advantages of Industry 4.0, such as enhancing productivity and quality, the equivalent for the construction industry, referred to as Construction 4.0 (European Construction Industry Federation, 2017), has only received limited attention in scientific literature compared to manufacturing (Oesterreich & Teuteberg, 2016). Although construction's digital transformation in the era of Industry 4.0 is moving slowly, it has the potential to strongly change the industry (Dallasega, Rauch, & Linder, 2018). Yet, the construction industry faces considerable challenges in the adoption of digitisation and automation technologies to keep up with productivity improvements of the manufacturing industry (Craveiro, Duarte, Bartolo, & Bartolo, 2019). The high number of interrelated processes and participating stakeholders in temporary coalitions at different stages of the construction lifecycle make construction a complex undertaking (Gidado, 1996). Furthermore, due to the unique, site-based character of construction activities, high degrees of customisation are applied to each project, limiting interproject learning (Adriaanse, 2014; Dubois & Gadde, 2002).

In order to deal with these inherent challenges of construction, four crucial keys to the digital transformation of the construction industry are: digital data, automation, connectivity, and digital access (Dallasega et al., 2018). In this regard, DT can be seen as a supportive concept in the digital transformation towards Construction 4.0. The widespread use of digital technologies and sensor systems in Construction 4.0, as supported by the DT, enables construction companies to increase productivity, reduce schedule and cost overruns, manage project complexity, and improve quality and resource-efficiency (Craveiro et al., 2019). Despite the slow adoption of industry 4.0 enabling technologies, the relevance of digital transformation in construction is beyond dispute. This is reflected by a recent survey on digitalisation amongst Dutch construction companies, which shows that about half of the participants indicate that the digital transformation of internal and external processes is the top priority (Canon, 2019).

Although DTs received considerable attention from both academia and practice in the recent years, and several DT related proofs of concepts (e.g. Haag and Anderl (2018)) have been developed as well as some commercial solutions are already available on the market, there still seems to be still a lack of consensus about what constitutes a DT (Eckhart & Ekelhart, 2019). This lack of clarity also prevails in the construction industry, where the concept is starting to gain momentum recently. A number of commercial parties in the construction industry claim to have a ''Digital Twin'' while the term is used to indicate different things, such as the ''Digitale tunneltweeling'' by COB (2020) and the DT building concept of Siemens (2018). It is therefore desirable to gain an improved understanding of what constitutes a DT and how this can be used to offer business benefits in the context of the construction industry in the light of Construction 4.0.

1.2 Heijmans

This research is conducted within the Infra department of the Dutch contractor Heijmans N.V. The business operations of Heijmans are divided in three departments: *Vastgoed*, *Bouw & Techniek* and *Infra*. The Infra department operates in the sub-fields of mobility, water and energy, where the main focus is on designing, constructing, operating and maintaining roads, civil engineering objects, and urban planning (Heijmans N.V., 2019).

Digitalisation at Heijmans

In line with the results of the survey from Canon (2019), digitalisation is amongst the top priorities of Heijmans for the coming years. The ambitions regarding digitalisation are included in the strategic agenda for 2023. The three cornerstones of this strategic agenda are *''Verbeteren, Verslimmen & Verduurzamen''*. Digitalisation is one of the two key focus areas within ''*Verslimmen*''. One of the concrete targets with regard to digitalisation concerns the objective of having a Digital Twin for each project by 2023, which forms the rationale for conducting this research (Heijmans N.V., 2019).

1.3 Research problem

Although Heijmans' ambitions regarding DTs are high, preliminary research has indicated that it remains relatively unclear how this ambition can be translated into concrete sub-goals that drive the change towards this target. Furthermore, there is a lack of unified insight in the organisation regarding what constitutes a DT for the construction industry. As a result, there is no clear picture of what value adding applications can be levered using a DT. This in turn complicates the ability to effectively define a route towards the goal of 2023 based on concrete sub-goals. An overview of the problems that are treated in this research is depicted in Figure 1.

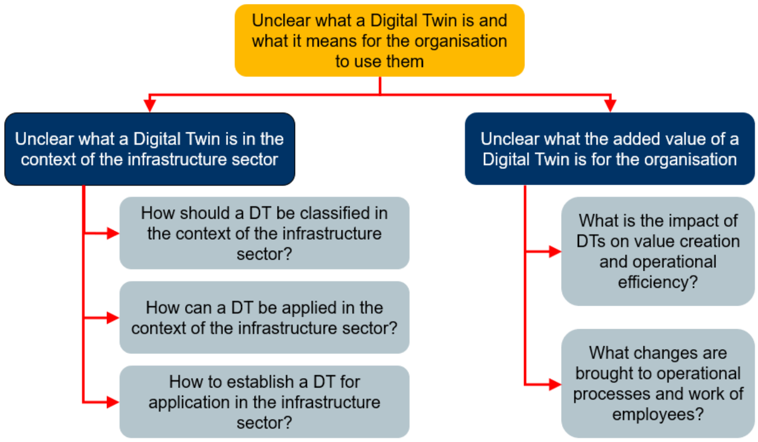


FIGURE 1: RESEARCH PROBLEM

1.4 Research goal

This research focuses on the integration of DTs in the primary business process of infrastructure contractors. Although a considerable amount of research has focused on classifying and developing DTs in the industrial domain, the DT concept in the construction industry is still underexposed. Taking the research problems of section 1.3 into consideration, the objective of this research is:

Contribute to the integration of Digital Twins in the operations of infrastructure contractors by developing a functional design for different types of Digital Twins and providing insight into the impacts and transformation areas associated with their use, enabling the assessment of the potential value that Digital Twins can deliver for the organisation.

The first step of this research is concerned with classifying the DT in the context of the construction industry. This should support in establishing a unified view on the concept within Heijmans Infra and provide the baseline for the identification of potential DT applications in the primary business process. Subsequently, application areas for DT in construction are proposed and two use-cases are selected, which form the content of the design task of this research. For these use-cases, a functional design is developed that enables to assess the impact and organisational changes associated with these applications. Finally, based on the findings from the use-cases, a conclusion is drawn regarding the potential added value of DTs in the primary business process of infrastructure contractors.

1.5 Research questions

Based on the identified research problems and the objective of this research, the main research question for this research is formulated as follows:

What is a Digital Twin in the construction industry and how can it be utilised to create added value in the primary business process of contractors in the infrastructure sector?

In order to answer this question, the following sub-questions are treated:

1. How can a Digital Twin be classified for application in the construction industry?
2. What kind of value adding applications for Digital Twin can be found in the primary business process of infrastructure contractors?
3. What essential elements should be included to establish a Digital Twin for application in the construction industry?
4. What are the impacts and transformation areas associated with the application of a Digital twin in the primary business process that drive value creation?

1.6 Research scope

This research focuses on assessing the potential added value of DTs in the primary business process of contractors in the infrastructure sector. It is therefore concerned with exploring how DTs can support the internal operations of the organisation and not how a DT can be used to exploit external revenue models. Furthermore, the scope of the research is limited to the design, construction planning and construction phase. Despite the fact that Heijmans Infra is increasingly performing maintenance activities, the main business model remains designing, preparing and subsequently constructing infrastructure assets. In addition, a consideration to focus on the initial phases of the asset lifecycle was that in order to enable data-driven operations and maintenance, it is essential that a proper information foundation is laid during the design and construction phase.

Another demarcation relates to the asset types that have been studied. Two types of assets were considered in this research: roads and movable bridges. The choice for these two asset types was made because they are common asset types in the operations of Heijmans Infra. Additionally, activities on these asset types also take place on other assets (e.g. a movable bridge has many similarities with a fixed bridge). Therefore, studying these asset types potentially increases the generalisability of the outcomes of the research.

1.7 Reading guide

The remainder of this research is organised as follows: chapter two presents the methodology that is used to conduct this research. After that, chapter three provides the theoretical foundation of the research, which serves to classify the DT concept for application in the construction industry. Chapter 4 builds further upon the established classification and focuses on identifying potential applications for DT in construction. Additionally, this chapter introduces the use-cases that form the scope of the design task of this research. Chapter 5 focuses on the essential building blocks to establish a DT and provides a generic framework that is used for the development of the functional design for the two use-cases, which is done in chapter 6 and 7. Finally, chapter 8 provides a discussion on the results and chapter 9 closes the report with the conclusions of the research and practical recommendations for Heijmans.

2 METHODOLOGY

This chapter introduces the methodology that is used to conduct the research.

2.1 Research strategy

This research is conducted using the design science methodology, which is suitable for studying an artefact in its context (Wieringa, 2014). An artefact should be understood as ‘’something created by people for some practical purpose’’ (Wieringa, 2014, p. 29). In this research, the artefact concerned the DT while the context was formed by the primary business operations of infrastructure contractors. Design science focuses on two main activities: designing the artefact and investigating the artefact in context. These activities correspond to the two types of research problems treated in design science, respectively design problems and knowledge questions. Considering the sub-questions of this research, these relate to both design problems and knowledge questions, as shown in Table 1.

TABLE 1: TYPE OF RESEARCH PROBLEMS IN THIS RESEARCH

Nr.	Research question	Problem type
1.	How can a Digital Twin be classified for application in the construction industry?	Knowledge question
2.	What kind of value adding applications for Digital Twin can be found in the primary business process of infrastructure contractors?	Knowledge question
3.	What essential elements should be included to establish a Digital Twin for application in the construction industry?	Knowledge question
4.	What are the impacts and transformation areas associated with the application of a Digital twin in the primary business process that drive value creation?	Design problem

2.2 Knowledge questions

Knowledge questions asks for knowledge regarding the real world but without calling for an improvement in the real world (Wieringa, 2014). In this research, three knowledge questions were treated. The research methods to answer these questions are discussed separately for each knowledge question:

2.2.1 Digital Twin classification

The first research question concerned a knowledge question that aimed to produce definitional knowledge regarding DTs in the construction industry (Johannesson & Perjons, 2014). For answering this question, a literature study was conducted. Literature was searched using multiple search engines, such as Scopus, IEEE Xplore and Google scholar. Relevant terms that were used to search literature concern (*Digital Twin) AND* (*Definition OR Typology OR* C*lassification)*. When this search string was complemented with (*Construction industry OR Infrastructure sector),* this yielded only a few articles. Therefore, the literature used to shape the interpretation of DT originated from multiple industries (e.g. manufacturing and aerospace). In addition, the literature study also devoted attention to the relation between Building Information Modelling (BIM) and DT. Based on the literature study, a classification for DT in construction consisting of a definition and typologies has been established.

2.2.2 Digital Twin applications

The second research question concerned a knowledge question that aimed to outline application areas for DTs in the construction industry. To answer this question, interviews, document analysis and literature study were used. Interviews and document analysis were performed to capture the current primary business process at Heijmans Infra and outline prevailing issues in this process. The interviews were conducted with knowledgeable persons in the organisation that are involved in various projects. Furthermore, persons in diverging roles were interviewed to collect data from multiple perspectives and thereby increase the reliability of the data (Yin, 2003) The interviews were conducted as semi-structured interviews in a face-to-face setting. The document analysis focused on several project management plans, existing process maps, and Heijmans’ normative process (BPS), which is based on best practices from completed projects.

To identify application areas for DT in construction, the captured process and identified issues in the process served as input. These were complemented with interviews and literature regarding applications for DT in industry. This literature comprised of both, academic publications and internet publications that have been searched using the following search string: *(Digital Twin) AND (Application OR Use-case OR Implementation).* From the identified application areas for DT in construction, two were selected to form the content of the use-cases. The relevance of these use-cases for the operations of Heijmans Infra was validated based on semi-structured interviews with several employees in diverging roles.

2.2.3 Digital Twin elements

The third sub-question was concerned with the identification of the essential elements to establish a DT in the construction industry. This knowledge question was answered based on a literature study regarding DT reference frameworks. Literature has been searched using the following search string: (*Digital Twin) AND (Architecture OR Building Blocks OR Framework OR Reference Model OR Model OR Properties).* Multiple search engines were used to increase the relevance of the study, such as Scopus, IEEE Xplore, Google Scholar and Science Direct. Besides academic literature also internet search was conducted to widen the search space and search for more practice oriented publications, as academic literature remains often at a more conceptual level that may not provide sufficient guidance for the operationalisation of the building blocks in this research.

2.3 Design problems

As opposed to knowledge questions, design problems call for a change in the real world and require an analysis of stakeholder goals (Wieringa, 2014). The fourth research question concerned a design problem that focused on the development of a functional design for the two DT use-cases. Design problems were answered using the design cycle (Figure 2), which consists of three main activities: (1) Problem investigation, (2) Treatment design, (3) Treatment validation. The outcome of the design cycle was a validated functional design for the two use-cases.

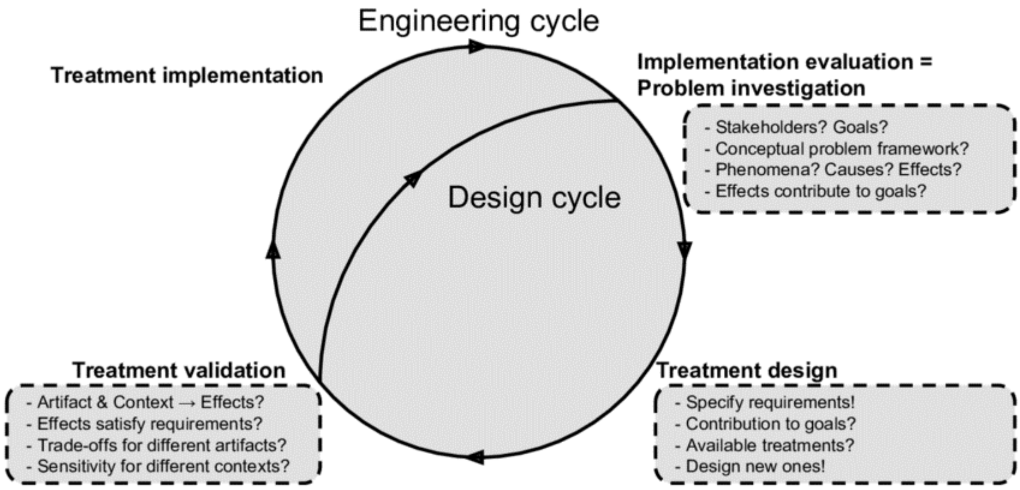


FIGURE 2: DESIGN CYCLE. REPRINTED FROM "DESIGN SCIENCE METHODOLOGY" BY WIERINGA, 2014

2.3.1 Problem investigation

The first task of the design cycle concerned problem investigation, in which improvement problems for the selected use-cases were analysed to gain a deeper understanding of the situation to be treated (Wieringa, 2014). This was done before requirements were specified and the functional design was developed. The following steps were performed during the problem investigation:

- Capture current work process;
- Identify activities with improvement potential;
- Identify the involved stakeholders and their goals and needs.

Case study

Problem investigation for the two use-cases was performed as a case study. Wieringa (2014) argues that observational case studies are useful for problem investigation because they give potential access to underlying mechanisms that produce real-world phenomena. Both use-cases were studied in a single case study setting. Yin (2003) gives five rationales for conducting a single case study, which are: the case is critical, extreme or unique, representative or typical, revelatory, or it concerns a longitudinal case. For this research, the selected case projects for both use-cases were considered to be a representative or typical case. Furthermore, a single case study can be performed as a holistic or embedded case study (Yin, 2003). In the former the case is considered as a whole, while in the latter different sub-units within the case can be distinguished. This study was performed as a holistic-single case study. In both case studies, data was collected using semi-structured interviews. These interviews were conducted in a face-to-face setting with Heijmans Infra employees. Based on the interviews, the current process for both use-cases was captured in a process map, activities with improvement potential were outlined, and stakeholder goals and needs for the DT design were identified.

2.3.2 Treatment design

The second task of the design cycle comprised of treatment design in which requirements were defined and available treatments were investigated. The following activities were performed during this phase:

- Translate stakeholder goals and needs into requirements;
- Define contribution arguments that justify the formulated requirements;
- Explore existing design solutions;
- Develop the functional design for the use-cases.

Data collection method

For treatment design, research strategies are usually less important, as the main goal of this activity is to produce an artefact design and to a lesser extent, the knowledge about it. On the contrary, creative methods such as brainstorming, participative modelling, and lateral thinking are more relevant for treatment design (Johannesson & Perjons, 2014). For both use-cases, stakeholder goals and needs were translated into requirements based on the perception of the researcher. By means of giving contribution arguments, the contribution of these requirements to the stakeholder goals and needs was justified (Wieringa, 2014). Existing design solutions were explored using literature and internet search. This involved searching for equivalent applications in other industries as well as searching for literature on individual parts of the functional design, such as only the data collection techniques to be used or simulation techniques. By combining knowledge from existing design solutions with the developed reference framework for DT, the functional design for the two selected use-cases was developed.

2.3.3 Treatment validation

The third activity in the design cycle concerned treatment validation, which focused on justifying that the treatment design would contribute to the stakeholder goal and needs. Furthermore, validation is concerned with the exploring the effect that the interaction between the DT and its environment would produce (Wieringa, 2014). Validity can be further decomposed into internal and external validity of the research.

Internal validity

Internal validity of the design relates to whether the design, if implemented in the problem context, would contribute to the achievement of the stakeholder objectives. Furthermore, internal validity relates to the certainty that cause-effect relations are justified based on the collected data (Bougie et al., 2017). Internal validity of the design was assessed by means of performing an expert session, where the outcomes of the research were fictional displayed on the case project and subsequently assessed whether the design would contribute to the stakeholder needs and goals.

External validity

External validity is concerned with the generalisability of the outcomes of the research (Bougie et al., 2017). In design science, this relates to whether the design if it would be implemented in a slightly different context, would also satisfy the criteria (Wieringa, 2014). This relates for example to the question if the DT design would be applied to other asset types than covered in the use-cases, would this also result in satisfactory results? This has to a certain extent be discussed in the expert sessions as well.

Assessment of the value

In order to assess the potential added value of integrating DTs in the business, a prediction was made of how the DT design for the use-cases would interact with its context. By means of an expert session, this assessment was performed. The designs were projected on the case projects and it was discussed how this would affect the operational processes, operational efficiency, value creation and work of the employees. The potential added value of DTs in the primary business process was expressed in qualitative terms.

3 THEORETICAL FOUNDATION

The theoretical foundation of this research is concerned with the exploration of existing theories regarding DT in literature. This chapter provides background on the concept and introduces a classification for DT that is suitable for the construction industry. Figure 3 gives an overview of the research steps treated in this chapter. The [#.#.#] at each process step in the figure refers to the corresponding section of this chapter.

3.1 (Digital) Twin principle

The inception of the Digital Twin (DT) concept can be traced back to a presentation by Dr. Grieves at the University of Michigan in 2003 (Grieves, 2014). In this presentation, which was given for the formation of a Product Lifecycle Management centre, a conceptual ideal for Product Lifecycle Management (PLM) was presented which assumes that each system consists of two systems: the physical system as always existed and a virtual system that includes more or less all information about the physical system, as depicted in Figure 4. Between these two systems a data flow from the physical to the virtual system and an information flow from the virtual to the physical system is assumed, which are maintained throughout the entire product lifecycle (Grieves & Vickers, 2017). In addition, the virtual system consists of multiple virtual spaces, as indicated by the blocks VS_1. . .VS_n in Figure 4, which allow to virtually put the system through destructive tests (scenarios) inexpensively (Grieves & Vickers, 2017).

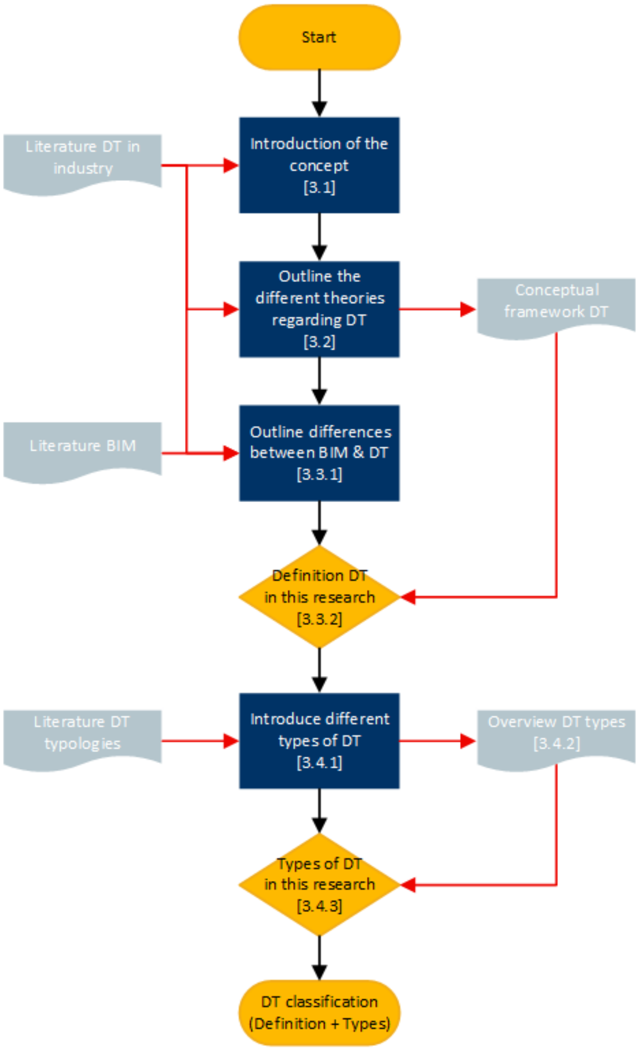


FIGURE 3: OVERVIEW RESEARCH STEPS CHAPTER 3

Although terminology has changed over the years, the concept presented by Grieves in 2003 corresponds to the basic principle of what is characterised as DT nowadays. The underlying principle of a DT was thus already introduced in 2003, however, it was only in 2010 that the actual term "Digital Twin" appeared for the first time in a scientific publication by the American space agency NASA (Shafto et al., 2010). Nevertheless, the notion of using a ''twin'' is already rather old, as it can be traced back to NASA's Apollo program in the late 1960s. The philosophy behind this twin concept was that an identical reproduction of the spacecraft remained on earth during the mission, allowing engineers on the ground to analyse the effects of control commands before sensing them to the remote spacecraft (Boschert & Rosen, 2016). Over the years, this approach became too expensive and due to technological developments in the field of connectivity and simulation technologies, the physical twin could be replaced by a virtual entity: the DT (Grieves & Vickers, 2017). At its establishment NASA defined the DT as: *''an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin''* (Glaessgen & Stargel, 2012, p. 7).

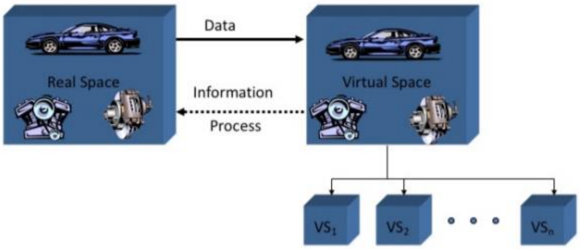


FIGURE 4: LECTURE SLIDE CONCEPTUAL IDEAL FOR PLM. REPRINTED FROM ''DIGITAL TWIN: MITIGATING UNPREDICTABLE, UNDESIRABLE EMERGENT BEHAVIOR IN COMPLEX SYSTEMS'' BY GRIEVES AND VICKERS (2017)

3.1.1 History of Digital Twin research

Considering the history of DT research, Tao (2019) concludes that the theoretical development of DT went through three successive stages. Starting with the period between the presentation of Grieves in 2003 and the first publication by NASA (2010), in which almost no further contributions to the body of literature were made, mainly because technology was not advanced enough yet at that time to turn Grieves' ideal into reality (Tao, 2019). However, due to the rapid pace at which enabling technologies, such as the Internet of Things (IoT), simulation technologies and Big data analytics, developed over the years, the concept was revisited and further detailed by NASA around 2010, which formed the start of a second stage. The second stage, as defined by Tao (2019), concerns the incubation stage, which started with the publication of NASA (2010) and ended with the first White paper on DTs by Grieves (2014). Since then, DTs have been increasingly subject of scientific research in various sectors, which is indicated as the growth stage by Tao (2019). In the recent years, DT is attracting much attention from both academia and industry in the context of various sectors (Cimino, Negri, & Fumagalli, 2019). In fact, research institute Gartner even states that DTs are among the top 10 strategic trends that will influence and reshape industries through 2023 (Cearley, Burke, Searle, Walker, & Claunch, 2018).

3.2 Classifying the Digital Twin

Over the years many definitions have been used by researchers to describe the DT in the context of various industries (V. Martinez, Neely, Ouyang, Burstall, & Bisessar, 2019). Therefore, the theoretical foundations of the DT concept are derived from multiple disciplines. The concept gained attention first in the context of the aerospace industry, where the focus was mainly on mirroring the life of air vehicles in operation, with the aim of vehicle health forecasting and remaining useful life predictions (Glaessgen & Stargel, 2012; Tuegel, 2012). Later, the concept was transferred to the context of the manufacturing industry by Lee, Lapira, Bagheri, and Kao (2013) with the initial focus on prognostics of manufacturing systems by simulating the health condition of the physical system in a virtual environment using physics models and condition data captured from the field (Eckhart & Ekelhart, 2019). Over the years, the concept expanded further to other applications in the manufacturing domain, such as product design, production layout planning and virtual verification, and the DT received a more prominent role in PLM (Kritzinger, Karner, Traar, Henjes, & Sihn, 2018; Tao, Cheng, et al., 2018). This embraced a shift in focus of the DT from being a high fidelity simulation model that reflects the behaviour of real assets during operations as close as possible to being an evolving dynamic digital profile that integrates historical and current behaviour, as well as all properties of a real asset, for decision support and optimisation along the lifecycle (Lim, Zheng, & Chen, 2019).

Given the variety of DT applications that have been proposed by researchers, many interpretations of the concept exist, which is reflected by the multitude of diverging definitions that can be distinguished in literature. To shape some clarity in the growing literature landscape, Negri et al. (2017) conducted a review on the roles of DTs in Cyber Physical Systems (CPS) based production systems. Within this research they provide an overview of the proposed DT definitions in literature in the period 2010-2016. This overview already comprises of more than 15 different definitions for DTs and given the growing interest in DT research, this number has further increased in the recent years. Therefore, it seems not feasible nor relevant to give a comprehensive overview of all DT definitions in literature. Instead it is considered to be more relevant to look at some of the most commonly used definitions and outline their main commonalities and differences and use this to shape the interpretation of a DT for this research. Table 2 gives an overview of some of the most commonly used DT definitions in literature (based on the number of citations).

TABLE 2: OVERVIEW OF DIGITAL TWIN DEFINITIONS IN LITERATURE

Author(s)	Digital Twin definition	Context
(Glaessgen & Stargel, 2012)	*''An integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin''*	Aerospace
(Rosen, Von Wichert, Lo, & Bettenhausen, 2015)	*''Very realistic models of the current state of the process and their own behavior in interaction with their environment in the real world''*	Manufacturing
(Boschert & Rosen, 2016)	*''A comprehensive physical and functional description of a component, product or system, which includes more or less all information, which could be useful in later lifecycle phases''*	Manufacturing
(Stark, Kind, & Neumeyer, 2017)	*"The digital representation of a unique asset (product, machine, service, product service system or other intangible asset), that compromises its properties, condition and behaviour by means of models, information and data"*	Manufacturing
(Grieves & Vickers, 2017)	*''A set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin''*	Manufacturing
(Qi & Tao, 2018)	*''Digital twin is to create the virtual models for physical objects in the digital way to simulate their behaviors. The virtual models could understand the state of the physical entities through sensing data, so as to predict, estimate, and analyze the dynamic changes. While the physical objects would respond to the changes according to the optimized scheme from simulation''*	Manufacturing
(Haag & Anderl, 2018)	*''A comprehensive digital representation of an individual product. It includes the properties, condition and behavior of the real-life object through models and data. The digital twin is a set of realistic models that can simulate its actual behavior in the deployed environment. The digital twin is developed alongside its physical twin and remains its virtual counterpart across the entire product lifecycle''*	Proof-of-concept
(Macchi, Roda, Negri, & Fumagalli, 2018)	*''A system's digital counterpart along its lifecycle. The DT can be considered as a virtual entity, relying on the sensed and transmitted data of the IoT infrastructure as well as on the capability to elaborate data by means of Big Data technologies, with the purpose to allow optimizations and decision-making''*	Asset lifecycle management
(Boschert, Heinrich, & Rosen, 2018)	*''The semantically linked collection of the relevant digital artefacts including design and engineering data, operational data and behavioral descriptions''*	Manufacturing

Considering these definitions, the following differences in interpretation on the concept were identified: *Simulation aspect, Lifecycle aspect, Content,* and *Physical twin*. Each of these aspects is discussed separately in the next four sections.

3.2.1 Simulation aspect

The first difference that was identified from the definitions in Table 2 concerns the role of simulation in the DT. Some researchers argue that a DT is a simulation model itself, for example Glaessgen and Stargel (2012). Alternatively, others argue that a DT is the digital representation of a physical entity that comprises its properties, condition and behaviour, which can be used for simulation of the actual behaviour of the physical entity in the deployed environment, for example Haag and Anderl (2018). Although simulation is not mentioned in each definition explicitly, a glimpse into the different publications of Table 2 yields that simulation is somehow included in each publication. Therefore, simulation can be regarded as a feature that is inextricably associated with the DT. The question is, however, what the exact role of simulation is in the DT. That is, whether simulation forms the essence of a DT and the concept should be regarded as a new generation of simulation models that enable (real-time) multi-physics simulation based on data collected by sensors on the physical entity, or whether its functionalities stretch beyond simulation and the DT should be regarded as a comprehensive digital profile of a physical entity where different types of simulations may be based upon. Hence, the first dimension to shape the interpretation of DT in this research concerns whether DT should be regarded as a digital environment that supports different types of simulation or is a simulation model itself.

3.2.2 Lifecycle aspect

Another aspect that is subject to disagreement in existing DT definitions concerns the lifecycle aspect. There is consensus in literature that the DT enriches during the operational phase of its physical counterpart by integrating historical and operational data. However, there is no consensus on the moment of inception of the DT. From the original definition proposed by NASA, it can be concluded that their vision focused on the operational phase of the physical spacecraft, as the DT should ‘’mirror the life of its flying twin’’ by providing a simulation of the as-built vehicle or system (Glaessgen & Stargel, 2012, p. 7). The DT thereby provides an instrument to support better predictions regarding failures that could occur during missions based on operational data obtained from sensors. Alternatively, a large proportion of the literature considers the DT as a dynamic digital profile that evolves along with the lifecycle of its physical counterpart. This vision mainly relates to the manufacturing domain, where the DT is closely related to PLM. Grieves and Vickers (2017) argue that a DT can be used for the creation, production, operation and disposal of a product by giving a virtual representation of either a potential or actual manufactured product. Additionally, Macchi et al. (2018) conducted an exploratory study on the application of DTs in asset lifecycle management in which it was argued that the DT could offer added value in all three phases of the asset lifecycle, respectively: "Beginning of life (BOL)", "Middle of life (MOL)" and "End of life (EOL)". Therefore, the second aspect to frame the interpretation of DTs for this research concerns if its existence is restricted to the operational phase or the entire lifecycle of its physical counterpart.

3.2.3 Content

The third difference that can be identified between existing definitions for DT relates to the content, in particular whether the DT provides a representation of all digital artefacts of a physical counterpart or only the relevant ones. Some authors argue that the DT reflects the collection of all digital artefact that are generated during the Lifecyle of the physical counterpart. According to Grieves and Vickers (2017), the ideal DT would enable to obtain any information that could be obtained from the physical object as well. Alternatively, Boschert et al. (2018) argue that the DT only includes the relevant data and models, which are designed specifically for their intended purpose. Another difference relates to the way in which the content of the DT is arranged. Some authors argue that the DT consist of models, information and data, for example Stark et al. (2017), while Rosen et al. (2015) appoint in their definition, only a model component. Boschert et al. (2018) propose a definition that also devotes attention to the relation between the components of the DT, as they state that the digital artefacts that form the DT are linked using semantic technologies. That is, semantics (meaning) has been added to the models and data so that it can be interpreted by computers and the linkage between different information constructs can be established while the data remains in its source location. Therefore, with regard to the content of a DT it should mainly be decided if all digital artefacts are included or only the relevant ones for specific purposes, what components they consist of, and how these are related.

3.2.4 Physical twin

The fourth characteristic that is subject to disagreement in existing DT definitions concerns the physical reference entity of the DT, thus the physical twin. From the definitions in Table 2 it follows that the DT is regarded as the virtual counterpart of respectively a system (e.g. aircraft), product (e.g. turbine), component (e.g. blade) or process (e.g. production process). Some authors argue that the DT provides a virtual representation of a system. (Boschert & Rosen, 2016; Glaessgen & Stargel, 2012; Macchi et al., 2018; Stark et al., 2017). Alternatively, others argue that the DT provides a virtual representation of a product (Boschert & Rosen, 2016; Grieves & Vickers, 2017; Haag & Anderl, 2018; Stark et al., 2017). It is also argued that the DT forms the virtual counterpart of a component (Boschert & Rosen, 2016). On the contrary, the DT can also be seen as the virtual counterpart of an process (Rosen et al., 2015). Therefore, the fourth dimension to frame the interpretation of the DT for this research is the nature of the physical twin.

3.2.5 Synthesis

A comparison of some of the most commonly used definitions for DT in literature found four dimensions that shape the interpretation of the concept. These dimensions serve as input for the classification of the DT in the context of the construction industry and comprise of:

- Simulation aspect (simulation model itself or digital environment that supports simulations);
- Lifecycle aspect (entire lifecycle or only the operational phase);
- Content (all digital artefacts or only relevant ones);
- Physical twin (System, Product, Component, Process).

Based on these dimensions, conceptual framework in Figure 5 has been developed.

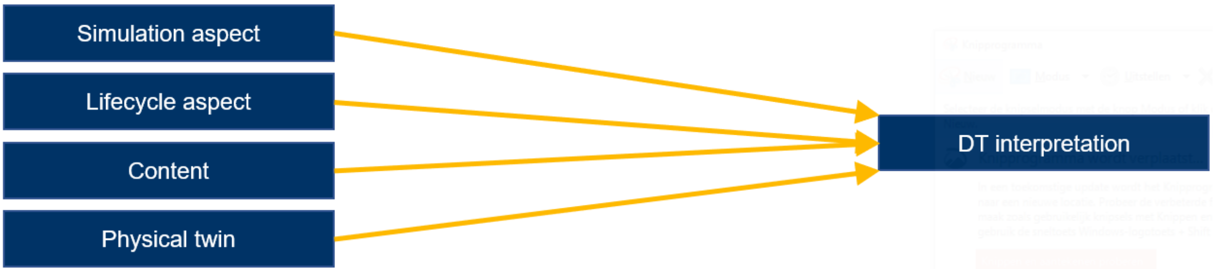


FIGURE 5: CONCEPTUAL FRAMEWORK DIGITAL TWIN INTERPRETATION

3.3 Digital Twin in construction

Given the variety of definitions for DT in literature, it is relevant to define what is understood by a DT in this research. DT related literature in the specific context of the construction industry is, however, limited and until very recently even almost absent. Furthermore, the available literature lacks unified guidance on the concept in construction. This can be deduced, among other things, from the fact that there is no consensus on the relation between DT and Building Information Modelling (BIM). Hence, the relation between these two concepts is discussed first before a definition for DT in construction is given.

3.3.1 Relation between BIM and Digital Twin

The lack of consensus on the relation between BIM and DT can be explained by the variety of definitions used for both concepts. Furthermore, the meaning of the ''M'' component in BIM is subject to disagreement, as it is used to indicate multiple things, such as: Building information Modelling, -Model and -Management (Jupp & Singh, 2014). Therefore, BIM can be regarded as either a product (Model) or a process/ work method (Modelling/ Management). Using diverging definitions for both concepts, multiple relations between BIM and DT can be assumed, as shown in the three examples below:

Example 1: A Digital Twin is part of BIM

DT as part of BIM in the construction industry can be supported with the following two definitions:

> According to Succar, Sher, and Williams (2012) BIM can be defined as *''a set of interacting policies, processes and technologies (Succar, 2009) generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä, 2006)''*
>
> A Digital Twin is "*the digital representation of a unique asset . . . that compromises its properties, condition and behaviour by means of models, information and data*" (Stark et al., 2017)

Following these definitions, it can be argued that a DT would be among the technologies making-up BIM in construction. In this example, BIM is regarded as a process/ work method that aims to manage project related information effectively using a set of policies, processes and technologies. DT could, among others, be included in the technology field of BIM.

Example 2: A Digital Twin is the same as BIM

DT and BIM are basically the same in construction can be supported with the following two definitions:

> A BIM is *''a rich information model, consisting of potentially multiple data sources, elements of which can be shared across all stakeholders and be maintained across the life of a building from inception to recycling''* (NBS, 2011)
>
> *''The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level''* (Grieves & Vickers, 2017)

Based on these two definitions, it can be argued that DT and BIM are basically the same in construction when the *''physical manufactured product''* in the definition by Grieves & Vickers would be replaced by *''physical built structure''.* In this example, BIM is regarded as a model, thus the product perspective.

Example 3: A Digital Twin is an extension to BIM

DT provides an extension to BIM by enriching the (static) BIM model with dynamic real-time sensor data during the operational phase can be supported with the following two definitions:

> *''BIM is a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward''* (NBIMS, 2015)
>
> *''The digital twin is a comprehensive digital representation of an individual product. It includes the properties, condition and behaviour of the real-life object through models and data. The digital twin is a set of realistic models that can simulate its actual behaviour in the deployed environment. The digital twin is developed alongside its physical twin and remains its virtual counterpart across the entire product lifecycle.''* (Haag & Anderl, 2018)

Following these two definitions, it can be argued that the ''condition'' aspect of a DT is an enrichment to BIM, which is regarded from the model perspective in this example. DT could extend this model based on sensor inputs, that allows to update the model and mirror the condition of the physical system.

The three examples demonstrate that using diverging definitions, multiple relations can be assumed between BIM and DT. These examples are not exhaustive and more relations can potentially be argued.

To frame this research, the relation between the two concepts has been defined and definitions for both concepts were established. In this research, the relation as argued in the first example is assumed, thus, a DT is a part of BIM in the construction industry. **Digital Twin is a (set of) technology**, whereas **BIM is a set of interacting policies, processes, and technologies** (Succar et al., 2012), as schematised in Figure 6. In this regard, BIM is considered from a process/ work method perspective. This relation is in line with the relation between PLM and DT in the manufacturing domain, where the DT is seen as a supportive technology for various PLM activities by many scholars (Tao, Cheng, et al., 2018). Since BIM can to a certain extent be seen as PLM's counterpart in construction, this relation is considered to be most appropriate. The two approaches share higher level objectives. Like PLM, BIM aims to integrate people and data processes throughout the design, construction and operation of an asset (Jupp & Singh, 2014).

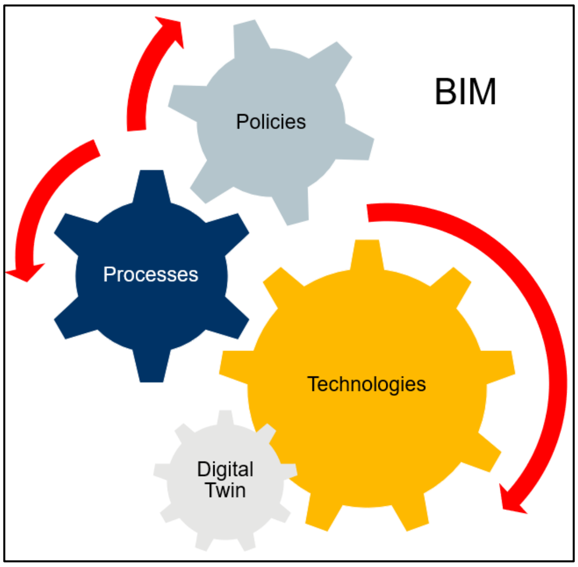


FIGURE 6: ASSUMED RELATION BETWEEN DIGITAL TWIN AND BIM

The interacting set of policies, processes and technologies that constitutes BIM is depicted as a set of gears in Figure 6 to reflect the interlocking character of the three fields (Succar, 2009). That is, they are mutually reinforcing and if one field is underdeveloped, it affects the effectiveness of the whole BIM workflow. Therefore, the technologies, including DT when implemented, have certain dependencies on the other two fields of BIM: processes and policies.

Although it is assumed that a DT would be among the technology field of BIM, it should be noted that a DT is not the same as current BIM technologies. Therefore, **DT provides an extension to current BIM technologies** (e.g. CAD). This means that when BIM is regarded to be solely the 3D object-oriented model with associated building information, DT provides an extension to BIM. To enable the identification of DT applications in the infrastructure sector, the differences between DT and current BIM technologies have been outlined by comparing current BIM uses with the opportunities that DT offers in other sectors. Current BIM uses for infrastructure contractors mainly comprise of (Siebelink, 2017):

- 3D coordination (clash detection/ interface management/ subcontractors/ suppliers);
- Design preview;
- Generation of 2D drawings from 3D design models;
- Information exchange between different parties/ disciplines;
- Quantity take-off;
- Coupling of 3D model and construction schedule (4D);
- Cost estimation based on 3D model (5D);
- Quality assurance/ Quality control;
- Compose As-built dossier;
- Purchasing management;
- Monitoring and supervising construction logistics;
- Positioning by laser and machine guidance techniques;
- Supporting Lean sessions with the coordination model;
- 3D modelling of formwork and temporary auxiliary structures.

These are considered as functionalities that current BIM technologies support for application in the infrastructure sector and are therefore not regarded as new opportunities that DTs could offer. This does, however, not necessarily mean that all contractors currently apply them. Taking the BIM uses above into consideration, it can be concluded that the focus of current BIM technologies is mainly ***collaboration, coordination and visualisation,*** with the aim of facilitating effective information exchange and digital collaboration between project participants.

Besides distinguishing the different BIM uses, it should also be noted that BIM reflects different things depending on one's perspective (NBIMS, 2019):

- *Applied to a project, BIM represents* ***Information management -*** data contributed to and shared by all project participants. Delivering the right information to the right person at the right time. The interaction between technology usage and guidance by means of predefined policies and processes should lead to structured information exchange throughout the entire project.
- *To project participants, BIM represents* ***an interoperable process for project delivery*** - defining how individual teams work and how many teams work together to design, construct, operate and maintain a structure. Different BIM policies define how teams ought to work together and how information should be exchanged between the project participants.
- *To the design team, BIM represents* ***integrated design*** - leveraging technology solutions, encouraging creativity, providing more feedback, empowering a team. BIM enabled design should lead to a design that is fit for purpose.

Differences between DT and BIM technologies

Considering the differences between DT and current BIM technologies, one of the main differences between BIM uses in construction and DT in other industries concerns that the majority of BIM uses still tend to focus on the early lifecycle stages (i.e. mainly the design & construction planning) whereas a large proportion of DT uses in other industries take place during the production and operational phase (e.g. prognostics & health management (Tao, 2019)). Although research efforts on BIM for operations and maintenance increased considerably over the past decade (Gao & Pishdad-Bozorgi, 2019), in practice the majority of BIM uses remain stuck at the design and construction planning phase. This is also reflected by the BIM uses above, which are mainly targeted towards the design and construction planning phase.

In terms of technologies, existing BIM technologies (e.g. CAD) emphasise on the digital world whereas DTs can be used to provide the bridge between the physical world and the digital world (Tao, Sui, et al., 2018). DTs enable to synchronise the physical and virtual world by means of a bi-directional data connection, creating a dynamic digital profile that utilises (real-time) data from the physical world to gain insights in the virtual world that can be used to take actions in the physical world accordingly. The DT thereby provides insight in ***what is currently happening*** or **what has *happened*** in the physical world, which can be analysed in the virtual world and communicated to users as **feedback**. By means of monitoring, analysing, simulating and predicting the performance and behaviour of a physical entity in the virtual world, DT can achieve the efficient exchange of information, optimal allocation of resources and reduction of cost in the physical world (Qi et al., 2019). On the contrary, due to the lack of automated synchronisation between the physical and virtual world, many current BIM technologies help at best to understand ***what should happen***, for example using visualisations**.**

Taking these differences into consideration, the characteristics used to discern DT applications from BIM applications in this research are:

- Bi-directional connection between a physical entity and its virtual model(s) / synchronisation between physical and virtual space (Negri et al., 2017);
- Interaction and convergence (Tao, Cheng, et al., 2018);
  - In physical space
  - Between historical and real-time data
  - Between physical and virtual space
- Self-evolution (DT evolves along with its physical counterpart) (Tao, Cheng, et al., 2018);
- Combining design, engineering details with operational data and analytics;
- Combining multiple data sources and applying intelligence (rules, logic, algorithms, predictions) to data to generate new insights (Tao, Sui, et al., 2018);
- Simulations and advanced analysis (Boschert & Rosen, 2016);
- Evaluation of different scenarios (what-if questions) (Qi et al., 2019);
- Monitoring, control, diagnostics and predictions (Tao, 2019);
- Closing the feedback loop, not only back to the physical system but also to early lifecycle phases (improving future generations/ learning) (Boschert et al., 2018).

From these characteristics it follows that the main focus of a DT is ***simulation, integration of various data sources, and the synchronisation between physical and virtual space***, with the aim of offering value adding services that can optimise business performance (Qi et al., 2019).

3.3.2 Digital Twin definition

To classify the DT for application in the construction industry, a hybrid version of the definitions in Table 2 has been composed using the four dimensions in the conceptual model of Figure 5. Additionally, the characteristics of DT in the section above were taken into account. This led to the following definition:

> *The Digital Twin is the semantically linked collection of models, information and data that fully describes a potential or actual physical system, as such it forms a representation of all aspects of its corresponding physical system (e.g. properties, condition and behaviour) that could be relevant for the current or subsequent lifecycle phases. The Digital Twin is developed alongside its corresponding physical system and remains its virtual counterpart across the entire lifecycle, where it can be used to monitor, analyse, simulate and predict the performance of the physical system, leading to actions in the physical world accordingly.*

Following this definition, the main characteristics of a DT are:

- Semantically linked collection of models, information and data. The DT is not a single massive data lake that contains all information regarding a physical system. Instead, it comprises of different digital models, information captured in (vendor locked-in) applications, and other data sources. These reflect together the physical system in the virtual world (Stark et al., 2017). The DT allows the realisation of interconnectedness between these models, information constructs and databases using semantic technologies (Boschert et al., 2018). The DT thereby centres on integrating information from multiple sources together in the virtual world at an appropriate level of detail for the application at hand.
- Potential or actual physical system (Grieves & Vickers, 2017). DTs can be applied throughout the entire lifecycle and evolve along with its physical counterpart, During the lifecycle, the DT can reflect multiple realities: *to-be, as-is* and *could-be* (Damgrave, 2019). Therefore, the DT reflects either a potential (to-be or could-be) or actual physical system (as-is).
- Physical system. Physical system is used as umbrella term for the physical twin and embraces different system components. These can have their own DT, making it a family of twins. System components may include both assets and processes.
- All aspects of its corresponding physical system that could be relevant for the current or subsequent lifecycle phases (Boschert & Rosen, 2016). The information that could be obtained from a DT is not only restricted to geometry or technical information. Ideally, any information regarding its physical counterpart that is relevant for the current or subsequent lifecycle phases can be obtained from the DT. The DT thereby takes a socio-technical perspective by also including its dynamics and relevant scenarios that help understanding and optimising how a system is designed, constructed, operated or maintained.

- Used to monitor, analyse, simulate and predict the performance of the physical system (Qi et al., 2019). The DT can be used to monitor the physical system based on data collected from the physical world and thereby display the as-is reality in the virtual world. This data can be analysed to provide users with feedback and assist them in decision making. Furthermore, the information and data captured in the DT can be used as input for simulation models, which can imitate the behaviour of the physical system and evaluate different scenarios. The DT thereby reflects the could-be reality, which can be used to optimise the to-be or as-is reality, as schematised in Figure 7. Finally, an advanced DT can also be used to predict the future behaviour and state of the physical system using simulation models and data captured in the DT.

For the remainder of this research, the definition as proposed in this section is intended when referring to a DT. The exact elements making up the DT (referred to as DT building blocks) are discussed in chapter 5 of this report. With regard to BIM, the term BIM is only used as standalone term in this report when it is intended to refer to a set of interacting technologies, policies and processes. When one regards ''BIM'' in a narrow sense, such as the development and use of a 3D coordination model (e.g. Revit model), this is referred as the use of BIM technologies or BIM models.

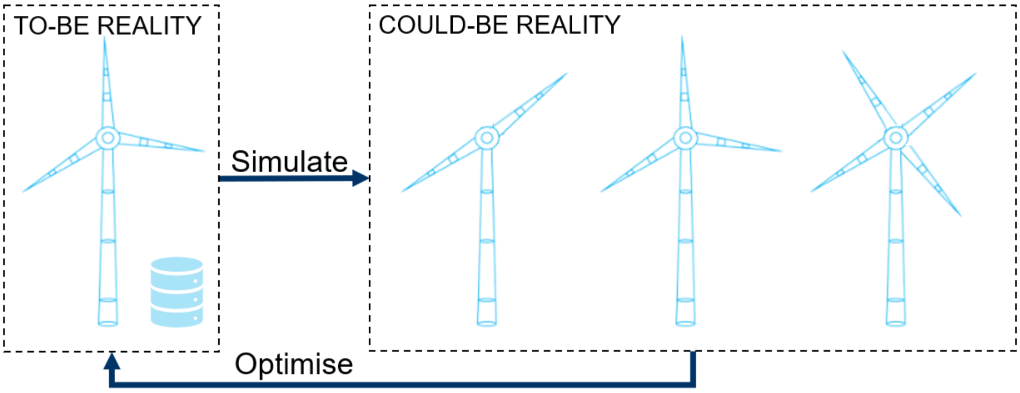


FIGURE 7: EVALUATION OF DIFFERENT WHAT-IF SCENARIOS IN THE COULD-BE REALITY TO OPTIMISE THE TO-BE (OR AS-IS) REALITY

3.4 Types of Digital Twins

Besides various definitions, literature also distinguishes different types of DTs. These typologies were used, together with the selected definition, to shape the interpretation of DT in this research.

3.4.1 Digital Twin typologies in literature

The first typology of DTs is proposed by Grieves and Vickers (2017), who argue that the DT concept can be decomposed in three generic types, as schematised in Figure 8:

- ***Digital Twin Prototype (DTP);***
- ***Digital Twin Instance (DTI);***
- ***Digital Twin Aggregate (DTA).***

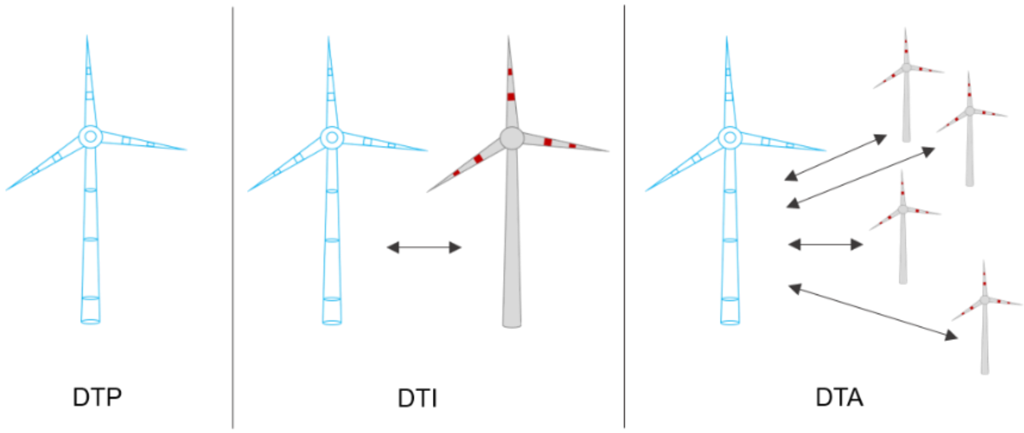


FIGURE 8: TYPES OF DIGITAL TWIN. REPRINTED FROM ''THE DIGITAL TRANSFORMATION OF THE PRODUCT MANAGEMENT PROCESS: CONCEPTION OF DIGITAL TWIN IMPACTS FOR THE DIFFERENT STAGES'' BY HOFBAUER, SANGL, ENGELHARDT, OBRENOVIC, AND AKHUNJONOV (2019)

The DTP relates to the set of linked information constructs that fully describes a potential physical object before it is realised (Grieves & Vickers, 2017). Ideally, the DTP behaves exactly the same as the physical object would and thereby allows testing and simulations to be performed on the DTP, enabling the optimisation of the design and production process until the desired behaviour throughout the lifecycle is achieved. The virtual representation of the physical object captured in the DTP can subsequently be used to physically realise it, generating an instance of the virtual prototype: the DTI. The DTI is the unique virtual representation of its corresponding physical object that remains connected throughout the entire lifecycle (Grieves & Vickers, 2017). A DTI is thus based on the DTP but incorporates the specific properties of its corresponding physical object (e.g. part numbers, maintenance history and current state). As such it forms an exact virtual representation of its corresponding physical instance on any given moment. The physical object can be equipped with sensors and actuators to establish a full bi-directional connection between the physical object and the DTI (Grieves & Vickers, 2017).

A DTP can generate multiple DTIs, which is especially common in the context of the manufacturing industry where one ‘’parent model’’ is used to produce multiple similar instances, which all have their own unique DTI after manufacturing that incorporates the specific properties and settings of that particular physical object. The DTA on the other hand is the collection of aggregated data from multiple DTIs that form a fleet of similar objects (Grieves & Vickers, 2017). The DTA integrates data from multiple similar physical objects and analyses it. This similarity does not necessarily have to be related to geometry but can also relate to similarities in parameters or the behaviour during operation (Boschert et al., 2018). A DTA can for example be used to analyse the performance of multiple similar instances for patterns. These patterns can subsequently be used to predict the future performance of a single instance more accurately or improve the design scheme for future generations of the product.

Another classification that can be used to discern between different types of DTs is proposed by Qi et al. (2019), who argue that the concept can be divided in ***Entity DT*** and ***Scenario DT***, *as depicted in* Figure 9. The Entity DT refers to a 3D geometric model that integrates information such as monitoring information, sensing information, service information, and behavioural information regarding the physical entity along its lifecycle (Qi et al., 2019). Therefore, the physical entity has a virtual equivalent that fully reflects its behavioural characteristics and current state. Scenario DT refers to the virtual representation of physical scenarios that utilise both static and dynamic data. The activities performed in the physical scenarios can be simulated and evaluated in the virtual world with the Scenario DT to optimise the physical scenario where the physical entity engages in (Qi et al., 2019). Considering applications for both types of DTs, some applications focus on the Entity such as behaviour simulation, status monitoring and health predictions, whereas others are more related to scenarios (i.e. finding the best conditions to perform specific activities such as production or logistics). An example of scenario DT is layout optimisation of a shop-floor in the context of the manufacturing domain. The maximum added value can be realised by the combination of the two types of DTs (Qi et al., 2019).

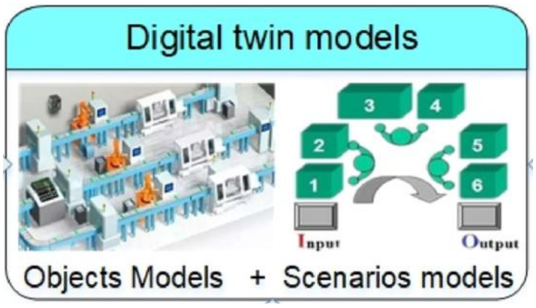


FIGURE 9: TYPES OF DIGITAL TWIN ACCORDING TO QI ET AL. REPRINTED FROM ‘’ ENABLING TECHNOLOGIES AND TOOLS FOR DIGITAL TWIN’’ BY QI ET AL. (2019)

Regardless of the exact definition used for DT, in synthesis the vision of a DT comes down to establishing a bi-directional connection between virtual and physical space (Schleich, Anwer, Mathieu, & Wartzack, 2017). To achieve this, integration and interaction between virtual and physical space is required. Therefore, integration of data, either historical or operational data, seems to be a key characteristic of the DT (Eckhart & Ekelhart, 2019). However, from literature there is no consensus on the minimum level of data integration between the virtual and physical object that is required to classify something as a DT. To provide some structure in the literature landscape, Kritzinger et al. (2018) proposed a classification of existing DT publications in three types based on the extent of data integration between the physical and virtual object. From their study it follows that the concepts ***Digital model*** and ***Digital shado*w** are often used in synonym with a ***Digital Twin***. These concepts differ, however, in the extent of data integration as depicted in Figure 10.

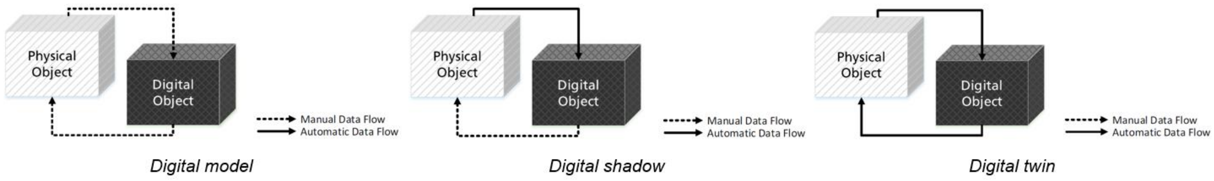


FIGURE 10: CLASSIFICATION DIGITAL TWINS BASED ON DEGREE OF DATA INTEGRATION. REPRINTED FROM "DIGITAL TWIN IN MANUFACTURING: A CATEGORICAL REVIEW AND CLASSIFICATION" BY KRITZINGER ET AL. (2018)

Digital model

A Digital model is a virtual representation of any planned or built physical object which has no form of automated data exchange between the physical and the virtual environment. Consequently, an alteration in the status of the physical object does not directly lead to a change in the status of virtual object and vice versa (Kritzinger et al., 2018).

Digital shadow

When compared to the Digital model, there is also an automated data flow in one direction from the physical object towards the virtual object, this is classified as a Digital shadow. Hence, a status change of the physical object automatically leads to a change in the status of the virtual object, but not vice versa (Kritzinger et al., 2018).

Digital Twin

If the data flows between the physical object and the virtual object are fully automated in both directions, this is referred to as a Digital Twin. A status change of the physical object thus leads directly to a change in the state of the virtual object and vice versa. This automated bi-directional direction between physical and virtual object reflects a seamless integration between cyber and physical space (Tao, 2019). Furthermore, this degree of data integration enables the virtual object to act as a control device for the physical object (Kritzinger et al., 2018).

3.4.2 Synthesis

From section 3.4.1 it follows that multiple authors have taken initiatives to classify DT in typologies based on different characteristics. While Grieves and Vickers (2017) mainly discern their types based on the lifecycle phase in which the DT is applied and whether it is reflects a single instance or a fleet of similar instances, the typology of Qi et al. (2019) is based on the attribute of the physical entity. That is, whether it reflects a physical product (Entity DT) in virtual space or a scenario where the physical product is engaged in (scenario DT). For application in the construction industry it is considered that the Entity DT would reflect the physical asset (e.g. road, bridge, tunnel, etc.) while the Scenario DT would be concerned with the virtual representation of physical processes associated with these assets, such as finding the optimal conditions to perform a certain construction activity. To reflect these processes (scenarios) in virtual space, it may be needed to capture other elements such as equipment in virtual space as well, these would then be part of the Scenario DT. Finally, the typology given by Kritzinger et al. (2018) is based on the extent of data integration between the physical and virtual object. Even though the three typologies are based on different characteristics, they can be combined as depicted in Figure 11. Beginning of Life

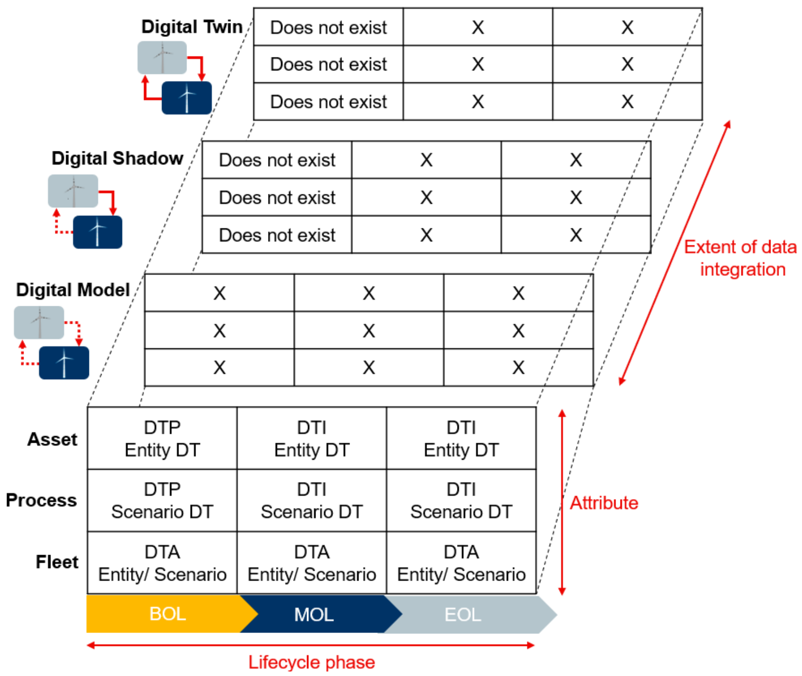


FIGURE 11: SYNTHESIS OF DIGITAL TWIN TYPOLOGIES IN LITERATURE

(BOL) refers here to the design and construction planning phase, Middle of Life (MOL) refers to the construction and operation & maintenance phase, and End of Life (EOL) refers to demolition planning phase. It should be noted that some combinations are non-existent: the DTP cannot be combined with the Digital Shadow and Digital Twin as introduced by Kritzinger et al. (2018) because during the BOL phase there is no physical entity yet so there is no automated data exchange between the physical and the virtual entity possible. A DTI and DTA on the other hand can utilise different extents of data integration, allowing them to map to respectively the Digital Model, Digital Shadow and Digital Twin in terms of Kritzinger et al. (2018).

3.4.3 Selection of Digital Twin types in this research

From section 3.4.2 it follows that multiple authors proposed typologies for DTs based on different characteristics. To complete the classification of DT in this research, a selection has been made regarding the types in Figure 11 that are most relevant for construction. The first aspect to consider relates to the lifecycle phases, since the scope of this research is limited to the design, construction planning and construction phase, the types targeted towards the EOL phase can be neglected and the focus is on the BOL and MOL phase. In terms of the attribute axis of Figure 11 assets and processes (scenarios) are considered to be relevant for application in the construction industry. This is because in the context of construction, applications can be devised that mainly focus on the functioning of an asset itself as well as applications that are more focused on optimisation of the processes related to the asset (e.g. construction or maintenance scenarios). Additionally, the aggregation of data from multiple similar assets/ processes is considered to be relevant as well. Therefore, all three types of DTs in terms of attributes could be relevant for application in the construction industry.

Considering the extent of data integration between the physical and virtual entity, it should be noted that in the context of the construction industry the majority of the objects are not (controlled by) mechatronic devices. Hence, they cannot be used to automatically take actions in the physical world based on insights gained in the virtual world (e.g. the roughness of asphalt can be monitored but cannot be automatically adjusted if it is insufficient). Although there are some cases within the infrastructure sector that could potentially have a full DT (e.g. sewage treatment plants or traffic control systems), for the majority of the asset types in the infrastructure sector the highest achievable extent of data integration would be a Digital shadow that provides a (near) real-time reflection of the state of the corresponding physical object. For these cases, manual intervention would still be required to change the state of the physical object based on insights gained in the virtual environment. Considering the two asset types that form the scope of the research, roads and movable bridges, these correspond mostly with this finding although it might be possible for a bridge's movement mechanism to achieve a full bi-directional connection where the bridge can be controlled from its virtual model. Still, given the fact that for most components of the asset types this finding is applicable, with regard to the extent of data integration, only a Digital Model and Digital Shadow were assumed within this research.

The demarcations regarding Figure 11 result in a set of nine remaining combinations, as depicted within the yellow contours of Figure 12. This forms the domain within which potential DT applications for the context of the construction industry are located that were studied in this research.

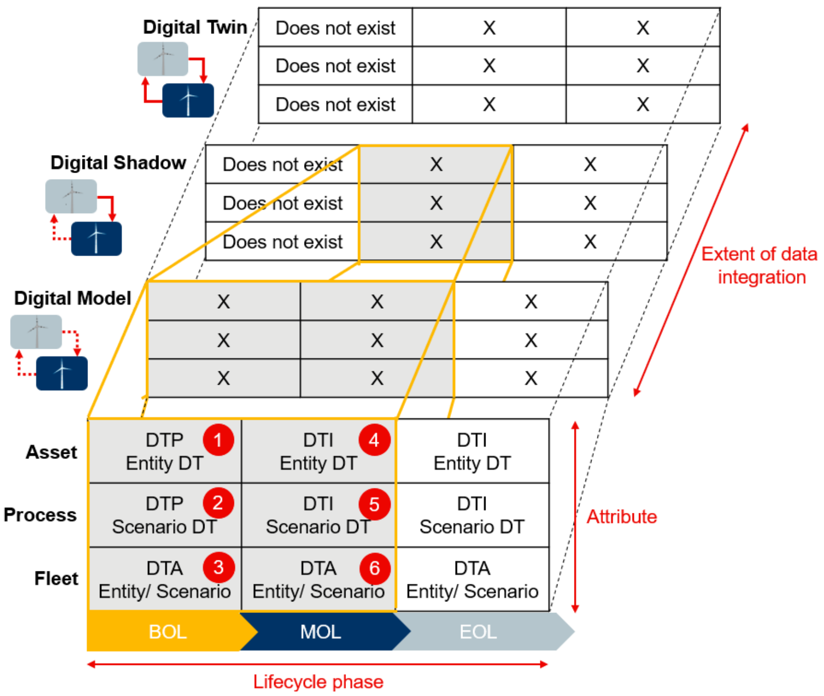


FIGURE 12: TYPES OF DIGITAL TWINS IN CONSTRUCTION

From Figure 12 it follows that nine different types of DTs can be identified. This is quite a large number which makes it less straight forward to distinguish between the different types. To mitigate this, the number of alternatives has been limited by not considering the extent of data integration as a separate dimension to discern different types of DTs. Instead, this dimension is used as a functional aspect that can be decided separately for each DT application. It is decided to exclude this dimension because this dimension makes the least fundamental difference between the different types. That is, both the difference between a DTP, DTI and DTA, as well as the difference between Entity DT and Scenario DT, are considered to be considerably more diverging characteristics than the extent of data integration. Consequently, there remain six types of DTs that are distinguished within this research. To give some more shape to these different types, Figure 13 gives a conceptual overview of what form the six different types of DT can take along the lifecycle.

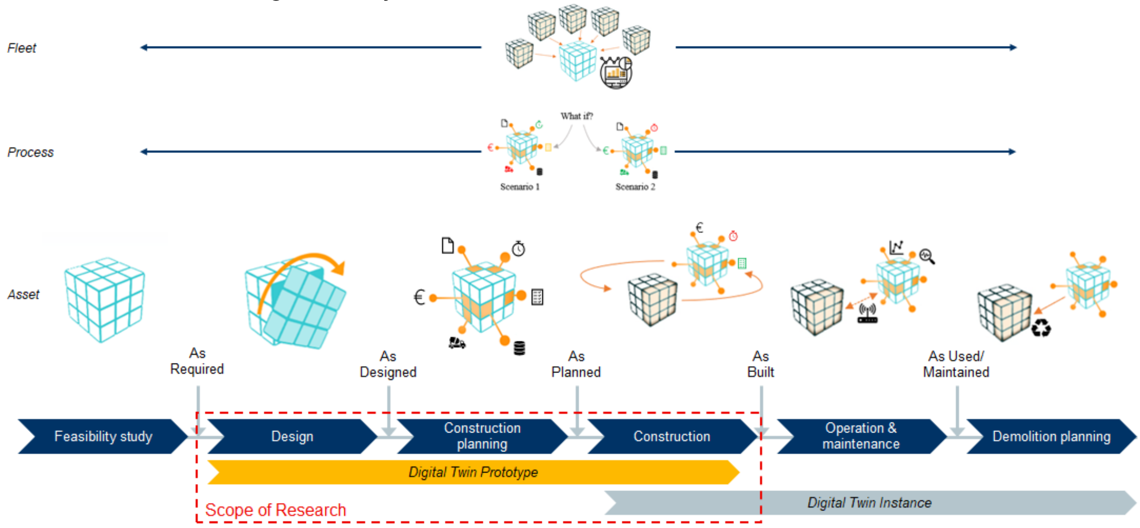


FIGURE 13: DIFFERENT TYPES OF DT ALONG THE CONSTRUCTION LIFECYCLE

3.5 Conclusion and outlook

This chapter focused on the classification of DTs in the construction industry. By means of performing a literature review regarding the interpretations of DT in various industries, a conceptual model was derived that describes how the interpretation of DT is affected by four variables, respectively the simulation aspect, lifecycle aspect, content, and physical twin. Using this conceptual model, a definition for DT in this research has been established, which reads: *''The Digital Twin is the semantically linked collection of models, information and data that fully describes a potential or actual physical system, as such it forms a representation of all aspects of its corresponding physical system (e.g. properties, condition and behaviour) that could be relevant for the current or subsequent lifecycle phases. The Digital Twin is developed alongside its corresponding physical system and remains its virtual counterpart across the entire lifecycle, where it can be used to monitor, analyse, simulate and predict the performance of the physical system, leading to actions in the physical world accordingly''*

To complete the classification for DT in this research, attention was devoted to the types of DTs that can be found in literature as well. Three relevant theories regarding DT typologies in literature were found that distinguish DT types based on different characteristics. These three typologies were combined into a single holistic framework that displays a total of 27 combinations. By projecting the scope of the research onto this framework, six types of DTs remained. These types can be distinguished according to the lifecycle phase in which they are applied and whether they reflect a physical asset, process or a fleet of similar assets or process steps. Each of these types can also reflects different realities, respectively the to-be reality for applications during design and construction planning, and the as-is reality during construction and operations and maintenance. Additionally, through the evaluation of what-if scenarios, the could-be reality can be reflected throughout the entire life cycle for all six types.

Now that a classification for DT has been established for the context of the construction industry, the next step of the research comprises of identifying potential application areas for the DT in construction, which is done in the next chapter. The definition and typology for DTs in Figure 12 provides the baseline for the identification of potential applications.

4 USE-CASES FOR DIGITAL TWIN IN CONSTRUCTION

This chapter is concerned with the identification of application areas for DT in the construction industry. To do this, the primary business process of Heijmans Infra has been captured and issues in the current workflow were identified. Based on this, directions for DT applications were proposed from which two promising alternatives were selected for further detailing. This chapter closes with introducing the two use-cases that form the scope of the design task of this research. Figure 14 presents the research steps treated in this chapter.

4.1 As-is process at Heijmans Infra

In order to identify potential DT applications at Heijmans Infra during the BOL (design and construction planning) and MOL phase (construction), the current primary business process during these phases has been captured in a process map. This was done to gain insight in the current workflow on Heijmans projects and reveal potential areas of improvement that could benefit from a DT. The process maps take the format of SIPOC[1] diagrams and visualise the high-level workflow from the start of the design phase till the end of the construction phase (i.e. from as-required till as-built). In total, four SIPOC diagrams were developed, which are presented in Appendix I. The process maps were developed based on various interviews, document analysis, and existing process maps for a Heijmans project developed by Autodesk consulting. The developed process maps were validated with the commissioning persons of the research.

4.1.1 Issues in the current process

From the interviews that were conducted for the development of the process maps, a list of issues has been composed that prevail regularly in the current workflow during the BOL and MOL phase. The interviewees possessed different roles to look at the process from multiple perspectives. It should be noted that the identified issues are not related to one particular project, as the interviewees were asked to share their general experiences of issues that prevail regularly on Heijmans Infra projects. The first round comprised of eight interviews that were conducted with interviewees in the following roles: design coordinator, design advisor, lead engineer, lifecycle engineering advisor, work planners and project manager. The interviews resulted in a list of 19 issues that the interviewees perceive in the current work process, which is presented in Table 3.

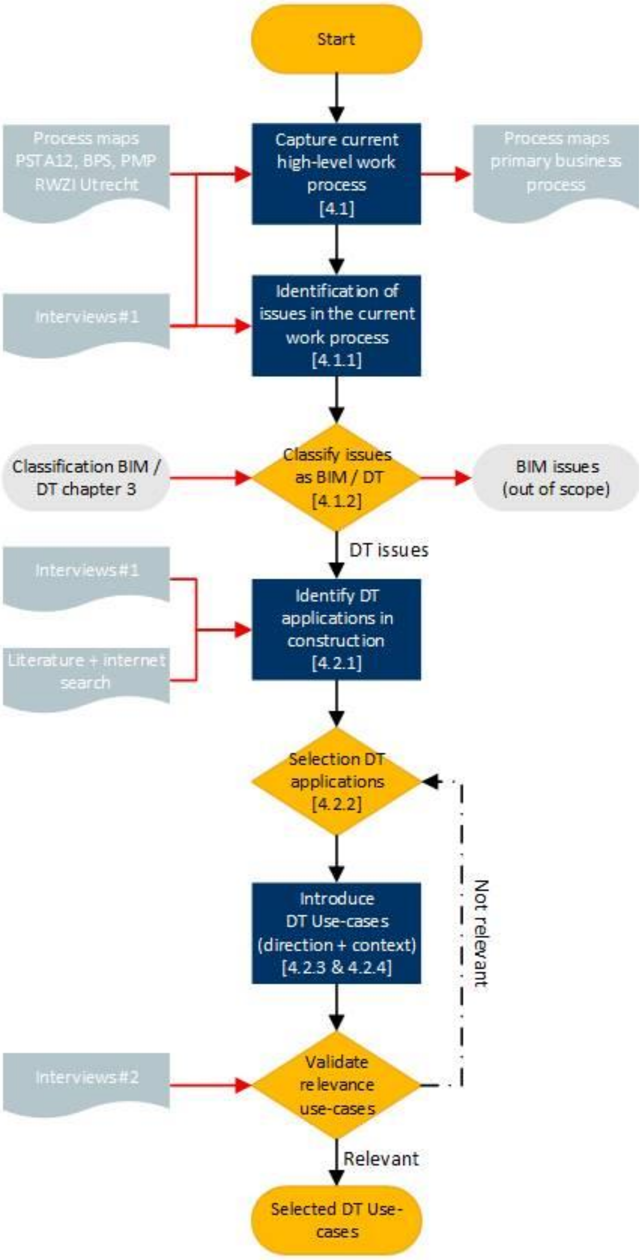


FIGURE 14: RESEARCH STEPS CHAPTER 4

[1] SIPOC is the highest order in mapping hierarchy and provides an overall view on a process by presenting its suppliers, inputs, outputs, customers and a number of (high-level) process steps (ICF International, 2013).

TABLE 3: ISSUES IN THE CURRENT WORK PROCESS

Nr.	Issue
1.	It remains relatively **unclear for designers what information is required during the Construction and Operation & Maintenance (O&M) phase** due to the lack of a proper feedback loop. This results in missing information during Construction and O&M, which could lead to mistakes and rework. Furthermore, if there is any form of feedback loop from Construction or O&M towards the Designers, the **information remains often stuck on the project level, hampering inter-project learning.**
2.	The successful application of ''1 ontwikkelproces'' is often restricted to the VO and DO stage. Due to an overlap between design and construction schedules it becomes harder during the UO stage to stick to the Gate reviews. **Not all relevant documents for construction are finished when the designs are finished while some construction activities already have to start.**
3.	The development of an availability analysis (FMECA) in RAMS management remains a manual task. Consequently, once changes are made in the design, the analysis needs to be manually updated. It occurs that the **design develops so fast that there is insufficient time to the update the FMECA and the Fault Tree accordingly.**
4.	The interfaces between the disciplines in ''1 ontwikkelproces'' are not properly defined. As a result, there is **insufficient coordination between design, realisation and O&M disciplines.**
5.	The realisation discipline often becomes later involved in the design process. Sometimes it is **not clear for them why certain design decisions have been made**. Trade-off matrixes could provide some guidance in the decisions that have been made but are not always easy to find.
6.	**Inspection reports are currently mainly developed to verify requirements** and complete the project, not for improving the own workflow and/ or quality of the products.
7.	Sometimes there is **too much information on the drawings**, leading to a drawing that could not be overseen and interfaces are being overlooked.
8.	There is often **no accurate overview of the actual progress on the projects**. In particular, this is the case at the installations and process automation activities.
9.	The **non-conformance and As-Built documentation processes are time consuming** and often have to be performed when the project team already partially left the project, putting pressure on the remaining project team members.
10.	A general **lack of structured information** within and between the projects.
	○ On a tactical level there is no quick overview of what type of asphalt is used on different projects and it is often not possible to identify the conditions at which realisation was conducted when damage occurs.
	○ At the beginning of the project there is often no clear IPB structure, which comprises of the Functional Breakdown Structure (FBS), System Breakdown Structure (SBS) and Work Breakdown Structure (WBS).
	○ Lack of a proper Heijmans' Object type Library (OTL) and Activity Type Library (ATL).
11.	The establishment of the SBS for roads is challenging due to the lack of physically demarcated objects. In practice objects are often defined after construction took place.
12.	Registration of some critical elements still takes place by scanning handwritten forms, making the **information not reusable** and limiting the learning from the registrations.
13.	**The consequences of changes to the original plans during realisation cannot easily be overseen in an integral manner** (e.g. when there is a change in the start date of an activity, it is challenging to identify the consequences of that decision downstream in the process).
14.	**Workplans/ -instructions are mainly created to verify realisation requirements and do not actually provide an instruction to perform the work** as the name would suggest. Therefore, it remains often unclear at the end of the design phase how the work will actually be conducted and if the design is constructible.
15.	Realisation often receives the designs very late resulting in a **lack of preparation time**.
16.	**Temporary structures and construction site logistics are insufficiently visualised**, resulting in clashes and rework during realisation.
17.	**Actual progress is not used to improve the schedules of future projects.** Similarly, actual costing is performed but it remains vague how this improves cost estimations for future projects.
18.	The scheduling of equipment deployment is based on experience, not optimised using simulation models.
19.	Coordination between RAMS management and Asset Management is limited when there is no Maintenance component included in the scope of the contract.

4.1.2 Classifications of issues as BIM or Digital Twin

The issues in Table 3 provide input for the identification of potential DT applications for contractors in the infrastructure sector. However, given the overlap between BIM and DT, as outlined in section 3.3.1, a look at the issues revealed that some of them are more closely related to BIM than DT. Therefore, the identified issues were classified as either BIM or DT issues to continue solely with the DT issues. This classification was done based on the definition and main characteristics for both concepts, as discussed in section 3.3. The classification method of the issues is schematised in Figure 15. A complete overview of the classification of all issues, along with explanatory notes why an issue is considered to be a DT or BIM issue, is included in Appendix II. A few issues could neither be classified as BIM nor DT issues.

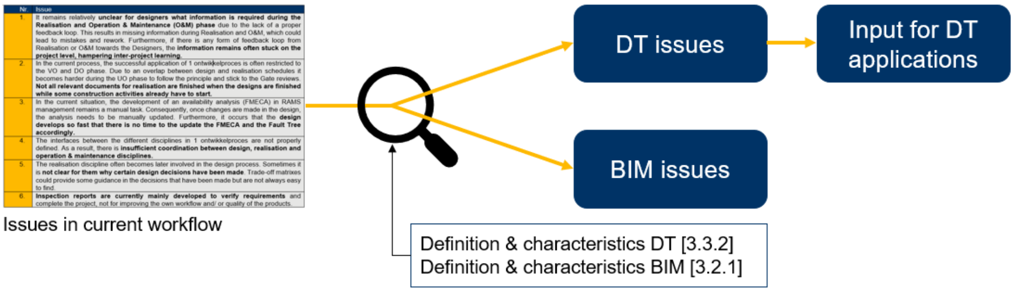


FIGURE 15: CLASSIFICATION OF ISSUES AS DIGITAL TWIN ISSUES OR BIM ISSUES

A large proportion of the issues in Table 3 were classified as BIM issues. This indicates that the opportunities that BIM offers are not fully exploited yet within Heijmans Infra. In particular consistent and structured information management seems to be a key issue that can be improved to reap the full benefits that BIM could provide. This highlights again the interlocking character of the three fields that constitute BIM, respectively *Processes*, *Policies* and *Technologies* (Succar et al., 2012). Without predefined agreements on how information ought to be managed throughout the construction lifecycle, the full potential of BIM technologies cannot be leveraged. Since it is assumed within this research that DT would be among the technologies making up BIM in the construction industry, BIM poses certain preconditions in the Processes and Policy field for the realisation of DTs. It may therefore be required that certain BIM issues must first be solved first before one can proceed to creating DTs. Although this is of great importance, the focus of this research remains on exploring what it means for the organisation to use DTs and how this can offer added value in the primary business process. The aim of this research is not devising solutions for BIM issues at Heijmans Infra. The identified BIM issues were therefore put aside and not further treated in this research.

Digital Twin issues

Even though the majority of issues found during the interviews were classified as BIM issues, six of them were assigned as DT issues. These issues can be linked to different characteristics of DT, as discussed in section 3.3.1. The combination of DT characteristics (blue) and DT issues (grey) is presented in Table 4.

TABLE 4: COMBINATION OF DIGITAL TWIN CHARACTERISTICS WITH ISSUES

Simulation and advanced analyses	
18.	The scheduling of the equipment deployment is based on experience. Not optimised using simulation models;
Monitoring, control, diagnostics and predictions	
8.	No overview of the actual progress on projects;
Combining design, engineering details with operational data and analytics	
13.	The consequences of changes to the original plans during realisation cannot easily be overseen in an integral manner;
Closing the feedback loop, not only back to the real system but also the early lifecycle phases	
1.	Lack of proper feedback loop from the Realisation and O&M back to the Design phase;
6.	Inspection reports are currently mainly developed to verify requirements and complete the project, not for improving the own workflow and/ or quality of the products;
17.	Actual progress is not used to improve the schedules of future projects. Similarly, actual costing is performed but it remains vague how this improves cost estimations for future projects.

4.2 Identification of Digital Twin use-cases

This section introduces application areas for DT in the construction industry. From these applications, two relevant alternatives for the operations of Heijmans Infra were selected. These have been translated into use-cases and form the content of the design task of this research.

4.2.1 Potential Digital Twin applications

Using the six DT issues and suggestions for DT applications that were given during the interviews, several application areas for DT in construction have been identified. Like with the issues, the majority of suggestions for DT applications given during the interviews concerned BIM applications (e.g. adding cost statistics to design models to generate more cost awareness at designers, which is part of 5D BIM). Complementary to the suggestions that were given during the interviews, literature and internet search were used to search for DT applications. The identified applications can be assigned to the types of DTs from section 3.4.3. Figure 16 provides a recap on the six types that are distinguished in this research. Additionally, to provide insight in where potential DT applications would be positioned in the primary business process, the identified applications are displayed on the process maps of the current high-level workflow (Appendix I).

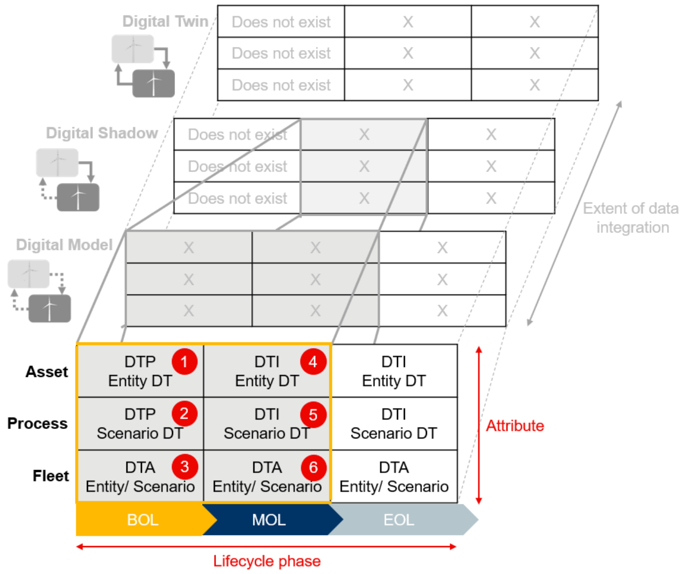


FIGURE 16: RECAP - TYPES OF DIGITAL TWINS IN THIS RESEARCH

Based on various interviews with persons at Heijmans infra, literature and internet search, the following applications areas for each type of DT have been identified in the context of the construction industry:

1. Digital Twin Asset – BOL phase

DT applications that can be headed under the DT Asset during the BOL phase have in common that the physical asset is not realised yet. Therefore, these applications focus on providing a comprehensive virtual representation of the to-be reality. Compared to current BIM technologies, this type of DT provides an extension by its ability to integrate information from multiple external data sources into a unified (3D) view of the to-be constructed asset. These data sources may comprise of enterprise tooling that includes static information regarding the asset, such as document management systems and requirement databases. Additionally, for projects where system integration is involved, control and monitoring systems can already be linked to the 3D model, which allows virtual testing and commissioning of the systems and software during the design phase (Macchi et al., 2018). That is, testing can be performed by letting the control system control the DT instead of the real asset. An example where real-time control systems are coupled to the 3D model of the to-be (re-)constructed asset for testing purposes concerns the concept of "Digitale tunneltweeling", which is explained in detail in COB (2020).

Besides providing a comprehensive representation of the to-be reality, simulation models in the DT can be used to conduct what-if scenarios and test the system response to (unexpected) scenarios (Rasheed, San, & Kvamsdal, 2020), such as emergencies (COB, 2020). In addition, DTs enable to try out and compare design configurations in a variety of virtual environments (Tao, Sui, et al., 2018). This enables to virtually evaluate the Reliability, Availability, and Maintainability (RAM) performance and Total Costs of Ownership (TCO) for various design alternatives (Macchi et al., 2018). Simulation outcomes can be used for optimisation of the asset design by selecting the optimal configuration. The DT can thereby be used to iterate between the to-be and could-be realities. In synthesis, the essence of a DT Asset BOL can be defined as feeding back insights to users to iteratively improve the to-be constructed asset based on a comprehensive information model, virtual test environment, and virtual data that is produced by simulation models. The following application areas of this type of DT have been identified:

- Simulation of asset behaviour (testing installations, motion, control systems)
    - Testability of software & control systems and virtual verification of requirements
    - Stakeholder communication
    - Virtual validation of design
- Simulation of usage scenarios
    - Sightlines (road users, CCTV)
    - Emergencies (evacuations, accessibility emergency services)
- Multi-layered data visualisation (enrich 3D model with external static data sources)
    - Complete insight in verification and validation progress status using 3D object-based representation and provide users with feedback regarding the state of V&V progress

2. Digital Twin Process – BOL phase

The DT applications that can be headed under the DT Process during the BOL phase have in common that there is no physical asset realised yet. As opposed to the DT Asset, the focus of this type of DT is not on the to-be constructed asset itself but on processes associated with the asset. This type of DT corresponds to its equivalent in the manufacturing industry that is used to optimise the production process before anything goes in production. DTs of production lines in manufacturing allow layout configurations, processes, and material flows to be tested and optimised before a manufacturing facility is commissioned (Dohrmann, Gesing, & Ward, 2019; Weyer, Meyer, Ohmer, Gorecky, & Zühlke, 2016). They can reflect every aspect of the production process, from its machines to plant controllers, in the virtual environment (Siemens, 2019). Transforming this idea to the context of the construction industry, it can be argued that the DT process during the BOL phase provides a virtual representation of various construction processes that can be optimised to produce the asset as efficient as possible. Using simulation models, various what-if scenarios related to the to be constructed asset can be evaluated that enable optimisation and better risk assessment (Rasheed et al., 2020). Additionally, training scenarios can be performed to do the actual work as efficient and safely as possible (COB, 2020; Tao, Cheng, et al., 2018). The following applications have been identified for this type of DT:

- Simulation based optimisation of construction processes
    - Equipment deployment (bottleneck predictions, optimise layout)
    - Evaluation of vehicle loss hours for different construction methods/ phasing
    - Evaluation of material flows for different construction methods/ phasing
- Training scenarios
    - Construction workers
    - Maintenance crew
    - Operators

3. Digital Twin Fleet – BOL phase

The DT applications under the DT Fleet during the BOL phase have in common that data is aggregated over multiple DTs. The following applications have been identified for this type of DT:

- Simulation based optimisation of equipment allocation over multiple projects
    - Simulation based optimisation of asphalt processing (production capacity, equipment- and transport allocation) over multiple projects that use the same asphalt plant.

4. Digital Twin Asset – MOL phase

The DT applications that can be headed under the DT Asset during the MOL phase are characterised by the synchronisation between the physical asset and its virtual representation. These applications exploit data coming from the physical world to monitor the physical system in the virtual world, and thereby give an accurate representation of the *as-is* reality. Based on sensor data, test and inspection results, maintenance records, etc., this type of DT gives a comprehensive representation of the current state of the physical asset. The ability to view an assets' state virtually can be particularly helpful for assets that are remote or dangerous to approach physically (Dohrmann et al., 2019). Furthermore, by integrating asset information that was otherwise scattered around multiple sources into a unified (3D) view, the DT can be used as repository for easy retrieval of information during construction and O&M that enables to have all information at a fingertip (Rasheed et al., 2020). The DT thereby enables information continuity along the entire lifecycle (Haag & Anderl, 2018).

Besides information retrieval, much attention from literature and practical applications for this type of DT focuses on the role of data science or Big data principles in the DT, which are used to derive insights based on the data collected from the physical asset. Multiple types of insight can be derived from the DT Asset MOL. In its most basic form, descriptive analytics describe what has happened or how the state of the asset has changed over time. A slightly more advanced DT may also make use of diagnostic analytics, that enable the investigation of the root-causes for state changes of the asset over time, and thus answer the question *why did it happen*? However, much DT related research is focusing on the next level of data analytics: predictive analytics, that provide insight in what will happen by predicting the future performance of an asset and thereby enable predictive maintenance to be performed (Tao, 2019). By combining sensor data from the physical asset with physics models and machine learning techniques, predictions regarding the deterioration and remaining useful life of an asset can be made (Nikolaev, Belov, Gusev, & Uzhinsky, 2019). Finally, prescriptive analytics are not only restricted to making predictions and recommendations on advised maintenance, but also automatically act and decide how, for example, maintenance can be performed most effectively.

It should be noted that the majority of the applications for the DT Asset MOL take place during the O&M phase of the asset and are thus excluded from the scope of this research. Still, the following DT applications have been identified during the construction phase:

- Real-time multi-layered data visualisation by enrich the 3D model with external static and dynamic data sources (Boje, Guerriero, Kubicki, & Rezgui, 2020)
    - Real-time insight in number of people on construction site
    - Complete insight in verification and validation progress status using 3D object-based representation and provide users with feedback regarding the state of V&V progress

5. Digital Twin Process – MOL phase

The DT applications that can be headed under the DT Process during the MOL phase are characterised by the synchronisation between the physical and the virtual world and focus on providing a virtual representation of processes associated with the physical asset. This type of DT exploits data coming from the physical world to gain insights in the virtual world, which in turn can be used to optimise the physical process. Like the DT Asset during the MOL phase, the insights derived with this type of DT may be descriptive, diagnostic, predictive or prescriptive. To realise this, the DT Process may be used to evaluate different scenarios that utilise (real-time) data coming from the physical process combined with simulation models. The following applications have been identified for this type of DT:

- Automated site progress monitoring using field data capturing technologies (Boje et al., 2020);
    - Descriptive – visualise progress discrepancies from the planned situation by analysing the collected progress data;
        - Assess actual progress against planned budget & schedule;
        - Inform project stakeholders about progress using visualisations;
    - Diagnostic– Identify and outline the factors that cause progress deviations.
        - Intervene on factors that regularly cause progress discrepancies;
    - Predictive – Consider the near past data to predict future progress trends through causation and correlation;
        - Inform stakeholders about predicted project outcomes;
    - Prescriptive – Find the best mode, route, manner or moves to operate based on collected data and simulation models.
        - Optimise planned situation to catch up on schedule in case of delays.
- Using field data capturing technologies for As-designed compliance check
    - Using scan-technologies to compare As-built with As-designed and take actions accordingly for deviations (compose non-conformance reports, take corrective actions)
    - Verify realisation requirements based on the virtual model of the as-is situation
- Evaluate what-if scenarios
    - Being able to study the impact of changes in the virtual environment before applying them in the real world (impact on schedule, capacity, budget, safety etc.).
    - Simulate complex or dangerous operations before they are performed in real life to reduce the risk of complications or accidents. This can relate both to construction activities as well as O&M tasks.

6. Digital Twin Fleet - MOL phase
The applications that can be headed under the DT Fleet during the MOL phase have in common that data is aggregated over multiple instances in the physical world. Data from multiple similar assets, components, or process steps is collected and analysed to gain an improved understanding of the behaviour and performance of the physical system based on cumulative data. The following applications have been identified for this type of DT:

- Trend analysis on data coming from multiple assets in use to optimise the design (e.g. the degradation process of a particular type of asphalt under different use conditions)
- Trend analysis on data coming from multiple assets in use to optimise the construction planning phase (e.g. maintenance costs of similar elements constructed using different construction techniques)
- Trend analysis on data coming from multiple assets in the construction phase to improve the design phase (e.g. costs and durations of construction process for different elements that fulfil the same function)
- Trend analysis on data coming from multiple assets in the construction phase to improve the construction planning phase (e.g. actual productivities and costs to improve future simulations)

4.2.2 Selection of use-cases

From the DT application areas proposed in section 4.2.1 it follows that for each of the six types of DTs, applications can be found in the construction industry. To develop a functional design for the DT, two application areas have been selected to reflect a use-case. These alternatives were selected based on their relevance for the operations of Heijmans Infra. This decision was made together with the commissioning person of the research and relied on the following criteria:

- Potential added value for Heijmans Infra (= absolute value – extra effort in the work process);
- Contribution to the objective of this research (contribution to primary business process);
- Development effort (Initial effort to develop the DT application);
- Timeframe (likeliness to be feasible in short-/ medium-/ long term).

Furthermore, the selection of two alternatives was subject to the following condition: one DT application should take place during the BOL phase and the other during the MOL phase. This enabled to outline the differences that exist between DT applications in the BOL and MOL phase, as the DT has different characteristics during these phases. It should be noted the selection is based on predictions regarding how such a DT application would function in the context of Heijmans Infra because the alternatives are not implemented in the organisation yet. Therefore, the criteria cannot be measured in an objective manner. Taking the assessment criteria into consideration, the following alternatives were selected:

- Simulation based optimisation of construction processes (DT Process BOL);
- Automated site progress monitoring using field data capturing technologies (DT Process MOL).

To explain why these alternatives were considered relevant, each assessment criterion is discussed in Table 5 and Table 6 for the two selected alternatives.

TABLE 5: RELEVANCE SIMULATIOIN BASED OPTIMISATION OF CONSTRUCTION PROCESS

Criterion	Relevance
Potential added value for Heijmans Infra	Better predictability of the outcomes of construction activities. Increased productivity/ efficiency. Making tacit knowledge explicit. Less dependent on expert knowledge.
Contribution to objective of the research	Provides a direct contribution to the primary process by making construction processes more efficient and reducing the number of wasted resources.
Development effort	New technology within the context of Heijmans Infra, which will take development efforts. Data needs to be collected in a structured manner to provide input for simulations. Users need to be trained to get acquainted the technology.
Timeframe	Technology is ready as simulation-based optimisation of processes is widely used across different industries (e.g. Discrete-event simulations or System Dynamics). However, within the context of Heijmans this is still quite rare so it will take some time to get acquainted and develop a useful value adding model.

TABLE 6: RELEVANCE AUTOMATED SITE PROGRESS MONITORING USING FIELD DATA CAPTURING TECHNOLOGIES

Criterion	Relevance
Potential added value for Heijmans Infra	Better in-control of the project. More accurate insight in work progress in virtual space which can be used as input for adjustment of the work process. Allows to develop a digital diary over time of the construction process and thus insight in what has happened and where potential progress discrepancies occurred.
Contribution to objective of the research	Better insight in the actual progress contributes to the objective of the research as progress monitoring and project control are part of the primary business process during the construction phase.
Development effort	It needs to be determined what should be exactly measured, in what frequency and how these measurements can be used to display the progress accurately. Furthermore, it should be determined how outcomes of progress monitoring can be used as overlay over the As-planned situation.
Timeframe	Underlying technologies such as sensors and (LIDAR) scanners are mature technologies and widely used in various industries. The use of sensors for the operational phase becomes more popular in the construction industry. The use of scan technologies for progress monitoring is gaining momentum recently.

The two selected application areas are broad and unspecific. Therefore, they were made more specific to reflect an actual use-case that can be used to develop a functional design and asses the added value in the primary business process. Transforming these broad directions into actual use-cases was done together with the commissioning person of the research. A condition that has been taken into account here concerns the compliance with the selected asset types for this research (roads and movable bridges), this results in the following use-cases:

4.2.3 Use-case 1: Simulation based optimisation of asphalt paving operations

The first use-case is concerned with simulation-based optimisation of asphalt paving operations. In particular the alignment between asphalt production, transportation and processing is an aspect that determines to a large extent the final quality of the asphalt layer as well as the costs and duration of the operation. The idea behind this use-case is that simulation models can be used during the construction planning phase to evaluate different scenarios regarding equipment deployment, which should lead to an optimised balance between costs, duration and risk while ensuring a high quality asphalt layer.

Validation of use-case relevance

Since the selection of use-cases was done in consultation with the commissioning person of the research but without the direct involvement of the concerning disciplines, the relevance of the selected use-cases has been validated. This was done by conducting several interviews with persons in the organisation that look at the use-case from diverging perspectives. During the interviews it was asked whether they recognise the identified issues in the current workflow and if they think that simulation models could aid in (partially) overcoming these issues. Table 7 shows that this use-case is considered to be relevant by all interviewees, albeit under certain conditions (e.g. only for large paving operations). Therefore, a functional design was developed for this use-case, which is presented in chapter 6 of this report.

TABLE 7: VALIDATION RELEVANCE USE-CASE 1

Role interviewee:	Use-case is relevant?
Work planner roads	Under certain conditions
Asphalt coordinator	Under certain conditions
Project manager roads	Absolutely
Master Lean Six Sigma black belt	Yes
Manager road	Under certain conditions

Issues in the current workflow

A consistent and uninterrupted paving process is pivotal for a high quality asphalt layer (Bijleveld, 2015). This in turn requires proper work preparation and organisation of the paving process. However, the current work practices in road construction still rely mainly on tacit knowledge, experience and craftsmanship for the allocation of equipment, while the decisions made have a large impact on the final quality of the asphalt layer as well as the costs and duration of the process (Bijleveld, 2015). Owing to the current work practice, consequences that may arise include a lower end quality of the asphalt layer due to fluctuating consistency of the paving process (start and stops) and a lower overall productivity due to misalignment between the capacity of the different types of equipment needed (e.g. trucks, pavers & rollers).

To utilise the maximum capacity of the equipment on site (e.g. paver and rollers), sufficient supply of asphalt is required. The ability to deliver this depends on the production and transport capacity. Consequently, for an optimal productivity and a high quality asphalt layer, proper alignment between the three cornerstones asphalt production, transport and processing is essential (Figure 17). However, the current work practices within Heijmans infra, which rely mainly on experienced guessing, most likely yields not the optimal results in terms of quality, costs and/or duration of the paving operation. Based on interviews with persons involved in the paving process, the following issues in the current process were identified:

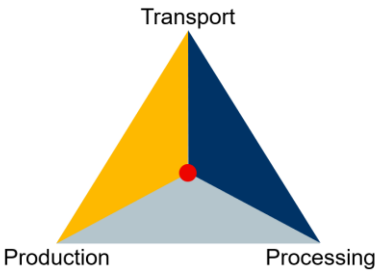


FIGURE 17: CORNERSTONES ASPHALT PRODUCTION, TRANSPORT & PROCESSING

<u>Lower production than possible</u>
Due to misalignment between the three cornerstones production, transport and processing, regularly it occurs that pavers are waiting for asphalt to arrive. Actual measurements show that cumulative waiting times for transport can reach up to two hours on an eight-hour workday. Furthermore, measurements of three different Heijmans projects that were consulted for this research reveal that the overall equipment effectiveness for asphalt pavers is only between 36 and 41% percent compared to the theoretically attainable production. Hence, there seems to be improvement potential for the productivity of the asphalt paving process. This issue was acknowledged by all five interviewees of Table 7.

<u>Lower end quality</u>
A lower end quality of the asphalt layer due to inconsistencies of the paver speed during the process is another issue that prevails currently, as depicted in Figure 18. Due to misalignment between paver-, transport- and production capacity, it regularly occurs that stops need to be made during the paving process to wait for transport. On the contrary, there are also situations with overcapacity in transport, which results in a queue of trucks waiting to unload on site while asphalt is cooling down in the truck. This can result in quality issues if the asphalt cools down too much. Another consequence may be that the paver operator decides to pave faster than planned because of the waiting trucks, which does not contribute to the quality either and can disturb the balance between production, transport and processing. Additionally, the decision to pave faster than planned may also result in exceedance of the roller capacity, meaning that compaction cannot be performed in time within the required temperature range. This issue was acknowledged by all five interviewees of Table 7.

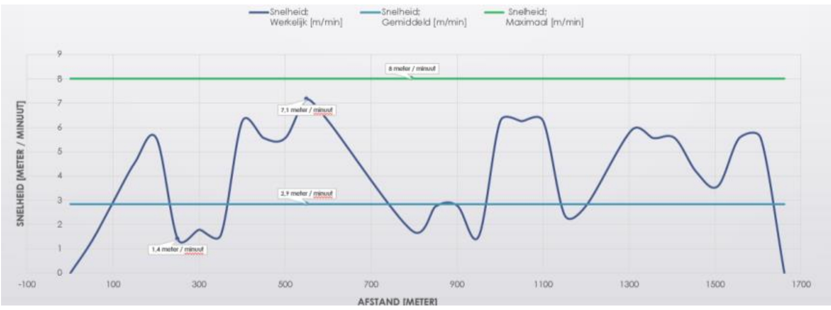


FIGURE 18: INCONSISTENCIES IN THE PAVER SPEED DURING THE PAVING PROCESS

<u>Limited insight in the consequences for the entire asphalt chain</u>
When the planned daily production is exceeded on a project this may seem beneficial on first sight because the actual production is higher than the planned production. However, this affects the entire asphalt production chain. That is, the asphalt plant may had to cancel or delay other orders to produce sufficient asphalt for the project that paved more than planned. Therefore, exceedance of the planned production may be more expensive in the end due to cancelled orders and working in overtime than thought on forehand. This issue was acknowledged by three of the five interviewees of Table 7.

Simulation models
This use-case is centred around the idea that simulation models could assist planners in making better decisions regarding equipment allocation during the construction planning phase. During the work preparation, choices have to be made regarding the deployment of pavers and trucks, paver speed, and the paving sequence. The use of simulation models may allow a more holistic approach to these decisions than the current work method, which relies mainly on experience. By coupling the simulation with cost statistics, planners can gain insight in the costs of alternatives, allowing the evaluation of the

cost effectiveness of different scenarios. For example, a planner can calculate if it is beneficial to allocate extra trucks to the project and whether this will result in reduced overall costs as a result of the increased productivity. Furthermore, simulation models can become more reliable over time by integrating historical data, which also decreases the reliance on expert knowledge as input. The hypothesis is that simulations could lead to reduced variability and increased consistency of the paving process, leading to a better end quality of the asphalt layer and better project outcomes in terms of cost and duration.

Figure 19 demonstrates the principle of this use-case, where the activities production, transport, paving, and compaction all have their own probability distribution function for durations or productivity rates, which allows to make estimates of the outcomes of the process with a certain confidence interval.

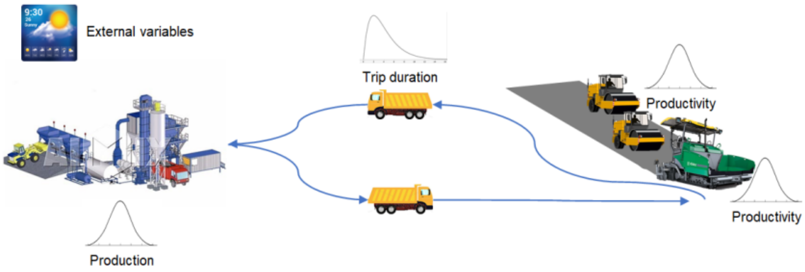


FIGURE 19: PRINCIPLE USE-CASE 1

4.2.4 Use-case 2: Automated site progress monitoring using field data technologies

The second use-case is concerned with the use of field data capturing technologies for progress monitoring to stay better in control of the project. This use-case is centred around the idea that data collected during the construction phase with scan- or measurement technologies can be used to gain more accurate insight in the actual progress of construction activities, in a demonstrable way. This information can subsequently be used as input for several activities, such as adjustment of the work process, budget and schedule control, purchasing management and invoicing.

This principle can be utilised for various construction activities and use several data collection methods. During a brainstorm with the commissioning person of the research the following options were coined:

- Using point-cloud models for progress monitoring of groundwork activities;
- Using the GPS sensors on the asphalt equipment for progress monitoring of asphalt paving operations;
- Using point-cloud models for progress monitoring of civil structures (bridges, sluices etc.).

Validation of use-case relevance

To decide which of the alternatives is further elaborated during the design task of this research, the relevance of the three alternatives was validated. This was done by conducting interviews with multiple persons in the organisation that look at the alternatives from different perspectives. The outcomes of the interviews are depicted in Table 8. Some of the boxes in the table remain empty because not all interviewees had an opinion about each application.

TABLE 8: VALIDATION OF RELEVANCE FOR USE-CASES PROGRESS MONITORING

Role interviewee:	Point-cloud groundwork	GPS asphalt	Point-cloud civil structures
Surveyor	++		+/-
Project manager geodesy	++		+
Manager roads	+	- -	
Project manager groundwork	++		+
Project manager roads		++	
Work planner roads	++	+	

From Table 8 it follows that all three options were considered to be relevant by some of the interviewees. The use of point-clouds for progress monitoring of groundwork activities was considered to be relevant by all interviewees. Therefore, this alternative has been selected to form the scope of the design task of this research. Given the time available for this research, the other alternatives have not been further detailed.

Issues in the current process

From an interview with a surveyor it follows that progress monitoring for groundwork activities is currently done in two ways within Heijmans Infra. On one hand this is done by surveyors that walk on the construction site and perform measurements at a few normative points with a GPS or total station. On the other hand, the equipment used for the groundwork activities (e.g. excavators) can be used to perform measurements using the pre-installed GPS sensors on the equipment. These measurements are captured in the Infrakit software, which is a cloud platform that allows to load the design models in the operator guidance systems and can also be used to perform measurements to check the completed work against the design. Subsequently, the measurements performed by either surveyors or in Infrakit can be used to reconstruct the as-is situation in virtual space by tying the measured points together. Based on several interviews at Heijmans the following issues in the current process were identified:

Inaccuracies

In current practice, inaccuracies arise in the reconstructed as-is situation, and thus the volumes that are supposed to be moved, due to a limited number of measurement points. Even though each point measured by the surveyor is highly accurate by itself, the surface created by tying the points together is not due to the limited number of points that the surveyor measures. This issue is demonstrated in Figure 20, by showing how the volume of a stockpile would be measured, where it can be seen that inaccuracies arise when tying the points together, as indicated by the red arrow.

FIGURE 20: INACCURACY IN THE CURRENT PROCESS OF PROGRESS MONITORING

Time-consuming

Another issue that arises owing to the current practice, as indicated during one of the interviews, is that it takes sometimes too long before the information regarding actual progress on-site (in terms of volumes) is returned to the project. The feedback loop between the groundwork activities on-site and Geodesy (responsible for performing and processing the measurements) takes sometimes quite long in the current practice. This information is needed to continue scheduling the work. Additionally, it is used to tune the material deliveries with suppliers, which can take multiple days to deliver for sand. Therefore, information regarding the actual progress in terms of volumes is essential to be in-control on groundwork activities. Furthermore, this information can be translated into the financial performance as well, which allows to see whether the project is performing within budget. Likewise, this information can be used to see whether the activities are performed according to schedule.

Progress monitoring using point-clouds

This use-case relies on progress monitoring using point-clouds of the as-is situation, which can be captured in different ways. The two most dominant data collection methods that are currently used to obtain point-clouds are laser scanning and photogrammetry (Kopsida, Brilakis, & Vela, 2015), both are explained in more detail in chapter 7. The use of point-clouds for monitoring allows to record the amount of material moved, excavated and filled as well as the tracking and monitoring of assets over the course of the project. It thereby provides a method of knowing what is happening on the construction site for all stakeholders concerned (Anwar, Izhar, & Najam, 2018). The point-cloud model of the As-is situation can be compared with the As-planned (BIM) model at various moments during the construction process to monitor the progress on-site, enabling to identify parts of the project that are going off-track and thereby offer the ability to prevent any causalities that may arise (Zaychenko, Smirnova, & Borremans, 2018). Additionally, it can be used as baseline for billing and the verification of requirements. Furthermore, by regularly capturing the progress in a visual way, it can be used for learning by looking back to see what went well on the project and what did not (Zaychenko et al., 2018). Regularly capturing the As-is situation furthermore allows to develop a digital diary of the project which forms a proper base for the O&M phase.

Figure 21 presents the principle of this use-case. In essence this use-case is concerned with providing an accurate representation of the as-is situation on the construction site in virtual space using a point-cloud and compare this with the As-planned situation (BIM), which forms the basis for decision making. On the left side of the figure, the principle is visualised while on the right side of the figure the steps that need to be taken are schematised, which are adapted from the framework of Anwar et al. (2018).

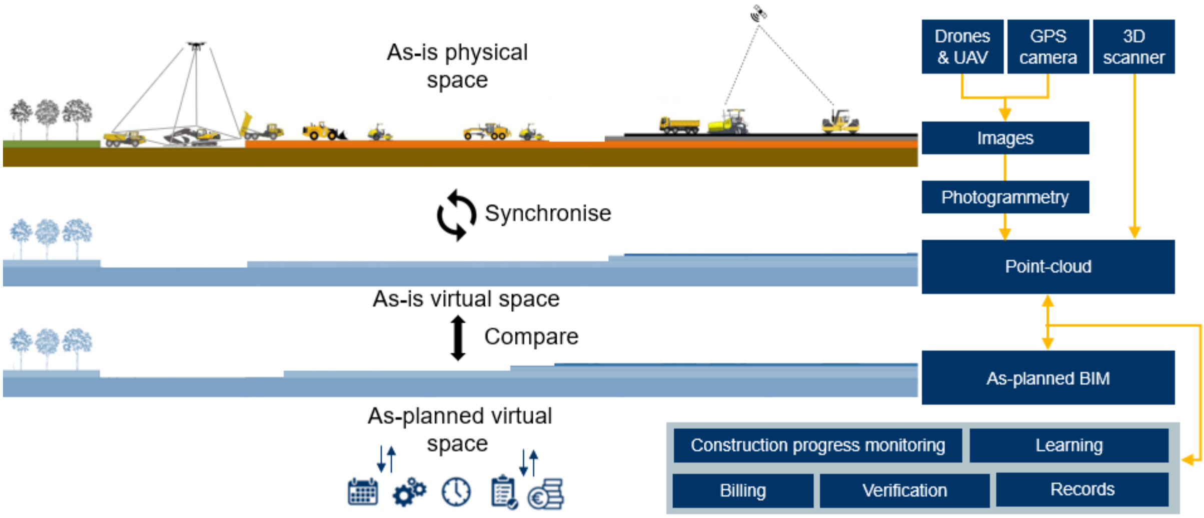


FIGURE 21: SCHEMATIC REPRESENTATION OF USE-CASE 2. ADAPTED FROM: '' CONSTRUCTION MONITORING AND REPORTING USING DRONES AND UNMANNED AERIAL VEHICLES (UAVS)'' BY ANWAR ET AL. (2018)

4.3 Conclusion and outlook

This chapter focused on giving a more practical interpretation of the classification for DT that was given in chapter 3. By capturing the current primary business process at Heijmans Infra, a list of issues was established that prevail regularly in the current workflow. These issues were analysed and classified as either DT or BIM issues, which led to the conclusion that six issues in the current workflow could be regarded as DT issues. These six issues served, together with literature and several practical DT applications from other industries, as input for the identification of DT applications in the construction industry. For each of the six types of DTs that were identified in chapter 3, application areas in the context of the construction industry were presented in this chapter. Considering these application areas, the DT applications that take place during the BOL phase are mainly focused on virtual testing of an asset and the simulation of various relevant scenarios. During the MOL phase, the main feature of a DT is the synchronisation between the physical and virtual world. The data that is collected from the physical world can be analysed in the virtual world which leads to insights that can be descriptive, diagnostic, predictive or prescriptive in nature. For each of these four types of insight, relevant applications can be found in the context of construction industry, which focus both on the asset itself as well as the associated processes.

From the proposed applications for DT in the construction sector, two relevant alternatives were selected that form the use-cases. The first use-case is concerned with the use of simulation models for process optimisation of the asphalt processing process. The second use-case concerns automated progress monitoring based on point-clouds for groundwork activities. For each of the two selected use-cases a functional design has been developed that allows to assess the potential added value that these DT applications can offer. However, to develop the functional designs, more insight in the essential elements of a DT was needed. Hence, the next chapter elaborates the generic building blocks that form the DT and the relations that exist between these elements.

5 DIGITAL TWIN BUILDING BLOCKS

This chapter is concerned with the identification of the generic building blocks of the DT and the interconnectedness that exists between them. This chapter first presents the results of a literature study regarding DT building blocks. Subsequently, the developed reference framework for DT in construction is presented. The research steps covered in this chapter are depicted in Figure 22.

5.1 Digital Twin building blocks principle

From the definition for DT in section 3.3.2 it follows that a DT concerns the semantically linked collection of models, information and data that fully reflects a potential or actual physical system along its entire lifecycle. This linked collection of models, information constructs and data can be considered as the **DT building blocks**, which can reflect nearly all information regarding the physical system. However, not all information is relevant for each stakeholder involved during the lifecycle. Therefore, there are multiple perspectives to present relevant information to particular stakeholders. These perspectives are referred to as **DT lenses** in this research. The different DT lenses refer to a set of information that is relevant for a specific (set of) stakeholder(s) or application. The information about an asset or process is, however, often scattered across multiple sources. By semantically linking different models, information constructs and (real-time) data, DT integrates the scattered information that is relevant for a stakeholder into a unified view: the DT lens. The principle of the DT with its building blocks and lenses, is depicted in Figure 23.

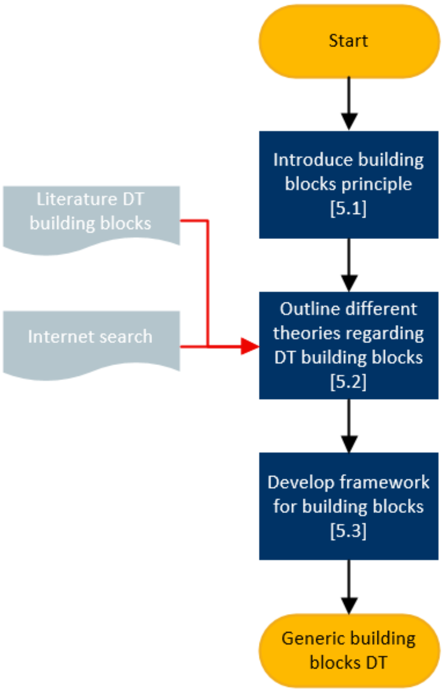


FIGURE 22: OVERVIEW RESEARCH STEPS CHAPTER 5

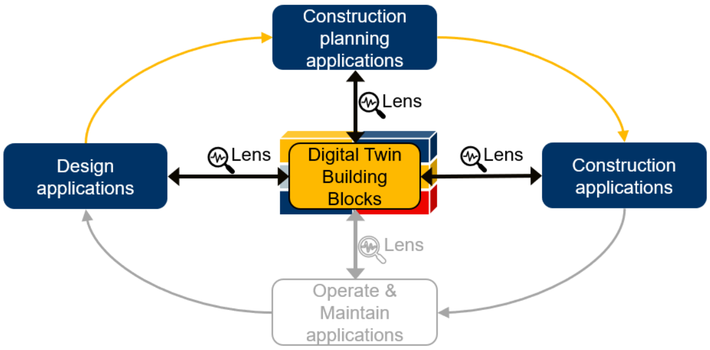


FIGURE 23: PRINCIPLE OF DIGITAL TWIN BUILDING BLOCKS & LENSES

5.2 Literature study Digital Twin building blocks

Several articles have been selected to form input for the identification of DT building blocks of this research, these are presented in Table 9. Additionally, this table indicates the context and type of article: whitepaper (WP), journal paper (JP), conference paper (CP) or commercial report (CR).

TABLE 9: LITERATURE USED FOR BUILDING BLOCKS

Author(s):	Context:	Type:
Grieves (2014)	Manufacturing	WP
Tao and Zhang (2017)	Smart manufacturing	JP
Josifovska, Yigitbas, and Engels (2019)	Cyber physical systems (CPS)	CP
Damjanovic-Behrendt and Behrendt (2019)	Smart manufacturing	JP
Wang, Ye, Gao, Li, and Zhang (2019)	Smart manufacturing	JP
Zhang et al. (2019)	Manufacturing system	CP
Zheng and Sivabalan (2020)	Smart manufacturing	JP
Parrott and Warshaw (2017)	Manufacturing	CR

The next section presents the basic reference framework for DTs that is most accepted in literature. After that, the commonalities and differences between the publications of Table 9 are discussed.

5.2.1 Basic Digital Twin framework

The most basic framework for the DT is given by Grieves (2014), who argues that the DT consists of three elements: the physical part, virtual part and connection part. The virtual part is connected to the physical part by the connection part, which facilitates the exchange of data and information between the two other parts. That is, the connection part establishes connections that feed (operational) data from the physical to the virtual part, and information and processes from the virtual to the physical part. This three-dimensional model was later extended by Tao and Zhang (2017), who added two dimensions (data & service) and proposed the five-dimensional DT model. Hence, the five dimensions of this model are: physical part, virtual part, connection, data, and service, as depicted in Figure 24. The physical part forms the foundation for the virtual part, which can be used for simulation, decision making, or even controlling the physical part if there is a full bi-directional connection between the two parts. Twin data is the central component of the DT and comprises of multiple types of data. Firstly, it includes data regarding the physical entity, which may be both static attribute data and dynamic condition data. Secondly, it comprises of data generated by the virtual models (i.e. simulation results). Thirdly, the DT includes data that is obtained from services as well as (domain) knowledge, which may be provided by experts or extracted from historical data. Fourthly, fusion data, which results from the combination of the aforementioned data types, can be included (Qi et al., 2019). Another dimension of the model is service, as the essence of a DT is offering value adding services that can enhance the convenience, reliability and productivity of the physical system. Finally, the connection part integrates the physical part, virtual part, twin data, and services (Tao, 2019).

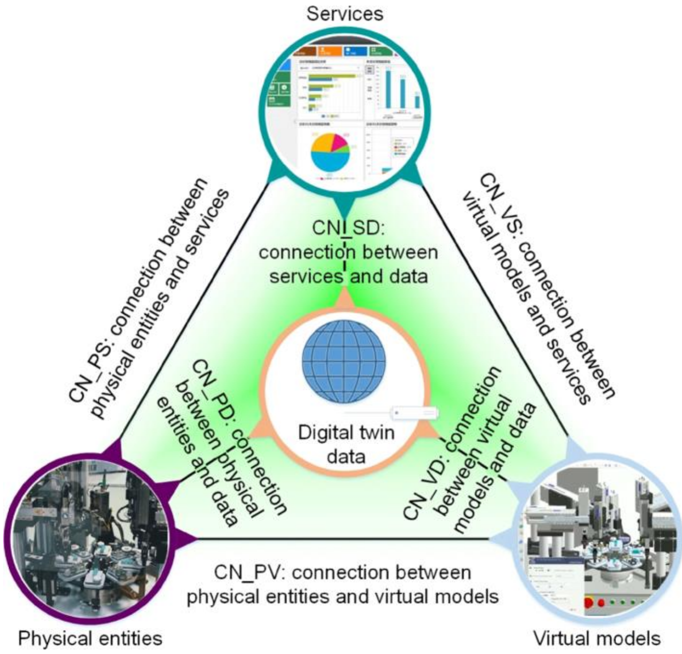


FIGURE 24: FIVE-DIMENSIONAL DT MODEL. REPRINTED FROM "ENABLING TECHNOLOGIES AND TOOLS FOR DIGITAL TWIN" BY QI ET AL. (2019)

5.2.2 Comparison of Digital Twin building blocks in literature

Besides the three- and five-dimensional DT models of Grieves (2014) and Tao and Zhang (2017), other authors proposed DT reference frameworks as well. A literature review of the remaining publications of Table 9 is included in Appendix III. To shape the interpretation of the DT building blocks for this research, the commonalities and differences between these publications are concisely discussed. The starting point for this discussion is the five-dimensional model of Tao and Zhang (2017), as it turns out that most other frameworks show commonalities with this framework.

Physical entities

The physical entities component in the five-dimensional model refers to the real-life physical system that is reflected by the DT. This can comprise of various physical entities, such as machines, materials and human operators in the context of smart manufacturing[2] (Tao & Zhang, 2017). Comparing the initial five-dimensional model with the other publications, it turns out that the majority of these publications defines a building block located on the physical side of the DT as well. These components are respectively referred to as: physical entity platform (Josifovska et al., 2019), devices & sensors and data sources (Redelinghuys, Kruger, & Basson, 2019), real world (Damjanovic-Behrendt & Behrendt, 2019), physical

[2] Smart manufacturing is a concept closely related to Industry 4.0 and covers a wide range of topics such as smart design, smart machining, smart monitoring, etc. where increasingly Internet-connected machinery is used to integrate the physical process with real-time insights in changing conditions (Zheng et al., 2018).

layer (Zhang et al., 2019), physical layer (Zheng & Sivabalan, 2020) and physical process (Parrott & Warshaw, 2017).

However, a difference between these publications is that some focus exclusively on a physical product (e.g. machinery), whereas others focus on a physical process (e.g. production process). Furthermore, some publications include both products and processes. The framework of Wang et al. (2019) does not explicitly define a building block on the physical side of the DT. Though, they define the presence of sensing measurements from a physical object so there must be a component located on the physical side of the DT as well. Therefore, the main point to consider is the content of this building block, as it turns out that this differs between the publications. The elements included in the physical layer differ depending on the context of application of the DT. This implies that in the construction industry, the components would differ from those in smart manufacturing as in construction, the final product as well as the processes needed to produce this product differ from those in the manufacturing industry.

Virtual models

The virtual models in the initial five-dimensional framework comprehend multiple models that reflect various dimensions of physical entities, such as: geometry-, physics-, behaviour- and rule models. Considering the publications of Table 9, all frameworks include a model component that represents the physical entities in virtual space. These components are referred as: virtual entity platform (Josifovska et al., 2019), models manager (Damjanovic-Behrendt & Behrendt, 2019), digital model (Wang et al., 2019), emulation and simulation (Redelinghuys et al., 2019), model layer (Zhang et al., 2019), cyberspace layer (Zheng & Sivabalan, 2020) and hybrid models (Parrott & Warshaw, 2017). However, the content of the models is not the same for all frameworks. Some publications discern based on specific aspects of the physical entity (e.g. geometry or physics models) while others discern between representation and computation models. Additionally, the simulation capability of the DT may be either included in an aspect models or may be a separate model. Therefore, with regard to the virtual models the main decision to be made concerns if the models are discerned based on the aspects of the physical entity (e.g. geometry, physics) or by the purpose of the model (representation, computation, simulation).

Digital Twin data

In the initial five-dimensional model of Tao and Zhang (2017), digital twin data is the central component and comprehends different types of data coming from the other building blocks. The majority of the other publications defines a component that includes DT data as well. These components are respectively referred to as data management platform (Josifovska et al., 2019), data manager (Damjanovic-Behrendt & Behrendt, 2019), knowledge base (Wang et al., 2019), cloud based information repositories (Redelinghuys et al., 2019), data layer (Zhang et al., 2019), permanent data storage (Zheng & Sivabalan, 2020), data lake (Parrott & Warshaw, 2017). However, a difference between the publications is that in the initial five-dimensional model, DT data is considered as the key component while Zhang et al. (2019) argue that the core component of the is the 5-dimensional RDT model, i.e. their model layer.

Services

DT services relates to the specific services that a DT can offer, thus its applications. Considering the other publications, it follows that some include a specific service component as well. These are respectively referred to as service platform (Josifovska et al., 2019), services manager (Damjanovic-Behrendt & Behrendt, 2019), service layer (Zhang et al., 2019). The purpose of this element differs, however, between the publications. Some see it only as the user interface that presents the specific DT applications to the end user while others see it as an intelligent component that supports underlying calculations and decision making for the DT applications. Additionally, there are also publications that do not include a service building block at all (Redelinghuys et al., 2019; Wang et al., 2019).

Connection

The connection component of the five-dimensional model by Tao and Zhang (2017) connects all building blocks with each other. In all other frameworks connections between the different building blocks are present as well. However, they differ in the building blocks that are directly connected to each other. In the initial five-dimensional model, each block is connected directly with each other. While in Josifovska et al. (2019) and Zhang et al. (2019) the physical component is not directly connected to the model component. Instead, these models are connected with each other by the data layer. Furthermore, the connection between the physical and virtual entity is obviously only applicable after the establishment of the physical object as during the development there is no physical object yet. This connection can be made as either a Digital Model, Digital Shadow or Digital Twin in terms of Kritzinger et al. (2018).

5.2.3 Synthesis

Various researchers proposed reference architectures for DTs. Although there is overlap between the reference frameworks in the different publications, they also show differences in the interpretation of the building blocks. The absence of a general accepted architectural template can partly be explained by the lack of consensus on definition for the DT. Consequently, researchers develop a reference framework while having different perceptions on the concept. It is therefore important to select a framework that fits well with the classification of DT in this research, as formulated in chapter 3.

5.3 Digital Twin Building blocks in construction

To define the DT building blocks in construction, a selection has been made regarding the reference framework that fits best with the classification of DT in this research. To gain an understanding of the prerequisites for the reference framework that follow from the DT classification, the definition of DT in this research is revisited, which reads:

''The DT is the <u>semantically linked</u> collection of <u>models, information and data</u> that fully describes a potential or actual physical system, as such it forms a representation of all aspects of its corresponding physical system that could be relevant for the current or subsequent lifecycle phases. The Digital Twin is developed alongside its corresponding physical system and remains its virtual counterpart across the entire lifecycle, where it can be used to <u>monitor, analyse, simulate and predict</u> the performance of the physical system, leading to actions in the physical world accordingly''

Several aspects in this definition pose conditions for the reference framework. Firstly, *semantically linked* is a characteristic that poses conditions on the connections between the DT building blocks. Secondly, *models, information and data* provides input for the content of the framework. Thirdly, *monitor, analyse, simulate, and predict* reflects functionalities that the DT should support and thereby imposes conditions on the elements that must be included in the reference framework to enable this.

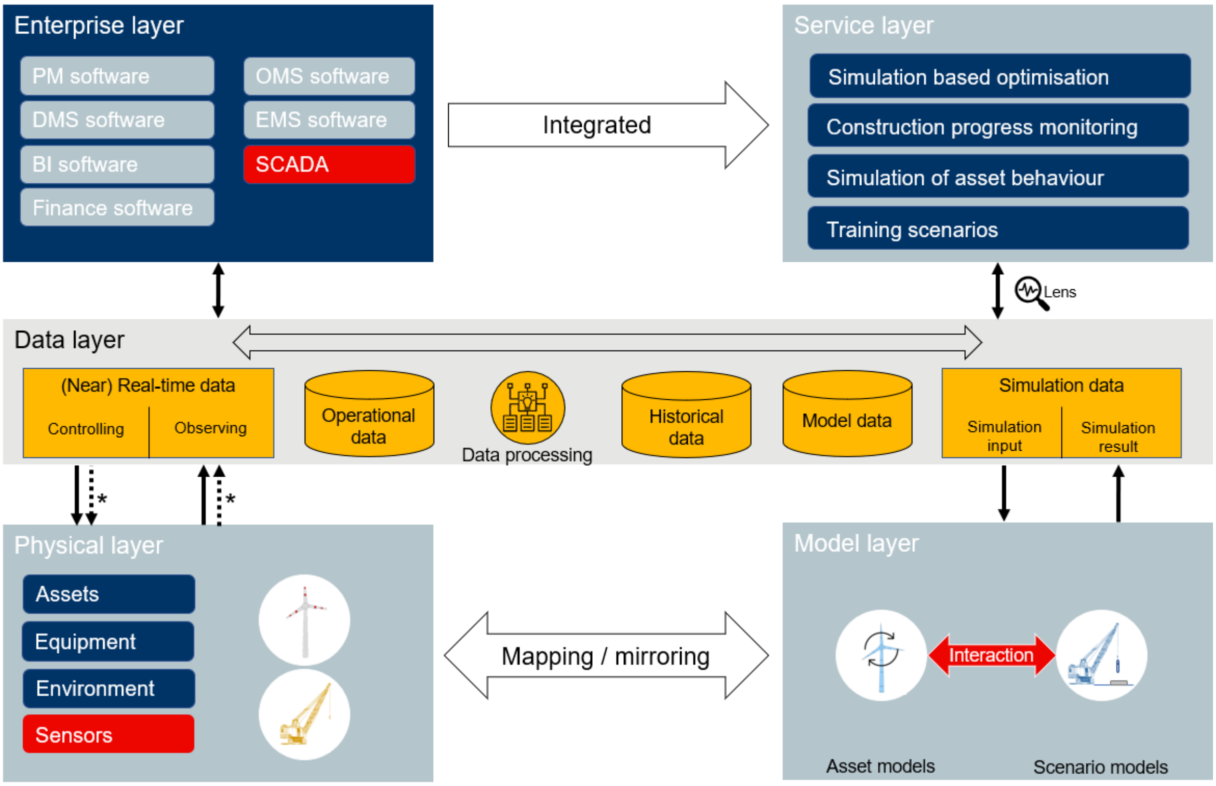
Besides the definition, the typology framework for DTs also provides input for the DT building blocks, as in terms of the extent of data integration only a Digital Model and Digital Shadow are assumed. The Digital Twin, which relies on fully automated bi-directional data exchange between the physical and virtual world, is not considered. Consequently, the *''leading to actions in the physical world accordingly''* in the definition needs to be initiated manually and responsive actions on the physical entity are not automatically performed by the DT. Hence, the reference framework does not need to support the control over the physical entity from the virtual world.

In synthesis, from the DT classification it follows that the DT building blocks should enable: the virtual representation of the physical system, processing and analysing data, simulating behaviours in the virtual environment, connections between physical and virtual world, and integrating asset and process-related information from different sources. Taking these prerequisites into account, the framework of Zhang et al. (2019) is considered most suitable from the frameworks in Table 9. Although, the majority of the frameworks reviewed include a model and data component and thereby comply with the idea of linking different models with static and dynamic data, an aspect that discerns the framework of Zhang et al. (2019) from the others is that it also provides the ability to interface with external software systems, which is considered to be a relevant functionality for DT in construction.

Even though a DT in construction may comprise of different models, tools and technologies compared to a DT in manufacturing, the overall architecture is expected to be generic (Boje et al., 2020). Therefore, the framework of Zhang et al. (2019) is considered as a suitable starting point for defining the DT building blocks in this research. Following Zhang et al. (2019), the main building blocks for the DT are:

- Physical layer;
- Model layer;
- Data layer;
- Service layer;
- Connection;
- Enterprise layer.

Figure 25 presents the reference framework for DT in construction. Some of the DT applications that were identified in chapter 4 are depicted in the service layer (other applications would be positioned in this block as well). These applications reflect the specific services that a DT can offer for contractors. The physical layer, model layer, data layer, enterprise layer and connections between these components form the remaining building blocks of the DT and provide the content to offer the specific applications. However, it should be noted that not necessarily all components in the DT building blocks are required for each application. Depending on the application, the required building blocks may differ.



* Depending on extent of data integration, either a Digital Model, Digital Shadow or Digital Twin (Kritzinger et al., 2018)

FIGURE 25: DIGITAL TWIN BUILDING BLOCKS FOR APPLICATION IN THE CONSTRUCTION INDUSTRY. ADAPTED FROM ''A RECONFIGURABLE MODELING APPROACH FOR DIGITAL TWIN-BASED MANUFACTURING SYSTEM'' BY ZHANG ET AL. (2019)

Figure 25 provides a generic overview of the DT building blocks. To explain the building blocks in more detail, a more comprehensive overview of each block is given in the next sections.

5.3.1 Physical layer

The first building block of the DT concerns the physical layer. Zhang et al. (2019) define the physical layer as ''a collection of all manufacturing resource entities for perception, data transmission, and execution''. This includes: Industrial robots, Sensors, Network equipment, Materials, Products, People and the Environment. Similar elements can be found in ISO 23247, a standard for DTs that is currently under development. The physical layer of this ISO standard includes: Personnel, Equipment, Material, Process, Product (Rexhepi - van der Pol, 2019). However, from section 5.2.2 it follows that the exact content of the DT building blocks depends on the application area. Therefore, the elements in the physical layer of (Zhang et al.) cannot be directly adopted for application in the construction industry.

For construction purposes, it is considered that the physical layer reflects all construction resources in the physical system that are needed for execution, observation, data transmission and the final end-product (built structure). The elements in the physical layer (Figure 26) can be divided in three categories:

- Observable entities;
- Observers;
- Data transmission components.

Observable entities relate to real world things that can be observed/ tracked but are not able to communicate to virtual space themselves (Josifovska et al., 2019). Observable entities comprise of assets, equipment, personnel, materials and processes. Additionally, the environment in which the other entities exist can also be observed and is thus an observable entity as well. This element differs, however, from the others in the sense that it can only be observed and not controlled. Observers relate to entities that have the ability to observe an observable entity and capture data from this entity. Elements that can be headed under observers in the construction industry comprise, amongst others, of sensors, cameras and (3D) scanners. Strictly speaking it should be noted that a sensor is part of a camera. Though, the distinction is made here based on output, respectively signals/ time series data, footage, and point-clouds. Data collected by the observers can be transferred to virtual space using network equipment as the transmission component where it enters the DT in the Data layer.

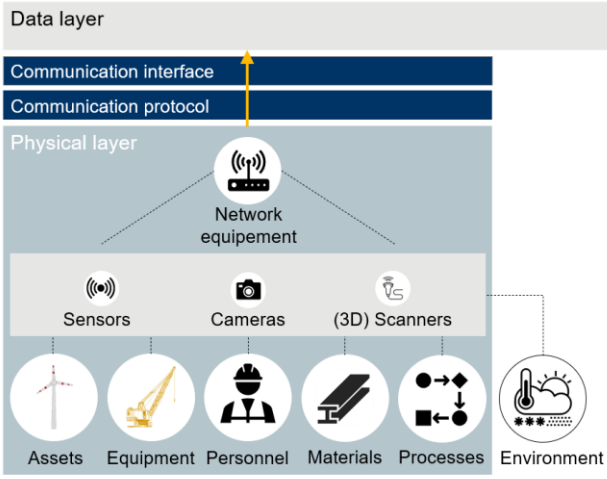


FIGURE 26: PHYSICAL LAYER BUILDING BLOCK

5.3.2 Model layer

The model layer comprises of multiple models that together fully represent the physical system in virtual space. From the types of DTs in section 3.4.3 it follows that a distinction can be made between *Entity DT* and *Scenario DT*. The former relating to the virtual representation of the physical asset itself and the latter to physical processes associated with the physical asset. To reflect the physical system in virtual space, the model layer of the DT is divided in asset models and scenario models as well. Similarly to the physical assets and scenarios, it should be noted that these two types of models are interrelated.

Asset model

The asset model comprises of a collection of models that reflect various aspects of the corresponding physical asset in virtual space. The models that together define the physical asset in virtual space are:

- Geometric model;
- Physics model;
- Behavioural model.

The geometric model defines the physical asset in terms of its shape, embodiment and appearance. A geometric model includes geometric information (e.g. points, lines, surfaces and bodies) and topological information (element relations such as intersection, adjacent, tangent, vertical, and parallel) (Qi et al., 2019). An example of a geometric model is a CAD model, which may take the form of a Revit, Civil3D, Sketchup, or Inventor model in the construction industry. It should be noted that some of these models are database-driven models, which are not restricted to geometry only but include more (building) information. These models provide already an overlap between the model- and data layer of the DT.

The geometric model describes the geometric information of an asset but does not define its features and constraints. Hence, besides a geometric model, the physical asset may be further captured in virtual space using a physics model. These models include information regarding the materials used and their performance (structural, thermal, etc.). Additionally, they may include information concerning accuracy, such as tolerances for different elements (Qi et al., 2019). An example of a physical model that can be integrated in the DT concerns a FEM model (Haag & Anderl, 2018), which may be developed in for example SCIA or RFEM in the construction industry.

The behavioural model captures the behavioural logic of the physical asset or its components. It defines the interaction between system components, state transitions and performance degradation over time. Behavioural modelling may take different forms, such as state modelling and dynamics modelling. State modelling comprises of state diagrams and activity diagrams, the former defines the dynamic behaviour of an element by giving a representation of a sequence of states, the latter describes activities required to complete an operation (Qi et al., 2019). System dynamics modelling builds upon stocks, flows, internal feedback loops, and time delays to reflect the behaviour of a system (Vahdatikhaki, 2019).

Scenario model

The scenario models in the DT reflect physical processes associated with the physical asset in virtual space. The exact models needed to reflect these processes may, however, differ depending on the application. For this research, four generic types of models have been assumed, which were determined taking into account the selected use-cases. Therefore, they may not give a comprehensive overview and additional models may be required for other DT applications. The models in the scenario model are:

- Environment model;
- Equipment model;
- Process model;
- Numerical optimisation model.

The environment model reflects the surrounding environment of the physical asset. This model may be used to simulate scenarios in their actual environment and is therefore mainly important for scenarios in which a truthful representation of reality plays an important role. Environment models can be developed using gaming engines, such as Unity.

The equipment models represent construction resources in virtual space. These models may be related to construction equipment (e.g. excavators) or auxiliary structures (e.g. scaffolding). Depending on the application of the scenario model, the equipment model may be restricted to a geometrical representation only or include behaviour as well. To realise this, the behavioural logic of construction equipment needs to be captured in a model, which can be done using state modelling.

A process model reflects the process steps in the physical scenario in virtual space. This model gives a representation of the activities and resources needed in the physical process. Process maps give a static representation of the process. However, to display the process in a dynamic matter, simulation techniques such as Discrete Event Simulation can be used to simulate the process in virtual space based on activities and resources (Karanjkar et al., 2018).

Numerical optimisation models enable to make a trade-off between different scenarios. Especially in the case of multi-objective optimisation, it can be less straight forward to select the ''optimal'' alternative. Numerical optimisation models, such as MATLAB, can be used to evaluate the simulation outcomes and select the alternative that complies best with the optimisation objectives.

Figure 27 presents the model layer of the DT, with the asset model (left) and scenario model (right).

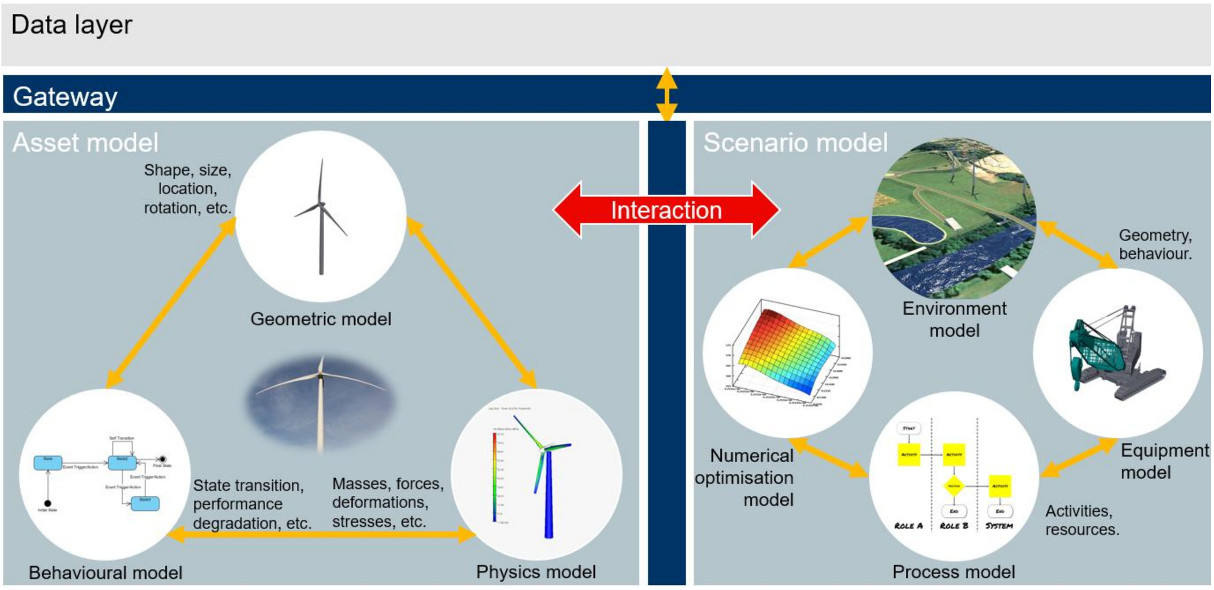


FIGURE 27: MODEL LAYER BUILDING BLOCK

5.3.3 Data layer

The third building block of the DT concerns the data layer, which includes elements responsible for the acquisition, processing, storage and integration of data. DT thereby utilises data science techniques and can be regarded as an information filtering and integration system (Tao, Sui, et al., 2018). The data layer is the central element of the DT (Tao & Zhang, 2017) and forms the connecting element between the Physical layer, Model layer, Service layer and Enterprise layer. To realise this, the data layer (Figure 28) fulfils the following functionalities (Qi et al., 2019):

- Data collection;
- Data transmission;
- Data storage;
- Data processing;
- Data integration/ fusion;
- Data visualisation.

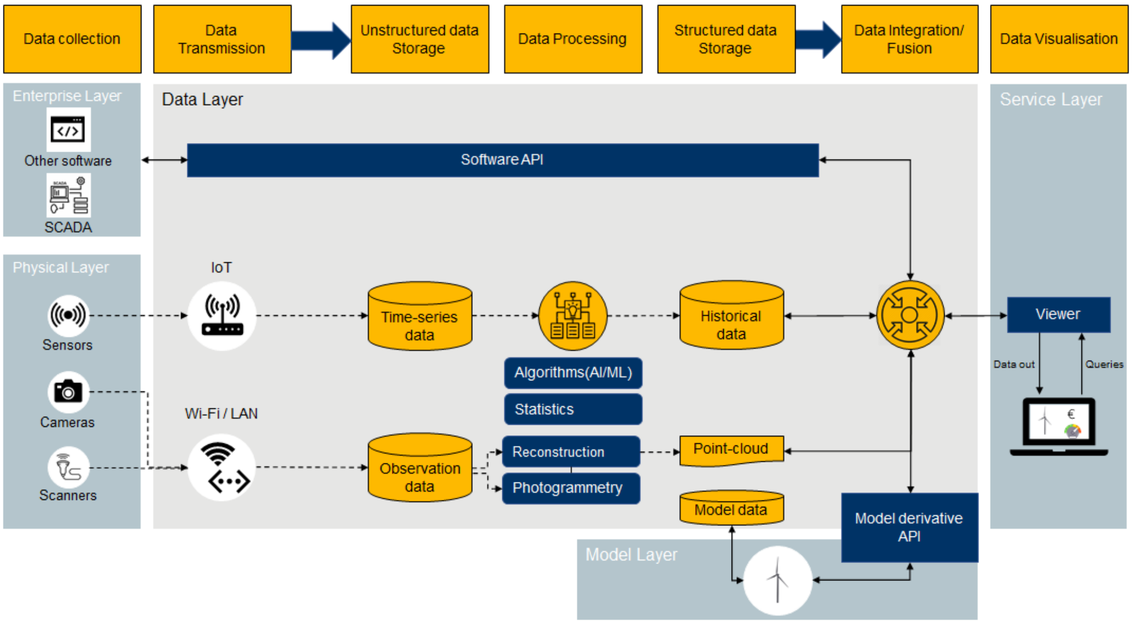


FIGURE 28: DATA LAYER BUILDING BLOCK

DT data is collected from multiple sources, which can be grouped in: Hardware, Software and Network sources (Qi et al., 2019). Hardware sources can be further decomposed in static and dynamic data. Static data describes the properties of observable entities in the physical layer, such as building parts and materials used. In construction, this includes both building information and geo-information, captured in respectively BIM or GIS models. These models, with associated model databases, are located in the model layer of the DT. An Application Programming Interface (API) can be used to provide the interface between these models and the data layer and extract the required information. Following the example of Autodesk Forge, a platform that can be used for DT development, this API is referred as the Model derivative API (Autodesk, 2020). Additionally, static data includes information regarding the placement of sensors and the type of data that is collected by the observers in the physical layer, which is required to process this data. Dynamic data concerns all data that is collected by the observers in the physical layer. This may include data regarding real-time performance, operation condition, material inventory levels, but also environmental conditions such as the ambient temperature (Tao, Cheng, et al., 2018). Dynamic data can for example take the form of sensor signals, footage and point-clouds.

Software concerns data that is retrieved from the Enterprise layer building block. Tao, Cheng, et al. (2018) name this Management data and argue that it includes data from information systems, such as Enterprise Resource Planning systems (ERP) and Supply Chain Management systems (SCM). This data includes order dispatches, production planning and finance. It can be collected using software APIs, which enable the interaction between the data layer and third-party applications. Request/ response is the most well-known pattern for this integration (ABN AMRO, 2018). An application that may be in the Enterprise layer and is noteworthy to elaborate is SCADA. This application may be connected with the DT using an API, but as opposed to the other applications, SCADA includes dynamic signals from the physical entity. Therefore, SCADA actually corresponds more to dynamic data than software data, the difference is however that these signals are already interpreted and processed in a supplier-specific manner in the application. Network data can be collected from the internet based on web crawlers, search engines or public APIs (Qi et al., 2019). This may include for example weather information. Although for some DT applications this type may be relevant, it is not included in Figure 28.

Data transmission techniques can be divided in wired and wireless technologies (Qi et al., 2019). Internet of Things (IoT) is widely used in various sectors for the transmission of sensor signals to a data storage. The data collected by cameras (footage) or scanners (point-clouds) can be transferred to a data storage via Wi-Fi or LAN. Subsequently, the data is stored before it is further processed. The data storage of unprocessed sensor data can take the format of a time-series data for sensor outputs, in which the signals are captured over time.

Data processing is concerned with extracting useful information from the large collection of data that is collected by the observers in the physical layer (Qi et al., 2019). The technology used for data processing depends on the type of data collected. Within this research, three types of data coming from the physical layer are assumed: signals/ time-series data, footage, and point-clouds. Sensor data can be analysed using algorithms, which interpret the data in a logical manner and are based on domain understanding in the form of rules. Alternatively, this data may be analysed using statistical methods that provide insight in the correlation or distribution of the data. With regard to footage and point-clouds, these both give an overview of the as-is situation of the physical entity. Footage can be converted into 3D information (point-cloud) using photogrammetry software. Then, point-cloud models are reconstructed to include surfaces.

Data integration is the process of combining data from different sources into a single, unified view. The concepts of data integration and data fusion are sometimes used in synonym, however, these have a slightly different meaning. Data fusion is the process of integrating multiple data sources to produce more consistent, accurate, and useful information than that provided by an individual data source (Qi et al., 2019). Data integration is thus concerned with the combination of multiple data sources and presenting them in a single view whereas data fusion combines multiple data sources to improve the quality of the data. Both can be used in a DT. Data fusion can be used to combine the data from multiple sensors and thereby improve the accuracy of insights gained based on the data. Data integration is a vital ability of the DT, as it is used to combine the data coming from the enterprise layer via software APIs, models via the Model derivative API and data obtained from the physical layer. Finally, the data is visualised in an appearing manner to present it to the end-user.

5.3.4 Service layer

The fourth DT building block concerns the service layer which presents the specific services that can be offered by a DT to the end-user. From the literature review it follows that the main point to consider with regard to the service layer is whether it only reflects the user interface for DT applications or a more intelligent layer that performs underlying calculations needed for the services. It has been decided that the former is applicable, thus it acts as the user interface for the applications that can be offered by the DT. From the existing frameworks, it is considered that the interaction layer of Zheng and Sivabalan (2020) reflects best the principle of a service layer for this research. The elements in the service layer are:

- Interactive Digital Model/ Dashboards;
- Applications/ Web Portal;
- Devices.

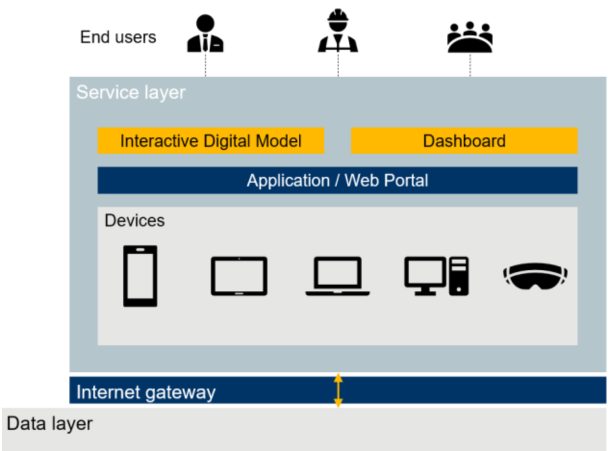


FIGURE 29: SERVICE LAYER BUILDING BLOCK. ADAPTED FROM "A GENERIC TRI-MODEL-BASED . . . SMART MANUFACTURING ENVIRONMENT" BY ZHENG AND SIVABALAN (2020)

From Figure 29 it follows that the interactive digital model and dashboards are the interfaces that present relevant information to the end user. These can be accessed in applications or a web portal and can be displayed on different devices such as mobile phones, tablets, laptops, PCs or VR/ AR glasses.

5.3.5 Connection

The fifth building block of the DT concerns the connection block, which connects the other building blocks to each other. In the reference framework of Figure 25, the main connections between the building blocks and their directions can already be seen. Therefore, this is not further elaborated here. However, an important aspect with regard to the connection building block follows from the classification of DT in this research: the different models, information constructs, and databases are **semantically linked**. Data linking is concerned with determining whether two object descriptions can be linked to each other to represent the fact that they refer to the same real-world object in a given domain or some kind of relation holds between them (Ferrara, Nikolov, & Scharffe, 2011). Semantics relate to making data meaningful and computer interpretable. Here, the use of data structures such as ontologies plays an important role. By making data meaningful and computer interpretable with data structures, the data model of one source can be made accessible with data from another source, which can create a network of linked data structures.

The use of ontologies as an instrument for data structuring is increasingly recognised as important in the recent years in the construction industry. An ontology can contain knowledge about both physical objects and non-physical objects, such as activities and events, with attributes, relationships, quantities, units, etc. In order to realise these data structures, one of the technologies that is often used concerns the W3C Linked Data/Semantic Web technology. Boje et al. (2020) argue that the use of DTs in the construction industry would require a change from prevailing data exchange formats with a static nature, such as IFC, to more open web-based formats such as W3C Linked Data/Semantic Web technology. These allow linking product data models and other relevant information to BIM models. The Semantic Web links facts, instead of connecting a particular document or program, and can instead refer to a specific piece of information contained in the document or program (Ferrara et al., 2011). Semantic web and linked data are seen as beneficial because they facilitate interoperability between large spectrums of application domains involved in the construction sector (Boje et al., 2020).

5.3.6 Enterprise Layer

The final building block of the DT concerns the enterprise layer. This block is indicated as *Manufacturing system software resources* in the framework of Zhang et al. (2019) and includes external software systems that can control the physical entity and are therefore relevant to integrate in the DT services offered by the service layer. For the applications in this research, relevant external software systems to integrate in the DT services are not necessarily control systems but comprise of various enterprise tooling (e.g. project- / operations management software). Therefore, this block is referred as Enterprise layer here. This layer comprises of various external software packages that are used within the organisation that include relevant information regarding an asset or the associated processes. The DT facilitates data exchange with these applications by means of a bi-directional connection between the Data layer and Enterprise layer. Because the activities performed during the asset lifecycle are often of an iterative nature, the connections between the data layer and the systems in the enterprise layer must support bi-directional information exchange (COB, 2020). Changes are made at the source, so in the systems of the enterprise layer, and the bi-directional connection ensures that this information is updated for the DT services.

5.4 Conclusion and outlook

This chapter focused on establishing a reference framework for DTs that can be used as guideline for the development of the functional designs for the two use-cases. A literature review of reference frameworks outlined that there is currently no general accepted architectural template for DTs. Furthermore, the literature study demonstrated that DT reference frameworks are context dependent and influenced by the classification used for DTs. Hence, the classification for DT in this research was taken into account at the selection of a reference framework. This framework was then tailored to the specific circumstances of construction. The developed framework comprises of six building blocks, which are respectively the physical layer, model layer, data layer, connection, service layer and enterprise layer. The elaboration of the different building blocks demonstrated that DT in itself is not a completely new technology. Instead, it relies on the integration of several existing technologies that were previously used as a standalone technique. These include but are not limited to modelling techniques (solid modelling, FEM modelling), simulation techniques (Discrete Event Simulations) and Data science principles (Data analytics). The developed framework serves as backbone for the design of the two use-cases, which is done in the next two chapters.

6 USE-CASE 1: SIMULATION BASED OPTMISATION OF CONSTRUCTION PROCESSES

This chapter is concerned with the development of a functional design for the first use-case: simulation-based optimisation of asphalt paving operations. The functional design has been developed using the design cycle of Wieringa (2014), which consists of three tasks: *problem investigation, treatment design*, and *treatment validation*. The research steps treated in this chapter are schematised in Figure 30.

6.1 Problem investigation

Problem investigation focused on studying the improvement problems associated with the preparation of asphalt paving operations. To gain insight in the problem context, the current preparation process of asphalt paving operations has been captured and improvement problems in this workflow were identified. Subsequently, the main stakeholders were identified and consulted for their goals and needs regarding the functional design. Problem investigation has been performed using a single case study approach, where data has been collected using multiple interviews.

Case project

For the development of the functional design, the case project concerns the A1 Apeldoorn – Azelo (A1AA). This is a large road extension project of more than 40 kilometres where a large proportion of the project scope comprises of asphalt paving operations. The budget of the project is approximately €175m, the contract form is Design and Construct, and the client for the project is Rijkswaterstaat (Heijmans, 2018). Realisation of the project started in 2019 and takes until 2021.

6.1.1 Capturing the current process

In order to capture the current preparation process for asphalt paving operations, an interview was conducted with the person responsible for scheduling the daily productions and arranging the asphalt transport on the case project (work planner). Additionally, another interview was conducted with the asphalt coordinator, whose responsibility is the scheduling of asphalt equipment (pavers and rollers) across all Heijmans projects as well as monitoring the production capacity of the different asphalt plants. The established process map is depicted in Figure 31, a full-scale version is presented in Appendix IV. The process map was validated with the work planner that provided input. In addition, a second interview was conducted with a colleague in the same role to perform another validation. Both interviewees acknowledged that the established process map gives an accurate representation of the current preparation process for asphalt paving operations on the case project.

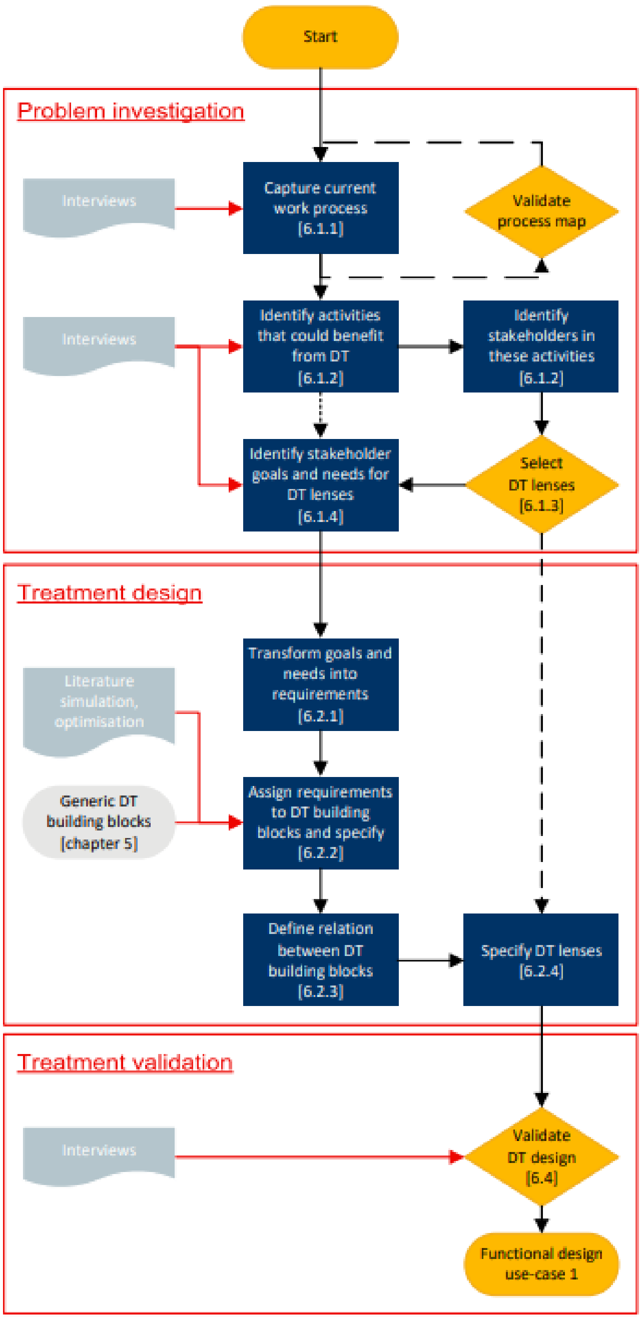


FIGURE 30: RESEARCH STEPS CHAPTER 6

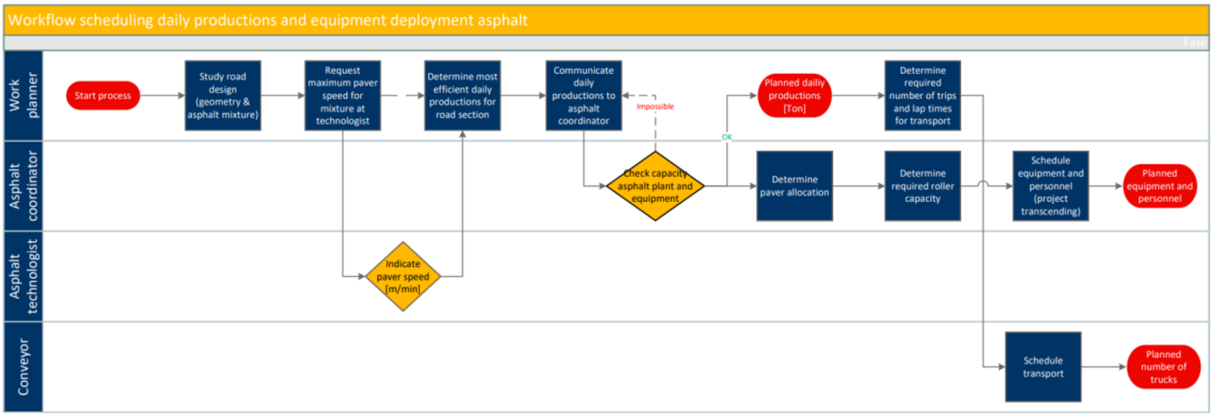


FIGURE 31: CURRENT PROCESS FOR PREPARATION OF ASPHALT WORK

6.1.2 Identification of improvement problems

In order to identify which activities in the process could potentially benefit from a DT, it was asked to the work planners what activities have most impact on the outcomes of the paving process in terms of duration, cost and risk. Additionally, it was asked what activities interviewees thought that could benefit from simulation-based optimisation. This yielded that the activities in the current workflow with improvement problems are:

- Determine most efficient daily productions for a road section;
- Determine required number of trips and lap times for transport.

Besides, it was indicated that determining the required roller capacity could potentially also benefit from simulation-based optimisation, although this has a lower priority. Hence, the focus was on the two activities above. To assess if DTs can support these activities, a deeper understanding of the current practice for these activities was needed. From interviews with the work planners and asphalt coordinator, the following descriptions of the current workflows have been derived:

Determine most efficient daily productions for a road section

Determining the most efficient daily productions is currently done by the work planner based on drawings of the road section. For the case project, road sections usually have a length that requires multiple days of work. Hence, the work planner needs to decide on the planned daily productions. Based on the asphalt mixture, the work planner consults with the asphalt technologist for the advised paver speed. This usually only occurs when there is a new mixture or when the work planner considers deviating from the advised paver speed. The theoretical maximum daily production is calculated by multiplying the advised paver speed times the duration of the workday. This distance is then compared with the length of the road section to see how it can be spread effectively over multiple days. The work planner determines this based on his own interpretation. In this decision, consequences for transportation (costs) are not yet taken into account. As indicated, the main objectives in planning the daily productions are:

- Prevent relocation of the paver as much as possible;
- Reduce production losses as much as possible.

Once the daily productions have been scheduled by the work planner, they are communicated to the asphalt coordinator who checks if these productions are possible on the proposed dates from the perspective of the asphalt plant capacity and equipment availability. The capacity utilisation for both the asphalt plant and equipment are monitored by the asphalt coordinator using spreadsheets.

Determine the required number of trips and lap times for transport

Determining the required number of trips and lap times for asphalt transport is done by the work planner. To determine the required number of trips, the work planner divides the planned daily production by the truck capacity, either manually or in a spreadsheet. Lap times for transportation are calculated by checking the travel distance between the construction site and the asphalt plant in Google maps and divide this by the average truck speed, which is an assumption based on logical reasoning and experience. It was indicated that this calculation speed is always the same regardless of whether paving takes place during the day or night. Based on the required number of trips and the lap times for transport, the work planner decides the number of trucks to be deployed.

6.1.3 Selection of Digital Twin lenses in this use-case

The process map in section 6.1.1 shows that multiple stakeholders are involved in the preparation of asphalt paving operations. All of these stakeholders can have their own lens towards the DT. Besides distinguishing the lenses based on the roles of stakeholders, another distinction can be made between the project-lens and the asphalt plant lens. The project lens focuses on *best for project* and aims to schedule the paving process for one project most efficiently. This lens corresponds mainly with the viewpoint of the work planner. On the contrary, it can be argued that there is also the asphalt plant lens that reflects *best for Heijmans* that aims to optimise the production process across multiple projects. It can be argued that this lens relates to the viewpoint of the asphalt coordinator. In this use-case, **only the project lens was considered.**

6.1.4 Stakeholder goals and needs

Since this use-case focused on the project lens, work planners were considered as the main stakeholders to be consulted for their goals and needs regarding the design. This was done by showing them an example of process simulation to get them acquainted with the concept and subsequently ask what functionalities they consider to be most important. The outcomes of these interviews are as follows:

A DT, when used for simulation-based optimisation of the asphalt paving process should:

1. Provide insight into the idleness of trucks in the process along with where and when it occurs;
2. Provide insight into production losses for the paver during operations;
3. Provide insight into the causes of waiting times or production losses;
4. Offer the possibility to include breaks and waiting times at the asphalt plant caused by trucks from other projects;
5. Be able to respond to sudden changes in equipment allocation to analyse the effects;
6. Enable the identification of improvement areas in the process.

6.2 Treatment design

The second task of the design cycle concerned treatment design, in which the stakeholder goals and needs were transformed into the design of the DT use-case. To do this, stakeholder goals and needs were translated into requirements and each requirement was assigned to one or multiple DT building blocks. Based on the requirements, the content of the DT building blocks was further specified.

6.2.1 Requirements

Requirements can be divided in technical and functional requirements. Since this use-case is concerned with a functional design, only functional requirements were defined. The requirements for the functional design have been defined in Table 10 according to the MoSCoW method, which is often used for defining and prioritising requirements in software development and reflects (Van Vliet, 2008):

- **Must haves** are requirements that are essential for a usable system;
- **Should haves** are requirements that are important for stakeholders, but not absolutely needed for a usable system;
- **Could haves** are requirements that are slightly less important for the stakeholders and should only be implemented if time allows so;
- **Won't haves** are requirements that can be relevant for stakeholders but will be left for a next design iteration and are not included in the functional design of this use-case.

In order to demonstrate how the requirements of Table 10 follow from the stakeholder goals and needs, the (#) behind each requirement refers to the corresponding number of the related stakeholder goal or need, as defined in section 6.1.4.

TABLE 10: FUNCTIONAL REQUIREMENTS USE-CASE 1: SIMULATION BASED OPTIMISATION ASPHALT PAVING OPERATIONS

Must haves	Should haves	Could haves	Won't haves
Simulation ability: simulation model must be able to mimic the behaviour of the actual paving operations over time from a project management (cost,	**Optimisation module:** simulation model should have an optimisation module that can automatically make a trade-off between scenarios (6)	**BIM coupling:** simulation model could have a coupling with BIM to automatically extract work conditions and constraints for the process (6)	**Real-time connection:** simulation model won't have the ability to simulate in real-time with the actual process (respond to dynamic

duration) point of view (1,2,3)			changes in the planned process)
Accurate: simulation model must give a sufficiently accurate representation of the actual process along with its main influential parameters (4)	**Insight in process:** simulation model should provide insight in how the process unfolds (display where waiting times occur etc.) (1,2,3)	**(3D) visualisation:** simulation model could have a coupling with a (3D) model of the environment and equipment involved in the process (1,2,3)	**Weather influences:** simulation model won't be able to simulate the influence of weather conditions on the available time for asphalt processing and compaction
Content: Simulation model must be able to mimic the interaction between asphalt transport and paver capacity (1,2)		**Analyse historical data:** simulation could automatically extract and analyse productivities and activity durations from historical data (6)	**Self-learning ability:** simulation model won't have self-learning ability by comparing simulation output with the outcome of the actual process and updating the model
Customisable: simulation model must be easily customisable for project specific circumstances (4,5)		**Optimise daily productions:** simulation could automatically optimise the scheduling of daily productions (multi-day simulation) (6)	**Multi-project:** simulation model won't be able to simulate the interaction between multiple projects that use the same asphalt plant

In order to justify that these requirements, if implemented in the design, would contribute to stakeholder goals and needs, a contribution argument was given for each requirement (Wieringa, 2014). Won't haves' requirements have not been incorporated in the design, and thus no contribution argument was given for them. The contribution arguments are presented in Table 11.

TABLE 11: CONTRIBUTION ARGUMENTS USE-CASE 1

Requirement	Goal	Contribution argument	P	M	D	E
Simulation ability	1,2,3	The model must be able to simulate the process, thus mimic the behaviour of the actual process over time to gain insight in waiting times and production losses that occur as a result of disbalance between asphalt production, transport and processing		X		
Accurate	4	The simulation model should include at least include the major influential parameters that affect activity durations and costs associated with the operations to give an accurate representation of the process that can be used as basis for decision making		X		
Content	1,2	The ability to mimic the interaction between paver capacity and trucks is essential to gain insight in overall waiting times and production losses during the process	X	X		
Customisable	4,5	Although the paving process itself is quite uniform, the circumstances differ per production and the simulation model should thus be easily customisable without the need of simulation expert knowledge		X		
Optimisation module	6	By coupling the simulation model with an optimisation module, the model can be used to evaluate scenarios and automatically select the optimal alternative within a range of possible options (e.g. number of trucks) based on a predefined optimisation objective (e.g. minimise costs)		X		X
Insight in process	1,2,3	The simulation model must be able to mimic the operations in the actual process over time to provide insight in where		X		

		and when idleness and production losses occur, and what are the factors that cause them				
BIM coupling	6	BIM models can provide a rich information source of project related information that form the conditions within which the process takes place, automatically coupling them with the simulation model could reduce the required manual input for simulation		X		
(3D) visualisation	1,2,3	Visualisations help to gain a better understanding of the situation and will therefore lead to better insight in respectively truck idleness, paver production losses, and the causes for them		X		
Analyse historical data	6	By integrating the ability to analyse historical process data automatically, simulation model can become more representative and indicate better improvement opportunities			X	
Optimise daily productions	6	By also including the ability to simulate multiple productions in one simulation, the process can be further optimised		X		X

6.2.2 Digital Twin building blocks in this use-case

The reference framework of DT building blocks, as introduced in chapter 5, provides the baseline for the functional design. Each functional requirement is assigned to one or multiple DT building blocks in Table 11, where P=Physical layer, M=Model layer, D=Data layer and E=Enterprise layer. The Connection and Service layer building block are not displayed in this table because they do not facilitate the content for a DT application, but rather the connection between the other building blocks and the user interface. Section 6.2.3 devotes attention to the connection between the building blocks and in section 6.2.4 the designed DT lens is presented as Service layer.

PHYSICAL LAYER

In this use-case, the DT represents a process (asphalt paving operations) related to a physical asset (road) during the BOL phase. Therefore, the DT reflects the to-be reality for a physical process that is not performed yet at the time when this DT application is used. Although the physical asset, or at least the road section concerned, is not realised yet, there are still elements in the physical layer. This concerns the equipment to be used (e.g. pavers), which can be tracked during other paving operations to collect process data and thereby provide input for simulation. Additionally, the environment in which the process takes place can be observed to collect information that could affect the process. To comply with the *Content* requirement, the equipment in the physical layer should comprise of trucks and pavers.

MODEL LAYER

From chapter 5 it follows that the model layer consists of the asset model and scenario model(s), which reflect respectively the physical asset and scenarios (processes) in virtual space. Since this use-case is concerned with simulation-based optimisation of the asphalt paving process, mainly the scenario model is relevant. However, the asset model is also important because it poses conditions for the process by specifying what should be constructed (road design). Hence, both models interact in this use-case.

Asset model

For this use-case, the asset model virtually represents the road section that will be paved. From the three types of asset sub-models introduced in chapter 5, only the geometric model is relevant here. From this model information can be derived regarding the shape of the road section, its dimensions, the type of asphalt mixture, and whether it concerns a base, binder or surface layer. The dimensions of the road section determine the required supply of asphalt while the shape of the road section can affect the productivity and impose limits on the maximum equipment deployment. The type of asphalt mixture is important because it affects the advised paver speed. This information is currently often captured in 2D drawings that are used by the work planner to schedule the process. To enable the automatic extraction of this information as input for simulation based optimisation, it should be modelled in a 3D (BIM) environment consisting of geometrically closed objects that correspond with the road section that will be paved and labelled with the associated SBS coding to make the information traceable. Doing this enables to comply with the *BIM coupling* requirement.

Scenario model

Besides providing a virtual representation of the asset, the model layer of the DT also includes scenario models that reflect the asphalt paving operation in virtual space. From chapter 5 it follows that the scenario model consist of a few sub-models, such as the process model, numerical optimisation model, environment model, and equipment model. For simulation-based optimisation, each of these models is relevant and discussed separately:

Process model

The process model is the central model that drives the simulation in this use-case. A simulation model provides an imitation of the behaviour of a real-world process or system over time (Banks, Carson II, Nelson, & Nicol, 2005). This can be achieved using several techniques, meaning that a decision should be made regarding the type of simulation to be used. Depending on the nature of the construction process and the objective of the simulation, three modelling techniques are common in the construction industry for process simulations (Vahdatikhaki, 2019):

- Discrete Event Simulation (DES);
- System Dynamics (SD);
- Agent Based Simulation (ABS).

DES models a process as a series of discrete events, which means that entities in the process are moving between different system states as time passes (Maidstone, 2012). Typically, DES includes a network of queues and servers, where entities wait in a queue to be served. This approach enables to identify areas in the process where problems may occur (i.e. entities queuing up for a service or idleness of service providing resources). DES can thereby be used to discover whether it would be advisable to add more server capacity or change the layout of the system (Maidstone, 2012).

SD is driven by a casual chain and considers the system from a higher level of abstraction than DES. Therefore, SD is mainly used for strategic management at the level of portfolio (Vahdatikhaki, 2019). SD is built upon stocks, flows and feedback loops and ignores the fine details of a system, such as individual events (Maidstone, 2012). It provides an overall representation of a complex system using a top-down approach (i.e. modelling a system by defining its major components and component interactions) (Macal, 2010). SD models are mainly suitable for systems that naturally include flows (e.g. water pipes) or when looking at large and complex systems at an abstract level (Maidstone, 2012).

ABS is driven by the behaviour of individual agents and is used for situations when actors need to interact in complex scenarios (Vahdatikhaki, 2019). ABS models a system as being made up of autonomous (self-directed) agents, whose behaviour is based on a series of predefined rules to achieve their objectives while they interact with each other and their environment (Maidstone, 2012). As opposed to SD, ABS relies on a bottom-up approach (i.e. modelling a system by defining individual entities that form the system and their interactions) (Macal, 2010). ABS models are therefore suitable to simulate ''emergent behaviour''. That is, the system behaviour that arises as a result of the interaction of individual entities with their environment, which is relevant for applications such as emergency scenarios.

Figure 32 schematises the three simulation techniques, where the DES takes the form of a flowchart with different (time-consuming) services. SD is based on stock, flows and feedback loops and SD is made up of self-directed agents whose rules are defined in a state chart.

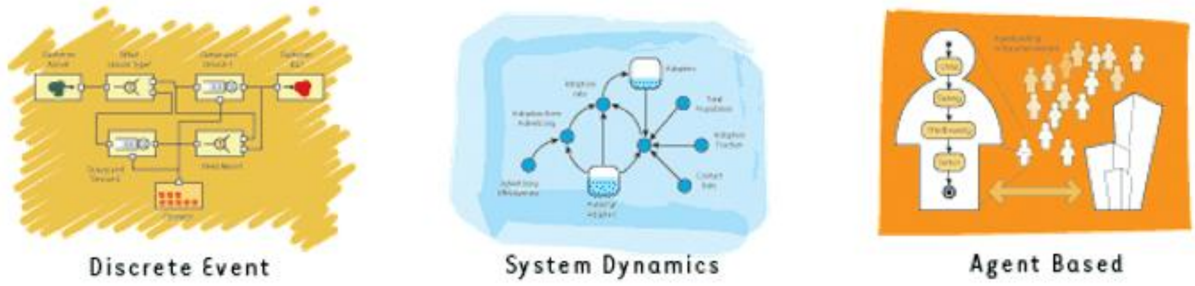


FIGURE 32: THREE TYPES OF SIMULATION MODELS. ADAPTED FROM '' DOMINATING SIMULATION MODELING METHODS'' BY FOCUS GROUP (N.D.)

To select the most suitable form of simulation, the characteristics of the three techniques were compared with the requirements. The *Insight in process* requirement provided guidance for this decision by stating that the simulation should provide insight in where and when idleness and production losses would occur in the process. Consequently, SD is unsuitable because it only gives insight in the whole process and not specific parts of it. Both, DES and ABS can provide more insight in the process on the level of the individual elements. However, DES particularly lends itself for systems which naturally involve queues (Maidstone, 2012), such as the current process where asphalt is waiting in an imaginary queue for different services (e.g. transportation, paving) that require resources (truck, paver) to perform. Hence, DES is considered to be the most suitable simulation technique for the asphalt paving process.

DES comprises of two main components:

- **Activities**, which are time-consuming tasks/operations (e.g. loading, hauling, paving etc.);
- **Resources**, which are components that initiate, derive, operate or eventuate from activities (e.g. trucks, pavers, asphalt, etc.).

In order to demonstrate how DES could be used in this use-case, the Graphical User Interface (GUI) for a simple DES model is depicted in Figure 33, a full scale version along with explanatory notes on the process and its components is included in Appendix V. It should be noted that this is a simplified representation where only the main activities in the process, such as loading, transporting, unloading and paving are included. The model lacks the main influential parameters that affect the outcomes of the process. Furthermore, this figure provides only a representation of the GUI of the main components in the model, the underlying logic (i.e. coding of the elements) that drives the simulation is not included. This example is based on STROBOSCOPE software, which is built upon Microsoft Visio. In other commercial software it would look different, as their exist many generic templated simulation modules in commercial software (e.g. Simulink, AnyLogic). Though, the essence of each DES model is similar.

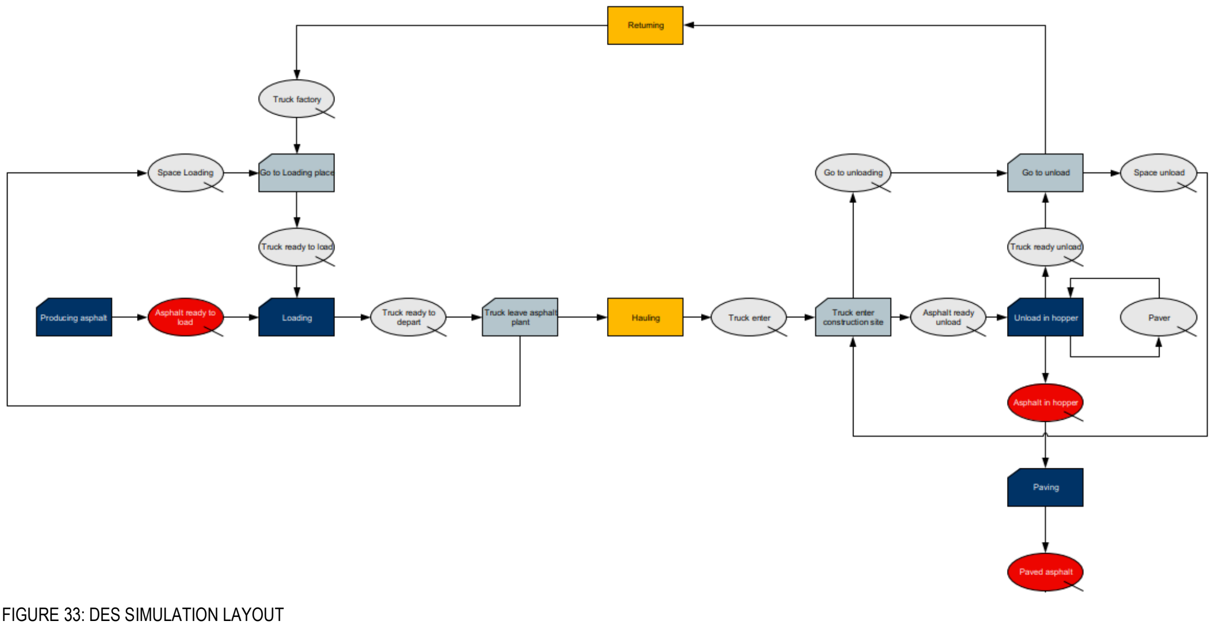


FIGURE 33: DES SIMULATION LAYOUT

Numerical optimisation model

Besides process simulation, optimisation is the other key focus of this use-case. Optimisation is concerned with selecting the best option within a number of possible alternatives (Arkadov, Getman, & Rodionov, 2012). In general, optimisation problems take the following form:

$$maximise \; / \; minimise \quad f(x), \qquad x = (x_1, x_2, \dots, x_n)$$

Here, $x = (x_1, x_2, \dots, x_n)$ are the decision variables and $f(x)$ is the objective function. The space formed by the decision variables is the search space, and reflects all possible combinations of input variables (Yang, 2008). Decision variables are usually subject to human control and optimisation seeks to find the set of decision variables that yield the minimum or maximum output value of the objective function, depending on the objective of the optimisation problem. When the objective function takes a simple mathematical form, optimisation problems can be solved using differential equations, since $f'(x) = 0$ yields the (local) maximum or minimum. However, for most real-life situations the form of $f(x)$ is not known and optimisation cannot be based on differential equations. These are situations where simulation-based optimisation provides an opportunity.

In simulation based optimisation, the objective function for a real-life situation is reflected by a simulation model that returns an output value for the inserted decision variables of the system being simulated (Alrabghi & Tiwari, 2015). To conduct simulation-based optimisation, an optimisation engine (numerical optimisation model in the DT building blocks) can be used to automatically select the decision variables for the simulation. Based on the optimisation strategy used, the optimisation engine selects the decision variables that are evaluated in the simulation model. Because the search space of an optimisation problem can be very large, and running simulations can be computationally intensive, optimisation strategies provide a means to deal with situations where not all combinations of decision variables can be evaluated. Depending on the paving operation simulated, this may also apply for the current use-case, as the following example of decision variables: #Trucks [20-30], #Pavers [1-3], would already give 10x3=30 alternatives to be simulated.

After the optimisation engine selects the decision variables based on the optimisation strategy, the simulation model runs the simulation for these variables and returns the outcome to the optimisation engine. This process continues iteratively between the simulation model and optimisation engine until it results in a satisfactory solution, all alternatives are evaluated, or the simulation is terminated (Alrabghi & Tiwari, 2015). Figure 34 gives a schematic representation of the interaction between the optimisation engine (numerical optimisation model) and the simulation model (process model). This interaction is essential to include in a DT to enable the automatic evaluation of alternatives and select the optimal alternative and thereby comply with the *Optimisation module* and *Optimise daily productions* requirement.

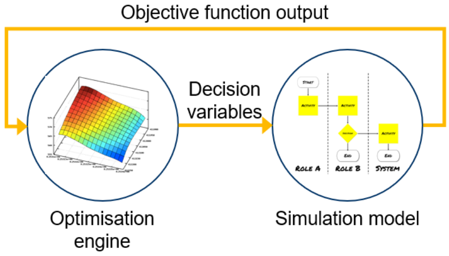


FIGURE 34: INTERACTION BETWEEN SIMULATION MODEL AND OPTIMISATION ENGINE

Equipment & Environment model
Besides the process and numerical optimisation model, other relevant models for this use-case comprise of the equipment and environment model, which give a virtual representation of the equipment used in the process and the environment in which the process takes place. Integrating these models in the DT satisfies the desire for visualisation of the process, defined in the *(3D) Visualisation* requirement. This should help work planners in gaining a better understanding of the process and provide insight in where and when problems could occur (e.g. where a queue of waiting trucks would arise). For this purpose, a simple 2D geometric model of the different types of equipment is considered sufficient. Similarly, a top view in the form of a GIS map is considered sufficient for the Environment model.

DATA LAYER

The data layer is responsible for data acquisition, processing and integration. For the data collection, a distinction can be made between hardware and software data. Hardware data consists of static and dynamic data. Static data comprises information on the to-be constructed road section and the layout of the process. The former follows from the asset model (BIM), as already discussed in the model layer section. Data regarding the layout of the process includes the location of the asphalt plant, length of the transport route, and location and layout of the construction site. The location of the project and the location of the building gates follow from the BIM model, assuming that the phasing / construction logistics is also covered in the model. Information on the asphalt plant used is captured in spreadsheets. The Distance between the project and asphalt plant can be determined using GIS software.

Dynamic data for this use-case concerns historical process data, which is captured from the physical process during previous paving operations. This data can be used as input for activity durations and productivity rates in the simulation. At Heijmans Infra, registration data regarding the asphalt paving process is available as part of the program ''Geboortekaartje asfalt''. Among others, this data includes time records for transport and the captured paver speed during the paving operations, which may provide valuable input for simulation.

For this use-case, data that to be captured from applications in the Enterprise layer (i.e. software data) concerns cost statistics (e.g. unit prices for trucks and paver deployment), which are captured in SAP and spreadsheets. Although this type of data is not essential for the simulation itself, it is needed to enable the trade-off between different scenarios and optimisation from a cost effectiveness perspective and thus to comply with the *Optimisation module* and *Optimise daily production* requirements.

Data processing is concerned with extracting useful information from a collection of (raw) data. This step is particularly relevant for the ''Geboortekaartje asfalt'' data, which can be aggregated and analysed for patterns. This can be performed as a standalone activity, where the results can be used to manually modify the simulation model. However, to comply with the *Analyse historical data* requirement, this step is ought to be performed automatically in the DT. Considering the registrations for the trucks, this data set can be analysed to capture the relation between travel distance and travel times along with the uncertainty involved, which can be expressed as a probability distribution. This probability distribution can then be used in subsequent simulations as input for the duration of the activity *transportation*. The use of probability functions for activity durations allows to design the simulation as a stochastic model. As opposed to a deterministic model in which input X always leads to output Y, stochastic model parameters are defined by random variables or distributions, which means that the model generates different outputs for the same input variable during different simulation runs and thereby reflects a more realistic representation of the real-life process (Renard, Alcolea, & Gingsbourger, 2013).

To verify whether the ''Geboortekaartje asfalt'' data can potentially be used as input for a simulation, a small data analysis has been conducted as part of this research. The full details of this analysis are included in Appendix VI. The data set comprised of the registrations of the pavers and trucks. By aligning the registration data of the pavers with data from the trucks, it was shown that it seems plausible to assume that the data is relatively reliable, although some errors were found in the data set. In particular the truck registrations seem a promising source of simulation input by converting them in a kilometre/time distribution. However, if one really intends to use this data as input for simulations, the transport registrations also need to record the departure time at the asphalt plant and the arrival time on the project. The current registration tooling offers this possibility, but in practice usually only the weighing time at the asphalt plant and the unloading time on the project are registered, which does not properly reflect the actual transport time and thus limits the applicability of the registrations for simulation input.

ENTERPRISE LAYER

The enterprise layer includes external software systems that comprise information regarding an asset or associated processes. For this use-case, data that should be extracted from the enterprise layer comprises of cost statistics and resource availability. Both are currently captured in spreadsheets maintained by the asphalt coordinator.

6.2.3 Relation between Digital Twin building blocks

This section discusses the relation between the different DT building blocks of this use-case. Although the simulation itself takes place in the process model component, this use-case includes connections with other DT building blocks as well. **In fact, if only the process model was considered, with DES being an existing technology, its separate use would not entitle the designation DT.** Neither would this be the case if the process model would only be coupled with an optimisation engine. Rather, it is the integration of various (external) data sources into the simulation model that makes this use-case a DT. The ultimate vision relates thereby to a situation where the simulation model for asphalt paving operations can automatically update based upon data inputs, either provided by the user or based on data captured in other software systems. This vision relates to the field of data-driven simulation, which is seen as supportive for Industry 4.0 initiatives and realising DTs (Goodall, Sharpe, & West, 2019).

Data-driven simulation

As a response to frequently mentioned claims regarding the use of conventional, standalone, simulation models, such as the required expert knowledge to implement adjustments in the model, data-driven simulation has been proposed as a technique that can update and automatically modify simulation models to reflect changes in the real world or planned system (Goodall et al., 2019). By parametrising the simulation model, changes in the physical process can be reflected without the need of hard-coding changes in the simulation model. This makes simulation a more accessible and suitable approach for day to day operations in frequently changing environments, such as flexible manufacturing (Goodall et al., 2019). Flexible manufacturing can to a certain extent be compared with asphalt paving operations, both use standardised machinery to produce frequently changing outputs. Therefore, it is considered that data-driven simulation may be beneficial for asphalt paving operations as well.

Goodall et al. (2019) developed a data-driven simulation for modelling the complexities of remanufacturing operations using a DES approach. Given the overlap in both the nature of the process (flexible) and the type of simulation used (DES), their study was used as guidance for arranging the DT building blocks. Translating their outcomes to the context of asphalt paving operations, the assumed relation between the DT building blocks in this use-case is schematised in Figure 35.

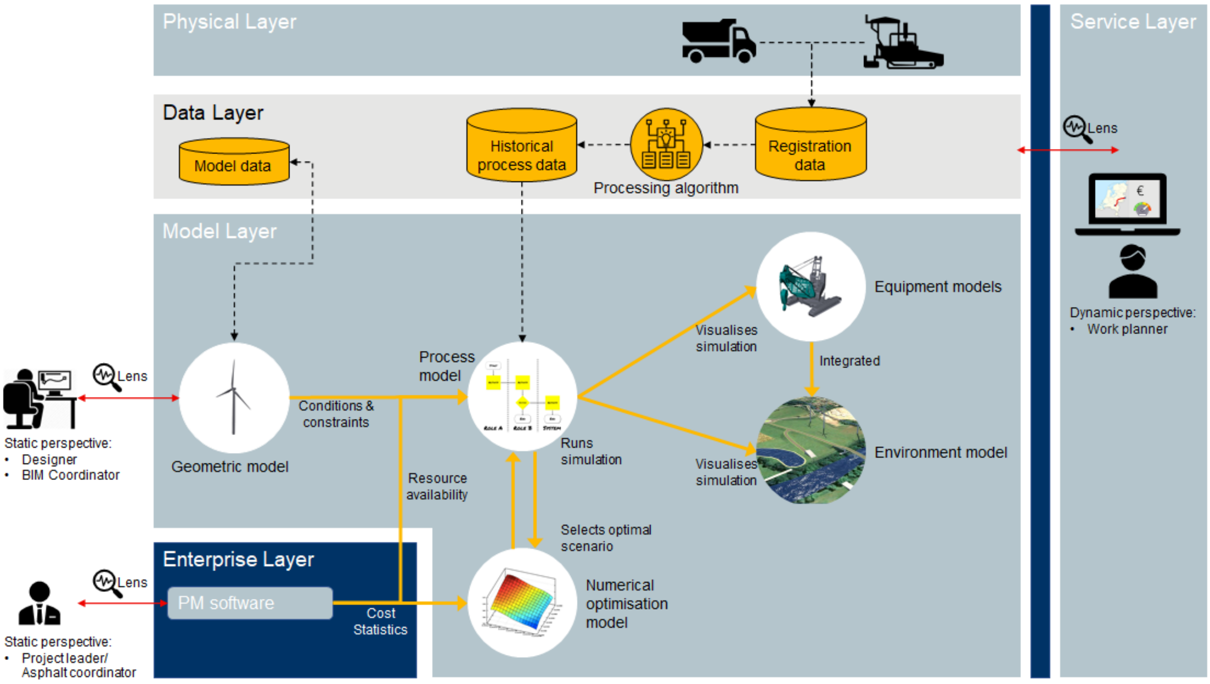


FIGURE 35: RELATION BETWEEN DIGITAL TWIN BUILDING BLOCKS FOR SIMULATION BASED OPTIMISATION OF ASPHALT PAVING OPERATIONS

In order to facilitate data-driven simulation, the process model should be completely parameterised, enabling data inputs to adjust the model and run simulations without the need for programming on the simulation model itself. Multiple degrees of parametrisation can be used. In a simple form, historical process data, captured in the data layer of the DT, can be automatically integrated in the process model, as depicted in Figure 35. In the data layer the collected measurements from the equipment in the physical layer are processed using data fitting algorithms into usable information, which forms input for the simulation activities. This approach enables to rely on dynamic data inputs for activity durations and productivity rates instead of relying on manually entered assumptions for these numbers. However, by only connecting historical process data to the simulation model, the layout of the simulation remains rigid and does not offer the possibility to reflect adjustments to the process components based on data inputs. Automated model generation, which automatically reconfigures the simulation components to reflect real world changes, is therefore seen as more supportive for data-driven simulation of asphalt paving operations. Using this type of data-driven simulation, the activities in the process can be adjusted based on data inputs from, for example, CAD models (Goodall et al., 2019).

Following the overall structure of Goodall et al. (2019) and translating it to construction, the realisation of automated model generation for asphalt paving operations requires three main types of input data:

- Information concerning the road section;
- Resource availability;
- Process information.

Information regarding the road section provides the conditions and constraints within which the process unfolds and specifies the desired end-product. This information includes the shape and dimensions of the road section as well as information regarding the asphalt mixture and construction site layout. It is extracted from the geometric (BIM) model using a coupling between the process model and the geometric model. Information regarding resource availability is extracted from the Enterprise layer, where currently the resource utilisation is tracked in spreadsheets. Finally, information regarding the process is captured in the process model and describes the relation between specific activities and their required resources. This component should be regarded as a library of generic activities that can prevail in the asphalt paving process. Based on other data inputs, the applicable activities in the process are selected and arranged in the right sequence to reflect the physical process.

Once the simulation is reconfigured based on the data inputs and properly reflects the layout of the physical paving operation to be simulated, optimisation of the equipment deployment can be performed. To do this a bi-directional connection between an optimisation engine (numerical optimisation model) and the process model is needed to evaluate different alternatives and select the optimal configuration. To enable the trade-off between alternatives on cost effectiveness, data regarding cost statistics is required in the numerical optimisation model. This data is queried from the spreadsheets in the Enterprise layer. Hence, there should be a connection between the Enterprise layer and numerical optimisation model. Furthermore, to better understand how the process unfolds, the process model is coupled with visualisations of the environment and the resources used the process, which are located in the environment model and equipment model. This allows the flat representation of a DES model, as shown in Figure 33, to be converted into a more dynamic visualisation, which also enables to better validate the model outcomes because errors are more likely to stand out in a visual representation.

Besides the connections between the DT building blocks, Figure 35 also specifies several lenses in this use-case. A distinction can be made between lenses that reflect an actual DT application and lenses to specific specialist software that provide an input source for the DT (e.g. the designer that uses Civil 3D). In this use-case, there is only one lens assumed that reflects and actual DT application, which is the perspective of the work planner. This lens is elaborated in section 6.2.4. However, the building blocks that enable this DT application need to be filled with information by certain stakeholders, who have their own lens towards information that forms the DT. This includes for example:

- The lens of the designer to the road design
- The lens of the work planner to the project phasing
- The lens of the project manager/ coordinator to financial project performance
- The lens of the asphalt coordinator to the resource availability schedule
- The lens of the data scientist to the data processing algorithms

This demonstrates that the development of a DT requires information from multiple sources and many stakeholders. All these stakeholders contribute information and domain knowledge to the DT regarding their own specialisation. That is, the road designer contributes domain knowledge regarding the guidelines that apply for road design, thereby meeting the requirements set with regard to road safety. When creating a DT, stakeholders would still perform their work in specialist software. The DT is thus not a replacement for these software applications. However, the information constructs that are now often still scattered and located in individual silos are linked using semantic technologies.

6.2.4 Specifying the Digital Twin lenses

To complete the functional design for simulation-based optimisation of the asphalt paving process, this section presents the DT lens for the work planners. This is done by presenting three alternative designs based on the requirement prioritisation of section 6.2.1 , respectively alternative "must haves", "should haves" and "could haves". These alternatives demonstrate that the use of simulations for process optimisation can be developed as a modular concept that does not require all functionalities immediately.

The first alternative considers only the must haves' requirements. This result in a standalone DES model that does not offer the possibility of automated simulation-based optimisation. The simulation model can still be used for optimisation, though, this should then be done manually by running a few simulations and select the best alternative based on simulation outcomes. This alternative provides a standardised reusable layout of the process that needs to be manually filled with project specific conditions, such as the geometry of the road section and the travel times and productivity rates for the different activities. In terms of the DT building blocks this, this application is fully concentrated around the process model and has no automated integration with other building blocks. Therefore, this design does not represent a DT yet. The functional design for this alternative is depicted in Figure 36.

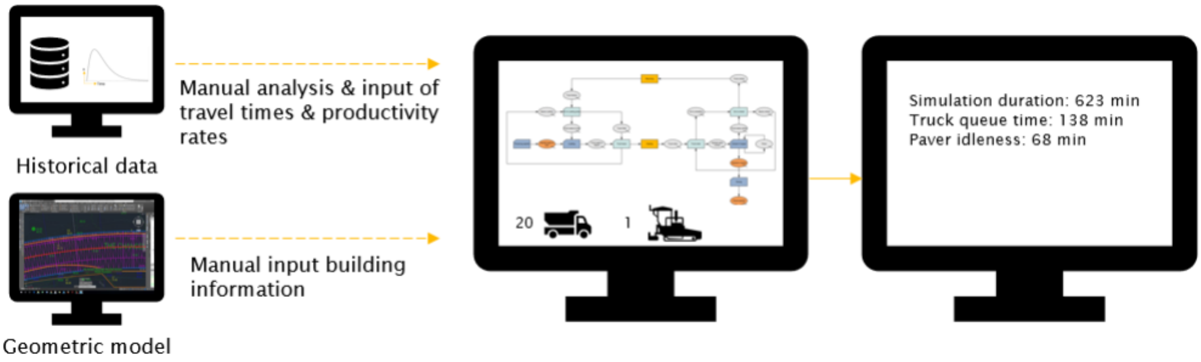


FIGURE 36: FUNCTIONAL DESIGN BASED ON "MUST HAVES"

The second alternative builds further upon the first one and includes the should haves' requirements as well, meaning that the possibility of simulation-based optimisation is included. This requires an automated bi-directional connection between the numerical optimisation model (optimisation engine) and the simulation model. The input of road section specific information as well as travel times and productivity rates for the simulation remains a manual task. Also equipping the numerical optimisation model with cost statistics is a manual task in this alternative. Therefore, there is no automatic data exchange between the Enterprise layer and the numerical optimisation model. Similarly to the first alternative, this design cannot be seen as a true DT yet. The functional design for this alternative is depicted in Figure 37.

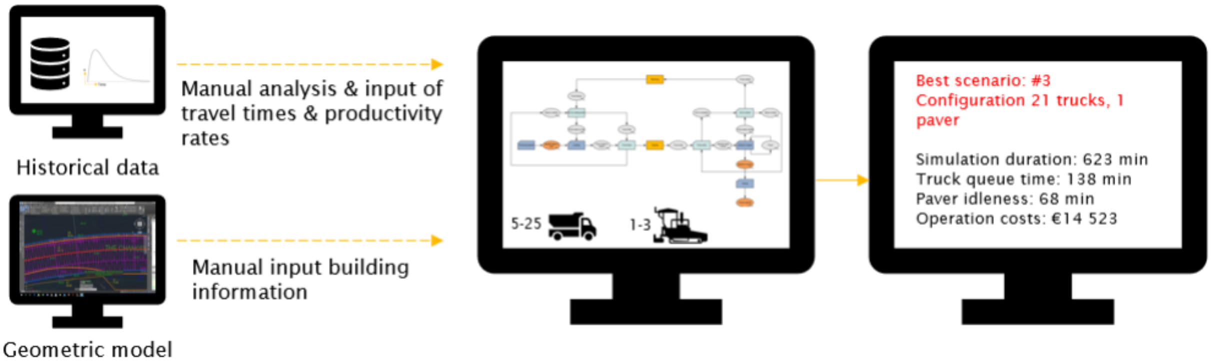


FIGURE 37: FUNCTIONAL DESIGN BASED ON "SHOULD HAVES"

The third alternative includes the Could haves' requirements as well. This means that the simulation model has an automated coupling with the geometric (BIM) model, which provides the required data regarding the layout of the road section and asphalt mixture. Additionally, an automatic connection with the historical process data from the paver and transport registrations in the data layer is present, which ensures automatic provision of transport times and productivity rates. Also, a visualisation option is included to make the simulation more understandable. In terms of the DT building blocks, this alternative utilises all connections depicted in Figure 35 and can therefore be classified as an actual DT that relies on data-driven simulation. The design for this alternative is depicted in Figure 38.

FIGURE 38: FUNCTIONAL DESIGN BASED ON "COULD HAVES"

Operational concept

Although developing an operational DT is beyond the scope of this research, a first attempt for a standalone DES simulation model was made. The reason for doing this was that it is considered to be helpful for the validation of the functional design, because prospective end-users can get a better impression of how a simulation could offer added value from a working concept. The simulation model was developed in AnyLogic software and uses the integrated GIS functionality. Figure 39 shows the developed model. The three boxes on the bottom of the figure demonstrate that DES models can insight in resource utilisation and supports stochastic modelling (different travel times). It should be noted that this model is still a simplified representation of the real process. Nevertheless, it demonstrated that the combination between a GIS map and simple visualisation of trucks, which move and stick to the route, enable to gain insight into how the process unfolds and make simulation thereby more understandable.

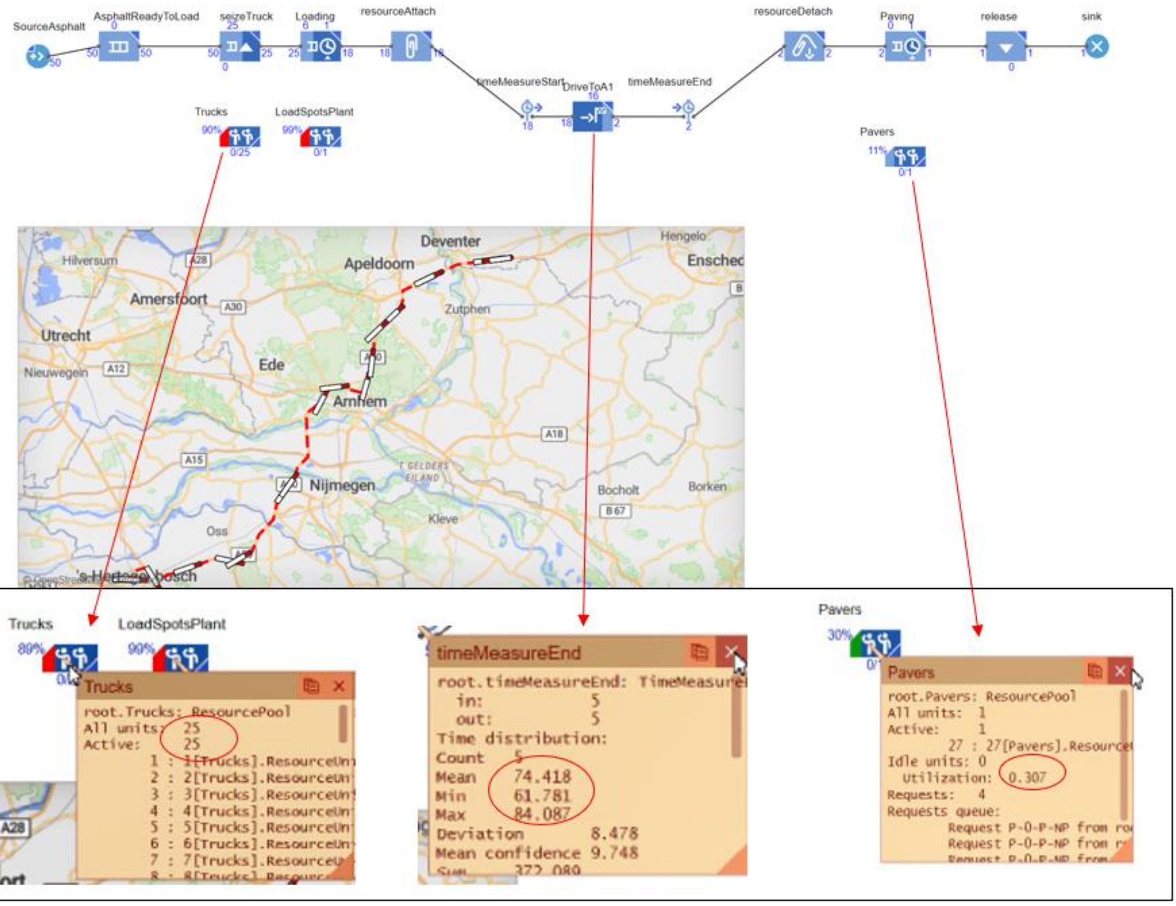


FIGURE 39: WORKING CONCEPT DES SIMULATION MODEL

6.3 Preconditions for Digital Twin application

Besides developing the functional design for this use-case, attention was devoted to the preconditions that apply to realise this DT application. These preconditions mainly relate to the collection process of historical process data and the metadata that should be attached to the different building blocks.

With regard to the collection of process data, it should be noted that durations can vary considerably for construction activities. Many data distribution fitting techniques assume that the collected data is (1) independent (i.e. data points are not interrelated) and (2) identically distributed (i.e. they are subject to the same distribution) (J. C. Martinez, 2010). However, this does not hold true for many construction activities due to fluctuating contextual factors. That is, the time it takes for a truck to transport asphalt along a route on a rainy winter day may differ significantly from the time it takes on a sunny day in the summer. (J. C. Martinez, 2010). Therefore, aggregating and analysing all collected transport data indiscriminately can result in a distribution that does not properly align with the process under consideration and using this distribution can yield invalid simulation outcomes. Therefore, when converting observation data in a probability distribution, the uncertainties in the data set need to be expressed as a function of other variables. For the truck hauling asphalt, this may require to model the duration of the transport activity as a function of the (expected) weather conditions (i.e. use a separate distribution for sunny and rainy weather) (J. C. Martinez, 2010). This in turn poses conditions on the data collection and means that besides capturing the activity durations, also contextual factors need to be captured for factors that significantly influence the activity duration or productivity rate.

Besides collecting historical process data, preconditions for this use-case relate to the metadata that needs to be attached to the building blocks to link them. In general, information must be stored in a structured manner to enable the integration of different data sources / applications. This requires interoperability between the different building blocks, which can according to Damjanovic-Behrendt and Behrendt (2019) be divided in semantic interoperability (decoding the meaning of data) and structural interoperability (decoding the organisation of data). Both should be ensured to integrate the different sources. At Heijmans Infra the IPB structure is used, which provides valuable input for semantic interoperability. The IPB comprises of seven interrelated structures:

- System Breakdown Structure (SBS);
- Work Breakdown Structure (WBS);
- Functional Breakdown Structure (FBS);
- Object Type Library (OTL);
- Locations;
- Activity Type Library (ATL);
- Project phases.

Where possible, the different building blocks should be equipped with IPB structure tags as metadata to establish semantic interoperability between them.

6.4 Treatment validation

The final step of the design cycle is treatment validation and is concerned with justifying that the design, if implemented in the problem context, would contribute to stakeholder goals and needs (Wieringa, 2014). This has been done based on expert opinion, where the design solution was presented to a panel of experts who imagined the interaction of the designed DT with the problem context. Based on this they made a prediction regarding the expected effects. Expert opinion for this use-case was performed with two work planners of the case project and served two main goals:

- Validating the completeness and prioritisation of the requirements
- Validating the developed functional design.

With regard to the requirements, the experts indicated that it appeared to them as a complete set of requirements (from a functional perspective) and could not formulate missing requirements. However, a change in prioritisation was proposed as they indicated that the requirement *Multi-project,* which is currently headed under the Won't haves, is more important. They argued that leaving this aspect out of the design can result in a conflict with the Must have requirement *Accurate,* which relates to the accurateness of the simulation. They elaborate this as follows: if the model is unable to simulate the arrival of trucks from other projects at the asphalt plant, a realistic representation of the process cannot be created. In practice it regularly occurs that the balance between production, transport and processing is disturbed due to waiting trucks at the asphalt plant because trucks from other projects have to be loaded first. Hence, on days when the asphalt plant is used simultaneously by multiple projects, a realistic representation requires the interaction with other projects in the simulation. This aspect is not taken into account in the current design and should be considered when implementing this use-case.

With regard to the validation of the functional design, the session mainly focused on how work planners would like to use this DT application (user-story) and whether the current design solution supports that.

User-story 1:
As a work planner, I would like to gain insight in the interaction with other projects. In particular the asphalt plant in den Bosch produces a lot for third parties. It regularly happens that we (A1AA) experience inconveniences because our returning trucks have to wait for these batches to load first. I would like to use a simulation to gain a better understanding of the time range within which our trucks return at the asphalt plant so that we can communicate to the asphalt coordinator that this time slot should be blocked for our project. When it turns out that this is not possible, then I would like to use the simulation model to understand whether it would help us to start half an hour earlier or later (i.e. if this would prevent waiting times at the asphalt plant).

Considering the functional design, this user-story seems not possible yet, as the functional design does not offer to option to include multi-project simulation. However, instead of simulating the entire process for multiple projects, time slots at the asphalt plant can be assigned to each project in the model, which would tell the simulation model that the asphalt plant is only available at certain times for the case project. This is possible based on the current functional design and therefore this user-story would be partly possible.

User-story 2:
As a work planner, when I notice in the paver registrations that the paver is often idle, I would like to be able to investigate what happens when additional trucks are deployed. I would like to answer the question: Are we using too few trucks in the current layout or would it make no difference?

Based on the current set-up of the functional design, this is an application that could be executed properly. This is a typical case of an optimisation issue that could be addressed by simulation and therefore the functional design is considered to be appropriate for this user-story.

7 USE-CASE 2: CONSTRUCTION PROGRESS MONITORING USING FIELD DATA TECHNOLOGIES

This chapter is concerned with the development of a functional design for the second use-case: automated progress monitoring using field data capturing technologies for groundwork activities. To develop the functional design, the design cycle of Wieringa (2014) has been followed, which consists of three tasks: *problem investigation, treatment design,* and *treatment validation.* Figure 40 schematises the research steps treated in this chapter.

7.1 Problem investigation

Problem investigation is concerned with gaining a deeper understanding of the problem context and identifying goals and needs of stakeholders regarding automated progress monitoring (Wieringa, 2014). Since progress monitoring is quite a broad concept that can be used to indicate multiple things, the meaning of the concept in this use-case was defined first to scope the problem investigation.

7.1.1 Progress monitoring

According to Golparvar-Fard, Peña-Mora, Arboleda, and Lee (2009, p. 391), monitoring can be defined as: ''collecting, recording, and reporting information concerning any or all aspects of project performance which highlights presence of progress discrepancies and facilitates project managers and decision makers to take corrective actions in a timely manner''. An important fraction of this citation concerns ''any or all aspects of project performance'', which indicates that progress monitoring can focus on various aspects, such as the classic project management aspects time, costs and quality, but also on safety performance or environmental impact. This use-case did not address all possible forms of progress monitoring and a choice was made regarding the focus. Together with the commissioning person of the research, it has been decided that the focus of this use-case is on progress monitoring in terms of schedule and budget. Other aspects that could be subject to progress monitoring have not been addressed in this use-case.

To conduct the problem investigation for progress monitoring of groundwork activities, a single case study approach was used.

Case project

The case project that has been used for this use-case concerns the A12 Poortwachter. This is a relatively small project located at an exit of the A12 highway near the city of Ede. The project has an integral scope that comprises of groundwork activities, road construction and the realisation of a small underpass. Realisation of the project started in 2019 and is scheduled to be finished by the end of 2020 (Parklaan, 2020).

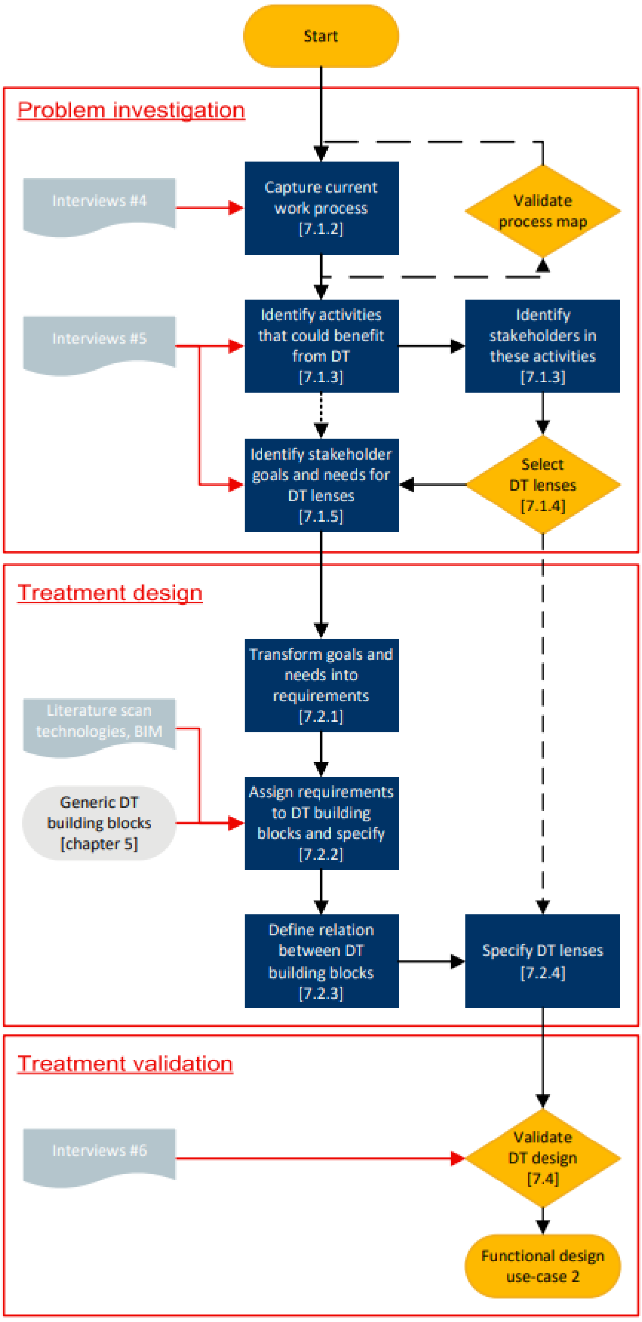


FIGURE 40: RESEARCH STEPS CHAPTER 7

7.1.2 Capturing the current process

In order to capture the current process for progress monitoring of groundwork activities, multiple interviews have been conducted. The first interview was conducted with the manager responsible for groundwork activities at Heijmans Infra and served to gain general insight into how progress monitoring is currently performed. Subsequently, two interviews were conducted with persons directly involved in the case project, in the role of project leader and ground flow coordinator. These interviews were used to capture the current process for progress monitoring of groundwork activities on the case project. The developed process map is depicted in Figure 41, a full-scale version is included in Appendix VII. The process map was validated with the project leader of the case project.

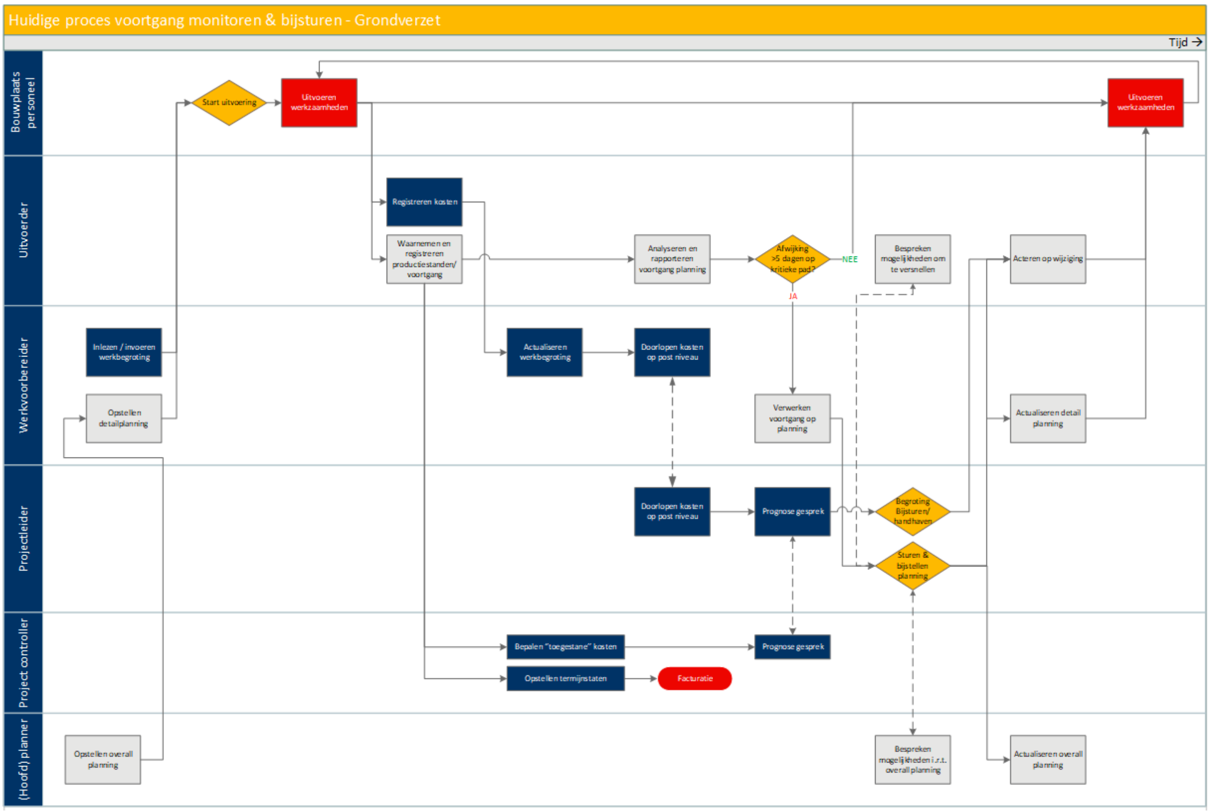


FIGURE 41: CURRENT PROCESS FOR PROGRESS MONITORING

7.1.3 Identification of improvement problems

To understand the improvement problems in the current process of progress monitoring, activities that can possibly benefit from this DT use-case were identified. This was done during a second interview with the project leader of the case project by asking what activities he thinks have improvement potential and could potentially benefit from automated progress monitoring. Furthermore, it was asked what issues are encountered when performing these activities currently. From this interview it followed that the activities with improvement problems are:

- Observe and record production levels / progress;
- Analyse and report progress against schedule;
- Adjust/ maintain budget;
- Adjust schedule.

To examine if these activities can indeed benefit from the application of a DT, a deeper understanding of the issues in the current process was needed. Based on the interview with the project leader, the following descriptions of the activities were derived:

Observe and record production levels / progress

This activity is concerned with capturing the work progress on the construction site and recording it. This activity is performed by the building foreman and is mainly based on visual observations and input obtained from the construction site personnel. Every 4 weeks the building foreman should enter the production levels in SAP, which forms input for budget control. Although this is ought to be performed by the building foreman, it was indicated that on the case project this is often done by the project leader in practice, who also bases it on his own visual observations.

The main issue that currently exists concerns a lack of insight in the actual realised productions (e.g. the cubic meters of ground filled). Production levels are mainly based on estimates of how far an activity is, which is prone to human errors. In practice it occurs that incorrect estimates are entered, meaning that there is still more (or less) work left than one would suggest based on these numbers. This in turn affects the prognose of the remaining costs, which are then estimated lower (or higher) than they actually are. Consequently, it may seem if the activity will be completed within budget, while in reality this is not the case.

Analyse and report progress against schedule
This activity concerns comparing the realised work progress against the schedule to identify potential deviations and is performed by the building foreman. Currently, it relies mainly on visual observation of the construction site and there is usually no quantified progress data involved in this task. For the comparison of progress against schedule, the critical path method is used. On the case project, the threshold for schedule deviations concerns 5 days on the critical path. If deviations remain below this threshold, the original schedule is maintained and activities proceed as planned. When this threshold is exceeded, the project leader is notified and consequences of the delay are examined. Noteworthy to mention is that it was indicated that on the case project the schedule is not updated based on actual start and end times of activities. This only occurs with deviations of more than 5 days on the critical path.

An issue that exist with regard to schedule control is that it is not always clear if activities are actually finished. In particular, this is the case for smaller (wrap-up) tasks that are part of overarching activities included in the schedule. Activities in the schedule are often defined at a higher level and consist of multiple sub-tasks. As indicated during the interview, examples of typical tasks that are sometimes overlooked concern verges that still need to be finished or a ditch that needs to be dug out. Another issue that occurs with regard to schedule control concerns limited insight in the progress within 1 activity. This particularly applies to activities with a long lead time, which is often applicable for groundwork. It is then insufficiently clear whether the progress within the activity is in line with the planned progress and whether the scheduled end date will be met based on the current deployment of equipment and labour.

Adjust/ maintain budget
This activity is performed by the project leader, who is responsible for the financial performance of the project. Based on the budget and production levels it is the task of the project leader to assess whether the remaining scope can be performed within budget, and if this is not the case to identify and act on it as early as possible. On the case project, the financial performance is examined in four-weekly prognose meetings. In the week prior to this meeting, the project leader meets with the budget holders of the different disciplines to discuss together the incurred costs at the cost item level. Project control calculates the allowable costs for the different cost items based on the production levels entered in SAP. The financial prognosis is then elaborated together with project control during the prognose meeting.

For this activity it was indicated that the main issue concerns difficulties in accurately determining the remaining costs. For groundwork activities, this is mainly due to limited insight in the remaining quantities to be moved. During the interview, the project leader indicated that equipment in particular is a cost item that regularly causes budget overruns. In the prognose meetings an estimate is made regarding the required equipment deployment for the remaining scope. However, it is often unclear how long an activity will exactly last and how much equipment is needed. Therefore, it is difficult for the project leader to identify cost items that are running out of budget in advance and act proactively on it.

Adjust schedule
In case of deviations from the schedule of more than 5 days on the critical path, the project leader is notified by the building foreman. The building foreman and the project leader, and potentially also the main planner, then jointly examine the possibilities to intervene on the schedule. Eventually, the decision to act is made by the project leader and based on his choice, the work planner updates the detailed schedule and the building foreman acts on possible changes (e.g. arrange extra equipment to accelerate the process). For this activity, the main issue is similar as for budget control, namely that it is not always

clear how much work the remaining activities are. This is mainly because progress estimations are based on visual observations and therefore prone to errors in the remaining quantities.

7.1.4 Selection of Digital Twin lenses in this use-case

From the process map of the existing process it follows that multiple stakeholders are involved in progress monitoring for groundwork activities. Each of these stakeholders has its own needs regarding project related information and could have their own lens towards information captured in the DT. However, given the limited time for this research, not all these lenses have been specified. From the activities with improvement potential and the interview with the project leader, it follows that the most important lenses to specify are the **lens of the building foreman and the project leader**. This corresponds with findings from two other interviews that were conducted with a project coordinator and a main planner, who were asked to reflect on this use-case and consider if it could be relevant in their work process as well. Although it might be helpful for them, they both acknowledged that the primary stakeholders in this process are the building foreman and the project leader. Therefore, it has been decided to focus on the lens of the building foreman and project leader.

7.1.5 Stakeholder goals and needs

From section 7.1.3 it follows that four activities in the current process include improvement problems that could potentially benefit from this DT application. These are performed by two main stakeholders: the building foreman and the project leader. To develop the functional design for this use-case, the goals and needs of these stakeholders have been identified. However, for this use-case only the project leader of the case project was interviewed. Nevertheless, the goals and needs of the building foreman regarding this DT application were still defined because the project leader has prior experience as building foreman and can therefore reasonably imagine the desires of a building foreman. Additionally, the project coordinator that was interviewed also provided input regarding the goals and needs from a building foreman point of view, which largely corresponded with those provided by the project leader. Together, this results in the following goals and needs for the two main stakeholders:

Building foreman

A DT, when used for automated progress monitoring should:

1. Visualise activities that are running off schedule and need intervention;
2. Visualise uncompleted tasks or locations where the constructed work is not in accordance with the design.

Project leader

A DT, when used for automated progress monitoring should:

3. Provide quantified insight in the productions realised;
4. Provide insight in the remaining quantities to be moved;
5. Visualise where the remaining quantities are located;
6. Provide insight into what causes potential deviations from the budget.

7.2 Treatment design

The second task of the design cycle concerned treatment design, in which stakeholder goals and needs were translated into the functional design for this DT application (Wieringa, 2014). To do this, first functional requirements have been specified. Subsequently, the design solution was developed by assigning the requirements to the DT building blocks and specifying them. Finally, the DT lenses for the building foreman and project leader have been specified.

7.2.1 Requirements

Based on the identified stakeholder goals and needs, the requirements for the functional design of this use-case have been defined. Like the first use-case, the requirements have been defined according to the MoSCoW method. Table 12 presents the functional requirements for automated site progress monitoring, where the (#) behind each requirement refers to the corresponding number of the related stakeholder goal or need from section 7.1.5.

TABLE 12: FUNCTIONAL REQUIREMENTS USE-CASE 2: AUTOMATED CONSTRUCTION PROGRESS MONITORING USING FIELD DATA CAPTURING TECHNOLOGIES

Must haves	Should haves	Could haves	Won't haves
Progress measurements: DT must be able to capture as-built progress data from the construction site (1-6)	**Diagnostic:** DT should be able to identify the underlying reasons that cause deviations from budget (6)	**Predictive:** DT could have the ability to automatically determine the expected completion date and costs based on progress data (1,4)	**Prescriptive:** DT won't have the ability to automatically suggest interventions that mitigate schedule or cost overruns based on progress data
As-planned: DT must have the ability to display the expected progress and associated costs over time (1)	**As-designed check:** DT could be able to compare as-built with as-designed and visualise deviations (2)		
Recognise objects: DT must be able to automatically recognise objects in the as-built representation (1,3)			
Progress estimation: DT must be able to automatically compare as-planned with as-built progress and estimate progress estimate schedule and budget progress (1)			
Visualise: DT must have the ability to visualise the progress status and potential progress discrepancies (1,5)			

In order to justify that these requirements, if implemented in the design, would contribute to stakeholder goals and needs, a contribution argument has been given for each requirement (Wieringa, 2014). The Won't haves' requirements have not been incorporated in the design, therefore no contribution argument was given for them. The contribution arguments are presented in Table 13.

TABLE 13: CONTRIBUTION ARGUMENTS USE-CASE 2

Requirement	Goal	Contribution argument	P	M	D	E
Progress measurements	1-6	To enable automated progress monitoring, the DT must be able to capture how the asset under construction is progressing over time in a computer understandable manner	X			
As-planned	1	The DT must be able to reflect the as-planned situation, both in terms of project completion and budget, over time to enable automated progress monitoring		X	X	X
Recognise objects	1,3	To provide quantified insight in the productions realised and visualise activities that are running off schedule, the DT must be able to identify objects in the as-built model			X	
Progress estimation	1	The DT must be able to automatically identify differences between as-planned and as-built to provide users with feedback regarding the progress status			X	

Visualise	1,5	The DT must be able to provide visual insight in the activities that are running of track		X	X	
Diagnostic	6	To provide insight into what causes deviations from the budget, the DT should be able to identify what aspects caused the deviation		X	X	X
As-designed check	2	To visualise uncompleted tasks or locations where the constructed work is not in accordance with the design, the DT should be able to identify deviations and visualise them		X	X	
Predictive	1,4	To determine what activities need intervention, DT could be used to give predictive insight in the expected completion date and costs based on costs and time required to realise the current progress		X	X	X

7.2.2 Digital Twin building blocks in this use-case

To develop the functional design, the reference framework of DT building blocks from chapter 5 provided the baseline. Each functional requirement was assigned to one or multiple DT building blocks in Table 13, where P=Physical layer, M=Model layer, D=Data layer and E=Enterprise layer. The Connection and Service layer building block are not displayed in this table because they do not facilitate the content for a DT application but rather the connection between the other building blocks and the user interface. Section 7.2.3 devotes attention to the connections between the other building blocks and in section 7.2.4 the designed DT lenses are presented, which reflects the Service layer.

PHYSICAL LAYER

From chapter 5 it follows that the elements in the physical layer can be divided in three categories: observable entities, observers, and data transmission components. To enable automated progress monitoring of groundwork activities, each of these three components is needed.

Observable entities

In chapter 5, several observable entities in the construction industry were proposed, such as Assets, Equipment, Personnel, Materials or Processes. Observing these entities can be useful to receive feedback regarding progress measurements, equipment and materials tracking, safety planning, or productivity tracking (Omar & Nehdi, 2016). For this use-case, the focus is not observing where or how much material is stored on the construction site, or where equipment and personnel are located. Neither is it about observing the productivity of individual personnel or equipment. Hence, the observable entities Equipment, Personnel and Materials are not relevant for this use-case. Instead, it is about feedback regarding progress measurements, thus observing the extent to which the asset under construction is progressing. Therefore, the observable entities are the assets under construction, such as the entrance and exit to the highway or underpass at the case project, as depicted in Figure 42.

FIGURE 42: OBSERVABLE ENTITIES IN THIS USE-CASE

Observers

From the *progress measurements* requirement it follows that the goal of observers is to capture how the asset under construction is progressing over time in a computer understandable manner. Omar and Nehdi (2016) performed a review of technologies for automated and electronic construction data collection where they divide technologies for site data acquisition in four categories: Enhanced IT, Geo-spatial, Imaging, and Augmented Reality, as depicted in Figure 43.They divide the process of progress tracking and status assessment in collecting as-built data, organising as-built data, analysing as-built data. While the former three may be used for data collection, Augmented Reality is mainly suitable for analysing as-built data and is therefore not considered as potential observer here.

Enhanced IT technologies serves to improve the communication between the construction site and the (site) office and thereby inform project managers about the progress made. Their use is, however, restricted to tracking and documenting a project's status manually (Omar & Nehdi, 2016).

Geo-spatial technologies can be used to track and visualise objects in real-time. Examples of Geo-spatial technologies include barcoding, radio frequency identification, and global positioning systems. These can assist in collecting, tracking, and visualising geographic and geospatial aspects of on-site construction objects. Additionally, they enable to track materials along their supply chain, from manufacturing to site installation (Omar & Nehdi, 2016).

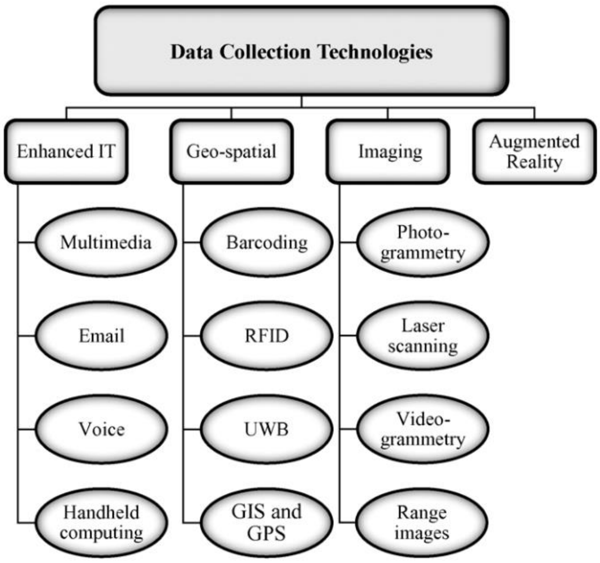


FIGURE 43: TECHNOLOGIES FOR CONSTRUCTION SITE DATA ACQUISITION. REPRINTED FROM OMAR AND NEHDI (2016)

Imaging technologies enable to generate 3D information (point-clouds or 3D models) of as-built construction objects. This can be used for progress monitoring. Suitable imaging technologies for construction purposes comprise of photogrammetry, laser scanning, videogrammetry and range images. These enable to determine quantities of work performed over a time interval between two observations, which enables to make estimates regarding the progress made (Omar & Nehdi, 2016).

Depending on the nature of the construction process, different technologies may be suitable for data collection. Enhanced IT improves communication on site and streamlines the process of transferring progress information from the construction site to the (site) office. However, its main limitation is that it remains a manual task. On the contrary, Geo-spatial and Imaging technologies can be used for automated progress monitoring. While Geo-spatial technologies are particularly suitable for material tracking and, from a practical point of view, mainly suit materials with a demarcated geometry (e.g. steel beams), imaging technologies can be used to determine quantities of work performed. Since progress monitoring for groundwork activities emphasises on the realised productions, thus the cubic meters of soil moved, the use of imaging technologies is considered to be most suitable for this use-case.

Figure 43 presents multiple imaging technologies, each with their own advantages and limitations. Within Heijmans Infra, two of these technologies are already used: photogrammetry and laser scanning. Prior research indicated that these two techniques are also the most common technologies for the majority of progress monitoring applications (Alizadehsalehi & Yitmen, 2019). Therefore, only photogrammetry and laser scanning have been considered in more detail.

Photogrammetry is a method to generate 3D models or point-clouds from many overlapping digital images (El-Omari & Moselhi, 2008). Depending on the number of images taken and the quality of the images, the point-cloud is relatively accurate. Photogrammetry is very affordable as it only requires a digital camera and software for the conversion process, making the technology also very portable (Omar & Nehdi, 2016). The range and efficiency can be increased with the use of drones with a digital camera. In this way, an entire construction site can be captured within minutes. However, photogrammetry also has limitations, such as the extensive computing power required to reconstruct the point-cloud, making the processing a time-consuming task. Other limitations include the sensitivity to shadow lines in images, which affects the processing (Omar & Nehdi, 2016). Furthermore, when drones are used, restrictions are imposed by the drones, such as no-fly zones and weather conditions that make it impossible to fly.

3D Laser scanning is a technology that relies on the pulse of a laser light to construct a point-cloud. By releasing the pulse of a laser light to a surface and calculating the distance to the target by timing the round trip time of the pulse to the point, 3D laser scanners can very accurately map the geometry of objects (El-Omari & Moselhi, 2008). Another advantage of 3D laser scanning is that it directly produces a point-cloud and no further processing is needed, which makes information available very quickly (Omar & Nehdi, 2016). 3D laser scanning can be performed using static scanners on a tripod that can map the environment 360 degrees around. In addition, there are also dynamic scanners that can be placed on a moving vehicle and can be used map larger areas. Both types are used within Heijmans Infra, although the latter is performed by external parties. The major limitation of 3D laser scanning is the high purchase value for the scanners and the limited range of static scanners (Kopsida et al., 2015).

To determine which of the two technologies is most suitable, the characteristics of the case project were considered. The case project covers quite a large area to be captured, which requires multiple scans of a static scanner. On the contrary, dynamic scans are usually performed from public roads. Since parts of the construction site are located quite far away from a public road and out of the line of sight, dynamic scans are unsuitable. The case project is located outside a no-fly zone, making the use of drones a possibility. The disadvantage of this technique is, however, that the point-cloud is less accurate than with 3D scanning. Nevertheless, as-built tolerances for the geometry of groundwork usually provide a clearance of a few centimetres, making the use of drone-based point clouds suitable. Therefore, the observer in this use-case is a drone camera.

Data transmission equipment
The progress data (images) need to be transferred to virtual space where it can be processed. For this use-case, the images captured by the drone camera are stored on a local SD card during the flight. After the drone is operated by the surveyor, the images are manually stored on a network drive from where they can be accessed for further processing.

MODEL LAYER

In this use-case the observable entity in the physical layer comprises of the assets under construction. Therefore, the models in the model layer should provide a virtual representation of the same assets, which means that the asset model is most relevant. This model can be further decomposed in different sub-models (i.e. geometry, physics, behaviour). For progress monitoring using point-clouds, a geometric comparison is made between as-built and as-planned on a reference date (Braun, Tuttas, Borrmann, & Stilla, 2015; Han, Degol, & Golparvar-Fard, 2018). Therefore, the geometric model provides the baseline for this use-case. The geometric model of the case project takes the form of a 3D CAD model and is displayed in Figure 44. This model provides the as-designed reality for the physical asset, which can become as-planned by linking it with the construction schedule and budget. These couplings are usually referred as 4D BIM (schedule) and 5D BIM (costs) (Eastman, Teicholz, Sacks, & Liston, 2011).

FIGURE 44: GEOMETRIC MODEL (AS-DESIGNED) OF THE CASE PROJECT

DATA LAYER

The data layer is responsible for the acquisition, processing, storage and integration of data and forms the core element of the DT. Within this use-case, the purpose of the data layer is to combine the as-planned data with as-built data and analyse it to detect potential progress discrepancies.

Data collection

Data collection for this use-case DT is based on multiple sources. Hardware data sources for the DT can be further decomposed in static and dynamic data. Static data describes the properties of the asset, such as dimensions and materials used, which are captured in the geometric model. In this use-case, dynamic data comprises of the images taken by the drone. Software data includes the data extracted from the construction schedule and the budget.

Data processing

Data processing is concerned with extracting useful information from the collected data by the observers in the physical layer. In this use-case, the collected data takes the form of images. In order to convert these images into a point-cloud of the as-built progress, photogrammetry is used.

Photogrammetry is a technique to reconstruct the position, orientation, shape and size of objects or surfaces from images (Kraus, 2011). A common technique within photogrammetry to convert images into a point-cloud concerns Structure from Motion (SfM). Mlambo, Woodhouse, Gerard, and Anderson (2017) describe the process of SfM in four steps:

1. Detecting and matching distinct features from overlapping images;
2. Generating sparse point clouds;
3. Clustering the sparse point cloud;
4. Densifying the sparse point cloud.

The outcome of these four steps is a point-cloud in an arbitrary coordinate system. Because the point-cloud is ought to be used for comparison with the as-planned model, it should be placed in the same coordinate system as used for the design. This step is referred as Georeferencing and transformation by Mlambo et al. (2017). For this use-case, the technical process of converting images into a point cloud using photogrammetry is not further detailed here, more information regarding the technical process of photogrammetry can be found in Mlambo et al. (2017) and Kraus (2011).

ENTERPRISE LAYER

For this use-case, the Enterprise layer includes information regarding the construction schedule and budget that enable to generate a representation of the as-planned reality.

Construction schedule

The construction schedule provides an overview of the project’s milestones, activities, and deliverables, along with their intended start and end dates. On the case project, the schedule currently takes the form of a Gantt chart. In order to use a construction schedule as input for the as-planned representation (4D BIM), the following elements should be included (Mathijsen, 2019):

- Activity ID;
- Activity Name;
- Activity types (WBS);
- Planned Start Date (Start);
- Planned End Date (Finish);
- SBS coding.

Budget

The budget for the project is established before the start of the construction activities and reflects the expected costs to be incurred. The budget provides the baseline for financial control activities during the construction phase. To control the budget, different cost breakdown structures can be used. During the interview with the project leader of the case project it was indicated that this can either be done based on the work packages, activities or objects. For the case project, budget control is based on the object structure, where each object has cost items for material, equipment and labour. In order to use the budget as input for the as-planned representation (5D BIM), the following elements should be included:

- Activity types (WBS);

- Cost types;
    - Materials;
    - Equipment;
    - Labour;
    - Sub-contractors.

Project management tool
While the budget forms the baseline for financial control, the actual costs incurred must be available to determine if the project is performing within budget. On the case project, SAP's project management tool is used to keep track of the costs incurred by the building foreman. In this tool the same cost items are used as included in the budget.

7.2.3 Relation between Digital Twin building blocks

In section 7.2.2, the building blocks for this use-case have been discussed separately. However, to reflect DT application, these building blocks should interact with each other. This section discusses the relation between the different DT building blocks and explains how they are interrelated.

As-planned
The baseline for progress monitoring is the as-planned reality, which reflects the expected construction progress and costs incurred over time. To represent the as-planned reality in virtual space, three components are needed:

- Geometric (3D) model;
- Construction schedule;
- Budget.

In order to link these information constructs with each other, the data in the different software should be interoperable and encoded. To realise this, objects in the 3D model should be encoded with their associated SBS tag. By incorporating both, the SBS and WBS, tags in the construction schedule, a link can be established with the 3D model and the budget, which is based on the WBS structure. Figure 45 provides the schematic representation of the as-planned reality.

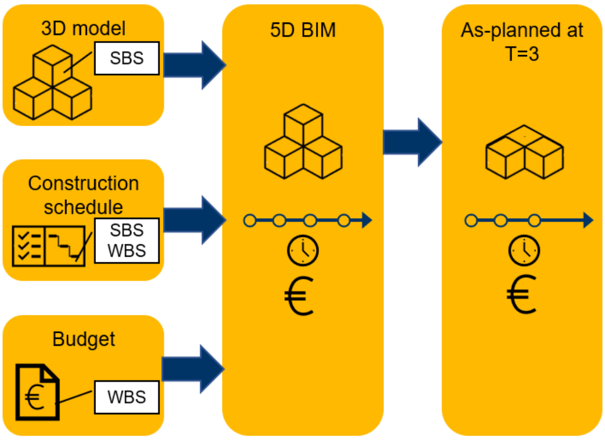


FIGURE 45: AS-PLANNED REALITY

As-built
To make an estimate of the progress, the geometry of the as-planned model is compared to the as-built point-cloud model on a certain reference date (Braun et al., 2015; Han et al., 2018). The as-built point-cloud model can be created by following the steps of Figure 46. Photogrammetry refers here to the four steps of the SfM process and Georeferencing as explained in section 7.2.2.

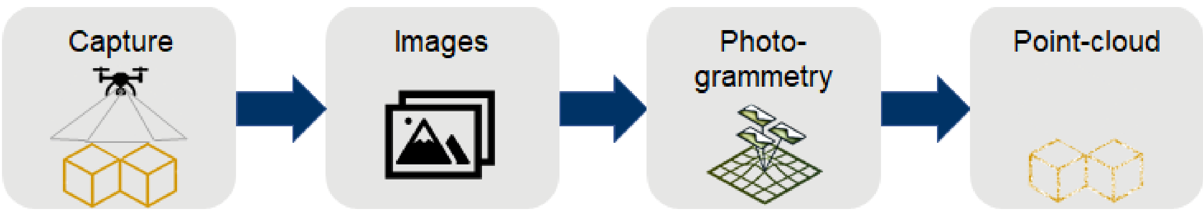


FIGURE 46: CAPTURING THE AS-BUILT PROGRESS ON SITE

Comparison between As-planned and As-built progress
The DT should be able to automatically compare as-planned and as-built status and report progress estimations to the end user. Various researchers have taken initiatives to develop a tool that automatically compares a 4D BIM (as-planned) with a point-cloud of some asset under construction to determine the progress, for example (Braun et al., 2015; Han et al., 2018; Turkan, Bosche, Haas, & Haas, 2012). Although the underlying methods used in these papers differ, the basic principle is the same. Translating the principle of these publications to the structure of the DT building blocks, the situation as depicted in Figure 47 is applicable.

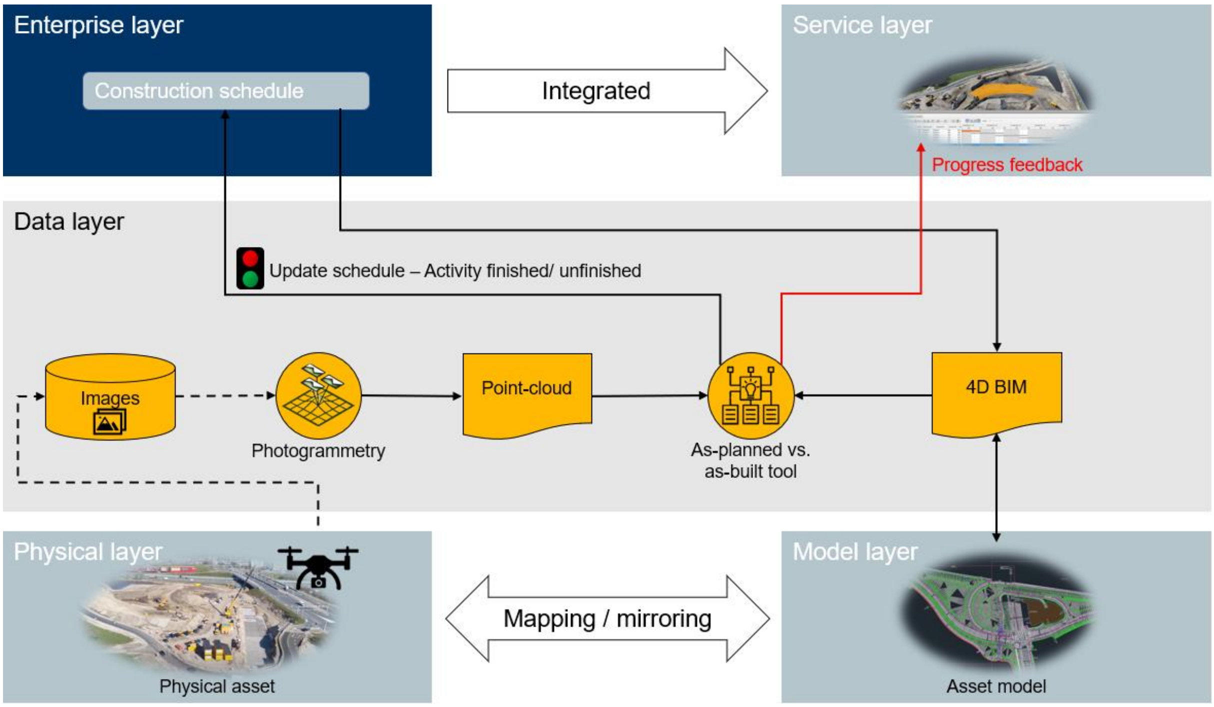


FIGURE 47: COMPARISON BETWEEN AS-PLANNED AND AS-BUILT PROGRESS

To enable the automatic comparison between as-planned and as-built point-cloud, Figure 47 includes the block ''as-planned vs. as-built tool''. Developing a tool that enables automatic comparison between as-planned and as-built and subsequently updates the construction schedule has been the focus of several studies where multiple techniques are used, for example (Braun et al., 2015; Turkan et al., 2012). One technique is to make use of voxel grids (the 3D equivalent of pixels) in both the as-planned model and the point-cloud and use a probabilistic approach to determine the progress (Braun et al., 2015). Another technique relies on the combination of geometry- and appearance-based reasoning methods (Han et al., 2018). Geometry-based reasoning detects the existence of BIM elements in the as-built point-cloud without differentiating between e.g. formwork and concrete. Hence, it checks if there is an element in place on a location where there ought to be an element but does not check whether it is the right element. Appearance-based reasoning adds the recognition of material textures and can detect operation-level progress. Since this use-case is concerned with the development of a functional design, the technical details of these techniques have not been further elaborated. For a detailed description on how the comparison can be realised between as-planned and as-built, reference is made to Tuttas, Braun, Borrmann, and Stilla (2014), Braun et al. (2015), and Han et al. (2018).

With regard to Figure 47, it should be noted that it is assumed that the progress estimates update the original schedule in the Enterprise layer. However, regularly the schedule used for a 4D BIM is not attached using a bi-directional connection but rather an export of the schedule in .CSV format. In these cases, the schedule that is updated concerns the schedule in captured in the 4D BIM environment.

Comparison between As-planned budget and actual costs

When compared to Figure 47 also progress monitoring in terms of budget is ought to be included, the Project Management Tool is added to the Enterprise layer and the 4D BIM is replaced by a 5D BIM by an additional coupling with the budget. To assess whether the project is performing within budget, the schedule should be updated first to reflect an accurate overview of the expected costs at that moment.

Furthermore, data analytics can be added to the data layer where they can be used to perform diagnostic and predictive analyses based on the progress data. This option has, however, not been fully elaborated by means of the DT building blocks. Figure 48 provides a schematic representation of the concept behind the inclusion of the budget and analytics aspect. In this figure the actual costs reflect the costs as captured in the Project Management Tool and the data analytics block reflects the analytical capabilities that can be included in a DT, these may take the form of both diagnostic or predictive analytics.

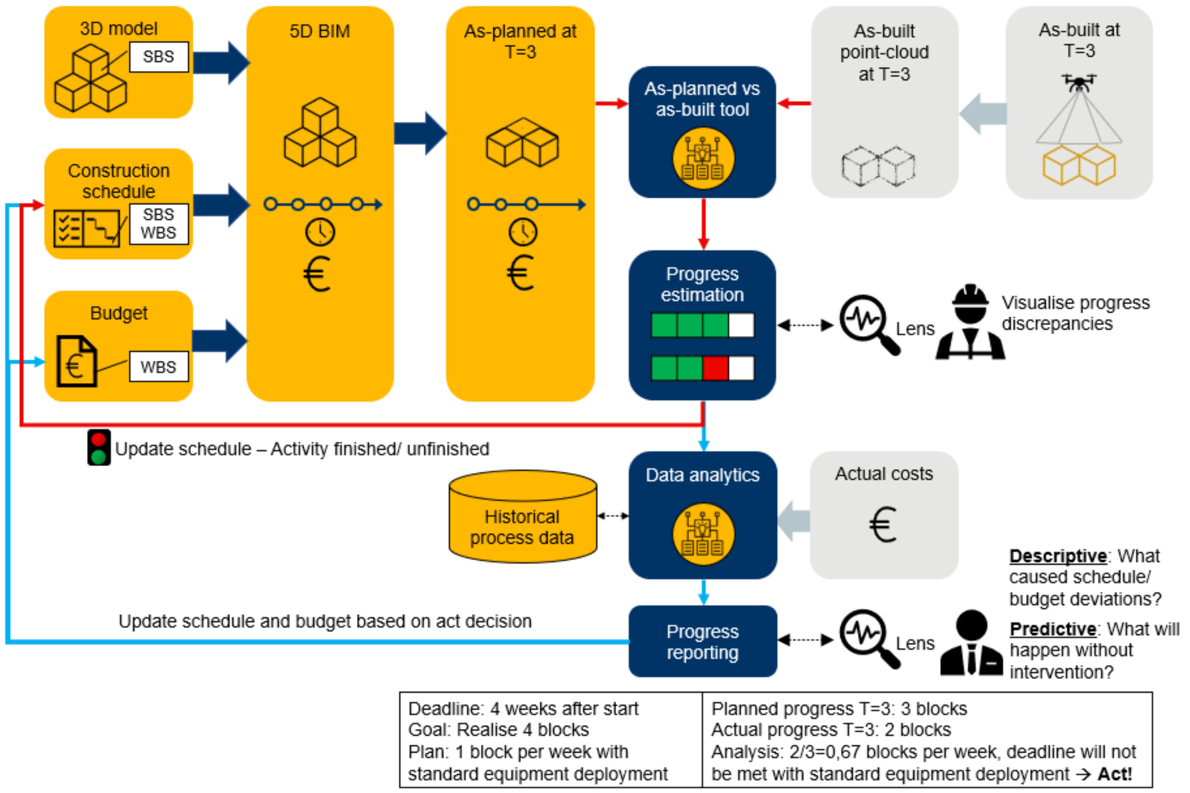


FIGURE 48: AUTOMATED PROGRESS MONITORING IN TERMS OF SCHEDULE AND BUDGET

Considering Figure 48, it should be noted that the loop represented by the red arrows corresponds to principle of Figure 47 and thereby reflects the concept of several previously described applications in BIM related literature. This loop enables visual insight in progress discrepancies, which could give the building foreman a better understanding of activities that are running off-track. However, since this loop has already been described several times in BIM literature, it can be questioned whether this should be regarded as a true DT. The blue loop, however, provides an extension to most prior research and adds reasoning capability and intelligence in the form of data analytics. It can therefore be argued that when this would be implemented, it reflects an actual DT.

In the blue loop, progress data is combined with the actual costs from the project management tool. The DT can thereby be used for automated reporting about the progress made along with the causes of potential delays or cost overruns. Furthermore, based on the combination of historical process data, current progress, and predictive analytics, predictions regarding the continuation of the process can be made. This enables to gain insight in what will happen without intervention, based on which the decision to act can be made. This decision in turn can initiate a change in the budget or schedule (e.g. by shortening the duration of an activity in the schedule due to additional equipment deployment).

7.2.4 Specifying the Digital Twin lenses

To complete the functional design for automated progress monitoring using field data capturing technologies, this section presents the DT lenses for the building foreman and the project leader. Based on the goals and needs of the stakeholders, three DT lenses have been specified.

1. Building foreman - visualise progress deviations (as-planned vs. as-built)
2. Building foreman – visualise deviations from the design (as-designed vs. as-built)
3. Project leader – quantified insight in the productions realised and remaining

The first lens concerns the lens for the building foreman that visualises the progress in terms of schedule. By means of highlighting objects in the model whose related activities deviate from the schedule, the building foreman can gain an improved understanding of the activities that need his intervention. This lens is based on the connections between the DT building blocks as presented in Figure 47 and includes a Gantt chart section where the activities that deviate are highlighted in orange and a visualisation section where the related object is also highlighted in orange. This lens is depicted in Figure 49.

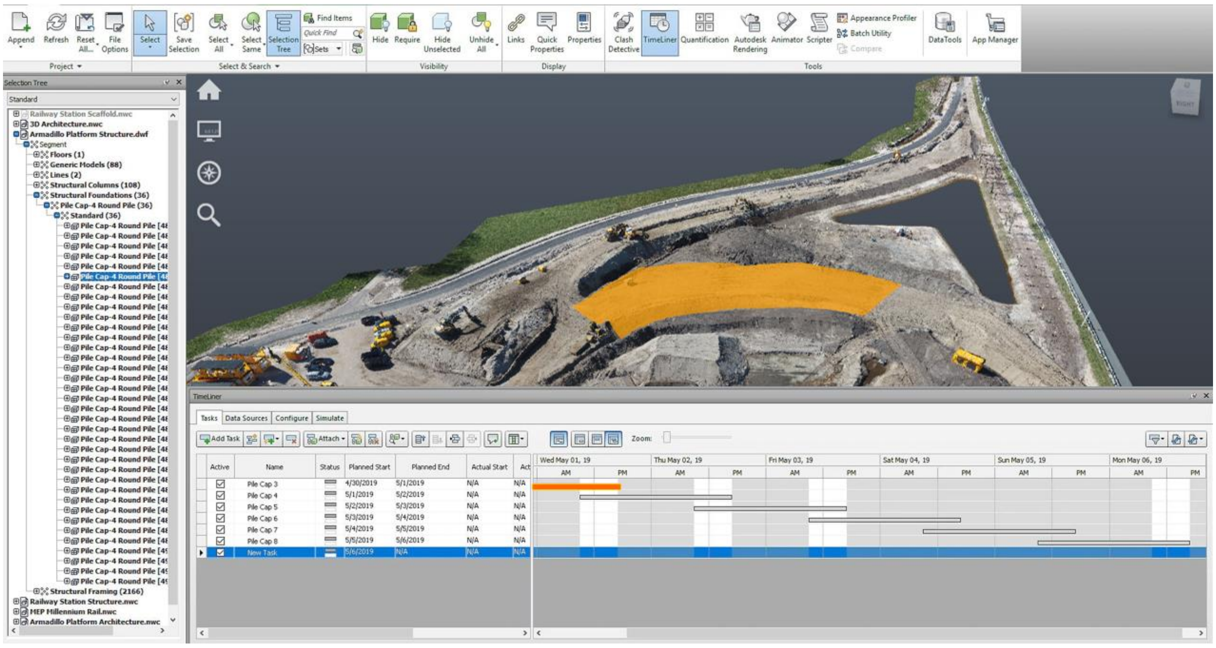


FIGURE 49: LENS OF THE BUILDING FOREMAN – VISUALISATION OF DEVIATIONS FROM SCHEDULE

The second goal of the building foreman relates to better insight in uncompleted tasks or locations where the constructed work is not in accordance with the design. Therefore, the second lens offers a comparison between the as-built point-cloud and the design of the asset (as-designed). It should be noted that the example for this lens is based on a road section on the case project because this road was already at its final location and could therefore easily be compared with the design. However, the principle would be similar for groundwork activities. The DT lens is presented in Figure 50, where a large red spot appears on the road, indicating that the surface of the asphalt is located too high. The ability to show the current site conditions around the deviation from the design in the point-cloud, as demonstrated in the upper right corner, provides insight in the situation and shows that a speed bump causes the deviation. The applicable tolerances for the colour scale should follow from the requirements for the road, which indicate how much the constructed work may deviate from the design. It should be noted that the colour scale used in this example is based on an assumption.

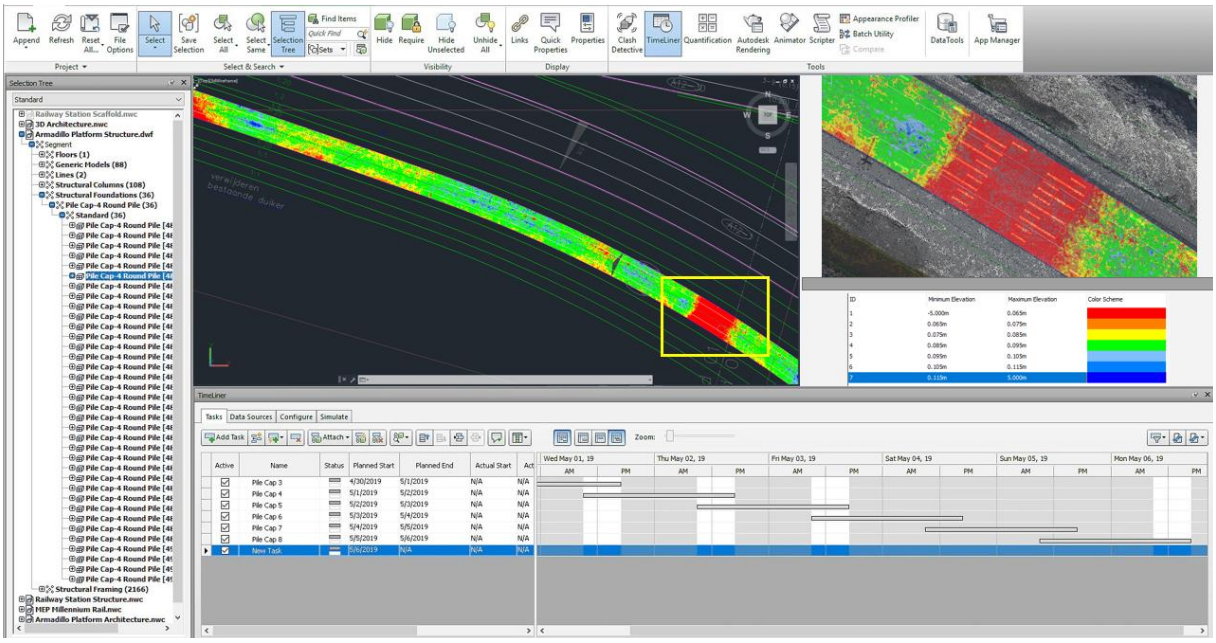


FIGURE 50: LENS OF THE BUILDING FOREMAN – AS-BUILT VERSUS AS -DESIGNED

The third lens that has been specified concerns the lens of the project leader that shows quantified insight in the realised productions and remaining quantities. This lens provides input for the financial prognose. In order to provide insight in the quantifies of soil moved between two successive reference dates, a comparison should be made between the as-built point clouds of these two moments in time. Figure 51 presents this principle by showing how automatically the volume of a stockpile of sand can be determined. The table in the lower right corner presents the associated quantities.

With regard to the remaining quantities, a similar approach can be used. The project leader of the case project indicated that he would like to have an overview of the quantities remaining along with an indicative location, which enables him to make a better prediction of the required equipment deployment and labour costs. Based on a comparison between the point-cloud of the as-built reality and the design, it can be determined how much soil needs still to be moved and where this is located. This is not shown in Figure 51, but relies on the same principle and would look similar.

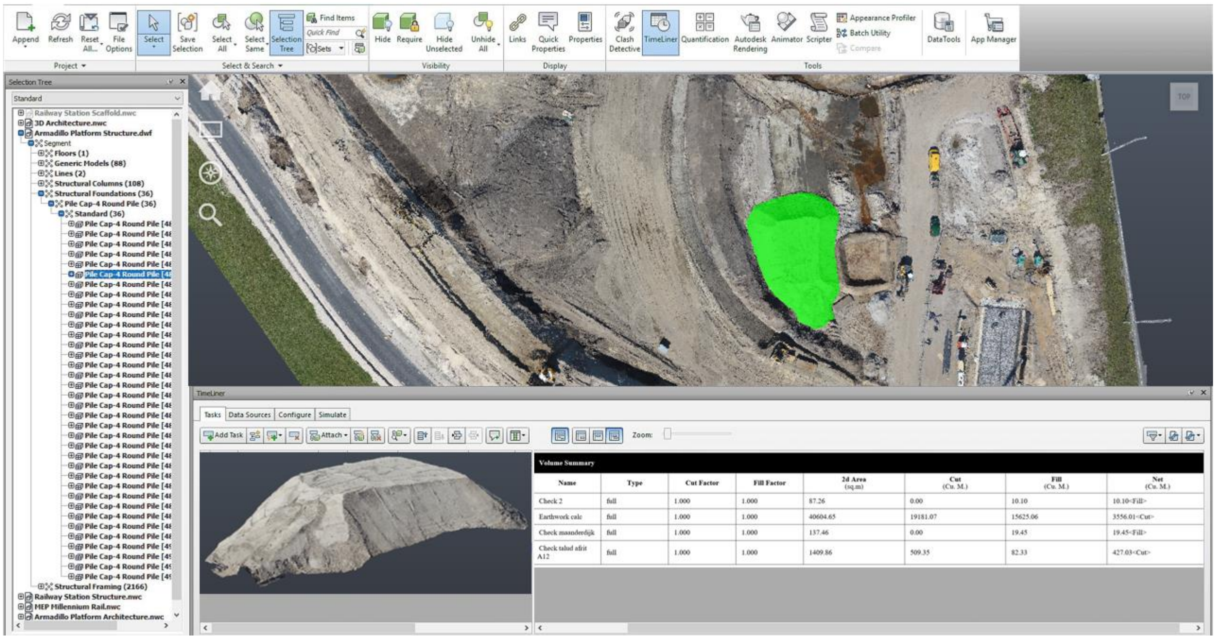


FIGURE 51: LENS OF THE PROJECT LEADER - QUANTIFIED INSIGHT IN REALISED AND REMAINING PRODUCTIONS

7.3 Preconditions for Digital Twin application

Besides developing the functional design for this use-case, attention was devoted to the preconditions that must be met to realise it.

For the data collection process, mainly the quality of the point-cloud is relevant because it is generally assumed that a higher quality of the point-cloud leads to improved monitoring results. Quality of a point-cloud is usually attributed to two parameters (Rebolj, Pučko, Babič, Bizjak, & Mongus, 2017):

- Density of the points;
- Accuracy of the points.

The required quality of the point-cloud depends on the purpose of the scan vs. BIM exercise and the type of object under consideration. In this use-case both as-planned vs. as-built comparisons and as-designed vs. as-built checks are proposed. Especially for the latter, the accuracy of the point-cloud is important to prevent invalid insights. With regard to the type of object, groundwork activities often relate to large objects with a relatively high non-conformance tolerance (a few centimetres), which allows to use a somewhat lower quality point-cloud than might be desirable for other object types (e.g. concrete).

Besides the quality of the as-built data, also preconditions apply on the quality of the as-planned data to enable automated progress monitoring. This mainly relates to the level of development (LOD) of the 3D model and the decomposition level of the WBS in the construction schedule (Han & Golparvar-Fard, 2015). The LOD of BIM models is often not sufficient for tracking progress on an element-by-element basis and 4D BIM models often have one-to-many relations with schedule activities. That is, multiple activities in the schedule are assigned to the same object in the 3D model. Furthermore, construction schedules regularly adopt a high-level WBS where one activity in the schedule reflects multiple activities that are executed sequentially in reality (e.g. form/ rebar/ pour concrete wall) (Han & Golparvar-Fard, 2015). To enable automated progress monitoring, the objects in the 3D model (and associated SBS) and the WBS must be defined at a corresponding level to link them, which depends on the desired monitoring level. This in turn may also pose conditions on the required quality of the point-cloud, as a more granularly as-planned model may require a higher quality point-cloud. Furthermore, the objects in the 3D model and the activities in the schedule must be encoded with their associated SBS and WBS code link them. For the 3D model, the following preconditions apply as well:

- Reflect the 3D geometry of the to be constructed asset;
- Consist of geometrically closed objects;
- Accordance with the building parts to be realised (e.g. distinguish between sand for embankment, sand for sand bed, etc.).

7.4 Treatment validation

The final step of the design cycle concerned treatment validation and focused on justifying that the design solution, if implemented, would contribute to stakeholder goals (Wieringa, 2014). This was done based on expert opinion, where the design solution was presented the project leader of the case project and a project coordinator. The aim of the validation was assessing how the developed DT lenses would impact the work process of the building foreman and the project leader.

From the interview with the project leader it followed that the main impact of this use-case would be the ability to determine more precisely the required equipment deployment and labour costs for the remaining work due to a more accurate understanding of the quantities left. This in turn enables to make more reliable prognoses, allowing to be better in financial control of the project. Furthermore, it was indicated that performing periodically a progress measurement enables to get more accurate insight into what the actual productivity has been and use this to make better estimates of the remaining costs.

Another added value that was indicated by the project leader concerns the ability to check the conformity with the design. The project leader indicated that by working with 3D models during the construction phase it is regularly assumed that the realised work is by definition in accordance with the design, while this sometimes not the case in practice. A comparison between what has already been realised and the design can therefore support in identification of deviations from the design that do not directly stand out by eye.

Besides the project leader, also a project coordinator was consulted for expert opinion. With regard to the first lens of the building foreman he indicated that this could assist in gaining a more accurate understanding of the progress and proposed that ideally, reasoning would be included as part of the design solution as well. That is, the ability to automatically indicate ‘’you are # cubic meters behind schedule, which means with your current production levels and deployment of equipment a delay of X weeks or X days’’. Additionally, the possibility to virtually adjust the production levels and see what the result of additional equipment employment would be was also considered as a valuable option that could potentially be integrated. Furthermore, it was indicated that visualising progress is particularly helpful for activities with a long lead time, which is often applicable for groundwork activities.

With regard to the second lens of the building foreman, where deviations from the design are highlighted, it was indicated that this could be very valuable when the point-cloud is sufficiently accurate. The project coordinator argued that the ability to accurately point out deviations from the design could also be beneficial to capture the production levels for asphalt, which usually forms a large proportion of the total costs on a project. By capturing the as-built situation and compare it with the design, it can be identified whether there is a deviation that may cause too few asphalt tonnages to be included in the prognose. However, the main value that this DT lens can convey is that by regularly capturing the as-built status, ideally after each critical activity, the possibility arises to analyse where potential deviations from the design started to occur. This provides the ability to gain accurate insight in what the consequences are. For example, if the asphalt surface is 2 centimetres too high, this can have multiple causes, which have different consequences for the budget and schedule (e.g. Is it due to a layer thickness exceedance for the asphalt or because the subbase was also positioned too high?). Regularly capturing the as-built progress status enables to analyse this and assess the consequences for budget and schedule.

8 DISCUSSION

This chapter provides a discussion on the results, presents the limitations of the research, and proposes directions for further research.

8.1 Discussion of the results

This research aimed to classify the DT in the construction industry and provide insight into how it can be utilised to create added value in the primary business process of infrastructure contractors. This study found that a DT concerns the semantically linked collection of models, information and data that forms a representation of all aspects of a potential or actual physical system along its lifecycle. DTs do not have a single embodiment but can be classified into six different types (Asset BOL, Process BOL, Fleet BOL, Asset MOL, Process MOL, Fleet MOL), each with potential applications in the construction industry. Furthermore, this study found that existing literature lacks consensus on the relation between BIM and DT. A DT can be considered among the BIM technologies when BIM is considered as a work method. When BIM is considered to be only the object-oriented model, DT provides an extension to BIM. Therefore, BIM as an object-oriented model that includes building information, forms important input for many DT applications in the construction industry. Besides BIM, other elements proved to be essential for DT application in the construction industry. These elements are covered in six building blocks: physical layer, model layer, data layer, service layer, connection, and enterprise layer. The added value of DTs in the primary business process seems to depend on the application area and has been demonstrated in two use-cases. Regarding simulation-based optimisation of asphalt paving operation, DT benefits mainly relate to the ability to proactively manage situations where there is an under- or overcapacity in transport. This ultimately results in an optimised process that lowers the costs incurred with the operation. Concerning progress monitoring of groundwork activities using point-clouds, DT benefits mainly relate to better informed decision making due to more accurate insight in the state of the asset during the process. This results in better financial control and cost reductions.

Classification of Digital Twin

Existing literature lacks consensus on the interpretation of DTs. In this study a definition for DT was established by reviewing literature from various industries and developing a conceptual model that guides the interpretation of a DT. This definition contributes to a clearer understanding of the DT concept in the context of the construction industry. Another key contribution of this study concerns the developed framework (Figure 52) that classifies DTs for construction applications in six types based on three dimensions. This framework is built upon three existing theories, including the typologies of Grieves and Vickers (2017) and Kritzinger et al. (2018), which are frequently used in scientific articles. The developed framework demonstrates that a DT can be classified based on the dimensions: Lifecycle phase, Attribute and Extent of data integration. From these types it follows that a DT can be the virtual equivalent of either a potential or actual asset, process, or fleet of similar assets or process steps.

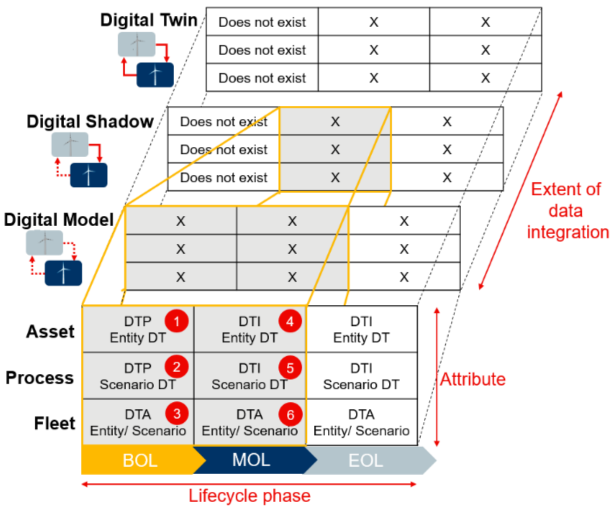


FIGURE 52: TYPES OF DIGITAL TWINS

Relation between BIM and Digital Twin

Digitalisation in the construction industry is currently centred around BIM as main driver. It is therefore evident that there would be a certain relation between BIM and DT in the context of construction. Literature lacks, however, consensus on this relation. By comparing diverging definitions for both concepts, it has been demonstrated that multiple relations can be propagated. This study assumed that for construction applications, a DT would be among the technology field of BIM, which in turn is complemented by two other fields: Policies and Processes (Succar et al., 2012). However, this classification needs to be interpreted with caution as there may be valid arguments that contradict this finding. For example, Boje et al. (2020) appoint the more holistic socio-technical and process-oriented characterisation of DT as argument to consider it as an extension to BIM, which consists of procedures, technologies and data schemas to realise a standardised semantic representation of building components and systems. Although the proposed relation leaves room for discussion, the results of this study clearly indicate that the relation between the two concepts depends on how BIM is interpreted (i.e. as a model or a process). The two practical use-cases in this study demonstrate that, regardless of the exact relation, the BIM model forms important input for DT applications in the construction industry.

Digital Twin building blocks

A DT in itself is not an entirely new technology but builds upon the integration of existing technologies for modelling, simulating, sensing, analysing, and connects previously siloed data sources. DT thereby consists of several building blocks with a distinct function. A literature study regarding DT building blocks demonstrated that there are various existing DT reference frameworks, which show both commonalities and differences. This finding is consistent with that of Josifovska et al. (2019), who argues that there is currently no architectural template that describes the main building blocks of a DT on a meta-level, their properties and interrelations. The most obvious finding that follows from the literature study concerns that existing reference frameworks are context dependent and affected by the classification used for DT. Hence, the definition and types of DTs in this research were taken into account to select a reference framework, which resulted in a reference framework consisting of six building blocks.

Practical applicability of Digital Twins

Literature defines many applications for DTs. To assess the applicability of the concept in the construction sector, a comparison between these applications and the primary business process of Heijmans Infra was made. This resulted in a list of potential value adding applications for DT in construction. However, this list should be regarded as non-exhaustive because the primary business process proved to be so substantial that it was impossible to provide a comprehensive overview of all potential DT applications. The proposed applications were mapped to the six types of DTs, enabling to view which type of DT is relevant for a particular application. This mapping allowed to derive a first insight regarding the added value of a DT in the primary business process, based on the described benefits from existing applications. However, these theoretical benefits need to be interpreted with caution, as they partially originate from other industries and therefore may not or only partially apply to the construction industry. The specific characteristics that make construction a complex undertaking, such as producing unique products at their final location, provides a possible explanation for this.

To demonstrate the practical applicability of DTs in construction, two use-cases were elaborated into a functional design. A point of discussion concerns, however, the extent to which these use-cases and their associated design comply with the classification for DT in this research. For simulation based optimisation of asphalt paving operations it was argued that this forms a DT in construction due to the proposed set-up as a data-driven simulation that integrates data from multiple sources and utilises data collected from the physical process as simulation input. In line with the definition, the DT is used here to *simulate* a potential process, which results in *actions in the physical world accordingly* in the form of the planned configuration of the process. With regard to progress monitoring using point-clouds, a considerable amount of BIM related literature focused already on automated progress monitoring, e.g. (El-Omari & Moselhi, 2008; Han et al., 2018). One could therefore argue that this concerns an existing BIM use-case. However, it is not common practice in the industry yet and it is not listed in the current BIM uses for infrastructure contractors, as discussed in chapter 3. Furthermore, when the synchronised data is also analysed (e.g. on which activities often cause schedule delays), it can certainly be entitled as a DT because it then enters the field of data analytics. When its use is restricted to monitoring services without applying further reasoning capability or intelligence, it becomes a semantic discussion if it should be classified as an existing BIM application, BIM+, or a DT. Nevertheless, both use-cases are supposed to meet the classification of DT in this research or have at least the potential to meet them in the future.

Added value of Digital Twins

Validation of the two use-cases demonstrated that improved predictability of process outcomes, cost reductions, improved communication, and better financial control are expected benefits of DT applications in the construction industry. The perceived benefits of the use-cases are in line with existing research from other industries, for example from the automotive industry where DTs enable process optimisation during the BOL phase by the ability to compare alternative configurations, resulting in cost reductions (Weyer et al., 2016). With regard to the second use-case, the results are in line with existing research from manufacturing that defines the ability to synchronise between the physical and virtual production process, and thereby enable status monitoring, process visualisation and fault diagnosis, as a major benefit of the DT (Lu et al., 2020).

Considering the results at a higher level of abstraction, the two use-cases provide examples that demonstrate that DTs do not directly change the way assets are constructed, as applies for other Construction 4.0 concepts such as robots (Craveiro et al., 2019). Rather they affect how users interact with information throughout the lifecycle. With information at a fingertip and the ability to synchronise between the physical system and its virtual equivalent, DT enables to make better informed decisions. Grieves and Vickers (2017) therefore argue that the core premise of a DT is information as a replacement for wasted physical resources, such as time, energy and materials. Furthermore, DTs' ability to gain insights on how an asset is designed, constructed, operated, and maintained, combined with simulation and analytic capabilities potentially paves the way to new or reshaped business models.

8.2 Generalisability & scalability of the results

This research focused on two common asset types in the operations of Heijmans Infra. Similarly, the two use-cases reflect operations that were selected because of their commonalities with other activities. This section discusses the generalisability of the results and scalability of the two use-cases.

The results of the first use-case showed that simulation-based optimisation of asphalt paving operations is considered to be relevant by work planners because it can support them in scheduling equipment deployment more efficiently. Although this use-case focused on the applicability for asphalt paving operations, the concept can potentially also be applied for other activities with similar characteristics. Characteristics that make asphalt paving operations suitable for simulation-based optimisation concern:

- Repetitive process;
- Requiring equipment deployment with interdependencies;
- Scheduled from a production perspective;
- Uncertainties in the time required to accomplish the task due to contextual factors;
- Automatic generation of historical process data (transport, paver registrations, etc.).

Additional validation of the functional design in a different context should reveal whether the same benefits would apply for activities with similar characteristics, such as: earth moving operations, placement of guide rails, placement of road marking, pouring concrete, etc. However, there are arguments that give reason to assume scalability to other activities. From the structure of the building blocks in this use-case it follows that:

- The actual elements in the physical layer would change for another activity, however, its goal (collecting process data) in this use-case would remain the same. Instead of capturing travel times the focus could, for example, be on capturing the productivity of an excavator.
- The models in the model layer are formulated generically. The Geometric model (BIM) provides input for the simulation in the form of conditions and constraints for the process. Since the use of BIM is not restricted to a particular asset type, it seems scalable to other activities as well. Likewise, Discrete Event Simulation offers a flexible approach to simulation that offers the possibility to add activities or resources in the process layout. Although the actual steps in the process would change for another case, the principle of the simulation would remain the same.
- The enterprise layer provides information regarding resource availability and costs statistics in this use-case. When this concept is used for simulation-based optimisation of equipment deployment for other activities, it seems likely that similar information would be needed to enable evaluation of alternatives. However, for other activities where equipment from subcontractors is used, the applicability may differ from the case of asphalt where the pavers are in-house.

The results of the second use-case demonstrated that automated progress monitoring, based on geometric comparisons with point-clouds, provides an accessible and accurate way to gain insight in the actual realised productions. This is considered valuable for progress monitoring, in terms of schedule and budget, for groundwork activities due to the quantified insight in the realised productions. Although, this use-case was studied for the example of groundwork activities, the outcomes may be applicable for other construction activities where the progress can be visually detected (i.e. based on visible changes in geometry over time) as well. Additional validation of the functional design should reveal whether the same benefits would apply for other asset types.

Regarding the scalability, it is assumed that for the second use-case the main issue with scalability is the quality of the collected data. That is, for the purpose of financial prognoses accurate information concerning the quantities is important. To scale the concept, other activities may require more accurate data capturing techniques than the current drone-based point-clouds. The points in the use-case had an accuracy of approximately 2cm. When a similar approach is ought to be used for quantifying the volumes of paved asphalt, and thereby the tonnages, this accuracy would most likely be insufficient as a margin of 2cm on a layer thickness of a few centimetres would allow significant margins of error. Likewise, the use of drone camaras imposes limitations for indoor environments (e.g. tunnels) and areas in a no-fly zone. However, alternative data collection methods in the form of 3D scanning may provide a possibility there. Further study of the concept will therefore have to demonstrate the scalability.

Finally, with regard to the classification of DTs, this research contributed with a new framework to classify DTs in types. By projecting the scope of the research and the construction context on the framework, it was demarcated and six relevant types for construction remained. However, the plain framework, thus without the specific framing for construction, can potentially also be used in other industries to classify DTs. Additional research will have to identify which types are relevant in that context.

8.3 Limitations

During the research, several issues were encountered that may limit the validity of the results. With regard to the classification of DT, the reader should bear in mind that the established definition and identified typologies for DT are based on literature from other sectors. Due to the limited amount of scientific literature regarding DTs in the context of the construction industry, it was not possible to properly substantiate potential differences between a DT in construction and other sectors. The effects of the specific characteristics of the construction industry on the classification for DT may therefore be underexposed, which could limit the applicability of the developed typology framework. Furthermore, the suitability of the established definition, types, and building blocks for the DT have only been validated with a limited number of persons at Heijmans Infra, which do not represent all business units or even the entire infrastructure market.

With regard to the two use-cases, an aspect that may limit the validity of the developed design solutions concerns that for both use-cases, the three tasks of the design cycle were only performed once. Ideally, these ought to be performed multiple times to give the design cycle its iterative character. Another limitation with regard to the use-cases concerns the set-up of the case study. Even though both case projects were considered to be representative cases and thereby justified the use of a single case study (Yin, 2003), the use of a multiple case study could have facilitated to perform a cross case analysis and thereby analyse the effects of case characteristics on the stakeholder goals and needs. Another limitation with regard to the use-cases concerns that only a limited number of stakeholders have been consulted for their goals and needs towards the design of the DT applications. Furthermore, the preconditions for both use-cases have not been validated with the stakeholders involved.

8.4 Directions for further research

This research provided insight in the classification for DT in the construction industry and explored several applications for DT in the primary business process during the design, construction planning and construction phase. Based on the results, several directions for further research can be formulated:

Validation of more practical use-cases

This research demonstrated based on two use-cases that it seems plausible that DTs can offer added value in the primary business process of infrastructure contractors. However, the established definition, types and building blocks for DTs in construction can take more forms than the two elaborated use-cases. To develop a full picture of the added value of DTs in construction, additional research could build upon the theoretical foundation of this research and focus on a more extensive validation of practical use-cases for DT in the construction sector.

Roadmap from BIM models to Digital Twins

Current digitalisation in construction is centred around BIM as main driver. To realise a shift from the prevailing reliance on the use of BIM models to using DTs, considerable steps need to be taken. There are still many unanswered questions about the exact relation between BIM and DT and it is insufficiently clear whether DTs can be established based on a further evolution of BIM models in their current form.

For example, Boje et al. (2020) appoint that current BIM processes and models enable improved collaboration with their common standards and formats but lack the interoperability and automation to support integration of monitoring data from the physical asset and the ability to perform complex computations (predictions, optimisation). They advocate that a shift is needed from static data schemes, like IFC, to open web linked data-based formats to enable the creation of DTs in construction. Additional research is required to investigate the steps and changes that are needed to realise a gradual shift over time from working based on BIM models towards working with DTs.

Technical feasibility
This research adopted a quite abstract and broad perspective on the applicability of DTs for infrastructure contractors. Technological limitations have only been considered to a limited extent. Further research could therefore take a more demarcated perspective and focus on the technical feasibility and limitations associated with a certain DT type or application. Additionally, future research could focus on giving a more technically detailed interpretation of the DT building blocks that were identified in this study.

Furthermore, the adopted scope of this research resulted in the disregard of several application domains that may provide interesting directions for DT related research:

Operate & Maintain phase
The focus of this research was on the applicability of DTs from the design phase till construction phase. Many DT related benefits in other industries, however, have been attributed to the O&M phase. A literature review by Tao (2019) shows that currently most DT research in industry takes place in the field of prognostics and health management, where it is for e.g. remaining useful life predictions and predictive maintenance. An interesting direction for further research would therefore be to assess the added value of DTs during the O&M phase for infrastructure assets.

End of Life considerations
End of Life considerations are becoming increasingly important in the light of sustainable construction. Recycling of resources to reduce waste streams associated with demolition is pivotal to reach the ambition of the Dutch Government for a complete circular economy by 2050. Recording which materials have been used in a materials passport provides information for recycling. DT could potentially assist in information retrieval regarding the materials used along the lifecycle. However, the potential role for DTs in EOL considerations is broader, as DTs facilitate to gain insight into how an asset is used along its lifecycle, and thereby the extent to which the materials are suitable to be reused. Therefore, an interesting direction for further research would be the contribution of DTs to a circular economy.

New business models
The focus of this research was on the added value of DTs in the primary business process of infrastructure contractors. However, the collected data along an asset's lifecycle using DTs provides a source of information that can potentially be used for offering data-driven services. Many industries are witnessing a shift from traditional product-centric business models to service-centric business models. In the context of manufacturing, DT proved to be supportive in this perspective (V. Martinez et al., 2019). Hence, an interesting direction for further research would be the possibilities to offer service business models using a DT in the context of the construction industry.

9 CONCLUSION & RECOMMENDATIONS

In this final chapter of the report, the key findings of the research are concisely summarised and the main research question is answered. Additionally, recommendations for Heijmans Infra are given in the light of their Digital Twin ambition for 2023.

9.1 Conclusions

The central problem of this research was that it remains unclear what a DT is and what it means for the organisation to use them. Consequently, this research aimed to answer the question: *What is a Digital Twin in the construction industry and how can it be utilised to create added value in the primary business process of contractors in the infrastructure sector?* This question centres around three cornerstones (i.e. what is it, how can it be utilised, and what is the added value?) that are answered separately:

What is a Digital Twin in the construction industry?

A DT is the virtual equivalent of a physical system that evolves along its lifecycle in a synchronous manner. DTs take a socio-technical perspective by reflecting both the elements and the dynamics of a physical system. Hence, they are not restricted to a representation of the technical details of an asset but also include relevant scenarios that help understanding and optimising how an asset is designed, constructed, operated or maintained. Based on a literature study, the DT in the context of the construction industry has been defined as:

> *The Digital Twin is the semantically linked collection of models, information and data that fully describes a potential or actual physical system, as such it forms a representation of all aspects of its corresponding physical system (e.g. properties, condition and behaviour) that could be relevant for the current or subsequent lifecycle phases. The Digital Twin is developed alongside its corresponding physical system and remains its virtual counterpart across the entire lifecycle, where it can be used to monitor, analyse, simulate and predict the performance of the physical system, leading to actions in the physical world accordingly.*

In this study, a framework has been developed that enables to classify DTs based on three dimensions:

- Attribute (Asset, Process, Fleet);
- Lifecycle phase (Beginning of Life, Middle of Life, End of Life);
- Extent of data integration (Digital Model, Digital Shadow, Digital Twin).

The novelty of this framework is that it merges three separate existing DT typologies into a single framework and thereby enables to substantiate six interrelated types of DTs for application in the construction industry. While the definition uses *physical system* as umbrella term to indicate the physical counterpart of the DT, the six types differentiate between Assets, Processes, and a Fleet of similar assets or process steps. In addition, the framework distinguishes between DTs deployed in the BOL phase (design & construction planning) and the MOL phase (construction and operate & maintain). While in the BOL phase the DT reflects a potential physical system, during the MOL phase it mirrors an actual physical system and synchronises the as-is reality. This synchronisation between the physical system and its virtual equivalent is established via data connections that can be either fully manual, partly automatic or fully automatic, respectively referred as Digital Model, Digital Shadow and Digital Twin. However, a full bi-directional connection (i.e. Digital Twin) is not possible for the majority of construction applications due to the limited ability of remote control over the physical system.

Ideally, the DT forms a representation of all aspects of its corresponding physical system. To realise this the DT comprises of six building blocks:

- *Physical layer* - all construction resources in the physical system;
- *Model layer* - virtual representation the physical system consisting of asset and scenario model;
- *Data layer* - responsible for the acquisition, processing, storage and integration of data;
- *Service layer* - user interface to the DT, presents the relevant information to the end-user;
- *Connection* - connects the other building blocks with each other using semantic technologies;
- *Enterprise layer* - external software tools in the organisation that could be linked to the DT.

These building blocks reflect the reference framework for DT in construction and give shape to the definition and types of DTs. They are based on a literature study regarding DT building blocks that found that existing reference frameworks are context dependent and influenced by the classification of a DT.

How can a Digital Twin be utilised?
DTs provide a means to monitor, analyse, simulate and predict the performance of physical assets and processes. They can thereby be used for virtual commissioning, evaluation of design and process configurations, (real-time) monitoring & control, (what-if) scenario & risk assessments, and information continuity along the lifecycle. Among others, these are proven value adding applications for DTs in industry. The applicability of DTs for infrastructure contractors has been studied by capturing the primary business process at Heijmans Infra and compare it with DT applications from different industries. This resulted in two practical examples for DT in the construction industry, which have been further detailed by means of developing a functional design:

- Simulation based optimisation of asphalt paving operations;
- Progress monitoring using field data capturing technologies for groundwork activities.

Simulation based optimisation of asphalt paving operations reflects an application for the DT Process BOL type. In this use-case, the DT assists work planners in making decisions regarding equipment deployment (trucks, pavers) by the ability to virtually evaluate multiple process configurations. The design adopts a data-driven simulation approach and relies on Discrete Event Simulations. The simulation model reconfigures automatically based on external data inputs to reflect changes in the process layout. Input data comprises of historical process data regarding travel times and productivity rates (Geboortekaartje asfalt), asset information (BIM model), resource availability, and cost statistics.

Progress monitoring using field data capturing technologies for groundwork activities can be classified as a DT Process MOL type. This use-case focused on progress monitoring in terms of schedule and budget and relied on a geometric comparison between the as-planned model (4D BIM) and as-built point-clouds on a reference moment. The DT automatically detects progress discrepancies compared from as-planned, which enables to derive progress estimations, visualise activities that are running behind of schedule, and highlight deviations from the design. Additionally, it can be used to provide project leaders with the quantities of work performed and work left as input for the financial prognosis.

What is the added value?
Validation of the two use-cases at construction practitioners revealed that DT applications can be expected to offer improved predictability of process outcomes, cost reductions, improved communication, and better financial control. These findings generally correspond to perceived benefits for DT applications in other industries, which comprise amongst other of greater efficiency, better informed decision making due to quantitative performance data and analytics, cost reductions, and better communication & documentation.

For the first use-case, work planners expect improved predictability of the process and cost reductions due to the ability to proactively manage situations where there is an under- or overcapacity in transport. In addition, simulation outcomes were considered to be a suitable communication tool towards asphalt production and transporters. The applicability for this use-case was considered to be the greatest for large projects, where potentially multiple asphalt plants are used simultaneously. To realise this value, this use-case affects the preparation process by a shift from working based on experience and assumptions to making decisions based on simulation outcomes.

The expected added value of the second use-case comprises of earlier identification of deviations with regard to schedule and better financial control through more accurate insight in the remaining quantities. This enables more reliable prognoses of the remaining costs. Furthermore, this type of DT can aid in finding the causes of deviations from the design, and thereby the implications for budget and schedule. In addition, when the progress is frequently captured using a point-cloud, it becomes better traceable when the deviations from the design started, which gives better insight of the affected activities. To realise this value, this use-case considerably affects the process of information retrieval from visual observation to a data-driven based workflow.

To conclude, Figure 53 summarises the main results of this research and their relation to the main question of this research. It also places the four sub-questions (RQ 1-4) that have been answered in perspective to the main question. The DT typology framework and DT building blocks are depicted in full scale in respectively Figure 12 and Figure 25.

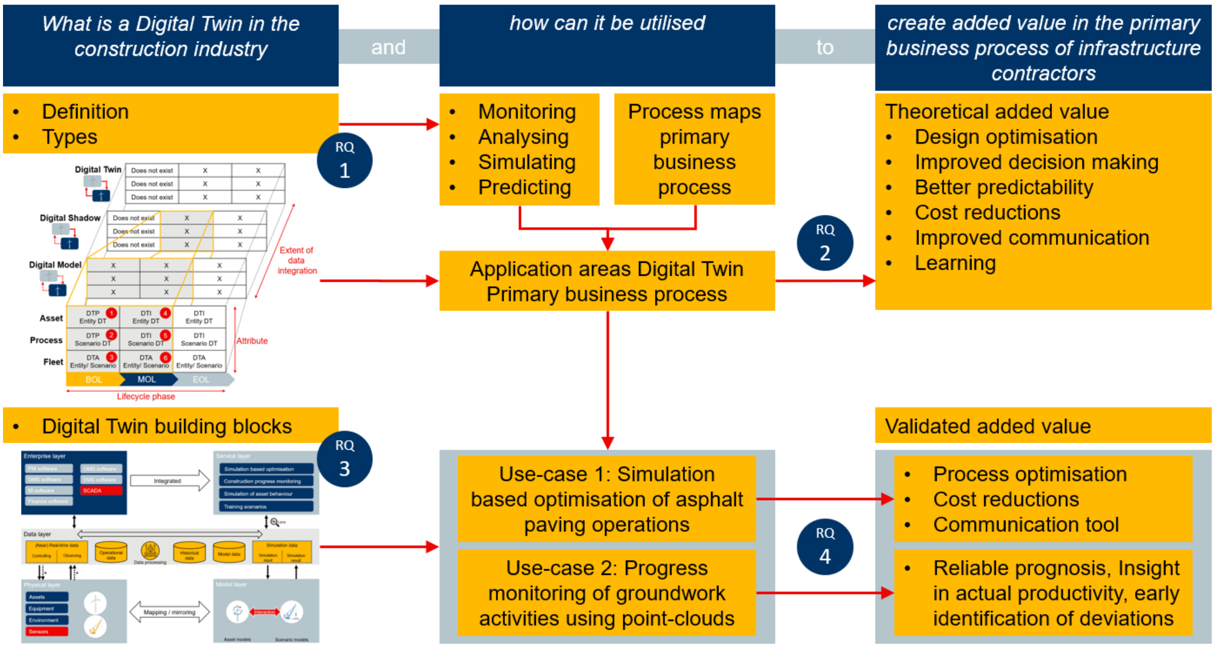


FIGURE 53: CONCLUSION IN ONE GLANCE

9.2 Recommendations

The rationale for conducting this research was Heijmans' ambition to have a DT on each project by 2023. The results of this research enable to make several recommendations with regard to this ambition:

- Focus on the DT process for relatively simple assets where no O&M is included in the contract;
- Validate the actual added value of the two use-cases with a Proof of Concept;
- Start with limited functionalities for both use-cases and build it modularly;
- Start with structured data collection using monitoring services;
- Focus on the digital skills and competences of employees.

One of the considerations to scope this research on the initial phases of the asset lifecycle was that Heijmans' business model is still centred around designing and constructing infrastructure assets. Many contract types only include the initial parts of the asset lifecycle (e.g. D&C). For these contracts, the added value of a DT Asset MOL is limited because typical applications for this type of DT (e.g. predictive maintenance) can be found in the O&M phase. Similarly, for projects that are rather simple in terms of the asset complexity and where no installations and system integration is involved, DT Asset BOL applications such as virtual testing have probably limited added value. For these types of projects, it is recommended to focus on the two DT Process types as these are expected to offer added value during the initial phases of the lifecycle. The two use-cases showed in a practical example how DTs can be used to optimise the process virtually using simulations and monitoring. The DT thereby provides a means of accurately knowing what is happening on the construction site and what has changed, which can be used as basis for decision making.

With regard to the two use-cases, validation showed that the stakeholders involved see added value in these applications. The concepts thus have potential, but the added value still needs to be validated in reality. The recommendation is therefore to select a pilot project for both use-cases and conduct a Proof of Concept (POC). In the POC it should be validated if the expected benefits as described in this research actually occur and whether the applications are indeed value adding. If this proves to be the case, the POC can be scaled up to multiple projects and possibly also the applicability of the concepts to other activities (e.g. progress monitoring for civil structures) can be considered.

To realise a POC, not all functionalities of the functional design have to be included immediately. Taking the example of simulation based optimisation of asphalt paving operations, the actual added value of this use-case can be validated by starting with a standalone simulation model that gradually grows towards a data-driven model if it proves to be valuable. During this process from a POC to operational application the robustness of the tool must be safeguarded.

Monitoring services during the construction phase with field data capturing technologies can provide a suitable step up to DT. It is recommended to start with monitoring services because the added value of monitoring is twofold. On one hand it facilitates accurate and reliable insights of what is happening on the construction site, which enables better control over the project. On the other hand, the collected data from monitoring provides valuable input for simulations during the design and construction planning phase. However, the case of asphalt paving showed that to realise this value, it may be necessary to capture other data than is currently done. That is, the usability of the transport registrations for simulation could be improved by also registering the departure time at the asphalt plant and arrival time at the project. Eventually, this enables the integration of site sensing measurements with digital models and the thereby structured recording of how assets are constructed. This would initially offer only limited possibility for analysis and reporting and leave insights open to human interpretation and decision-making. Gradually, the integration of intelligence in the DT in the form of data analytics (diagnostic, predictive, prescriptive) can provide more insights and enable optimisation services.

To wrap up, the integration of DTs in the primary business process provides not just a new digital technology but can considerably change the way processes are performed (e.g. by a shift from relying on experience to relying on simulation outputs). Most underlying technologies for DTs are mature or develop at a rapid pace. However, the structure of the DT building blocks and lenses reveals that various stakeholders need to contribute to the realisation and use of a DT throughout the asset lifecycle. Hence, in the light of the ambition for a DT on each project by 2023, it is pivotal that sufficient attention is paid to the digital transformation to examine what this ambition requires from employees in terms of digital skills and competences. Ultimately, this may be the biggest bottleneck in scalability of the DT concept.

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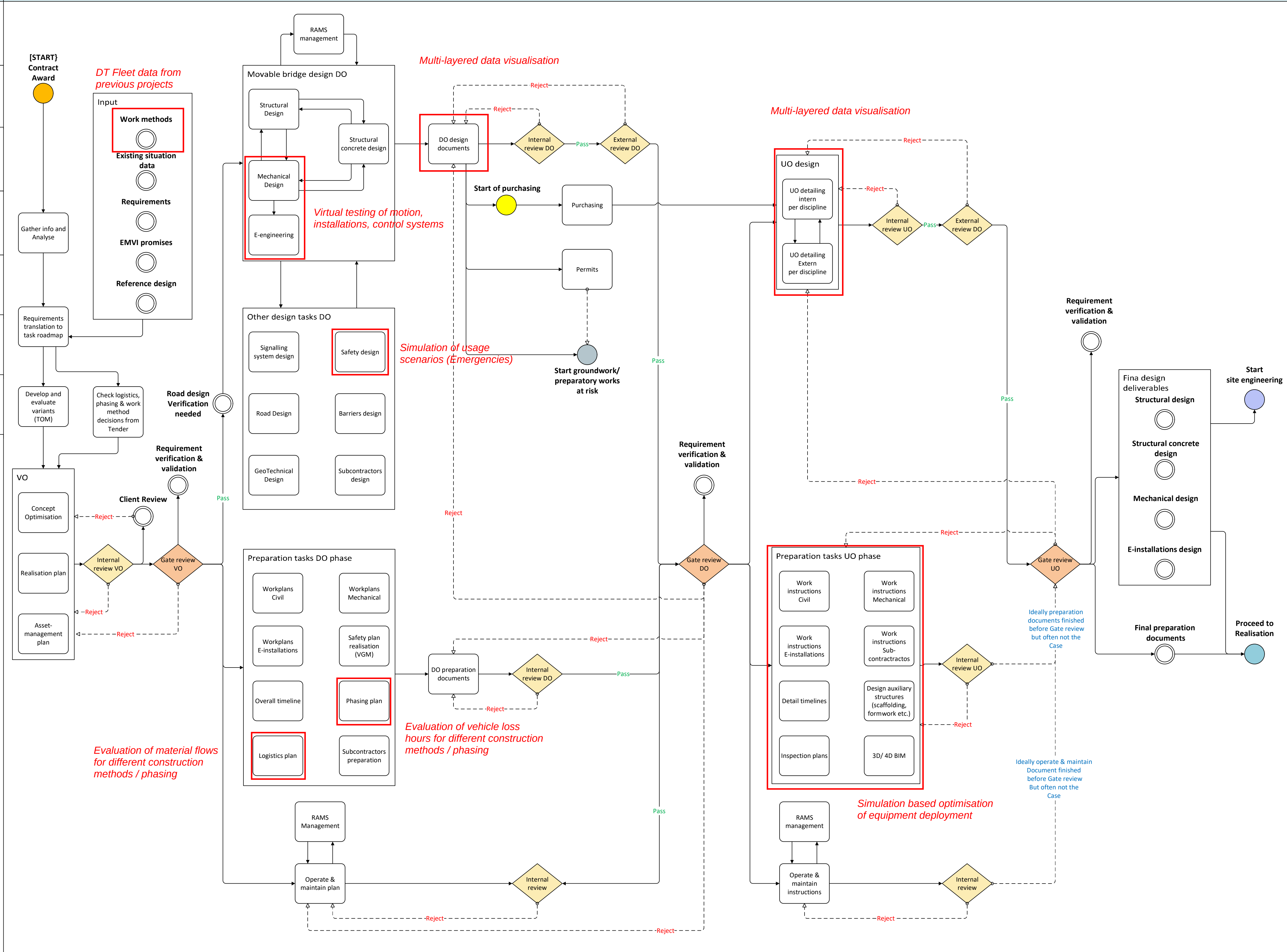
APPENDIX I – HIGH-LEVEL PROCESS MAPS PRIMARY BUSINESS PROCESS

SIPOC Diagram (Agreement of Process)	Customer		Version
	Location		Date
Objectives/Goals	Process Name	Sheet X of Y	Agreed By / Date
High-level process BOL phase - movable bridges	Process Manager		
	Process Owner		
	Stakeholders		

Supplier	Input
• Client	• Requirements • Work boundaries
• Tender team	• EMVI promises • Risks & opportunities
• Heijmans	• Design strategies • Work methods • Operate & maintain concepts
• Existing situation data (Multiple suppliers)	• Height map • Built environment • KLIC • Environmental conditions
• Architect	• Reference design
• Landscape Architect	• Reference design
• Design codes	• Calculation mehods • Input for loads

Process



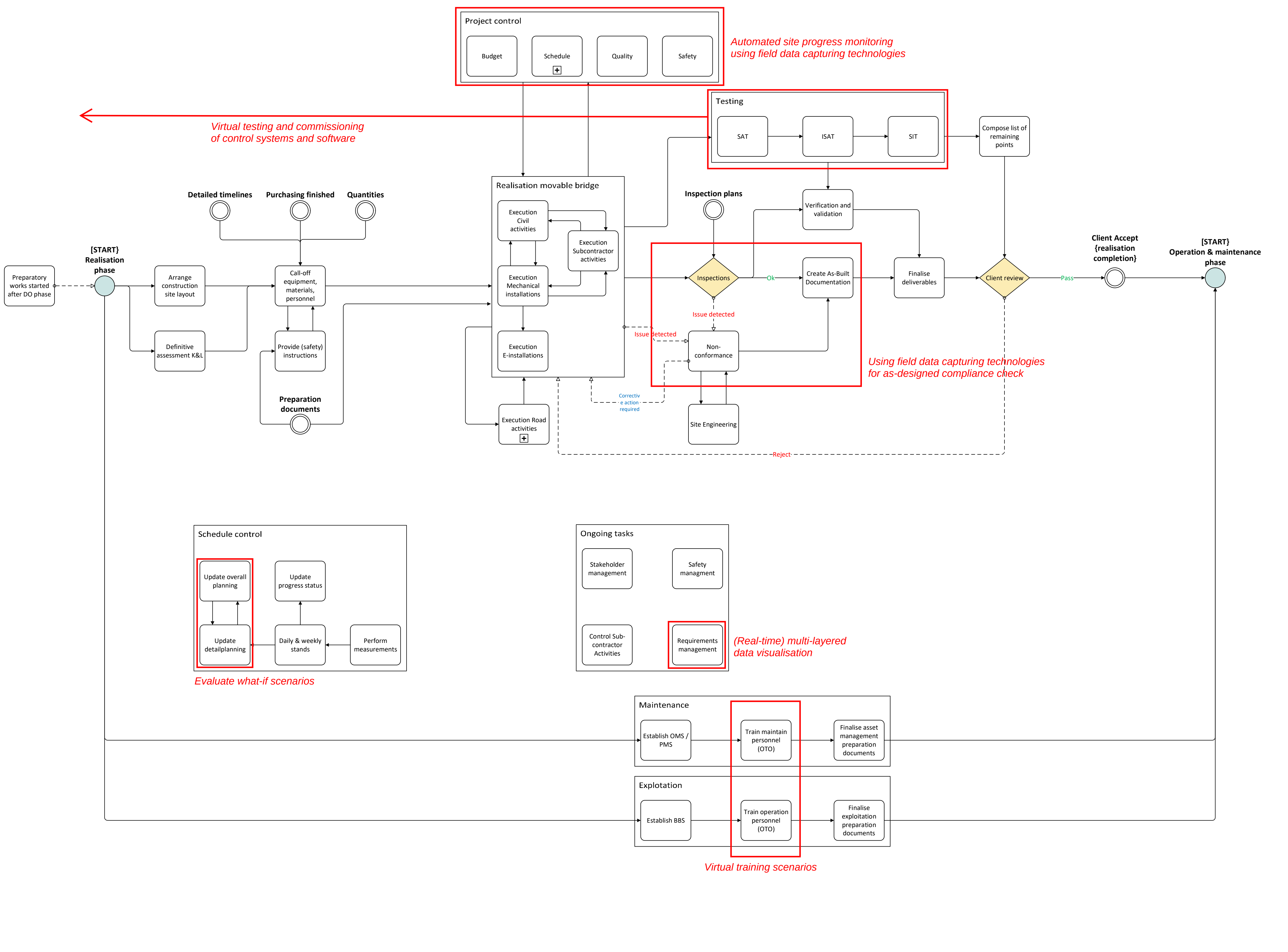
Output	Customer
• DO models & drawings	• Client • UO design team • Purchasing team • Permits • Subcontractors
• UO models & drawings	• Client • Realisation team • Subcontractors
• Preparation documents	• Realisation team • Client • Subcontractors • Suppliers
• Asset management documents	• Maintenance team • Eploitation team

Issue/Risk	Effect	Mitigation	Assumptions	Data Collected	Format/Technology	Participants

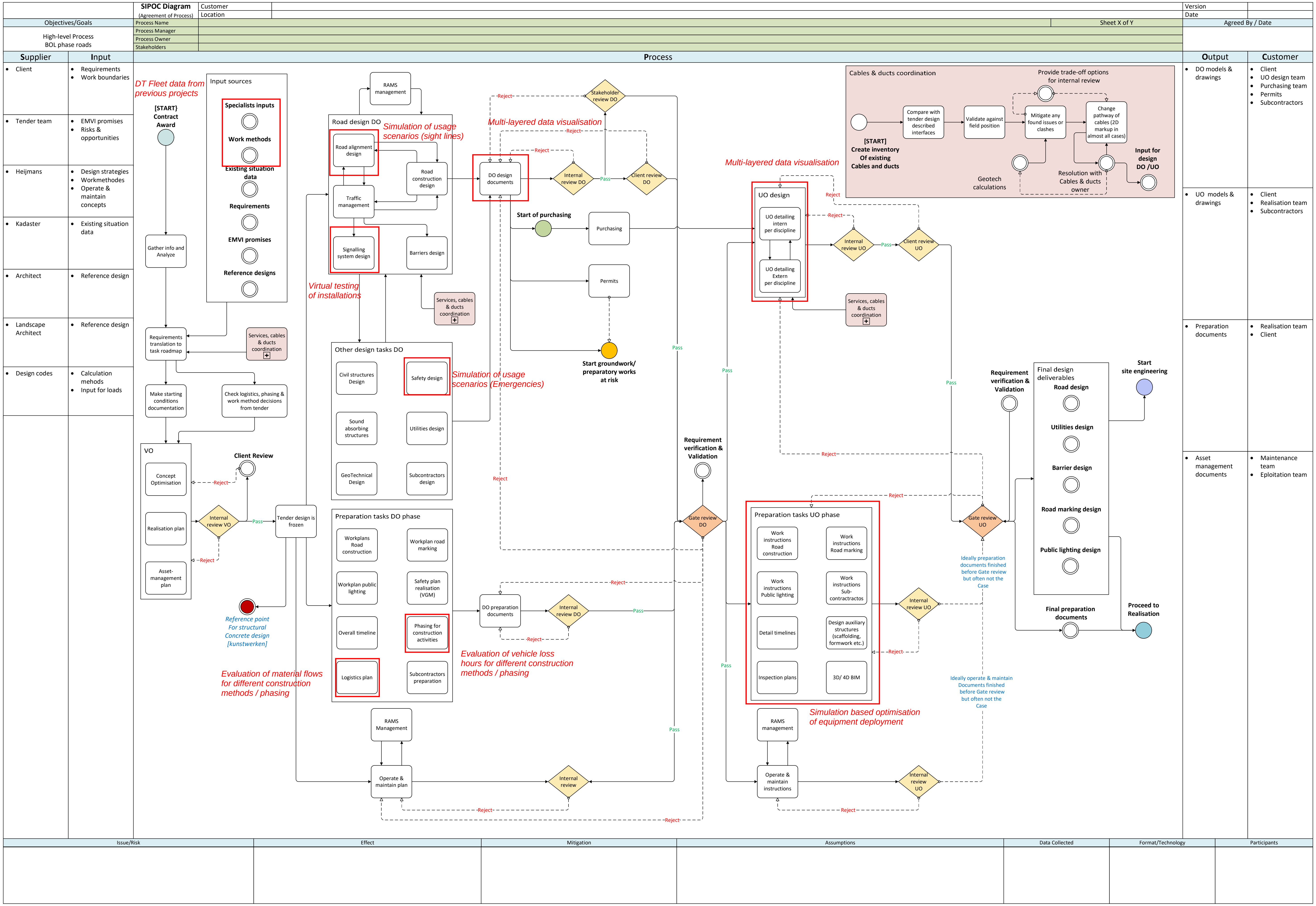
	SIPOC Diagram (Agreement of Process)	Customer		Version	
		Location		Date	

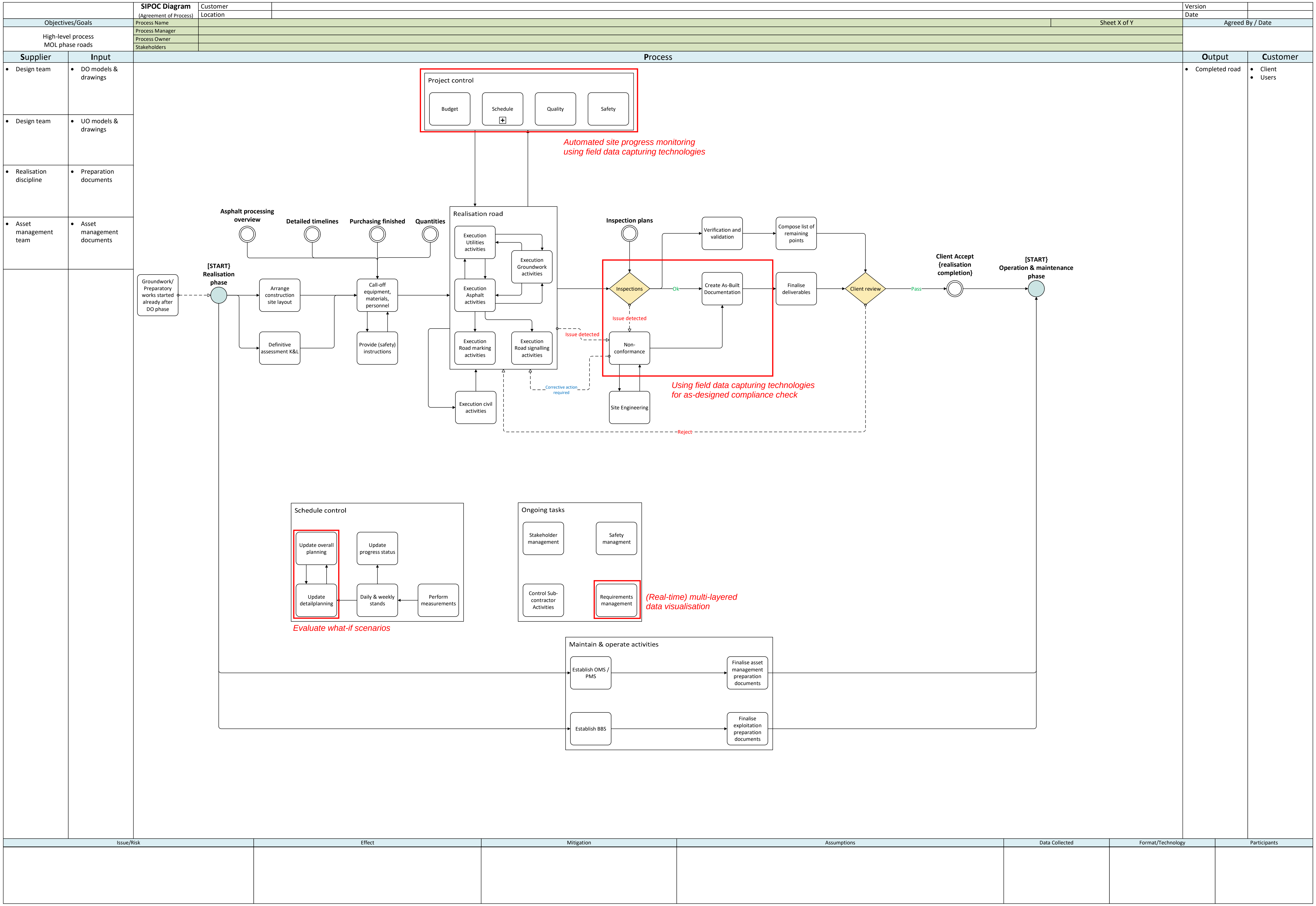
Objectives/Goals	Process Name		Sheet X of Y	Agreed By / Date
High-level process MOL phase movable bridges	Process Manager			
	Process Owner			
	Stakeholders			

Supplier	Input	Process	Output	Customer
• Design team	• DO models & drawings	(see diagram)	• Completed asset	• Client • Users
• Design team	• UO models & drawings			
• Realisation discipline	• Preparation documents			
• Asset management team	• Asset management documents			



Issue/Risk	Effect	Mitigation	Assumptions	Data Collected	Format/Technology	Participants


SIPOC Diagram
(Agreement of Process)
Customer
Location
Version
Date
Objectives/Goals
Process Name
Process Manager
Process Owner
Stakeholders
Sheet X of Y
Agreed By / Date
High-level Process
BOL phase roads
Supplier
Input
Process
Output
Customer
Client
Requirements
Work boundaries
Tender team
EMVI promises
Risks & opportunities
Heijmans
Design strategies
Workmethodes
Operate & maintain concepts
Kadaster
Existing situation data
Architect
Reference design
Landscape Architect
Reference design
Design codes
Calculation mehods
Input for loads
DT Fleet data from previous projects
[START] Contract Award
Input sources
Specialists inputs
Work methods
Existing situation data
Requirements
EMVI promises
Reference designs
Gather info and Analyze
Requirements translation to task roadmap
Services, cables & ducts coordination
Make starting conditions documentation
Check logistics, phasing & work method decisions from tender
VO
Concept Optimisation
Realisation plan
Asset-management plan
Internal review VO
Client Review
Tender design is frozen
Reference point For structural Concrete design [kunstwerken]
Evaluation of material flows for different construction methods / phasing
RAMS management
Road design DO
Simulation of usage scenarios (sight lines)
Road alignment design
Road construction design
Traffic management
Signalling system design
Barriers design
Virtual testing of installations
Services, cables & ducts coordination
Other design tasks DO
Civil structures Design
Safety design
Simulation of usage scenarios (Emergencies)
Sound absorbing structures
Utilities design
GeoTechnical Design
Subcontractors design
Preparation tasks DO phase
Workplans Road construction
Workplan road marking
Workplan public lighting
Safety plan realisation (VGM)
Overall timeline
Phasing for construction activities
Logistics plan
Subcontractors preparation
RAMS Management
Operate & maintain plan
Internal review
Evaluation of vehicle loss hours for different construction methods / phasing
DO preparation documents
Internal review DO
Stakeholder review DO
Multi-layered data visualisation
DO design documents
Internal review DO
Client review DO
Start of purchasing
Purchasing
Permits
Start groundwork/ preparatory works at risk
Requirement verification & Validation
Gate review DO
Reject
Pass
Cables & ducts coordination
Provide trade-off options for internal review
[START] Create inventory Of existing Cables and ducts
Compare with tender design described interfaces
Validate against field position
Mitigate any found issues or clashes
Change pathway of cables (2D markup in almost all cases)
Input for design DO /UO
Geotech calculations
Resolution with Cables & ducts owner
Multi-layered data visualisation
UO design
UO detailing intern per discipline
UO detailing Extern per discipline
Internal review UO
Client review UO
Services, cables & ducts coordination
Preparation tasks UO phase
Work instructions Road construction
Work instructions Road marking
Work instructions Public lighting
Work instructions Sub-contractractos
Detail timelines
Design auxiliary structures (scaffolding, formwork etc.)
Inspection plans
3D/ 4D BIM
Simulation based optimisation of equipment deployment
RAMS management
Operate & maintain instructions
Internal review UO
Internal review UO
Gate review UO
Ideally preparation documents finished before Gate review but often not the Case
Ideally operate & maintain Documents finished before Gate review but often not the Case
Requirement verification & Validation
Final design deliverables
Road design
Utilities design
Barrier design
Road marking design
Public lighting design
Final preparation documents
Start site engineering
Proceed to Realisation
DO models & drawings
Client
UO design team
Purchasing team
Permits
Subcontractors
UO models & drawings
Client
Realisation team
Subcontractors
Preparation documents
Realisation team
Client
Asset management documents
Maintenance team
Eploitation team
Issue/Risk
Effect
Mitigation
Assumptions
Data Collected
Format/Technology
Participants



SIPOC Diagram
(Agreement of Process)
Customer
Location
Version
Date
Objectives/Goals
Process Name
Sheet X of Y
Agreed By / Date
Process Manager
Process Owner
Stakeholders
High-level process
MOL phase roads
Supplier
Input
Process
Output
Customer
Design team
DO models & drawings
Design team
UO models & drawings
Realisation discipline
Preparation documents
Asset management team
Asset management documents
Completed road
Client
Users
Project control
Budget
Schedule
Quality
Safety
Automated site progress monitoring using field data capturing technologies
Asphalt processing overview
Detailed timelines
Purchasing finished
Quantities
Realisation road
Execution Utilities activities
Execution Groundwork activities
Execution Asphalt activities
Execution Road marking activities
Execution Road signalling activities
Execution civil activities
Groundwork/ Preparatory works started already after DO phase
[START] Realisation phase
Arrange construction site layout
Definitive assessment K&L
Call-off equipment, materials, personnel
Provide (safety) instructions
Inspection plans
Inspections
Ok
Issue detected
Non-conformance
Site Engineering
Corrective action required
Verification and validation
Compose list of remaining points
Create As-Built Documentation
Finalise deliverables
Client review
Pass
Reject
Client Accept {realisation completion}
[START] Operation & maintenance phase
Using field data capturing technologies for as-designed compliance check
Schedule control
Update overall planning
Update progress status
Update detailplanning
Daily & weekly stands
Perform measurements
Evaluate what-if scenarios
Ongoing tasks
Stakeholder management
Safety managment
Control Sub-contractor Activities
Requirements management
(Real-time) multi-layered data visualisation
Maintain & operate activities
Establish OMS / PMS
Finalise asset management preparation documents
Establish BBS
Finalise exploitation preparation documents
Issue/Risk
Effect
Mitigation
Assumptions
Data Collected
Format/Technology
Participants

APPENDIX II – CLASSIFICATION OF BIM / DIGITAL TWIN ISSUES IN THE CURRENT PROCESS

CLASSIFICATION OF DIGITAL TWIN / BIM ISSUES IN THE CURRENT PROCESS

Nr.	Issue
1.	It remains relatively **unclear for designers what information is required during the Construction and Operation & Maintenance (O&M) phase** due to the lack of a proper feedback loop. This results in missing information during Construction and O&M, which could lead to mistakes and rework. Furthermore, if there is any form of feedback loop from Construction or O&M towards the Designers, the **information remains often stuck on the project level, hampering inter-project learning.**
	The first issue ''unclear for designers what information is required during realisation and O&M'' is concerned with information management, as it is about delivering the right information to the right person at the right time. Therefore this issue can be classified as a **BIM issue.**
	The lack of a proper feedback loop from the Realisation and Operation and Maintenance (O&M) phase to the Design phase can be considered as a **DT issue**, as it is concerned with the synchronisation between physical (Realisation & O&M) and virtual space (Design). In the context of the manufacturing industry, it is widely discussed how a DT can improve Designs by leveraging designers insight in the manufacturing process, usage and wear of physical products.
	The lack of inter-project learning is **neither a specific BIM issue nor DT issue**, however, both concepts can support in the improvement of inter-project learning. Structured information, as cornerstone of BIM, is a prerequisite for effective inter-project learning. Additionally, DT technologies can be used to gain a better understanding of the actual performance of physical objects during operations and provide insights that could not directly be obtained by just looking at the physical object (e.g. using trend analysis).
2.	The successful application of 1 ontwikkelproces is often restricted to the VO and DO stage. Due to an overlap between design and construction schedules it becomes harder during the UO stage to stick to the Gate reviews. **Not all relevant documents for construction are finished when the designs are finished while some construction activities already have to start.**
	The issue ''Not all relevant documents for realisation are finished when the designs are finished'' concerns a **BIM issue**, as it mainly relates to information management and in particular delivering the right information to the right person at the right time. Furthermore, the issue regarding the unsuccessful application of 1 ontwikkelproces can be classified as a process/ workflow issue, which is more closely related to BIM than DT given the fact that BIM can be defined as ''a set of interacting policies, processes and technologies'' whereas DT is a technology.
3.	The development of an availability analysis (FMECA) in RAMS management remains a manual task. Consequently, once changes are made in the design, the analysis needs to be manually updated. It occurs that the **design develops so fast that there is insufficient time to the update the FMECA and the Fault Tree accordingly.**
	This issue is concerned with the ability to deliver ''an integrated design solution'', where also the goals and needs from the O&M phase are taken into account. As offering an integrated design represents BIM from the viewpoint of designers, this issue can be seen as a **BIM issue.** However, it should be noted that the evaluation of the effects on the availability of different scenarios, potentially using data from the field, can be regarded as a DT application. Therefore, this BIM issue may be mitigated using a DT.
4.	The interfaces between the disciplines in 1 ontwikkelproces are not properly defined. As a result, there is **insufficient coordination between design, realisation and O&M disciplines.**
	The fourth issue that has been identified concerns a lack of ''an interoperable process for project delivery''. This issue is concerned with how individual teams work and how different teams work together. This issue is mainly related to the collaboration of different disciplines on the project which is one of the key aspects of BIM. Therefore, this issue can be classified as a **BIM issue.**
5.	The realisation discipline often becomes later involved in the design process. Sometimes it is **not clear for them why certain design decisions have been made**. Trade-off matrixes could provide some guidance in the decisions that have been made but are not always easy to find.
	The fifth issue that has been identified is concerned with information management. Once again, this is an issue that is concerned with the delivery of the right information to the right person on the right team. Therefore, this issue can be classified as a **BIM issue.**

6.	**Inspection reports are currently mainly developed to verify requirements** and complete the project, not for improving the own workflow and/ or quality of the products.
	This issue mainly relates to a lack of learning within and between projects. Therefore, this issue does not concern a specific BIM or DT issue. However, if inspections reports should be used for the improvement of the own workflow and/ or quality of products, it can be argued that this concerns a **DT application** (e.g. trend analysis). The DT aspect here is that data from the construction or O&M phase of an asset (physical data) is brought to virtual space to improve the performance of another asset (physical space). Therefore, a bi-directional connection between virtual and physical space is established, which is the key characteristic of a DT.
7.	Sometimes there is **too much information on the drawings**, leading to a drawing that could not be overseen and interfaces are being overlooked.
	Another issue that has been identified concerns an overload of information on drawings leading to misinterpretations during the realisation phase. This issue is concerned with the visualisation of information, which could be more done in a more immersive way by exploiting different technologies (e.g. 3D/ VR/ AR). Besides the focus on the delivery of the right information to the right person at the right time, it can be argued that a fourth aspect of information management should be the delivery of information in the right manner. Therefore, this representation issue is classified as a **BIM issue.**
8.	There is often **no accurate overview of the actual progress on the projects**. In particular, this is the case at the installations and process automation activities.
	This issue is concerned with a lack of real-time insight in the progress of activities. Insight in the physical state is required to compare it with the as planned situation, which is virtual, to be able to adjust the As-planned situation based on actual progress. Therefore, this issue is concerned with the synchronisation between physical and virtual spaces and can thus be classified as a **DT-issue.**
9.	The **non-conformance and As-Built documentation processes are time consuming** and often have to be performed when the project team already partially left the project, putting pressure on the remaining project team members.
	This issue can be classified as **neither a BIM nor a DT issue**. It relates mainly to the current workflow used on the projects. However, if the building model would be updated according to the actual progress, it would provide a good basis for the generation of the As-Built dossier. Progress monitoring of construction activities provides the link between physical and virtual space and can be seen as a DT application.
10.	A general **lack of structured information** within and between the projects.
	○ On a tactical level there is no quick overview of what type of asphalt is used on different projects and it is often not possible to identify the conditions at which realisation was conducted when damage occurs.
	○ At the beginning of the project there is often no clear IPB structure, which comprises of the Functional Breakdown Structure (FBS), System Breakdown Structure (SBS) and Work Breakdown Structure (WBS).
	○ Lack of a proper Heijmans' Object type Library (OTL) and Activity Type Library (ATL).
	All issues above are related to information management and interoperability between different information constructs. The current information structure does not always effectively facilitate the delivery of the right information to the right person at the right time, which is a **BIM issue.**
11.	The establishment of the SBS for roads is challenging due to the lack of physically demarcated objects. In practice objects are often defined after construction took place.
	Similarly to the previous issue identified, this issue is concerned with a lack of structured information and therefore also related to information management, thus a **BIM issue**.
12.	Registration of some critical elements still takes place by scanning handwritten forms, making the **information not reusable** and limiting the learning from the registrations.
	This issue is related with the reusability of information, which is a subset of information management. Therefore, this issue can be classified as **BIM issue**. BIM requires structured information that can be reused throughout the entire lifecycle for the different purposes and shared between the different project participants.
13.	**The consequences of changes to the original plans during realisation cannot easily be overseen in an integral manner** (e.g. when there is a change in the start date of an activity, it is challenging to identify the consequences of that decision downstream in the process).
	This issue is concerned with the interplay between the actual progress in the real world and the planned situation in virtual word. Therefore, this issue is concerned with the bi-directional

	connection between the virtual and the physical space. Consequently, it can be considered as a **DT issue.**
14.	**Workplans/ -instructions are mainly created to verify realisation requirements an do not actually provide an instruction to perform the work** as the name would suggest. Therefore, it remains often unclear at the end of the design phase how the work will actually be conducted and if the design is constructible.
	The issue ‘’workplans/ -instructions are mainly created to verify realisation requirements’’ is concerned with an imperfection in the process/ workflow that is currently used. Workflow/ process issues are closer related to BIM than DT. Furthermore, it is concerned with information management, thus delivering the right information to the right person at the right time. Therefore this issue can be seen as mainly a **BIM issue.**
15.	Realisation often receives the designs very late resulting in a **lack of preparation time**.
	This issue is related to the delivery of the right information to the right person at the right time, thus information management. Consequently, it can be classified as a **BIM issue.**
16.	**Temporary structures and construction site logistics are insufficiently visualised**, resulting in clashes and rework during realisation.
	This issue relates to the lack of an integrated design process where also temporary structures and construction logistics are taken into account. Therefore, it can be classified as **BIM issue.** Furthermore, visualisation of temporary structures and construction site logistics can already be supported by current BIM technologies.
17.	**Actual progress is not used to improve the schedules of future projects.** Similarly, actual costing is performed but it remains vague how this improves cost estimations for future projects.
	These issues relates to a lack of learning from the construction phase for future construction planning phases. At a higher level of abstraction, this can be seen as bringing physical data to virtual space to improve physical space. Consequently, it can be argued that this relates to the synchronisation between physical and virtual space, thus a **DT issue.**
18.	The scheduling of equipment deployment is based on experience, not optimised using simulation models.
	The evaluation of different scenarios regarding equipment deployment using simulation models can be seen as an **DT issue** as the use of different kinds of simulations is among the key characteristics of a DT.
19.	Coordination between RAMS management and Asset Management is limited when there is no Maintenance component included in the scope of the contract.
	The final issue is concerned with ‘’an interoperable process for project delivery’’. It is about the way that different disciplines/ teams work together, which can be classified as a **BIM issue.** This issue can be seen as a collaboration issue between different disciplines.

APPENDIX III – LITERATURE REVIEW DIGITAL TWIN BUILDING BLOCKS

LITERATURE REVIEW DIGITAL TWIN BUILDING BLOCKS

This appendix provides a literature review of the publications that were concisely discussed in the main report.

Digital Twin building blocks - alternative 1
The first reference framework for DT building blocks is proposed by Josifovska, Yigitbas, and Engels (2019), who argue that the DT comprises of:

1. Physical Entity Platform (PEP);
2. Virtual Entity Platform (VEP);
3. Data Management Platform (DMP);
4. Service Platform (SP).

Their research focused on the development of a DT reference framework (Figure 1) for Cyber Physical Systems.

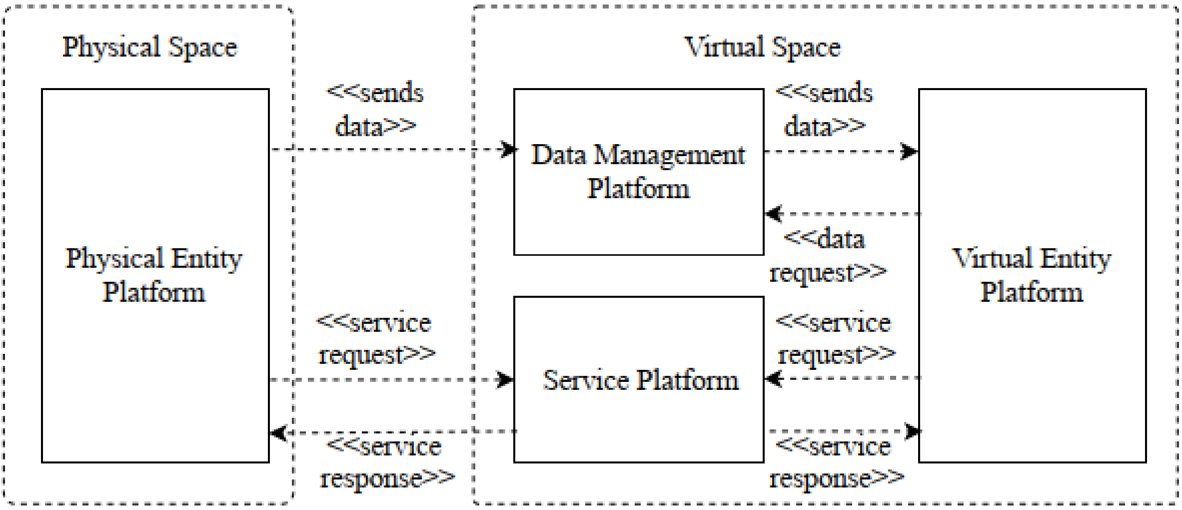


FIGURE 1: DIGITAL TWIN BUILDING BLOCKS. REPRINTED FROM " REFERENCE FRAMEWORK FOR DIGITAL TWINS WITHIN CYBER-PHYSICAL SYSTEMS" BY JOSIFOVSKA ET AL., (2019)

The PEP is located on the physical side of the DT and comprises two main elements: the physical object and the physical node. The physical object does not have abilities to communicate or to perform actions in the physical environment itself (i.e. it concerns an observable object that can be observed by other sensory devices). These sensory devices are included in the physical node, which reflects an entity that has the ability to observe a physical object.

The second element of the framework is the VEP that describes the aggregation of information from multiple models to represent various dimensions of the physical entity. These models include:

- Geometric model (shape, size, position);
- Physical model (function, capacity, applicable force);
- Behavioural model (communication with other entities);
- Rule model (domain knowledge in the form of rules);
- Process model (describes the underlying process in which the physical entity is active).

The DMP is responsible for the acquisition, management, storage of data. This building block comprises of data models and data management methods. The former integrate physical-, service-, virtual- and fused data. The latter is used for data collection, transmission, storage, integration, processing, cleaning, analysis, data mining and information extraction.

The SP enables the provision of services by the DT, which should ultimately lead to optimisations on the physical object. This layer comprises of service models and service management layers. The former relate to concrete services or applications that can be offered. The latter are concerned with controlling and managing the concrete services and ensuring service provisioning. Services can be found that relate to both the physical entity and virtual entity. The former includes for example monitoring, analysis and optimisation and the latter model testing, validation, calibration and process optimisation.

Digital Twin building blocks - alternative 2
Another classification for DT building blocks in existing literature is proposed by Damjanovic-Behrendt and Behrendt (2019). Their research focuses on the development of an open source architecture for the DT in the context of smart manufacturing. The DT building blocks of their framework comprise of:

- Virtualisation manager
- Monitoring manager
- Decision making manager
- Simulation manager
- Interoperability manager

As depicted in Figure 2, the *virtualisation manager* is the central element of the DT and can be further decomposed in the *data manager*, *models manager* and *services manager*. The *data manager* comprises of a *data acquisition* (e.g. sensor data, expert knowledge, historical data) and *data analytics* component. The *models manager* includes *data representation models* (static, structural models) and *data computation models* (dynamic, behaviour models). The *services manager* comprises of *analytics based services, connectivity services, visualisation dashboards* and *notebooks*. Another element of the DT framework is the *monitoring manager*, which provides the connectivity between the *virtualisation manager* and the physical assets. The *decision making manager* is the component responsible for the presentation formats of feedback that is generated using the analytics services of the *Virtualisation manager*. The *simulation manger* provides the simulation formats based on visualisation dashboard services of the *virtualisation manager*. The *interoperability manager* is responsible for the communication and integration between the different sub-systems.

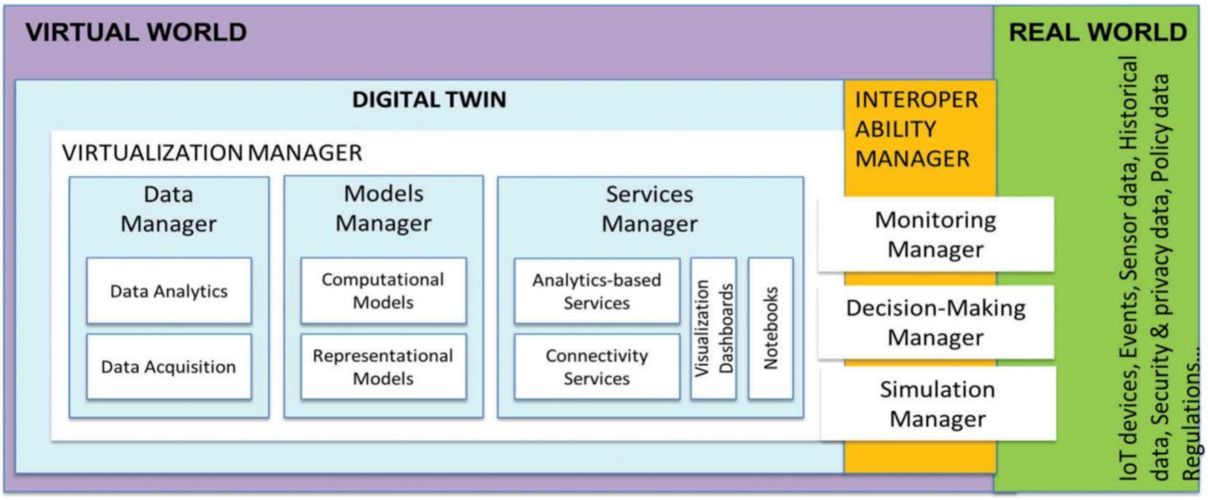


FIGURE 2: DIGITAL TWIN BUILDING BLOCKS. REPRINTED FROM "AN OPEN SOURCE APPROACH TO THE DESIGN AND IMPLEMENTAITON OF DIGITAL TWINS FOR SMART MANUFACTURING" BY DAMJANOVIC-BERENDT & BERENDT (2019)

Digital Twin building blocks - alternative 3
The third publication that defines DT building blocks (Figure 3) is Wang et al. (2019), who proposed a DT architecture for fault diagnosis in smart manufacturing. In their publication the following three DT building blocks are proposed:

- Digital Model
- Analytics
- Knowledge base

The *Digital Model* describes the structure of the subsystems, subassemblies and components. This block creates a unique model for each specific system including collected sensing measurements from manufacturing, operations and

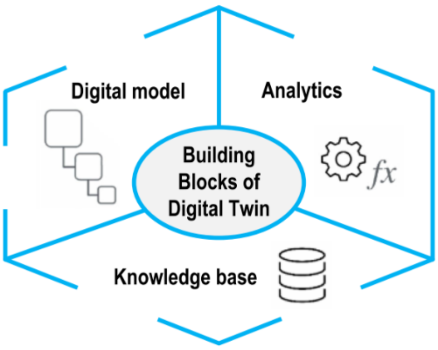


FIGURE 3: DIGITAL TWIN BUILDING BLOCKS. REPRINTED FROM " DIGITAL TWIN FOR ROTATING MACHINERY . . ." BY WANG, YE, GAO, LI, AND ZHANG (2019)

environmental factors. Additionally, the *Digital model* can be used to perform simulations with the aim of detecting normal and abnormal behaviour. *Data analytics* supports health management by providing digital simulation and data driven intelligence. The *Knowledge base* is formed by an analysis of repair reports and diagnostic experts. It reflects a collection of derived insights that include among other things failure modes, health indicators, diagnostic rules, threshold settings and operational risks. The *Knowledge base* grows along during the lifecycle of the physical asset as more data is analysed.

Digital Twin building blocks - alternative 4
Redelinghuys, Kruger, and Basson (2019) proposed a six layer architecture for DT in the context of the manufacturing industry. In addition, they also provide a six layer approach for the DT Aggregate, which defines how the connection between multiple DTs can be made. The six building blocks that they define are respectively: Devices and sensors, Data sources, Local data repositories, IoT gateway, Cloud-based information Repositories, and Emulation and simulation, as depicted in Figure 4. From this figure it follows that this architecture can be applied for a single instance as well as multiple instances. Additionally it is demonstrated how the two types of DT are interrelated.

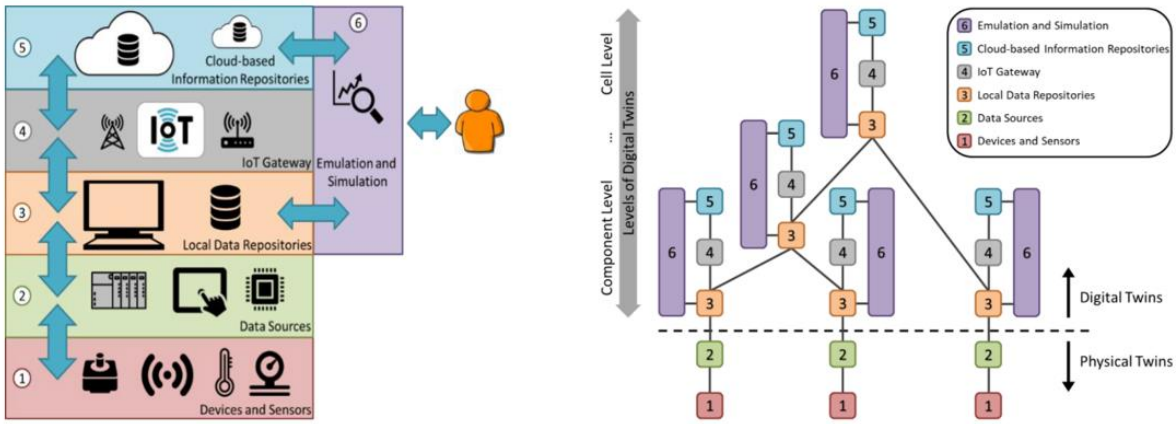


FIGURE 4: DIGITAL TWIN ARCHITECTURE. REPRINTED FROM REDELINGSHUYS ET AL. (2019)

Digital Twin building blocks - alternative 5
The fifth publication that proposes DT building blocks is Zhang et al. (2019). This publication focused on the development of a reconfigurable layout for DTs of manufacturing systems, which comprised of the following building blocks:

- Physical layer
  - All manufacturing resources
- Model layer
  - Geometric model
  - Physical model
  - Capability model
  - Behaviour model
  - Rule model
- Data layer
  - Operating data
  - History data
  - Knowledge data
  - Model data
- Service layer
  - Upgrade design
  - Reconfiguration
  - Status analysis
  - Components library
  - Result prediction
  - Data management

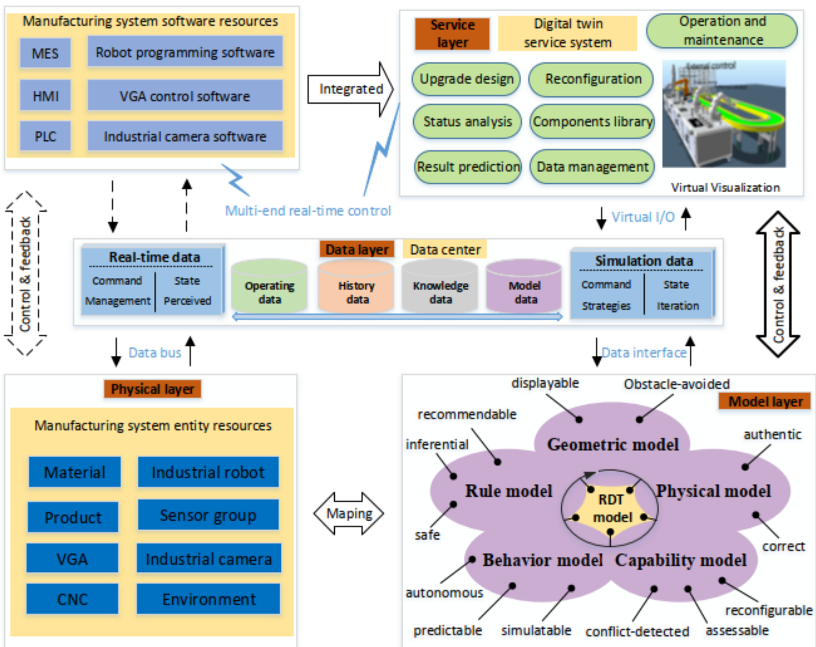


FIGURE 5: DIGITAL TWIN BUILDING BLOCKS. REPRINTED FROM "A RECONFIGURABLE MODELING APPROACH FOR DIGITAL TWIN BASED MANUFACTURING SYSTEM" BY ZHANG ET AL. (2019)

The DT reference framework of Zhang et al. (2019) is depicted in Figure 6. The physical layer is located on the real-world side of the DT and concerns the collection of resources that the DT mirrors or requires to mirror the corresponding physical entity (e.g. sensors). The model layer is located on the virtual side of the DT and forms the key element of the DT framework. The five-dimensional RDT model, which is located in the centre of the model manager, reflects the ontology of all entities in the physical layer. It describes each physical entity in terms of its geometry, physics, capability, behaviour and rules. Thereby it fully mirrors the corresponding physical entity. The data layer comprises of databases, data transmission protocols and data interaction channels, which are responsible for transferring and storing the process data, operation data, model data and knowledge data. This supports not only the visualisation of the real-time manufacturing process status and data, but can also be used for upgrades and optimisations based on historical data and knowledge. The service layer integrates the functions of various software and employs data processing algorithms to form a DT service system with a virtual platform and capabilities of simulation, remote monitoring, controlling, dynamic data analysis, system design, performance evaluation, results prediction, reconfiguration, etc. (Zhang et al., 2019).

Digital Twin building blocks – alternative 6

Zheng and Sivabalan (2020) developed a DT framework in the context of smart manufacturing. They argue that the DT can operate in two main modes: monitoring mode and control mode. In the former, the DT mirrors the physical entity while having limited supervisory control over the physical entity whereas in the latter the DT exercises the complete control over the physical entity and acts as a controlling device for the physical entity. The four DT building blocks included in their framework are:

- Physical layer
- Data extraction and consolidation layer
- Cyberspace layer
- Interaction layer

The physical layer includes all physical elements in the physical environment. Additionally it comprises of communication protocols and communication interfaces. During the control mode, the physical layer is the end actuated layer while in the monitor mode the physical layer is the initiation point.

The data extraction and consolidation layer forms the connecting element between the physical layer and the cyberspace layer. This layer receives the data from the physical entities, processes the data and converts it into a machine readable format before processing it to the cyber layer. In the control mode, this element acts as the bridge from the cyberspace layer to the physical layer by distributing the consolidated information that is received from cyber layer to the physical entities.

Cyberspace layer forms the core of the DT architecture and is the layer in which DT is established. The cyberspace layer contains the Tri-model DT. These three models are interconnected and controlled by a Digital Twin API that is also responsible for data transmission and reception to and from the cloud storage. The three models included in the cyber layer are digital model, computational model and graph based model. The digital model provides the virtual representation of the physical entity as well as the environment in which it is active. Besides the geometrical constraints, the laws of physics that govern the physical object must be added to a digital model to make it a 'real twin'. It is also necessary to include these physical attributes so that the digital twin can be used in a simulated run to determine the point and cause of failure before operating the physical system. This is captured in the computational model. interactions and relations can be defined in a graph-based model, where a complex and innumerable amount of interactions and relations can be set up and stored.

The interaction layer is the final layer of the DT framework and enables the interaction of human operators with the physical system using the DT. It provides the user interface

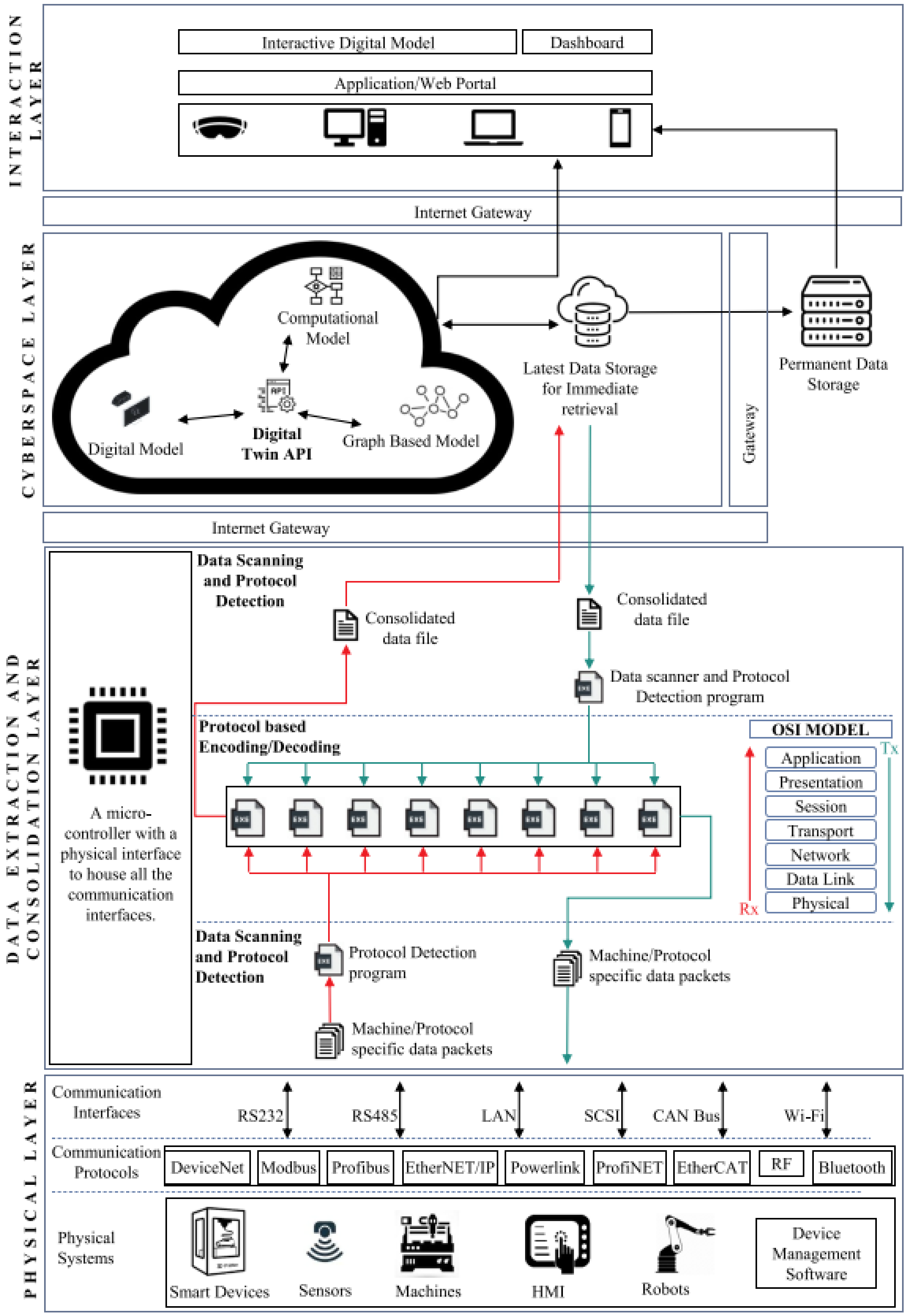


FIGURE 6: DIGITAL TWIN BUILDING BLOCKS. REPRINTED FROM "A GENERIC TRI-MODEL-BASED APPROACH FOR PRODUCT-LEVEL DIGITAL TWIN" BY ZHENG AND SIVABALAN (2020).

Digital Twin building blocks - alternative 7

Another framework for DT building blocks is proposed by Parrott and Warshaw (2017). Their architecture for the DT aims at giving an overview of the enabling components that form the DT of a manufacturing process. They argue that the DT ''conceptual architecture may be best understood as a sequence of six steps'', which are: Create, Communicate, Aggregate, Analyse, Insight and Act. To perform each of these steps, different enabling technologies are used, which are depicted in Figure 7. Different modelling techniques are used to represent the physical process in virtual space. Sensors are used to collect operational data as well as contextual information from the process, which are transferred to the virtual platform using different communication interfaces. Additionally, the data captured from the sensors may be augmented with process based information from the manufacturing execution system, enterprise resource planning systems or CAD models. Subsequently, the data is processed in virtual space using different data processing techniques. The outcomes of the data analysis can be presented using notifications, visualisations or dashboards. The actionable insights that are presented using these data representation methods can be used to take actions accordingly. This can be done either manual or using actuators. The latter options reflects a fully autonomous bi-directional connection between virtual and physical space.

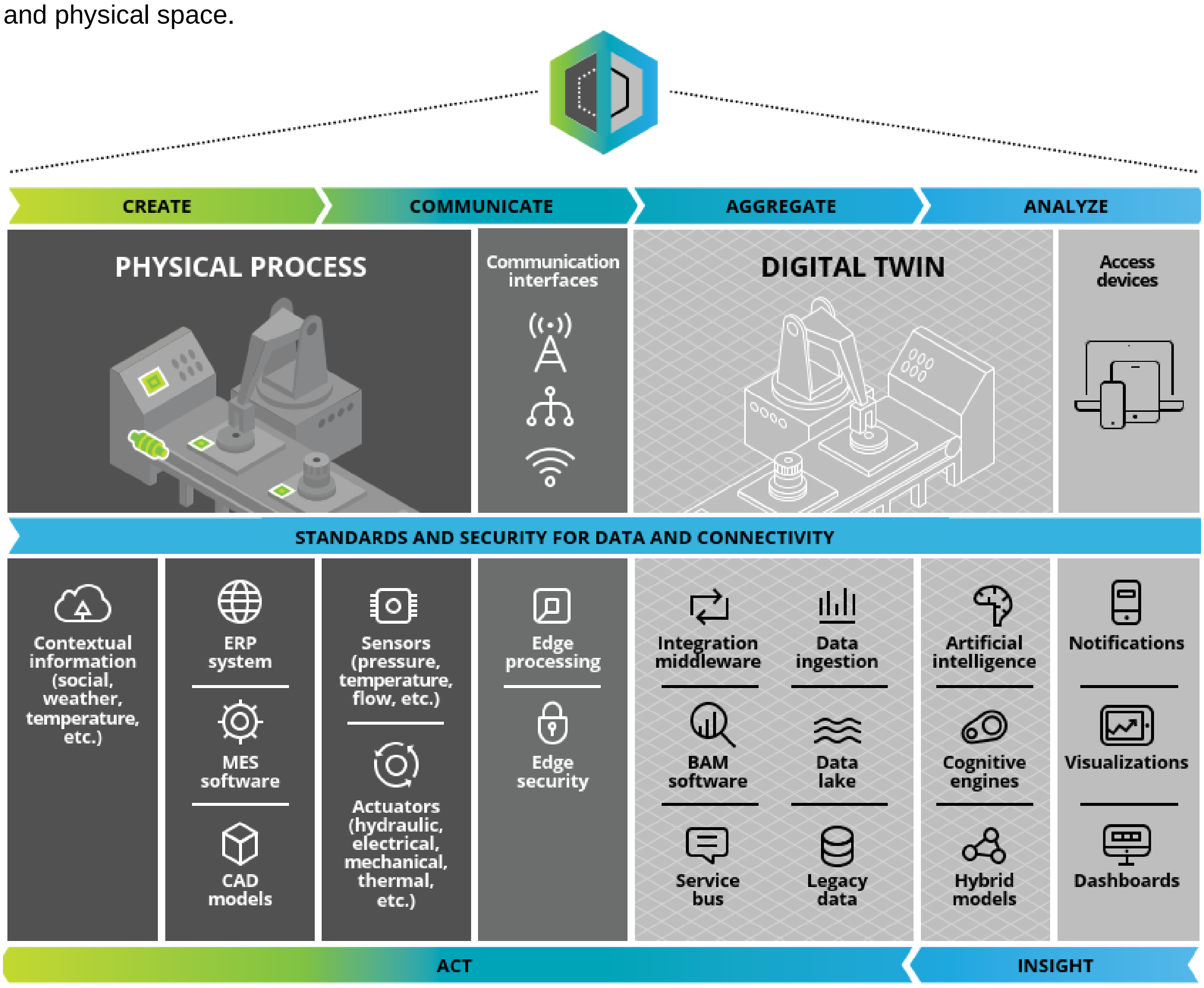
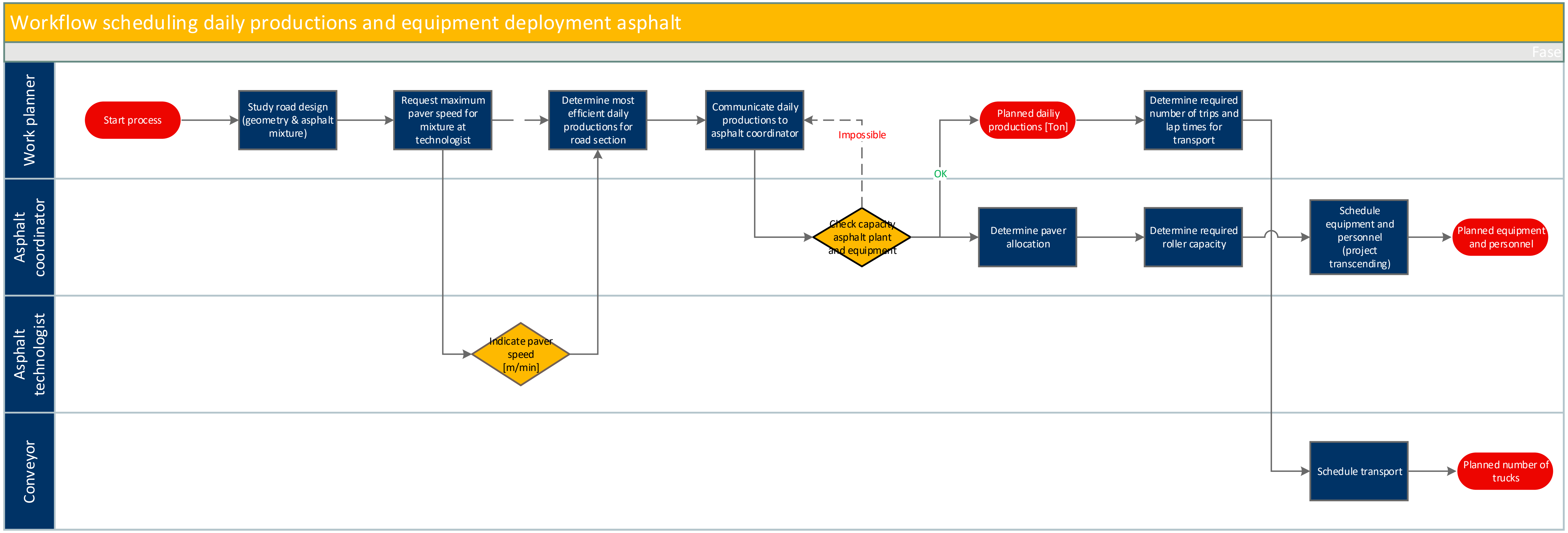
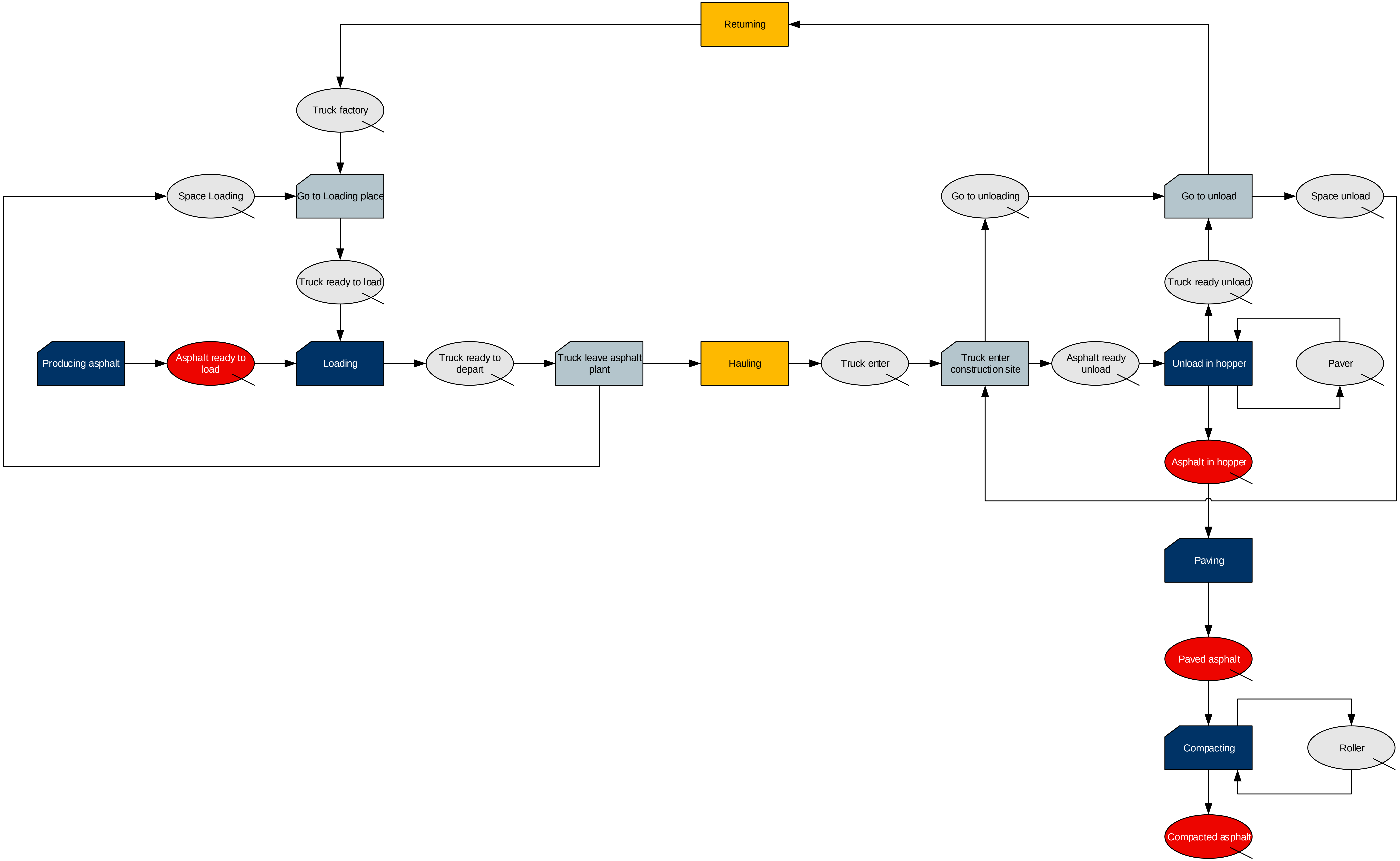


FIGURE 7: DIGITAL TWIN BUILDING BLOCKS. REPRINTED FROM '' INDUSTRY 4.0 AND THE DIGITAL TWIN'' BY PARROTT AND WARSHAW (2017)

APPENDIX IV - CURRENT PROCESS PREPARATION ASPHALT PAVING OPERATIONS

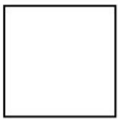
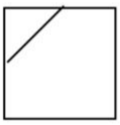
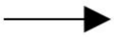

Workflow scheduling daily productions and equipment deployment asphalt
Fase
Work planner
Asphalt coordinator
Asphalt technologist
Conveyor
Start process
Study road design (geometry & asphalt mixture)
Request maximum paver speed for mixture at technologist
Determine most efficient daily productions for road section
Communicate daily productions to asphalt coordinator
Impossible
OK
Planned dailiy productions [Ton]
Determine required number of trips and lap times for transport
Check capacity asphalt plant and equipment
Determine paver allocation
Determine required roller capacity
Schedule equipment and personnel (project transcending)
Planned equipment and personnel
Indicate paver speed [m/min]
Schedule transport
Planned number of trucks

APPENDIX V – DISCRETE EVENT SIMULATION LAYOUT ASPHALT PAVING OPERATIONS


Returning
Truck factory
Space Loading
Go to Loading place
Truck ready to load
Go to unloading
Go to unload
Space unload
Truck ready unload
Producing asphalt
Asphalt ready to load
Loading
Truck ready to depart
Truck leave asphalt plant
Hauling
Truck enter
Truck enter construction site
Asphalt ready unload
Unload in hopper
Paver
Asphalt in hopper
Paving
Paved asphalt
Compacting
Roller
Compacted asphalt

DISCRETE-EVENT-SIMULATION LAYOUT ASPHALT PAVING OPERATIONS.

The appendix provides a brief explanation on the example of the DES layout for asphalt paving operations that was presented in the main report. The DES model includes multiple symbols, which have the following meaning:

Symbol	Name	Definition
	NORMAL	The normal work task modeling element, which is unconstrained in its starting logic and indicates active processing of (or by) resource entities.
	COMBI	The constrained work task modeling element, which is logically constrained in its starting logic, otherwise similar to the normal work task modeling element.
	QUEUE	The idle state of a resource entity symbolically representing a queuing up or waiting for use of passive state of resources.
	ARROW	The resource entity directional flow modeling element.

From the DES simulation layout, it follows that the elements included in dark blue are the time consuming COMBI activities and the yellow blocks are the NORMAL activities. The elements in grey and red reflect the Queues that may arise for COMBI activities. Considering the process, loading of the trucks at the asphalt plant is an activity that is constrained in its starting logic by the queues ''Trucks Ready to Load'' and ''Asphalt ready to Load''. If one of these queues is empty (i.e. if no resource is available), the activity does not commence. Once the activity commences, the resources are busy and the simulation clock advances for the pre-determined time based on the inserted probability distribution that defines the time loading takes. After loading, the truck is ready to depart from the asphalt plant, this in turn releases the resource ''Space loading'' that reflects the loading space at the asphalt plant that was seized during the loading activity. Subsequently, hauling to the construction site takes place, which is an unconstrained activity after the truck left the asphalt plant and is therefore modelled as a NORMAL in the model. The ''truck enter'' queue reflects a spot where trucks can wait until they allowed to enter the construction site, as the site may have limited capacity to accommodate trucks. Once the truck is allowed to enter the construction site it arrives in a queue where it waits for an unloading spot to be released (i.e. until the preceding truck moves away from the paver / shuttle buggy). Subsequently, the truck dumps the asphalt in the hopper of the paver/ shuttle buggy and returns to the asphalt plant, and thereby releases the unloading spot for trucks waiting. Once the truck arrives back at the asphalt plant it waits in the queue ''Truck factory'' until a loading spot at the asphalt plant is released and the truck can be loaded again.

APPENDIX VI - DATA ANALYSIS PAVER & TRANSPORT REGISTRATIONS

DATA ANALYSIS PAVER & TRANSPORT REGISTRATIONS

A large collection of historical process data regarding asphalt paving is available at Heijmans as part of the internal improvement program ''Geboortekaartje asfalt''. In order to check whether this data could potentially be used as input for a simulation model, a small data analysis was conducted. The data set for this analysis comprised of the registrations of the pavers and trucks for the case project.
The data analysis aimed to answer three questions:

1. Can stops in the paving process be traced back to waiting for trucks to arrive?
2. What does the distribution of the travel times look like?
3. Does the data indicate opportunities for improvement of the paving process?

The first question aimed to check the reliability of the data based on some random samples. This is mainly relevant for the transport registrations, as these are partly registered by manual handling (reporting of the unloading times). Although some errors were found in the dataset (e.g. 10 trucks were unloaded in 1 minute), the majority of the data seemed relatively accurate. This was checked by comparing the paver registrations (which are automatically captured) with the transport registrations and see if stops of the paver can be traced back to waiting for trucks to arrive. A sample of the dataset showed that this was often the case, one of these examples is depicted in Figure 1. From this figure it follows that there is a long stop during the process. On first hand, the stop seems to take around 70 minutes, however, by zooming in it can be seen that it concerns two consecutive stops of respectively circa 70 and 60 minutes, thus a total of more than 2 hours waiting time. Comparing this with the transport registrations, it can be seen that the one truck was reported unloaded at 10:00 and the next one at 12:06, which corresponds with the waiting time registered by the paver. Based on a number of samples, similar observations were found. Therefore, it seems that the data gives a good representation of the actual transport movements. However, this is based on a small sample that should not be regarded as a significant outcome. Further analysis is needed to establish this with certainty.

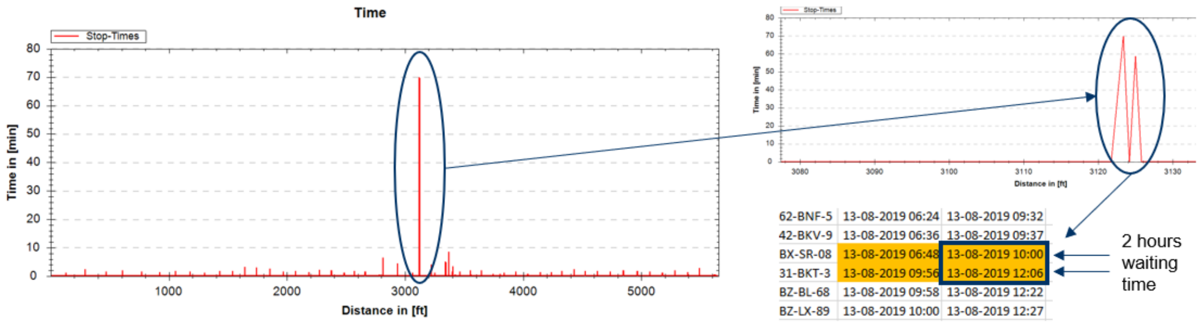


FIGURE 1: CHECKING RELIABILITY OF TRANSPORT REGISTRATIONS

The second question aimed to identify the distribution of the travel times. To answer this question, all data sets available for the transport were merged and the registrations for the case project were filtered out. The majority of registrations only included the weighing time at the asphalt plant and the unloading time at the project. Consequently, the actual travel time could not be deduced from these registrations. For some registrations, however, the departure time at the asphalt plant and the arrival time at the project were entered as well. These measurements provide an indication of the actual transport time. From Figure 2 it follows that this applied for 85 registrations, which had an average transport time of 1 hour and 43 minutes as opposed to an average time of 2 hours and 44 minutes between weighing and unloading for the same asphalt plant. This indicates that on average, waiting on the project to unload and the unloading itself takes approximately one hour.

A1AA [WEEGTIJD-LOSTIJD]			
	Den Bosch	Amsterdam	Deventer
MEAN	02:44	03:19	01:00
STDV	00:39	01:36	00:29
n	636	104	90

A1AA [AANKOMST PROJECT-VERTREK CENTRALE]			
	Den Bosch	Amsterdam	Deventer
MEAN	01:43		
STDV	00:17		
n	85	2	0

FIGURE 2: TRANSPORT TIMES

To visualise the distribution of the transport, the 85 registrations that reflect the actual travel times were plotted. The hypotheses was that a right-tailed distribution would occur, as travel times have a certain minimum which cannot be shorter while they can be much longer due to delays. From Figure 3 it follows that the actual distribution indeed shows a distribution which tends to take the form of a right-tailed distribution. However, it is not a smooth line, which can have multiple causes. Firstly, the small sample size, as it is based on only 85 measurements. Secondly the assumption here is that all registrations would have the same travel distance, which is not the case in reality because it concerns data from paving operations on multiple parts of the project. Thirdly, the originates from paving operations that are performed during weekdays, weekends, and nights, which could affect the travel times.

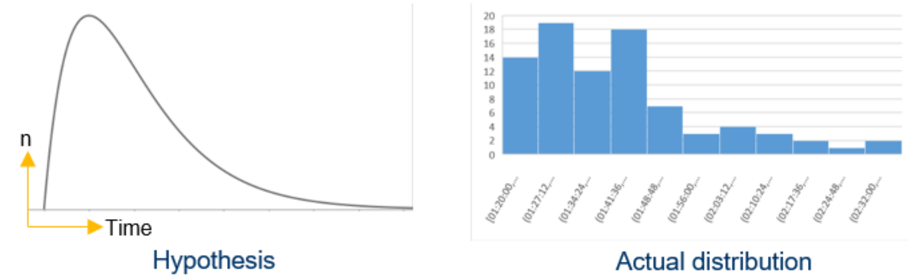
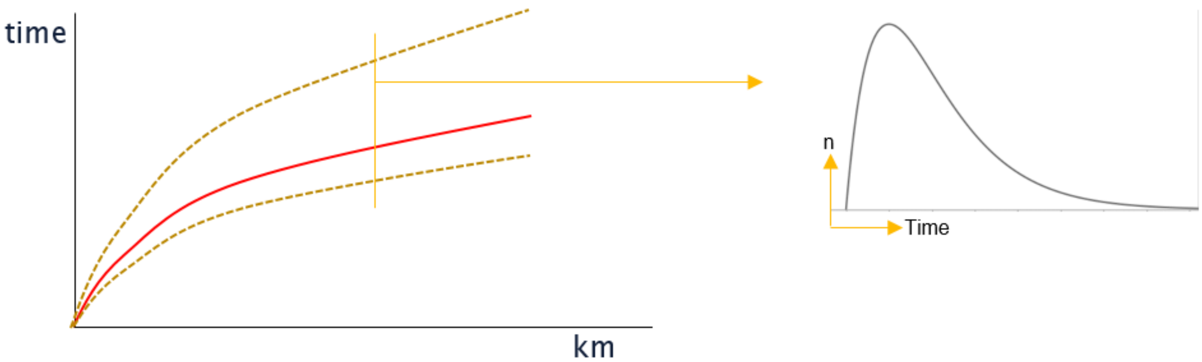


FIGURE 3: DISTRIBUTION OF TRAVEL TIMES

Figure 3 shows the distribution of the travel times for 1 specific project, however, as input for a simulation it would be better to have reusable information. This can be realised by establishing a kilometre/ time factor for each of the asphalt plants based on historical data. Every transport registration includes the origin (asphalt plant) and the coordinates of the destination (unloading spot). Hence, it would be possible to determine for each trip the exact travel distance and couple this to the corresponding travel time. Doing this manually would be unfeasible, however, there exist different types of software that can be used to automatically determine the road distance between two points in a matrix. These include for example Azure Maps API, Google distance matrix API of BING distance matrix API. The hypothesis is that performing such an analysis would result in a distribution as depicted on the left side of the figure below. A cross section of this figure would give a right-tailed distribution on any travel distance. A further data analysis should demonstrate whether this is actually the case.



The third question that was investigated concerned if the data indicates opportunities for improvement of the paving process. This was done by analysing a typical day at the case project. Given the large travel distance between the project and the asphalt plant, the trucks drive only two trips on a day and asphalt is produced in two batches at the plant. In addition, it is decided to operate the paver at a higher speed during batch 1 to let the trucks return to the plant as soon as possible. The difference in paver speed between batch 1 and 2 can clearly be seen from Figure 4.

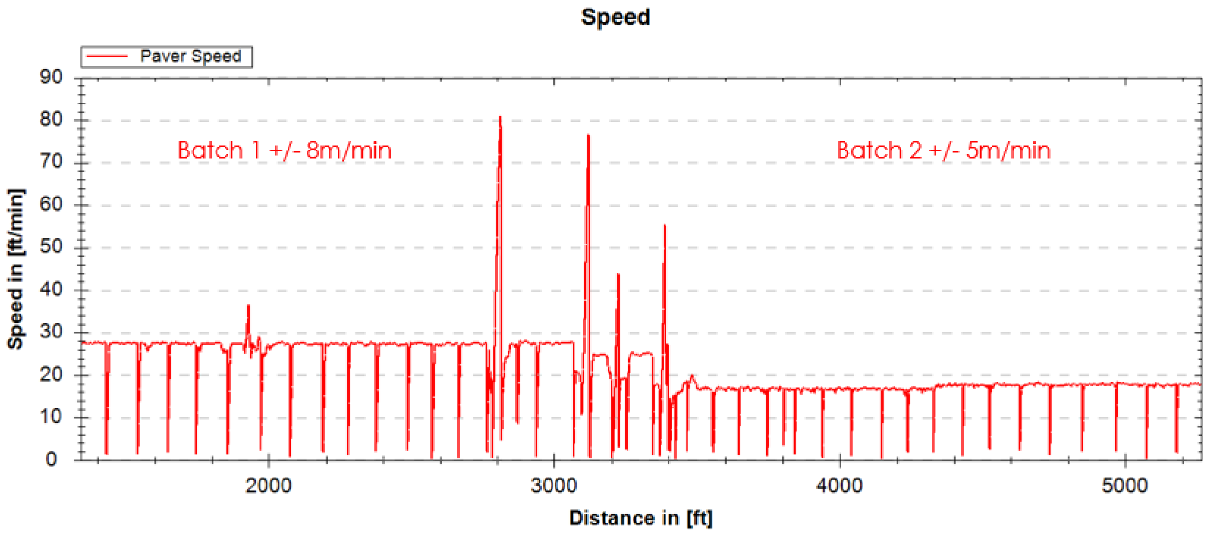


FIGURE 4: DIFFERENCE IN PAVER SPEED DURING BATCH 1 & 2

However, from the data it follows that the decision to use different speeds during batch 1 and 2 results in waiting trucks during batch 2, as explained in the figure below. This may cause unnecessary costs. Additionally, the decision to use a higher paver speed during batch 1 may result in a lower end quality.

	Frequentie weegtijden	Frequentie lostijden
MEAN ALL	00:05	00:08
STDV ALL	00:03	00:04
MEAN Batch 1	00:05	00:06
STDV B1	00:04	00:03
MEAN Batch 2	00:05	00:09
STDV B2	00:03	00:05

Deviation in average time between 2 unloading moments in Batch 1 & 2 → in Batch 1 a truck is unloaded every 6 min on average (corresponding with a paver speed of 8m/min), while in Batch 2 this is every 9 min (corresponding with a paver speed of 5,5m/min).

Assuming equal travel times, the waiting time per truck will increase by 4 min on average. So after 10 trucks +/- 40 min. Total waiting time $\sum_{i=1}^{n} 4i$ min which gives 1200 minutes for the 24 trucks used.

No difference in the average time between two weighing moments in Batch 1 &2 → on average each 5 min a truck leaves the asphalt plant for both Batch 1& 2

APPENDIX VII – CURRENT PROCESS PROGRESS MONITORING GROUNDWORK ACTIVITIES

Huidige proces voortgang monitoren & bijsturen - Grondverzet