Digital twinning development in manufacturing SMEs – the design of a supporting methodology and evaluation tool

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Master thesis

DELWIGROENINK MACHINEFABRIEK

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Information page

Master thesis

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Preface

This combined thesis assignment marks the end of my master programmes Industrial Design Engineering and Mechanical Engineering. Throughout my master I enjoyed the opportunity to dive deeper into the field of IDE while also expanding my knowledge with course from the ME programmes. While related, both fields have a very different approach and perspective on how to deal with the challenges and opportunities to which I was introduced during my studies. Both of my master tracks, Management of Product Development and Design & Manufacturing, perfectly came together in this thesis assignment.

Over the past year, I worked on my thesis assignment for DelwiGroenink Machinefabriek. The goal of this assignment was to assess and design the required support for manufacturing SMEs, like DelwiGroenink, to introduce digital twinning to their manufacturing environment. During this assignment I had the chance to show what I have learned over the past few years and how I can apply this in a practical context. I really enjoyed experiencing how the abilities and ways of working I was taught at the University of Twente translated to working in the manufacturing industry. All in all, working on my thesis assignment provided me with new knowledge that has been a valuable addition to what I have learned during my studies.

I would like to thank DelwiGroenink for giving me the opportunity to work on this assignment. Even though they did not have experience with providing a master assignment to a university student, they were welcoming and very open to the ideas I presented for my assignment. While there was a lot of work to be done, everyone was always open to free up some time to answer any questions I had. I would like to thank my daily supervisor Piet Soering in particular, for the support, input, wisdom, and enthusiasm he provided during my time at Delwi.

Furthermore, I would like to thank Roy Damgrave for being my thesis supervisor during my assignment. I appreciate the feedback and guidance that you provided me both during, and outside of our meetings. Also, many thanks for the encouraging words that you gave the couple of times that I indicated that I felt stuck. Indeed, zoom out a little bit, refocus, and you will quickly find your flow again. Finally, I would like to thank my family and friends for providing me with the opportunity to put my mind of my assignment every once in a while.

I hope you enjoy reading my thesis!

Abstract

Manufacturing companies are met with a variety of challenges that require them to produce more flexible, efficient, fast, and reliably. While this can in part be realised through improving their current manufacturing methods, this is likely not enough. To address these challenges, manufacturers must work towards a 'smarter' production environment. The main component of such a smart production environment is an increased level of digitalisation. Research on how such digitalisation can provide value to a company is often too broad or too specific. Furthermore, much of it is tailored to MNEs while SMEs face similar challenges. The aims of this thesis are therefore to identify how manufacturing SMEs can create value through digitalisation of their manufacturing environment and how this value, once realised, can be maintained. The potential value of an increasingly digitalised manufacturing environment was examined by analysing the concept of Industry 4.0. Next, the concepts of the digital twin and digital twinning were discussed to assess how this potential value of can be captured. Lastly, the barriers that might prevent manufacturing SMEs from capturing this value were discussed and translated into technological and organisational considerations for such companies. Based on the findings of this analysis, the necessary support for manufacturing SMEs to develop their digital twinning capabilities was defined. The first part of this support was an approach to translate the motivators for a company to introduce digital twinning, into the functionalities that were required of a digital twinning application. This was further distilled into the information need and its expected use both now and in the future. By making this distinction, the approach aided in the formulation of a roadmap for the application's further development. The second part of the support was a tool to keep track of the information captured in the different roadmaps resulting from iterations of the designed approach. This tool enables an aggregated view of how the different applications and their components relate to each other. The tool thus allows a manufacturing SME to examine and analyse the overall digital twinning landscape of the company. This captured knowledge base can then be used for decision-making regarding digital twinning within the organisation. Both the approach and tool were verified and validated through various case studies.

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List of Abbreviations

AI	Artificial Intelligence
AML	Advanced Manufacturing Landscape
AR	Augmented Reality
CPPS	Cyber Physical Production System
DSR	Digital System Reference
DTA	Digital Twinning Application
DTOT	Digital Twinning Overview Tool
ERP	Enterprise Resource Planning
HMLV	High-Mix Low-Volume
IoT	Internet of Things
KPI	Key Performance Indicators
LMHV	Low-Mix High-Volume
LT	Long-Term
MNE	Multinational Enterprise
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
RAMI4.0	Reference Architecture Model Industrie 4.0
RUL	Remaining Useful Life
SME	Small and Medium-sized Enterprise
ST	Short-Term

1 Introduction

This chapter outlines the aim and scope of the assignment. The first section presents the project's background and introduces the problem that this project aims to solve. The second section introduces the company where the case study will be conducted. Next, the main research question and its sub-questions are defined. Finally, the structure and scope of this thesis will be discussed.

1.1 Project background

Many companies operating in the EU face increased competition from developing economies such as those in Asia. This in combination with the globalisation trends of the past decades resulted in many companies outsourcing or 'offshoring' their production facilities to these developing countries as due to the significantly lower production costs. Political and economic changes in recent years however, have prompted many companies to reconsider their overall logistics and global value chains [1, 2]. Consequently, companies are exploring the possibility of 'reshoring', particularly their manufacturing operations, back to their regions of origin.

This however presents its challenges. Manufacturers are met with changing consumer expectations and demands like mass customisation, shorter delivery times, and higher quality. Meanwhile there is pressure from both governmental institutions and consumers to transition to more sustainable production practices. All require changes to be made to existing factories. For manufacturers in developed economies, an added challenge is the increasing shortage of skilled workers. This is a result from an ageing population and low birth rates which is typical for modern European countries [3]. Sectors that require physical labour, such as industry or healthcare, are particularly affected. According to a recent report by the Dutch government, the percentage of technical workers that were aged 55 or older had increased to 26% in 2021 [4].

To remain competitive, businesses will have to produce more flexibly, efficiently, fast, and reliably. Optimisation of current production methods will contribute to reaching these goals, but its effect will ultimately remain limited. To truly enhance their production environments, businesses will need to introduce novel innovations to their company. There are a wide range of emerging technologies available that could help these businesses work 'smarter'. These technologies are typically characterised by a (further) digitalisation of the manufacturing environment. The concept of digital twinning is a key enabler in facilitating this digital transformation.

Currently, primarily large multinational enterprises (MNEs) are implementing tools associated with Smart Industry, such as digital twinning. Meanwhile, small- and medium sized enterprises (SMEs) contribute to more than half of all the value added by the EU's manufacturing industry [2]. SMEs encounter more barriers than MNEs when attempting to introduce such tools. Many manufacturing SMEs lack an overview of how to start, and what to consider, when wanting to improve their production environments through digitalisation. As a result these companies are at a risk of becoming data rich but insight poor in their strive to keep up with the technological developments going on around them.

1.2 Company cooperation

This thesis assignment was formulated in cooperation with DelwiGroenink Machinefabriek, or Delwi in short. Delwi is a metalworking company that located in Enschede, the Netherlands. The company was established in 1992 and currently employs approximately 80 people. Over time the company has gradually grown in size and expanded their capabilities, especially in the last few years this growth has been substantial. Delwi is a contract manufacturer. This means that they do not design or manufacture their own products. Instead, their production relies on designs and specifications provided by original equipment manufacturers (OEMs). OEMs can outsource only parts of their production to contract manufacturers or, in some cases, a contract manufacturer will facilitate in the entire production needs of the OEM. Since 2018, Delwi has been focussing on providing the latter in what they call the ‘all under one roof’ concept (Figure 1). Currently, Delwi offers sheet metal cutting, bending, sawing, turning, milling, welding, sanding, coating, assembly and engineering support. This wide offer of (machining) operations can be interesting to OEMs as it negates the need for more complex logistics during the production of their equipment.

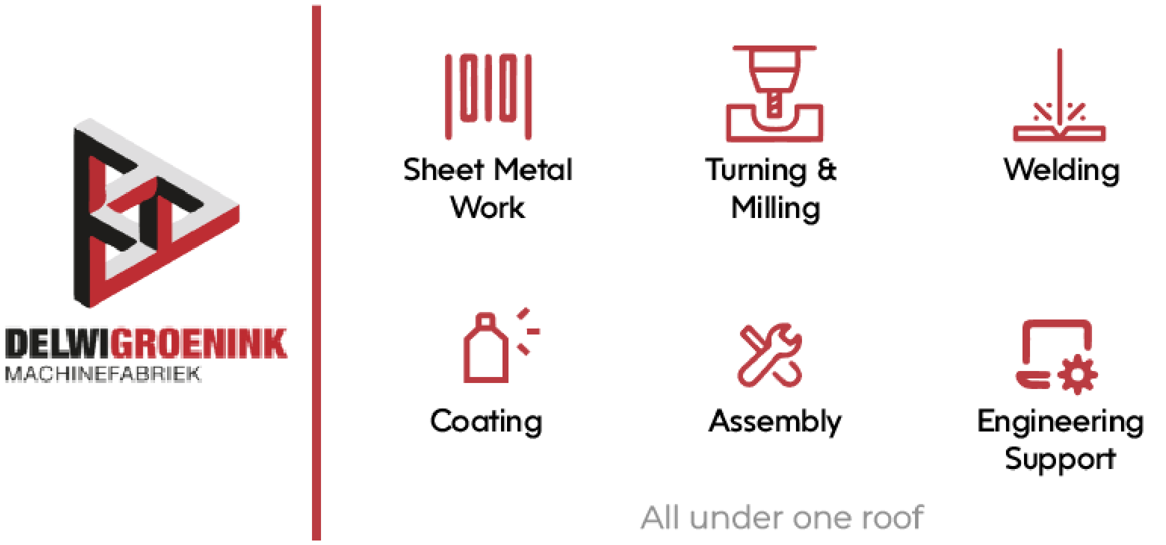

Figure 1: Delwi’s ‘all under one roof’ concept

1.2.1 DelwiGroenink’s manufacturing environment

Delwi defines two main types of manufacturing projects within their factory. The first type, which takes up more than 50% of the overall production capacity, is the continuous production of skiploaders for a large international customer. The remaining capacity is used to meet the needs of other customers. Figure 2 shows skiploaders being assembled, providing an indication of the size of these products. Per year, Delwi produces around 1000 skiploaders. During the manufacturing of a skiploader all production departments within Delwi are involved. The client ordering the skiploaders provides a wide range of customisation options to their customers. This in combination with the variability of other projects mean that Delwi is faced with high-mix low-volume (HMLV) production. This type of manufacturing could often not benefit from cost saving practices commonly found in low-mix high-volume (LMHV) mass production facilities [5].

Delwi’s pricing is determined by the materials and, more importantly, the time spent on fabricating a customer’s order. The input for these factors are often assumptions that are made by looking at known data of previous batches or similar orders. The accuracy of this process however, is highly dependent on the quality of the available data. Also, as a significant part of labour remains manual, cycle time variation is common. Delwi is continuously looking for ways to monitor and improve their manufacturing processes. Some of the most recent examples include the introduction of robotics to further automate the production environment, dashboarding of Key Performance Indicators (KPIs), and a system to take the first steps towards paperless production. Delwi is interested in exploring how further digitalisation and the introduction of novel technologies to their production environment can help to enhance their value creation process.

Throughout the thesis, context will be given on how discussed theories and concepts apply to a real-life scenario by relating them to DelwiGroenink's manufacturing environment. This context was gathered through case studies and discussions with various employees within Delwi.

Figure 2: Assembly of skiploaders (Source: [6])

1.3 Problem definition

As described at the start of this chapter, manufacturing SMEs are currently met with a variety of challenges. While the potential of a more digitalised manufacturing environment to overcome many of these challenges is generally recognised, the details often remain ambiguous. Current research and technological developments often referred to as Industry 4.0 and digital twinning, are crucial in industry's pursuit of 'smarter' manufacturing. Research on these topics however, has often been either too broad or too specific for manufacturing organisations to apply to their own practices [7-9]. Furthermore, much of it is tailored to large companies that are rich in capital. This is a logical result as these new technologies have often been funded and developed in cooperation with MNEs [7]. Although met with many of the same challenges as MNEs, manufacturing SMEs are left with an incoherent view of what technological developments like Industry 4.0 and digital twinning entail and how they can lead to value for their own organisations.

The aims of this thesis are therefore to identify how manufacturing SMEs can create value through digitalisation of their manufacturing environment and how this value, once realised, can be maintained.

1.4 Approach and structure of thesis

In order to come to a solution to the problem defined above, it is first necessary to create more understanding of the underlying concepts that drive and contribute to digitalisation within the manufacturing industry. This analysis will start by relating the current state of industry to an envisioned future state. This future state is commonly referred to as Industry 4.0. This concept, its application space, and its associated technologies are explained to indicate how broadly digitalisation can impact industry. As digitalisation concerns the use of data and information, a method with which to structure this use is needed. To that end, the concepts of digital twin and digital twinning are explored. The analysis is concluded by identifying common barriers for manufacturing SMEs aiming to integrate digital technologies into their operations. The outcomes of the analysis phase are distilled into a formulation of the support that SMEs require to sustainably exploit the value that digitalisation can offer.

In the second part of this thesis the requirements for the tools that should offer this support are drawn up. These requirements are then used in the further development of these supporting tools, which are tested through various case studies carried out at the case company to assess their validity.

1.5 Scope

The subjects covered in this thesis are broad, encompassing various technologies and their applications that vary in complexity and maturity. Furthermore, some topics that will be discussed have multiple definitions. More detailed explanations of the way in which the concepts are understood, and to what extent they are used in this thesis, can be found in the relevant chapters. The purpose of this section is to provide an indication of the applicability of the findings presented in this thesis.

First of all, it should be noted that companies are constantly seeking to improve their operations. Digitalisation of their manufacturing environment is just one of the options available to do so. It is possible that some of the problems outlined in the following chapters could be resolved using alternative methods rather than further digitalisation. This thesis however, focuses on digitalisation through the method of digital twinning, rather than the problems it can help solve. Next, the goal of this thesis is to define supporting tools for manufacturing SMEs that are not familiar with or have limited knowledge of digital twinning and its concepts. These results were tested and developed at the case company described in section 1.2. This means that it is possible that not all findings apply the same to SMEs that e.g. do not share the same technological, geographical, or cultural characteristics.

The focus of this thesis is not to propose specific digitalisation projects, but rather to provide tools that support the case company in effectively formulating and pursuing their own. Further development of applications based on the outcome of the approach laid out in this thesis is left outside the scope of this work. To validate the proposed approach, however, some mock-ups of applications will be created to facilitate discussions on its outcomes.

2 Analysis

In this chapter, it is examined what factors drive companies to want to adopt a more digitalised way of working and how they can be supported in this transition. To that end, this analysis starts with exploring the concept of Industry 4.0 which is the term that is often used in literature and industry to represent this digitalised manufacturing environment. As explained in chapter 1 however, there exists a plethora of different definitions and views on the concept of Industry 4.0. The goal of the first subchapter, chapter 2.1 is therefore to provide the definitions and common concepts that together represent the digitalised manufacturing environment that industry is pursuing. Having such an environment does not necessarily guarantee any benefits to a company however. Hence, once it is established what a digitalised manufacturing environment entails in the context of this thesis, it will be explored how such digitalisation can actually yield value to a company. This is done in chapter *Digital Twinning*. In this subchapter, it is identified how an organisation can structure the information that they can capture through digitalised manufacturing. This should be done in such a way, that it can be used for purposeful applications. Next, technological and organisational considerations for a manufacturing SME wanting to introduce digitalisation to their production environment are discussed. These considerations are important as they can influence an organisation's ability to adopt the Industry 4.0 and digital twinning practices described in this chapter.

The goal of the analysis is to map the relevant aspects, techniques, and requirements that manufacturing SMEs should consider when aiming to capture value through digitalisation in their manufacturing environments. Subchapters 2.1, 2.2, and 2.3 will form a foundation from which the support that manufacturing SMEs require for this value capture process is defined.

2.1 Industry 4.0

The term Industry 4.0 was first coined in 2011 in a strategic plan for the German manufacturing industry. It was used to describe a variety of emerging technologies that, when combined and applied, would mark a new type of industrialisation. This new type of industrialisation was deemed necessary for Germany's industry to remain competitive and to be able to adjust to shifting market demands such as mass individualisation of products and to better deal with challenges like logistical disruptions [10]. Around the same time, other parties also recognised the possibilities offered by these technological developments. While some perceived these developments as the beginning of a fourth industrial 'revolution', hence the name Industry 4.0, others viewed them as more of an evolution of existing technologies. Thus, they opted for different terms like smart industry, factories of the future, and advanced manufacturing [10, 11]. All terms, however, indicate that the (manufacturing) industry will undergo significant changes over the coming years. In this thesis the different terms will be used interchangeably.

Figure 3 shows Industry 4.0 in relation to its three preceding revolutions. The first industrial revolution took place at the end of the 18th century. Technologies like steam engines allowed for more complex machines to take over work that was previously done by hand. This industrial revolution was marked by mechanisation. Next, around the start of the 20th century, the second industrial revolution took place. In this period the electrification of industry led to the introduction of the first assembly lines, conveyor belts, and greater possibilities for mass production. From the seventies and onwards, with industry 3.0, more and more manual labour was replaced by automated assembly lines. During this period Information Technology and other electronics were introduced. The fourth revolution is a direct continuation of this computerisation within manufacturing environments. It represents a digitalised and interconnected manufacturing environment [12]. New and future technological developments associated with Industry 4.0 can result in value chains in which operators, machines, and even entire companies are much closer connected to one another. Using technologies like the Internet of Things (IoT), physical entities and processes are linked to digital controllers to form so called Cyber Physical Production Systems (CPPSs).

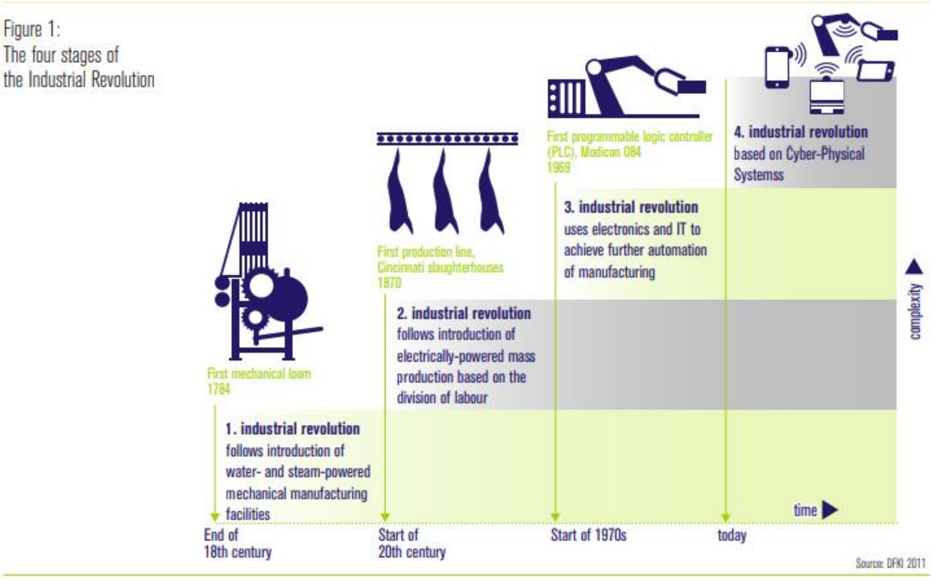

Figure 3: The four industrial revolutions (from [10])

In these connected manufacturing environments, devices, machines, products and other elements are able to exchange information and respond accordingly thus creating a more intelligent manufacturing environment [13]. Industry 4.0 is closely related to current production systems as it is built upon an existing technological foundation. As shown in Figure 4, the fourth industrial revolution is more of an evolution that expands basic computerisation to systems that offer more value by providing insight into what is happening, why it is happening, and what will happen in the future. At its highest level the manufacturing environment might even be able to run fully autonomously [10, 14, 15]. Although many companies are still in the transitionary stages of Industry 4.0, there are already some parties mentioning of Industry 5.0 or even 6.0 [16, 17]. What exactly these terms entail and how they differ from Industry 4.0 is debatable however. Like Industry 4.0, they are terms used to represent a certain technological advancement of industry.

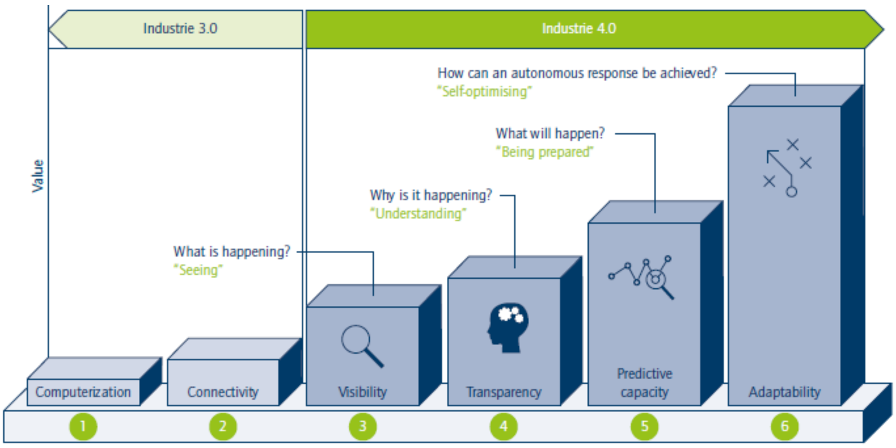

Figure 4: Evolution of Industry 3.0 towards 4.0 (from [14])

2.1.1 Paradigms of Industry 4.0

Industry 4.0 is a relatively new term and used to describe a predicted course of technological developments rather than an existing set of production technologies. As such there is a plethora of different definitions and opinions on what exactly it entails. In this section the main paradigms of Industry 4.0 as it is used in this thesis is explained. Industry 4.0 involves the use of rapidly improving (digital) innovations found in our society in the context of manufacturing environments. Oesterreich and Teuteberg [18] described that, from a technical point of view, this leads to an increasingly digitalised and automated manufacturing environment which facilitates new methods of communication between its actors through the creation of a digital value chain. In the context of this thesis, this value chain will be considered up until the factory level as this is where the manufacturing SMEs have by far the most influence. Weyer et al. [19] discerned three different types of actors within such a smart factory environment: the Smart Product, the Smart Machine, and the Augmented Operator.

Smart Product
The Smart Product is based on the idea of an expanded role of a work piece. Rather than simply being the outcome of a series of production steps, the workpiece assumes an active role within the production system. The individual product receives its own memory or can communicate its identity to link to a digital version of itself that stores the relevant operational data and any specific requirements. This allows the product to become the orchestrator of the production system that it is to be produced in. Their influence can even extend beyond the production environment as certain types of Smart Products could even be enabled to gather and communicate operational data [13]. This could then be used to e.g. improve its design.

Smart Machine
Another main component of a manufacturing environment are of course its machines. Smart Machines gather and communicate data about their operations and status. In a smart factory, these machines are interconnected with other machines, components, devices, production modules, and products to allow for self-optimisation, increased autonomy, increased flexibility, and increased adaptability.

Augmented Operator
A third type of actor, that tends to often be overlooked when discussing Industry 4.0, is the worker that interacts with the production environment. Human operators will always remain the most flexible and adaptive contributors to the production system [19]. Responsibilities and tasks of the operators will likely shift as a result of the changing manufacturing environments. Part of the technologies encapsulated by Industry 4.0 will therefore be aimed at support of the workers interacting with the systems. This could be by providing new ways of interacting with the machines or by providing previously unavailable insights.

2.1.2 Associated technologies

Numerous technologies contribute to achieving a more interconnected and digital manufacturing environment, and the advantages it can entail. Given the fact that there is so much research going on in the area, there is no clear consensus of the exact technologies that together form Industry 4.0. To provide some context however, the aim of this section is to give an overview of the primary domains to which the technologies contribute. Technologies can contribute to *Connectivity, data, computational power*, *Analytics and intelligence*, *Human-machine interaction*, or *Advanced Engineering* within industry. Figure 5 shows these four foundational technology groups and their most characteristic technologies. Please note that Figure 5 does not provide an exhaustive list of technologies, most technological developments will however contribute to one or more of the stated domains. Digitalisation will often involve the introduction of new technologies to existing manufacturing environments. These groups provide an idea in what way such technologies can influence the organisation.

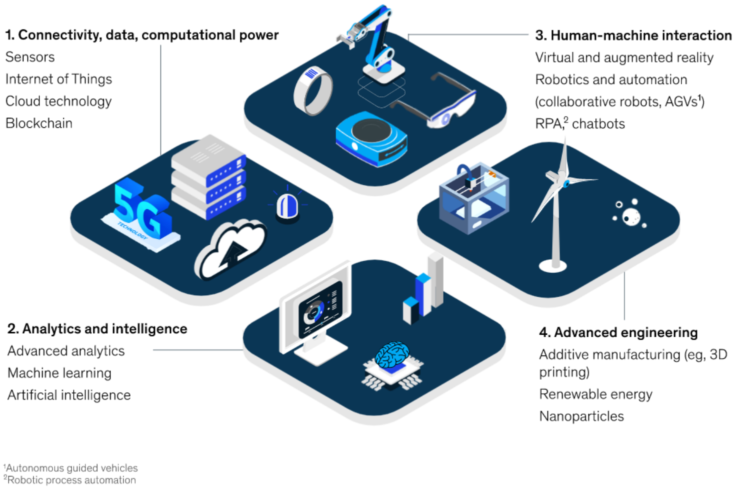

Figure 5: The four foundational technology groups within Industry 4.0 (from [20])

Connectivity, data, computational power

These technologies revolve around the gathering, processing, and communication of data. This includes the development of various kind of sensors to capture data about a part or process. Internet of Things (IoT) is used as a means of communication within the smart manufacturing system, and aspects like its formatting and used protocols are continuously being developed. Research is also being conducted into the use of cloud technology as a means of increasing the computational power that a business as at its disposal. Finally, blockchain is also often associated with Industry 4.0 as it enables the tracking of information throughout a value chain [21].

Analytics and intelligence

The second group of technologies involves those that enable a manufacturing environment to become 'smart'. This includes advanced analytics of the data that is captured, or simulated [21], within the production environment. The data from the factory is processed and communicated in such a way that it provides new insights to the factory operators. Furthermore, new machine learning models and artificial intelligence can increasingly take over this interpreting role and allow for further automation of the manufacturing environment. It can also identify patterns and provide optimisation suggestions that may be difficult, if not impossible, for a human operator to discern.

Human-machine interaction

The third technology group comprises technologies that facilitate new ways of interaction between humans and machines within a factory. In part this can be driven by other technologies enabling a type of interaction that is not available or common presently. On the other hand, it contains technologies that enhance current human-machine interaction. Technologies include virtual and augmented reality, collaborative robots (cobots), AGVs, and digital assistants such as chatbots.

Advanced Engineering
This group encompasses new developments within industry that do not fall under any of the previous categories. Advanced Engineering involves new production techniques, materials, and sustainability considerations.

While the first three groups are quite closely related to one another, the fourth group is not. Advanced engineering technologies are often considered part of Industry 4.0 as they are likely to be incorporated into future generation factories. However, they do not necessarily contribute towards a factory as a CPPS in which the digital- and physical domains interact to form a coherent whole. This technology group is therefore left outside of the scope of this thesis.

2.1.3 RAMI4.0

The preceding sections demonstrated the breadth of the concepts encompassed by industry 4.0. It covers the entire production space and entails technological developments of both software and hardware. Additionally, many technologies are interrelated, and the development of some technologies may depend on progress made in related technologies. Therefore, their development cannot always be viewed as separate. This is a good example of the complexity and interconnectedness between the technologies and their applications. The versatility and broadness of these concepts can render it difficult to discuss and decide how they fit together in the manufacturing space that Industry 4.0 represents. For any developments in that space however, it is helpful if the parties involved agree on how technologies relate to one another. To that end, this thesis follows the RAMI4.0 model [22, 23] to describe the different dimensions of Industry 4.0. The model is shown in Figure 6. It was created to provide companies and academia with a common understanding and nomenclature of the dimensions of Industry 4.0 based on existing standards. It can be used to assess how and where technologies contribute to Industry 4.0 [24]. The model is three-dimensional and consists of three axes: the Life Cycle and Value Stream axis, the Hierarchy Levels axis, and the Layers axis.

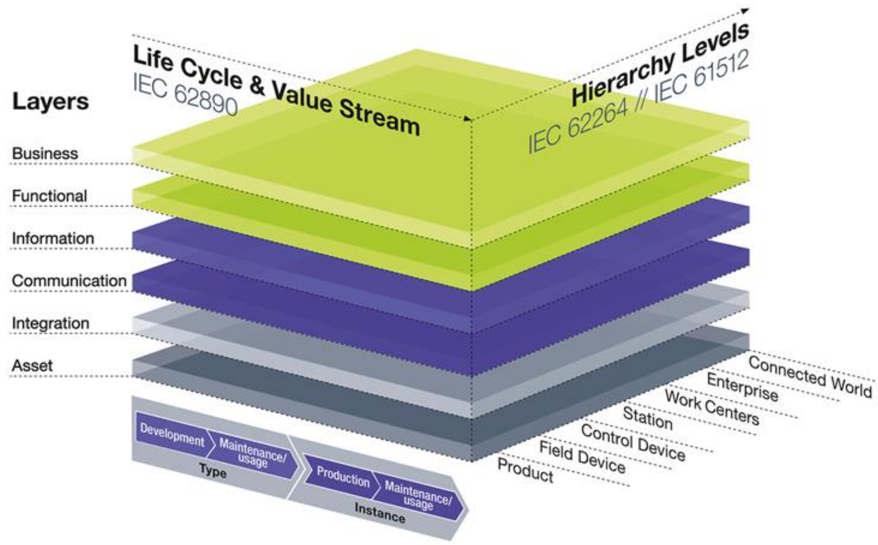

Figure 6: Reference Architectural Model Industry 4.0 (RAMI 4.0) (from [22])

The *Life Cycle and Value Stream* axis represents the life cycle of a product or facility. In this framework this lifecycle starts at development or design and ends in the use phase. In RAMI4.0, the disposal phase is not part of the lifecycle. While some technologies will be aimed at postponing the disposal phase, the focus then primarily lies on extending the use phase. The second horizontal axis represents the various hierarchy levels present in a manufacturing environment. A factory in industry 3.0 has five hierarchy levels [23]. At the top there is the Enterprise itself, the enterprise is built up of one or more Work Centres which in turn are built up of work Stations this continues all the way down to the Field Devices which are things like sensors or actuators. The product is viewed as separate from the factory hierarchy as it has no direct interaction with the other levels. In industry 4.0 the hierarchy is expanded with a Product level as the lowest level. Individual products can be connected to the levels above and directly influence them. This could mean that for example a defect in a product could automatically lead to the settings of a machine being altered. At the top the Connected World level is added, this level represents enterprises being connected to external parties to form multi-actor service networks [22]. The last axis, the vertical Layers axis represents the typical architecture of a digitalised production environment. It represents the digitalisation processes found in Industry 4.0 systems. The Layers axis contains six layers. The Asset layer contains the physical objects in the real world like parts, documents and even operators. The Integration layer represent the transition from the physical world to the digital world and vice versa. This Integration layer contains things like sensors, computer control of production processes, and human-machine interface devices. The Communication layer deals with how information is communicated through the cyber-physical systems and processes. Data formats and standardisation are examples of what is considered in the Communication layer. The Information layer holds the information of a physical asset in a form that is interpretable for humans or machines. At the Functional layer this information is used for e.g. decision making and control. The available information is used and communicated in this layer. At the top is the Business layer, this layer contains business strategy, business environment, and business goals.

RAMI 4.0 demonstrates the broad impact that new technologies can have on industry. It can have an impact on the business side of a company by enabling a company to expand or improve its services. On the other side it also encompasses changes to production like assisting operators in their work or changes to how a product is designed. This underlines that Industry 4.0 can best be seen as a toolbox. Depending on their goals, companies can select the tools, or technologies, required. This does require the companies to have a clear understanding of what value they are pursuing and how different tools relate to this.

2.1.4 Selected dimensions

At its core Industry 4.0 is about creating a digitalised and interconnected manufacturing landscape [12]. Its applications can range in size from single products to complete logistical value chains and are found from the design to the use phase. Whatever the scope of the application however, a translation from the physical asset level to a digital functional and business level is required. The technology that best encapsulates this flow is that of the digital twin. When examining the technology groups outlined in *Associated Technologies*, the digital twin could best be placed at the intersection of the Connectivity, data, computational power, Analytics and intelligence, and Human-machine interaction. This is shown in Figure 7. Considering the first group, a digital twin requires a data foundation which is created based on real-life assets or systems. Considering the second group, the digital twin of an asset can be used for analytics. Lastly, the data and its analyses need to be communicated in some way to a (human) stakeholder as a basis for decision making. In this thesis the digital twin concept will therefore be used as a focal point as it involves the concepts that are typical for the broader digitalisation of industry.

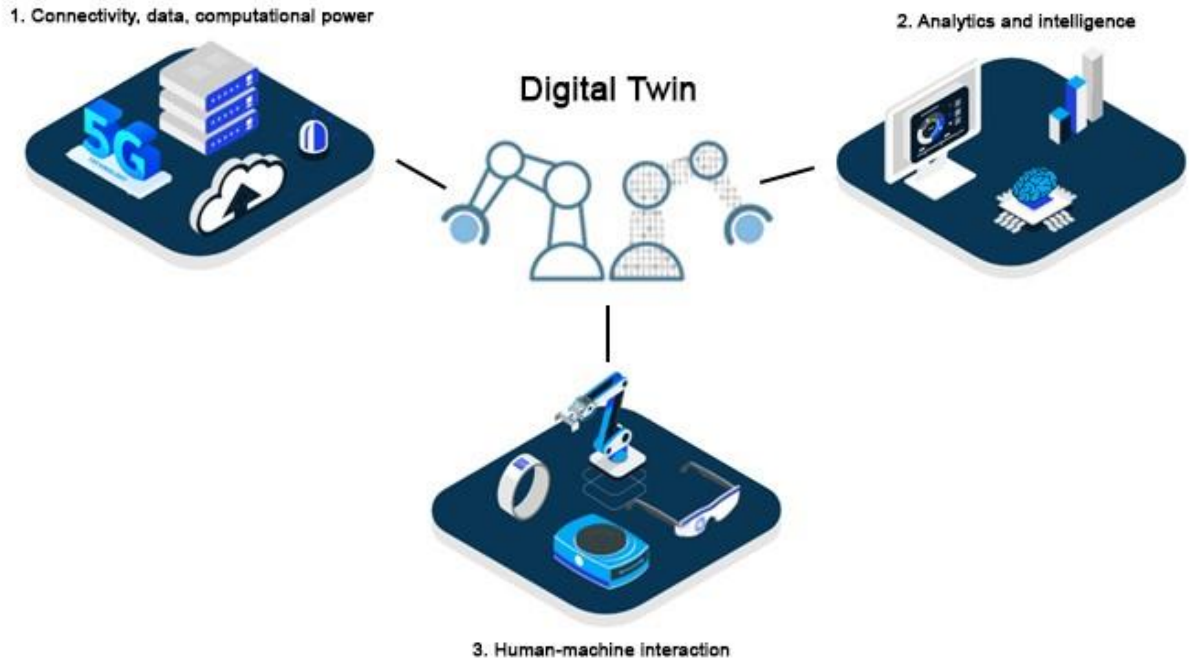

Figure 7: Digital twin at the centre of three of I4.0's main technology domains

2.1.5 Conclusion

In this chapter the ongoing transition in industry towards more digitalised ways of working was explained. This future state of industry is often referred to as Industry 4.0. Industry 4.0 is characterised by a strong focus on capturing and using data, as well as a high degree of interconnectivity between different actors within the manufacturing environment. These characteristics in combination with other ongoing technological developments will enable organisations to get more grip on their production environments. Initially the technologies will help create more visibility into what is happening in the factory. As capabilities increase however, more transparency is created to allow companies to identify why these things happen the way they do. Over time this might be expanded with predictive capabilities which will ultimately allow for a (near) autonomous production environment.

Industry 4.0 can transform the manufacturing space in various ways. Its technologies can be applied all along the lifecycle of a product or facility. Moreover their influence can be exerted on a scale of individual products to entire value chains. Whatever the application however, physical attributes of an asset or system will first have to be translated to a digital domain. Only then can digitalisation lead to value on a business or organisational level. Digital twin technology is instrumental in this process as it incorporates data handling, analytics and human interaction aspects. The following chapter will therefore delve deeper into the digital twin and related concepts.

Industry 4.0 in DelwiGroenink

As stated in the section 1.2 of the introduction, Delwi is constantly seeking ways to improve their work practices. Since its establishment in 1992, the company has evolved into a business incorporating many of the elements now referred to as Industry 3.0. Being a continuation of Industry 3.0, elements of Industry 4.0 have found their way to Delwi's manufacturing environment as well. This first theory-in-practice block will therefore focus on Industry 4.0, or more specific its associated increased digitalisation, in DelwiGroenink. Delwi's main drivers for digitalisation are discussed in the next paragraph. This is followed by examples of technologies and developments found in Delwi that resulted from these drivers.

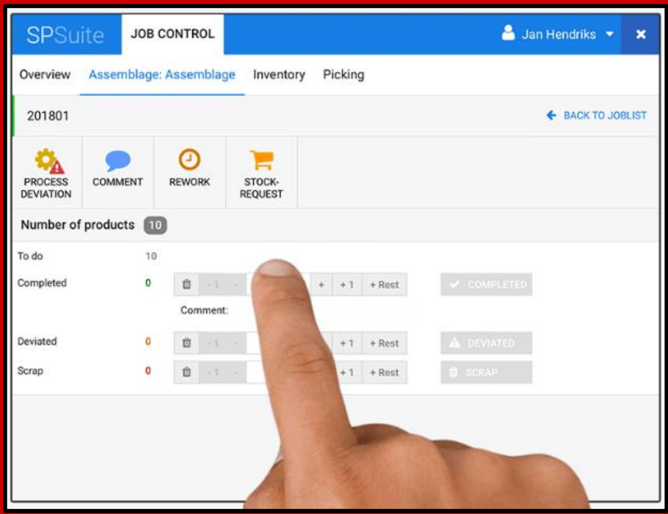

Figure 8: Sample dashboard of Delwi's paperless production software

The primary driver for Delwi has been, or is, the overall desire to create more insight in what is happening in the organisation. As can be seen in Figure 4, this places Delwi at the start of their digitalisation journey in pursuit of Industry 4.0's potential value. This increased visibility is desired from many aspects of their manufacturing environment. Having more metrics concerning the production of a product could for example eliminate some of the guesswork that is currently required. This could in turn lead to increased profit margins or improved utilisation of the available production capacity. More visibility in the manufacturing environment could however also indirectly yield benefits. It is expected that certain problems or opportunities within the production that are currently nearly invisible, will be made perceptible through the created data and information. Another driver for digitalisation is the desire to reduce errors and the time spend on manual (often repetitive) work by automating parts of the production or information flows within the company. The first example of a development within Delwi that illustrates their current digitalisation efforts was the introduction of a paperless manufacturing system. The used system, depicted in Figure 8, is an off-the-shelf solution optimised for coupling with Delwi's Enterprise Resource Planning (ERP) system. The system was implemented to better track the status of work orders, provide operators with an overview which orders they should work on next, and to automatically track the hours an operator spent on a specific order. Previously, this was done manually on paper accompanying the orders as they moved through the factory. However, this was both time-consuming and often inaccurate. The goal of the paperless system was therefore to increase visibility and reliability of the production and its data. The used software does offer more functionalities, but these are currently not implemented at Delwi.

Other digitalisation projects within Delwi have as their main focus the automation of repetitive tasks. One such task is for example the manual conversion of invoices to be used in Delwi's IT systems. This used to require an employee to open, read, interpret, and transfer the data found in the invoices. These tasks have now been taken over by software which only requires the employee to perform a final check on the validity of the interpreted and converted data. Another example is the addition of QR codes to manufacturing orders. These can be scanned to automatically load the correct program in the bending machines.

2.2 Digital Twinning

In this thesis, a distinction is made between the concept of a digital twin and the activity of digital twinning. The digital twin is a core concept for companies which pursue an increasingly digital manufacturing environment under Industry 4.0. As with Industry 4.0, there is no single agreed definition of what a digital twin entails, due to its novelty and broad applicability. This chapter will therefore begin by providing the definitions of digital twin and digital twinning that will be used in this thesis. Next, the concept of digital twinning will be explained in its relation to the current and future state of industry. The last sections of this chapter deal with the characteristics of a purpose-driven digital twinning approach that allows for continuous improvements to be made to its contents.

2.2.1 Digital twin

The term 'digital twin' was coined in 2002 and used in describing the wish to move product (life cycle) data from the physical 'paper' domain to the digital domain [25, 26]. Although some progress related to the subject was made in the first years following its introduction, the topic in its current form has especially been gaining attention in recent years. It is increasingly used in the context of Industry 4.0 as the digital twin unites many of its aspects. This has sparked both academic and commercial interest in the subject. While this surge of attention has a positive influence on related research, it has also led to a wide range of definitions and ideas about what a digital twin entails [26]. Many existing definitions are based on the use cases for which the different twins were intended and also differ per sector as its concepts can be applied beyond just the manufacturing industry. In this thesis the following definition is followed: the digital twin is the conglomerate of data, information, models, methods, tools and techniques to represent current states of an instantiated system coherently and consistently [27]. It is important to note that this does not necessarily mean that each and every aspect of a physical system needs to be represented in its digital twin. Next to the fact that this is near impossible, this would only cause the twin to become needlessly complex. If for example only the power use of an asset is of interest, there is no need to include a CAD model containing the exact geometry of the asset in the digital representation. Instead, the asset could in this instance be reduced to a simple text field that only shows the current power usage of the asset.

One aspect that all definitions do agree on, is that the digital twin is described as being the digital counterpart of a physical asset. However, differences become visible when the data exchange, a vital part in digital twinning, between the two is considered. Kritzinger et al. [26] identified three subcategories when considering the digital twins found in literature. The distinction was made based on the way data is communicated by the physical asset to its digital counterpart and vice versa. This degree of data integration between the two counterparts, is referred to as the level of integration. The three levels are shown schematically in Figure 9 and explained below.

Level of Integration I
This is the lowest level of data integration possible for a digital twin. At this level there is no automatic data flow between the digital and physical version of the asset. The digital asset functions as a snapshot description of the physical object at one point in time. A change in the physical object does not directly induce a change in the digital object. Most organisations can relatively easily create digital twins with this level of data integration based on their current digital infrastructure and know-how.

Level of Integration II

At the second level of data integration, the first level twin is enriched with an automatic data flow from the physical to digital domain. At this level a change in the physical asset leads to a change in the corresponding digital representation of that asset. This allows for better grip and supervision of e.g. the status of a machine. Any optimisation in its configuration however, would still need to be handled by a human operator. The decision-making process is left to the relevant stakeholder(s) [28].

Level of Integration III

The last category, Level of Integration III is the level at which there is an automatic data flow in both directions between the physical and digital object. At this level a change made to the digital object will directly impact its physical counterpart. This enables e.g. automatic optimisation of a machine's settings based on a desired outcome. The responsibility for decision-making is transferred from a human to the digital domain. A factory composed entirely of digital twins with this level of data integration might be able to run completely autonomously.

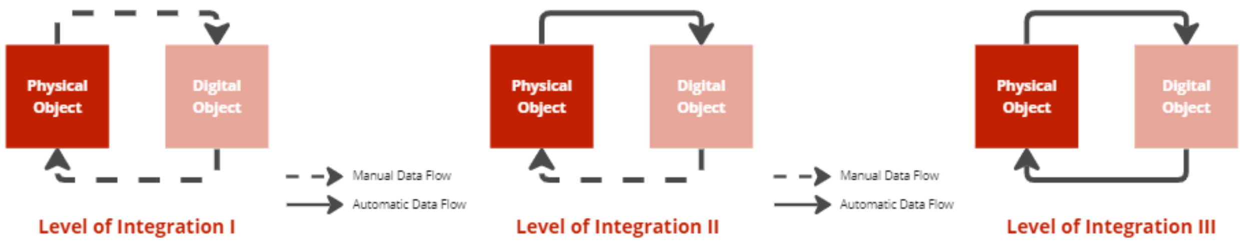

Figure 9: Digital twin subcategories (adapted from [26])

Although a digital twin with third level data integration allows for more possibilities and functionality than an instance of the first level category, it is not necessarily better for an organisation to focus on creating third level systems right away. Creating a fully-fledged digital twin that allows for bi-directional automatic data flow and state control, will likely require more investments than the creation of a first- or second level twin. This is because at the lowest level all data is transferred manually while at the second and third level, sensory capabilities and actuating capabilities have to be added respectively. Depending on the intended application, the information as its captured in lower level digital twins might already yield the desired results. A digital twin that can facilitate more autonomous capabilities has likely gone through the different levels of data integration through its development and evolved as more experience is gained with the relevant concepts. Especially in intermediary stages, data transfer between a physical asset and its digital representation will likely rely on a combination of both manual and automatic data flows. Which level of data integration suffices is in the end determined by the digital twin's purpose, this is explained in more depth in the next section.

2.2.2 Digital System Reference (DSR)

It is important to note that the term 'digital twin' is different from the term 'digital twinning'. While a digital twin represents a single instance of an asset or system, digital twinning is the process of translating this captured data and information to a purposeful application [29]. Without an idea of the intended purpose it becomes nigh impossible to validate and define the scope of the twin. As such, having a digital twin solely for the sake of having it should never be the goal. It is only when digital twins are used in digital twinning that value can be created. In the above definition of digital twinning, the flow through the Layers dimension of the RAMI4.0 framework (Figure 6) can be discerned. A digital representation of a physical asset is created (the twin) which is then used for certain functional applications driven by a business' needs (the purpose).

To illustrate how the digital twin fits into the concept of digital twinning, the Digital System Reference can be used [27, 30]. This architecture is shown in Figure 10. In this reference, as-is instances of a system (the Digital Twin) are extended with a to-be Digital Master and could-be Digital Prototype view. The Digital Master is the envisaged state of the system and can be seen as a representation of the idealised version of the system. The Digital Prototype is the envisaged state of the system under consideration based on what-if simulations, models, and aggregated experience. These receive inputs from the to-be and as-is representations of the system [27]. A digital twinning application will rely on these different perspectives on the system under consideration. The DSR thus allows stakeholders to incorporate current, future, and potential states of a system in any decision-making related to the system [27, 30, 31]. Considering these different views results in the captured information in a digital twin always being tied to some envisioned outcome, thereby ensuring a purposeful application.

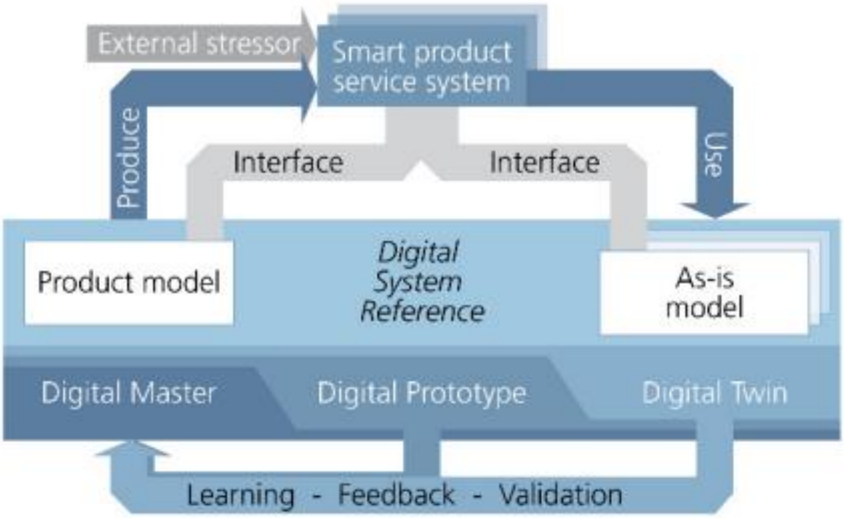

Figure 10: . Digital System Reference [30]

2.2.3 Advanced Manufacturing Landscape

Digital twinning can yield numerous benefits to existing manufacturing environments, provided that a suitable twin of a physical asset can be created. This does require the necessary data to be available within the company. This data can be retrieved or created from a variety of sources like existing databases, sensors, or manual inputs. Data can however have more than one application, so rather than acquiring the data separately for every application it should be collected and stored in such a way that it becomes part of a greater data foundation within the organisation containing reusable data. This data foundation then becomes the basis from which the twin receives its inputs [32]. The relationship between this data foundation, digital twins and the manufacturing environment in which they are placed is shown in Figure 11, the Advanced Manufacturing Landscape (AML). At the top of the landscape lies the intelligence level. Intelligence in this context encompasses the making of knowledge-based decisions, adaptive processes or autonomous decision-making [33]. These decisions rely on the information captured in a digital twin and its associated analytics. In turn, this information is created by capturing various forms of data from the manufacturing environment and making that accessible. The landscape also shows that this layered approach of going from a data foundation to making informed decisions can be applied throughout the lifecycle of a product or production environment.

In the context of this thesis, data is referred to as stand-alone facts, concepts, or instructions independent of these facts and concepts; suitable for communication, interpretation, or processing by humans or automated systems. When combined with a specific context and interpreted from a particular perspective, this data becomes information that can be used to facilitate decision-making [32, 34]. Following this definition, decision-making can theoretically take place directly from any of the information systems comprising the foundational data layer. This kind of decision-making however, is limited in the sense that it usually must follow a predefined workflow set by the system, is tailored to one perspective, and relies on a limited set of data. Decision support based on a digital twin on the other hand can be made perspective-dependant and can ideally integrate inputs from all data available within an organisation. This does however require a digital infrastructure which is adaptable and enables interoperability between its data provision components [32]. Such a digital infrastructure is represented in the AML as the combination of the data layer and the middleware layer. Middleware are the systems and ways in which the various data provision components in a production environment communicate and are connected to one another and the methods in which their captured data is made available for use outside of the individual systems.

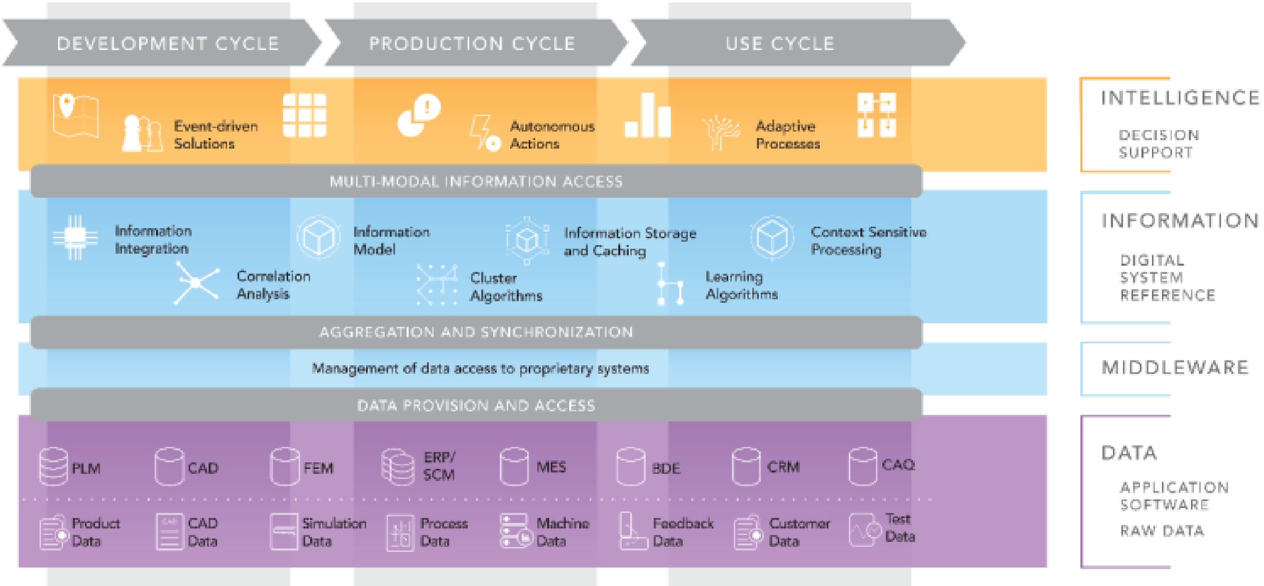

Figure 11: The Advanced Manufacturing Landscape (from [32])

2.2.4 Criteria for continuous digital twinning development

Digital twinning is closely tied to current and future technological developments. As a result, the field around digital twins is constantly changing and evolving. The introduction of digital twinning or the development of a digital twin should therefore not be seen as a one-off project. This sets it apart from more traditional changes to the manufacturing environment like the introduction of a new production machine. Due to the erratic nature of enabling technologies, it is extremely difficult to create a twin that will retain its value over time. New developments, experiences, and wishes will influence the expectations of the digital twin. Developing a digital twin that can fully account for all these changes right away is nigh impossible, this is however also not necessary nor desirable. A digital twinning framework that allows for the gradual development of a digital twin is more valuable to a company as it allows for growth based on the company's digital maturity and experience and keep the solution flexible in the face of unknown future developments. While the details might differ, a digital twinning framework should at the very least satisfy certain criteria to enable this continuous development. These criteria are explained in more depth using the main requirements for a generic approach for instantiating digital twins as defined by Slot et al. [29]: flexibility, modularity, and interchangeability.

- Flexibility. Developing a digital twin should be seen as an ongoing project. It is an iterative process that requires constant evaluation and adjustment of the twin. This will inherently induce changes in the data deemed relevant for the twin. The digital twin should therefore be dynamic and flexible for the addition and removal of features, data streams, visualisation components, user requirements and stakeholder perspectives, while also preparing for unforeseeable options and functionalities [29]. A digital twin that offers this flexibility is an effective tool for a company to build up experience with digital twinning while at the same time keeping initial investments costs low [28].
- Modularity. A digital twin is built upon a digital infrastructure containing several different data provision components and data sets. Additionally, it can be linked to a Digital Prototype which relies on models and simulations. The outcome of which are communicated in some way to an actor being either a human or machine. This is true for all digital twinning applications, regardless of their exact content. The different aspects of the digital twins can be viewed as modules which, depending on the context and purpose of the twin, interact in a certain way. The advantage of considering the twin's constituents as modules is that it allows for the re-use of modules in order to create new digital twins or to expand their functionality. Furthermore, a modular approach enables evaluation of separate aspects of the twin rather than only the twin as a whole. Collecting these different modules for future use in a repository requires a system in which the type and in- and outputs of the modules are documented clearly as they are built.
- Interchangeability. Following this modular approach, a digital twin should still function when one of its modules is changed with another module that has (largely) the same functionality. The workings within the module can differ as long as its interfaces to other modules stays the same.

Digital twins can be built and updated fast and reliably when a repository of modules is created and employed. This does require a structured approach to the instantiating of digital twins that considers the integration of existing modules [29, 35]. The modules should be collected and documented unambiguously to keep the repository usable now and in the future. When different digital twins in a company follow this modular framework, it becomes possible to link these digital twins into a network through shared modules. This allows digital twins to be composed of other digital twins. An example of this is a digital twin of a production environment which gets its inputs from the digital twins of individual machines. Complete digital twins themselves can then be seen as modules of the larger networked twin. This is visualised in the framework model in Figure 12. This framework shows how, following the requirements set out above, a digital twin is related to modules and configurations of modules. The different layers represent the different perspectives on the data and information content of the twin that stakeholders can have. While each perspective focusses on the same twinned asset, the exact modules of the twin that are relevant may differ. Two stakeholders might for example require a different level of accuracy in the data or the method of visualisation might differ.

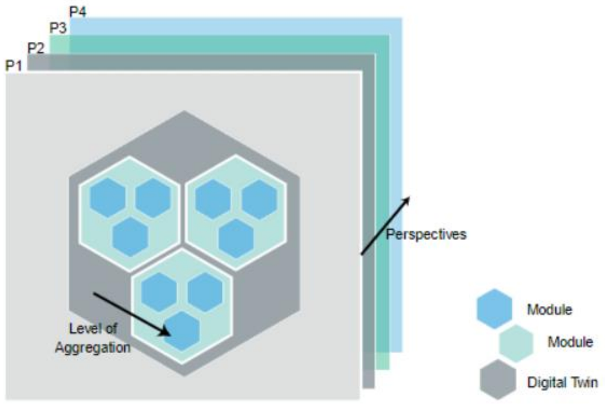

Figure 12: Reference model for the modular structure of digital twins (from [29])

2.2.5 Purpose-driven digital twinning

One of the primary effects of Industry 4.0 and its associated technologies is the ever increasing ability and desire of many companies to gather data. This tendency is created by the strong technology-push stance that is currently taken in industry. While it is true that Industry 4.0 has the potential to offer huge benefits, this is by no means guaranteed. To begin delivering value, organisations should first define the reasons for further digitalisation of their production environments. At the moment however, fear of missing out tricks many companies into becoming “data-rich but insight poor” [31]. Digital twinning has the potential to provide the insights needed to make sense of this data avalanche and so allows for its effective and efficient utilisation. Similarly to Industry 4.0 in general however, digital twinning can only become useful once its intended outcomes are defined. Or, as Slot and Lutters [31] define it, the purpose of the digital twinning application should be known. This intended purpose stems from the value that the organisation is aiming to achieve. While value is often expressed in monetary terms from a management or business perspective, to an individual operator, it may mean safer or optimized work practices leading to higher job satisfaction. This illustrates that value is a subjective concept [36].

The purpose for employing digital twinning can thus best be defined by engaging with the stakeholders who have an interest or influence on a problem or opportunity that is considered. By mapping their roles and their views on how the purpose of a digital twinning application relates to them, the required data and information, functionalities, and requirements become known. Furthermore, it enables the capture of the various perspectives that should be supported and facilitated within the digital twinning application. Through this process a digital twin can be established that will lead to purposeful outcomes for all stakeholders involved. It must be noted that the purpose and underlying goals of a digital twinning application can change over time as a result of changing stakeholder perspectives. This highlights that an effective twin must be kept flexible to account for these changes. To allow for continuous and fast initial evaluation, priorities can be assigned to the different requirements and functionalities that should be captured in the twin [31]. These priorities can be also used to set the scope for the first iteration of a digital twinning application. The practices and considerations outlined in this section effectuate a purpose-driven approach to digital twinning.

2.2.6 Conclusion

The goal of this chapter was to demonstrate how value can be created from the information that is captured in a digitalised manufacturing environment. To that end, this chapter began by explaining the difference between a digital twin and the process of digital twinning. For the digital twin a distinction was made in the way it communicates data to and from its associated physical counterpart. Based on this level of integration, the digital twin can be used for a variety of different applications. Throughout their development, digital twins will likely decrease their reliance on manual data flows but instead be expanded with sensory or even actuating capabilities. Moreover, it was shown that digital twinning cannot only rely on information captured in the as-is digital twin but also on information resulting from what-if simulations and information defined in a to-be view of the asset under consideration (together these views form the DSR).

What level of integration or what elements of the DSR are required of a digital twinning application is ultimately determined by its purpose. Digital twinning that starts from a defined purpose, ensures that only the data and information that is necessary to reach this purpose is captured in the manufacturing environment. This prevents a company from becoming data-rich but insight poor which would hinder an organisation's ability to capitalise on the value that digitalisation can offer. It was noted however that such a driving purpose, like the needs and wishes of an organisation, will inevitably change over time. To ensure that they can continue to be of value, digital twinning applications should account for these changes by offering flexibility, modularity, and interchangeability of their content.

Digital twinning at DelwiGroenink

Effective digital twinning is only possible if the data and information required by an application is available and accessible. This segment will therefor discuss examples of how Delwi captures information in their existing manufacturing landscape. These systems work as enablers for the creation of digital twins within Delwi. Furthermore, some current applications of the gathered data are described. The examples given are all from recent projects, so most of the systems that will be discussed are rather new for Delwi. Although Delwi did not refer to these projects as digital twinning themselves, they do illustrate the concept and show how it enables the creation of new insights. Below, Delwi's current systems for the capture of information and example applications are provided.

Gathering data and information

The primary source of information within Delwi is their ERP system. This system contains information concerning orders, production progress, stock levels, invoices, deviations during production, planning, drawings, specifications, and more. Most of this information is manually created and accessed by various stakeholders within Delwi. Some systems, like the paperless shopfloor software, automatically writes information about e.g. production progress to the ERP system's database. In the other direction, the paperless system bases its content on the planning and order specifications defined in the ERP system. Other information, less focussed on the enterprise as a whole but more on individual components like machines, is collected by a variety of sensors. Delwi's welding robots for example contain a variety of sensors that collect information concerning the machine status and operational parameters. Older legacy equipment often does not have extensive sensory capabilities. Machines in the turning and drilling department are examples of legacy systems that Delwi deploys. These machines have been extended with secondary sensing equipment using Programmable Logic Controllers (PLCs).

All in all, there are many systems present in Delwi that capture and store information about the manufacturing environment. Not all information captured is currently accessible however. Especially sensory information stored within machines is difficult to access. Some machine manufacturers do offer software to access this information. Delwi recently purchased software from CLOOS, their welding robot supplier, that allows for the retrieval of information that is otherwise unavailable from the robots. Such middleware will however not always be readily available for all equipment.

Example applications
Below, two examples are shown of how available and captured data is used by Delwi to create more insights regarding their manufacturing environment.

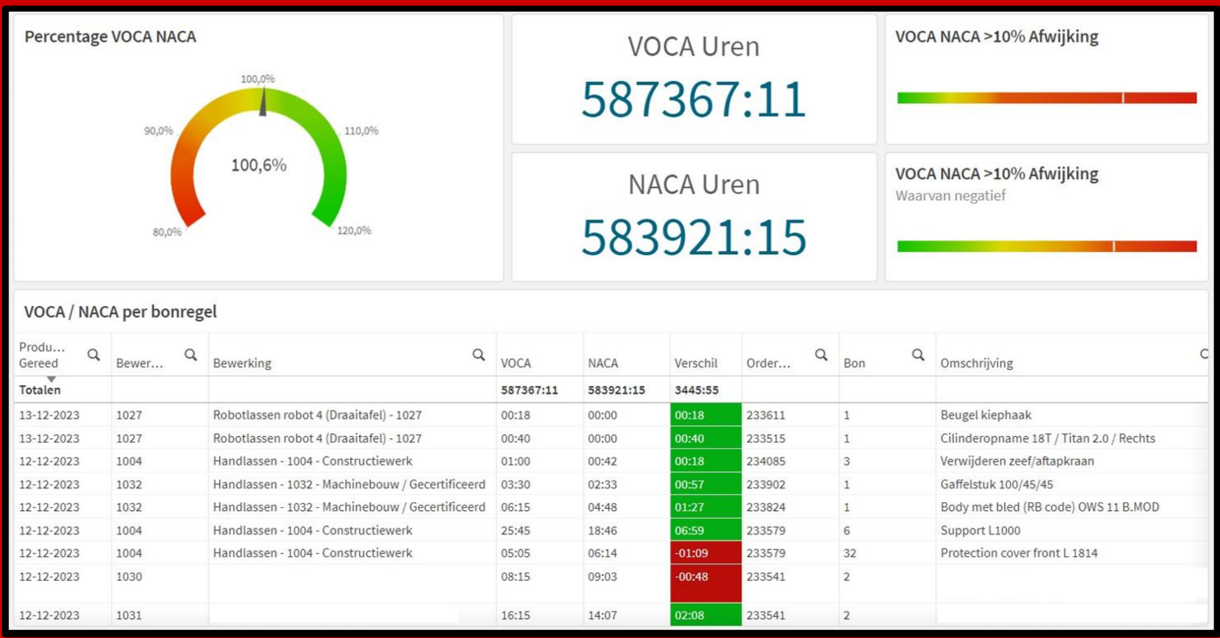

Figure 13: Qlik dashboard used in Delwi to track difference between predicted and logged production time (cells containing sensitive information have been emptied)

The first example is that of dashboarding. Such a dashboard is shown in Figure 13. Delwi used third party software from Qlik that allows for the creation of digital dashboards to visualise data for analyses purposes. The input for these dashboards is information stored in Delwi's ERP system. The dashboard shown in Figure 13 can be used for analyses concerning the predicted (VOCA) and actual time (NACA) it took to complete an order. This information

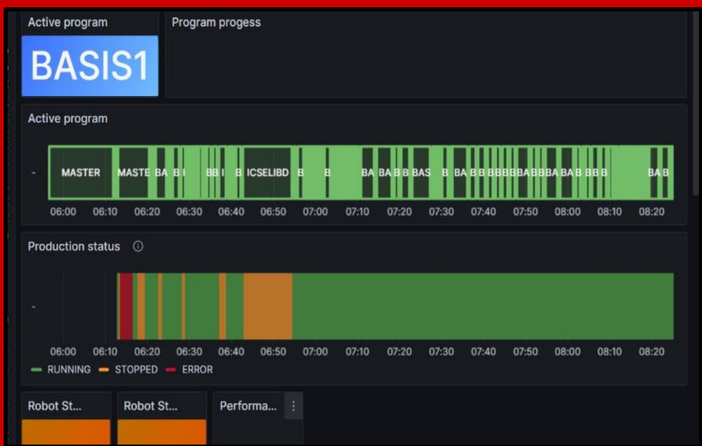

Figure 14: Dashboard for a welding robot

was supplied to the ERP system by the paperless manufacturing system. The dashboard allows for filtering of information to assess the performance of orders adhering to a certain set of specifications. Information from the ERP system is converted to a format usable in Qlik every hour. During the next conversion cycle this information is retrieved by Qlik. Qlik thus presents the as-is situation with a two hour delay. This is fine for the insights that Delwi wants to create from this particular dashboard. Such a delay would however not be suitable for a system meant to support quick responses in case of machine failure.

A different kind of dashboard was made for the large welding robots operated by Delwi. Currently, the information captured is limited. The dashboard presented in Figure 15 shows which program is and was run by a robot. Also, the machine status over time is shown.

Figure 15: Dashboard for a welding robot

This initial version of the dashboard could thus be used to determine which programs led to an error. At the moment however the programs communicated by the robot's software do not tell which order was manufactured but only during which internal program an error occured. This is thus the focus of the next steps in the dashboard's development.

2.3 Introducing digital twinning in manufacturing SMEs

Depending on its application, digital twinning can involve the introduction of many technologies that are new to an organisation. While potentially offering great benefits, these technologies can often be challenging to implement in a company. It might require the company to make changes to their machinery and IT systems, employee responsibilities, or to the company's business strategy. This section explains the main barriers which a manufacturing SME, like DelwiGroenink, faces when looking to introduce digital twinning. Subsequently, enabling characteristics for a company wanting to introduce digital twinning will be defined and discussed.

2.3.1 Barriers for introducing digital twinning

Especially in the context of Industry 4.0, barriers related to the introduction of novel technologies have been well researched. The barriers indicated below are the main difficulties that both MNEs and SMEs encounter when implementing new (digital) technologies. Given the large overlap, the barriers for implementing digital twinning are largely the same as those encountered for other technologies that fall under the umbrella of Industry 4.0. The barriers set out in this section are an aggregation of those most frequently mentioned in literature.

Lack of skilled workforce

The manufacturing industry is an industry with many established practices. Many technologies and ways of working prevalent today have often been around for decades. Effective implementation of new work practices will require retraining existing employees [7, 37, 38]. Small changes to processes are often easy to convey and getting used to and will therefore give rise to little conflict. Technologies that are more disruptive to the existing manufacturing environment on the other hand will lead to more resistance within organisations. Some employees will not be able to keep up with the technical developments while others might perceive some elements as a threat to their job security. These problems are mostly encountered among older employees [37] which, as stated in *Problem definition*, make up an increasingly large percentage of the workforce. Implementation of new technologies is best done more gradual instead of via a big bang approach. This promotes early acceptance of the technologies which is vital to retain the commitment of employees to change their ways of working.

Limited resources
Any changes or additions to a manufacturing environment will require investments both in terms of funding and time. Larger changes of course require more investments to be made. Companies often lack a strong technological base, particularly in terms of IT, on which to build their smart manufacturing environments. As a result, the process of enabling the actors in such environments to be used in CPPSs is associated with relatively high initial costs [7, 39]. This does not have to be a limiting factor when it leads to acceptable returns on the investments made. For technologies such as digital twinning however this is difficult to assess, this is even more so as industry's experience which such implementation projects is still very limited [15, 38, 40, 41].

Lack of technical know-how
Even when the necessary resources are available and the workers are willing and able to work with the new technologies, a company might still struggle with their implementation. Digitalisation of the production environment requires certain skills that might be insufficiently available in the company [38, 42, 43]. These skills might be related to managing the overall complexity of digitalisation processes [7, 42] or they might be related to competencies such as programming and data science [43]. New employees or third parties who can offer the missing expertise must be found in order to make the new digital technologies work.

Data security
The further digitalisation and interconnectivity of the manufacturing industry presents both opportunities and new challenges to the businesses involved. These challenges are primarily related to the issues of cybersecurity and data ownership [7]. Cybersecurity is related to the data of individual companies, a more digitalised manufacturing environment means that attacks such as data theft or ransomware infection will have a higher impact. Data ownership concerns will especially be relevant once the horizontal integration within a supply chain increases. Businesses will then be required to share information some of which might be confidential. While such levels of integration will only be widespread in the long term, it does necessitate the formulation of frameworks and regulations to facilitate these scenarios [15, 44]. While legal aspects can help mitigate some of the risks, it will eventually be down to manufacturers themselves to imply measures to ensure the safety of their data [44].

Technical integration
The introduction of new technologies to a production environment is seldom done via a greenfield approach. Most of the time the changes will be implemented in an existing, brownfield factory. This comes with its own challenges as it requires the legacy elements in the company to be able to be expanded upon using the new technologies. So, while the commitment to introduce new technologies needs to be there, the existing components, tools, methods, and systems should also allow their technical integration [7, 40, 45]. Another challenge connected to brownfield factories is that making changes or introducing new, sometimes immature, technologies to the factory can affect the overall stability of the existing production systems [7, 39, 41, 46]. This is a risk to manufacturers as an unstable production environment can cause negative effects like increased downtime or lower product quality, which can both hurt the company.

Organisational culture
An organisational culture that is not open to change and innovation will not be able to effectively implement new technologies and tool [43, 45]. This organisational culture is mostly influenced from a managerial level. Commitment from top level employees is therefore vital as they are the ones that will lead the implementation of technologies with which the company is unfamiliar [15,

42]. In their position, managers wield the most power to facilitate change within the company and to persuade other employees [39]. Still managerial commitment is influenced by many factors such as the ones outlined at the previous barrier explanations. An organisational culture resistant to changes to the status quo resulting from new technologies does not flip overnight. Rather this is a gradual process that is mostly driven by examples of successful introduction of new technologies within the company.

All in all, these barriers indicate that the road towards more digitalisation in the production environment comes with a lot of aspects that need to be taken into account. This may cause companies to adopt a “wait and see” approach, where they wait for competitors to display successful integration of digital tools. Instead, it would be better for companies to build up their own competences in the field. This does require the company to have a clear vision of what they aim to achieve and it requires an answer to a the question: Where to start [42]?

2.3.2 Implications for SME

The aforementioned barriers each come with their own implications for a company wanting to adopt digital twinning into their production environments. These implications can largely be divided into technological implications and organisational implications. How the barriers relate to each is illustrated in Table 1. Note that shortage of resources is included by both. Some of the considerations pointed out in this section relate to enablers for the creation of digital twins, others are more related to the process of digital twinning. The focus of this thesis is the latter which is why some of the considerations mentioned will also be used as requirements in chapter 3.

Type of implication	Barrier
Technological implications	Technical integration Data security Limited resources
Organisational implications	Lack of skilled workforce Lack of technical know-how Limited resources Organisational culture

Table 1:Types of implications and their connected barriers

Technological implications

For manufacturing SMEs, introducing digital twinning means that changes might have to be made to their existing production environment. Phasing out all older machines and replacing them by more modern equipment that have the required capabilities for use in digital twinning from the get-go is often not viable due to the high costs involved. Instead, a compromise must be found by exploring ways to enable legacy equipment to be used for digital twinning purposes, if possible [45]. This can for example be done by connecting sensors and PLCs to existing machines from which relevant information can be deduced. What information is considered relevant depends on the purpose of the digital twinning tools and the knowledge of the stakeholders involved in their development. It is therefore possible that the information required from the machines may change over time. Therefore, it is advisable that components that enable legacy equipment to be used for digital twinning can be replaced as a result of changing wishes. Additionally, modifications to existing equipment should be done gradually, especially at the beginning. Larger changes will often mean that the machines involved will be unavailable for production for longer periods of time. Moreover, large abrupt changes have a higher risk of inducing instability in the manufacturing system. Again, this is paired with high costs which might render them unviable. In these cases it could be better to add an intermediary step during which the production equipment is first enabled to be used for digital prototyping purposes to assess the effect of the considered changes.

Next to the machines, the supporting IT infrastructure in a company should also be able to facilitate digital twinning. Initial iterations of digital twinning will largely have to rely on existing data and information that is available in the company. For instance, CAD and ERP information systems are typically already present in a company and contain data which might be made available to a digital twin. Most of these systems however have been created with a certain purpose and perspective in mind, therefore they might not always allow for their contents to be used outside of the scope that they were created for. A company will therefore have to assess if their current systems allow for data exchange for digital twinning purposes [47]. If not, and if there is no workaround available, a system will have to be replaced with one which does allow for these types of connections [32]. It must be noted that using workarounds to overcome problems such as missing data, incompatible IT systems, or missing expertise are not necessarily undesirable. Ultimately, having a functioning tool is the goal. Using workarounds can however lead to extra complexity and should thus be treated as an indicator that aspects of the company's data/IT infrastructure might require an update [43]. Replacing workarounds as more robust systems become available is always an option. Finally, a company's cybersecurity measures must evolve with technological changes that are made. A more digital manufacturing environment, especially one that is interconnected with third parties, is also more vulnerable to digital threats. The potential impact of these threats is also dependant on the degree of data integration in the environment. The overall effects of malfunctioning supervisory systems will for example be smaller than for malfunctioning systems that facilitate autonomous machine responses.

Organisational implications

Next to technological implications, the barriers give rise to considerations that apply more to the organisational side of a company. Implementing digital twinning and other related concepts, has many implications for an organisation's workforce, management, practices, and overall culture. To start, the company needs to be open to change. A mentality of "but we have always done things this way" renders any innovation project useless. The different actors that will be interacting with the digital twinning applications should be convinced by their potential to lessen the effects of any organisational resistance that is left [15, 45]. Especially management has an important role to play as they will be the ones responsible for initiating projects aimed at growing the organisation's acceptance of further digitalisation of the production environment. Identifying these change leaders is crucial to ensure a smoother implementation of digital twinning. Ideally, they take on a role as 'grounded dreamers'. These individuals serve as visionaries of where the company should be, while retaining a strong connection to the current state in order to determine how the company should move forward [42]. Change management in relation to digital twinning should therefore be seen as a transformational process rather than a transactional process. This means that change in this context will be an open-ended, continuous process [41].

On the shop floor, proper inclusion of employees in the development project is vital. Most workers will have little to no experience with digital twinning but will be the ones interacting with its results [45]. Here again step-wise introduction of the new tools might help to reduce resistance from the shop floor while at the same time wishes and ideas can be identified early on in the development process. Even so, it might still be necessary to retrain some employees to work with any new technologies. Some competences, especially those required for the development of more complex data-driven tools, will not be acquired by training existing personnel. Developing more complex tools will require experts with a different background than are now often present in the company. The company's knowledge about aspects like production processes, material handling, and IT will have to be expanded with domains like data science, industrial automation, and advanced robotics. Of course, not all expertise needs to be present within the company itself. (Part of the) development of digital twinning tools and their upkeep can be outsourced to third parties. This does however come at a cost to the flexibility of the tools' development. However, whether development is outsourced or not, an organisation must first have a clear definition and vision of what they want to achieve with digital twinning.

The next step that needs to be taken is to define a starting point for the development of digital twinning tools. This starting point can be a simple use case for which a simple data-driven tool is required. Such a tool can be developed in a relatively short period of time and will thus be tied to low costs. Especially if the tool makes use of existing and readily available data. Initially the tool might offer limited added value. The tool should be seen however as a basis from which more functionalities and capabilities may be planned and added. For that reason, the tool should be set up in such a way that it allows for continuous changes to be made to its content. Next to its direct functionalities, there to assist the organisation with their production, this tool also has an indirect function of being a learning base. First versions of the tool serve as proof of concepts for the organisation. As the tool is expanded or new tools are added, an organisation learns about digital twinning and how they can best approach such projects. Gradually moving from simple to more complex tools has the added benefit of keeping required investments relatively low. This in turn means that more experimentation is possible and that some projects may be allowed to fail. Both contribute to an agile trial-and-error approach which generally yields greater learning outcomes [15, 42, 48].

2.3.3 Acceptance of digital twinning in manufacturing SMEs

The technological and organisational implications laid out in the previous section contain a series of practices and prerequisites for the introduction of digital twinning. While individually these are important as enablers, they all contribute to one fundamental condition: the acceptance of the technologies. An organisation can be fully ready for digital twinning from both a technological and organisational perspective, if the company and more specifically the users are not accepting of digital twinning, it will not be adopted. Acceptance is linked to the intention of an individual to make use of a certain technology. This intention in turn is influenced by the way in which the technology is perceived by the user. The most determinate aspects of this perception are the perceived usefulness, perceived ease of use, social influence and facilitating conditions [49]. The perceived usefulness is the degree to which the user believes the technology will improve their job or task. The perceived ease of use is the expected effort that is required to use the technology. The social influence is the degree to which an employee believes 'important others' want them to use the system. Important others in this context could for instance be fellow colleagues, supervisors, or managers. Facilitating conditions refer to the perceived availability of the required organisational and technological infrastructure to support the use of the technology [49, 50]. The influence of the aspects towards the actual use of a new technology are visualised in Figure 16.

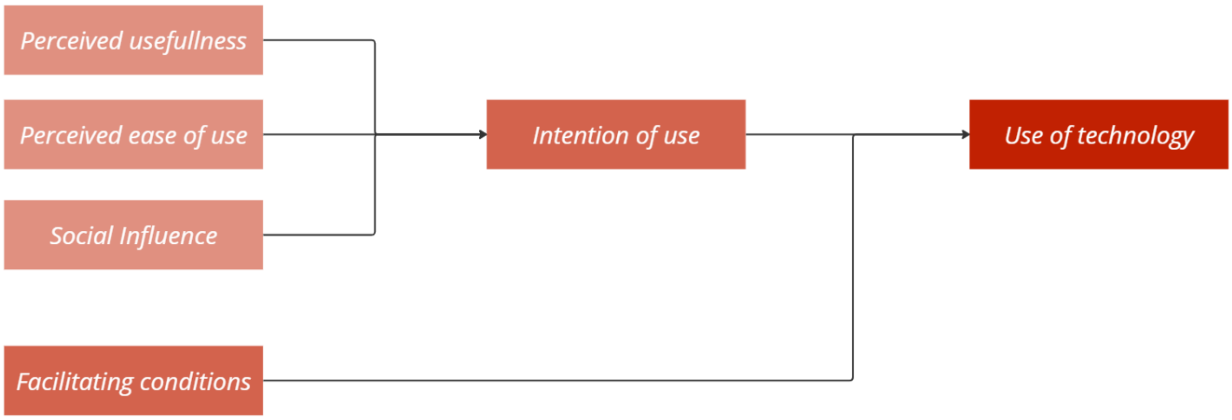

Figure 16: Influence of the different factors on the acceptance of new technologies (adapted from [50])

Of the four influencing factors shown in Figure 16, social influence and facilitating conditions have been covered in the previous section as these are most about the environment in which the technology is to be used. Also, their effects on the acceptance of a new technology are limited when compared to the other two. Facilitating conditions for instance do have a very strong influence on initial acceptance of new technologies, however this effect decreases after the first successful deployment of the technology. Social conditions can be strong drivers for acceptance of new technologies when users are inspired to use the technology, this use however can also be mandated by the organisation [50]. Although mandated use of a technology is not preferred, it does not have to hinder acceptance as long as other factors have a strong impact. Perceived usefulness and perceived ease of use are the factors most closely related to the technology itself. Which, in the context of this thesis, is digital twinning. For digital twinning applications to get accepted within the organisation, they must thus satisfy the criterion of being useful enough to justify the effort required to use them.

2.3.4 Conclusion

In this chapter, the main barriers that SMEs face in their journey to a more digitalised manufacturing environment were outlined. Based on these barriers, both technological and organisational implications for an SME were defined. Introducing digital twinning in an organisation will require changes to be made within the company. These changes should be implemented via a transformational change process, meaning that the required infrastructure and knowledge within the company is continuously developed over time. This ensures that the organisation's digital twinning applications can grow to match their maturity in the field. All of the implications laid out in the chapter furthermore contribute to one important condition: acceptance of digital twinning within the organisation. To this end, it is important that digital twinning applications are developed in close collaboration with their users. Including their perspectives early on ensures that the usability and required effort to use the applications are aligned with their wishes. Once these are established, manufacturing SMEs can start developing purposeful digital twinning applications for their organisation. While initially limited, the value of these applications can quickly increase as the company develops its capabilities to add more complex functionalities.

Barriers for DelwiGroenink

In this block, the main barriers discussed in the previous section will be related to DelwiGroenink. While their general implications have been discussed above, this section aims to provide a short analysis of both technological and organisational aspects of Delwi connected to the barriers. The information presented below were based on various conversations that were had with Delwi employees.

Lack of skilled workforce

Especially over the last few years, Delwi's manufacturing landscape has changed quite a bit. Most of the technological changes were aimed at departments with administrative tasks that were to be automated. On the other hand, there has also been the introduction of more robotics and the paperless manufacturing system. These systems required existing employees to be trained in their use. For Delwi it was important that the employees that would have to work with the new systems had a good idea of what these could offer. Projects in which employees were less invested often resulted in disinterest in learning how to use them.

Limited resources

One of the main barriers experienced by Delwi is the need to make choices due to limited resources. Any resources not spent on the company's daily operations must be divided among various improvement projects. Employees will only work on digital twinning projects if they have been given priority over other projects. In the past three years, Delwi has primarily focused on larger improvement projects that were expensive and will take time to yield results. As a result, Delwi currently prioritises low-cost projects that can provide tangible results in a relatively short amount of time.

Lack of technical know-how

In recent years, Delwi has hired a variety of new employees that brought new skills and knowledge to the company. This has been vital for the introduction of new technologies and work practices to the company. The most recent examples include an employee with experience in production automation and robotics, a software engineer, and a factory engineer. Currently, these employees bring the required expertise and capacity for further digitalisation projects. The automation expert has also begun training other employees to for example do the offline programming of the robots. his is necessary because he currently has too little time to work on other automation projects. Moreover, Delwi recognises their dependence on this engineer in the automation of their production. They want to ensure that parts of his knowledge will be retained in case he for whatever reason leaves the company. This example illustrates how a lack of technical know-how can slow down the overall digitalisation and implementation of new technologies to the manufacturing environment.

Data security

Delwi feels that they currently have secured their data in a safe way. For that reason, data security is currently not viewed as a major barrier in Delwi's journey towards the implementation of digital twinning applications. Nevertheless, the company acknowledges the importance of continuously monitoring data security, especially if they decide to share data with third parties in the future.

Technical integration
Options for the technical integration of digital twinning applications is something that Delwi is currently researching. There have been some initial projects in which PLCs were used to capture data of various machines. Moreover, inquiries have been made regarding different kinds of machine software to see if and how these can be connected to other software. The applications of these projects remain limited however and it will likely still take some time before such projects can yield real value for Delwi.

Organisational culture
DelwiGroenink has recently introduced a management team to their organisational structure. This team is responsible for initiating and leading improvement projects within the company. The first step for Delwi is to establish commitment within this team to work towards an increasingly digital manufacturing environment. While some actors support this transition, others remain for now more hesitant. This management team must first be convinced of the advantages before a wider culture of change within Delwi can be facilitated. This management team, as well as the employees on the shopfloor, suggest that this acceptance will likely increase following successful projects. As stated under *Limited Resources,* there is currently a strong preference for projects that provide tangible results.

2.4 Support for digital twinning development

As stated in the problem definition, manufacturing SMEs generally lack a comprehensive understanding of data-driven manufacturing in the context of Industry 4.0 and how it can be benefit their organisation. In the *Analysis* chapter, the different dimensions of the Industry 4.0 concept were discussed with a special focus on the role digital twinning plays in this. Next, common barriers encountered by manufacturing SMEs aiming to introduce technologies like digital twinning were translated to their technological and organisational implications.

Manufacturing SMEs must build up their knowledge and experience with digital twinning. This is best done gradually so that initial investments can be kept low. Moreover, incremental development of digital twinning applications allows an organisation to adopt a learning-by-doing approach and provides a degree of flexibility which are both needed as its supporting technologies mature. The organisations must be supported in the initial formulation of digital twinning applications as well as in the management of their development over time. Over time the overall complexity of digital twinning and data usage within the manufacturing environment is expected to increase. The knowledge regarding the current state and future directions of these applications must be structured to allow for informed decision-making on digital twinning within the organisation.

The required support for digital twinning development within manufacturing SMEs can be divided into two parts:

1. An approach is needed to translate a defined purpose for digital twinning in an organisation to the data that is required. The outcomes of this approach must furthermore be usable to serve as a basis for a first version of the digital twinning application while at the same time providing pointers for its further development.
2. A tool is required to keep overview of how data is used and what data is required by the organisation's digital twinning applications. Properly structuring this information allows

it to act as a knowledge base to support stakeholders in their decision-making regarding the development of digital twinning applications in their organisation.

Example applications of digital twinning

Digital twinning is a versatile concept which has an extremely broad range of applicability. While previous chapters explained the underlying theory and gave some context of how this applied to the case company, this section will provide some more in depth examples of what digital twinning has been used for by other parties. The provided examples are limited to the manufacturing industry. However, it must be noted that the potential of digital twinning has also been recognised in sectors like healthcare, defence, and city management [51-53].

In the manufacturing industry, digital twinning can be found throughout the different hierarchy levels (Figure 6). Twins can be made from individual machines or even from entire factories or supply chains. Moreover, digital twinning can be applied all along an assets lifecycle. Below are some example application areas for digital twinning.

Virtual testing and prototyping

Digital twinning can be used for testing and prototyping purposes. While testing and prototyping can be done fully physically, adding a virtual component yields certain benefits. This is illustrated by using the example shown in Figure 17. Figure 17 shows four stages in the development of a new production environment through the use of digital twinning [27]. The digital master of the factory that is to be built is expanded with digital twins of existing assets. In this case these assets are various machines. Once twinned, these assets can be copied and added to a virtual factory. This allows for testing and what-if analyses without the need to invest in more physical instances of the machines. Moreover, changes to the layout are much easier to make virtually than physically. The last panel demonstrates how it might even be possible to add machines that are not already owned by the company so long as there is a reliable twin of the machine available. This method of facility design based on validated asset behaviour has a much higher fidelity than traditional design which is usually built on assumptions and estimates. The main advantage of this approach however is that it the required investments in terms of both time and money.

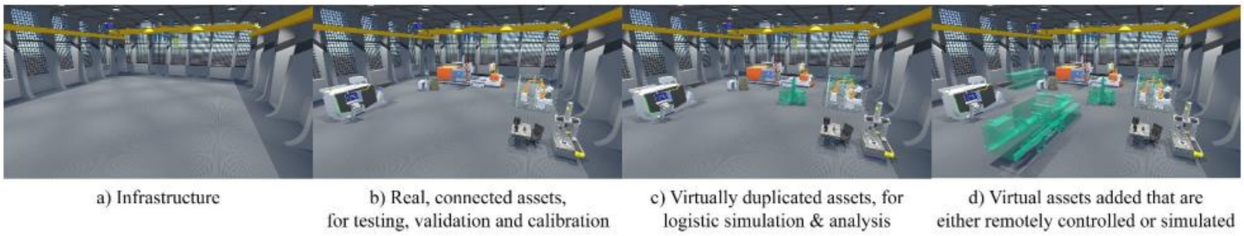

Figure 17: Different stages in the development of a production environment (from [25])

Asset monitoring

At its core a digital twin is a live representation of a physical asset, process, or system. Live meaning that the information communicated through the twin represents the as-is situation at an acceptable latency. As such, depending on the application, the data does not have to be updated real-time if this not yield additional benefits. For example, for a twin used for tracking a product as it moves through a factory, an update to its location data might only be necessary as it enters or leaves a station. A digital counter-part of an asset that tracks its location or even something simpler like its state (on/off/error) can be used to spot unexpected behaviour without needing an operator to constantly be present at the asset itself. Figure 18 shows a concept for asset monitoring at the shop floor, here the info of the assets can be accessed by using an Augmented Reality (AR) interface. This allows a mechanic to promptly identify the most relevant information about the asset; in this case its production capacity, uptime, pressure and energy state.

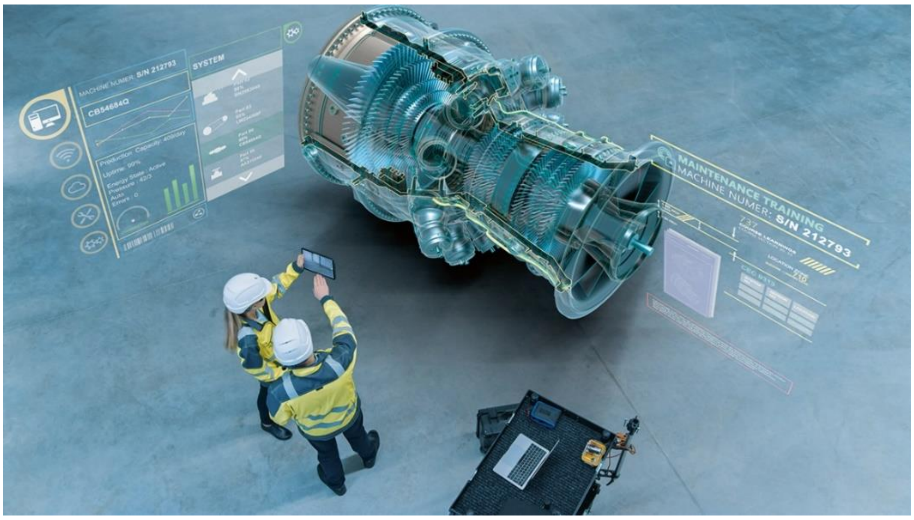

Figure 18: Live asset monitoring using AR (concept) (from [52])

Process evaluation & optimisation

Traditionally, manufacturing systems operate based on set, predefined instructions. While this will largely result in acceptable products, minor differences in the used materials and components will yield final products of varying quality. Based on periodic quality checks, manual adjustments to machine settings are made where necessary. However, the increasing demand for small batch production of customised products leave less or no room for these improvement cycles. A digital twin of a machine working in conjunction with digital twins of the products it produces can enable continuous evaluation and optimisation of the production process. For this to be effective, data acquisition and its translation to actionable information needs to take place in near real-time. A case study of this digital twinning-enabled production control was conducted for the production of a diesel engine part [54]. After identifying the relevant and required data components and their formats, and translating this to digital models to represent the machine's behaviour, a multifunctional twin was created. The functions were monitoring the current status of the machine, simulating future machining operations, and to reconfigure the machine based on the evaluated data. The different elements of the DSR can be recognised in these functions. The goal of this twinning application was to yield insights into process capability to yield acceptable products and into the quality of the machine operations. The results can then be used to optimise the order of production steps for a product or for real-time adjustments to the parameters of a process. These functions and their relation to the governing digital twins are visualised in Figure 19.

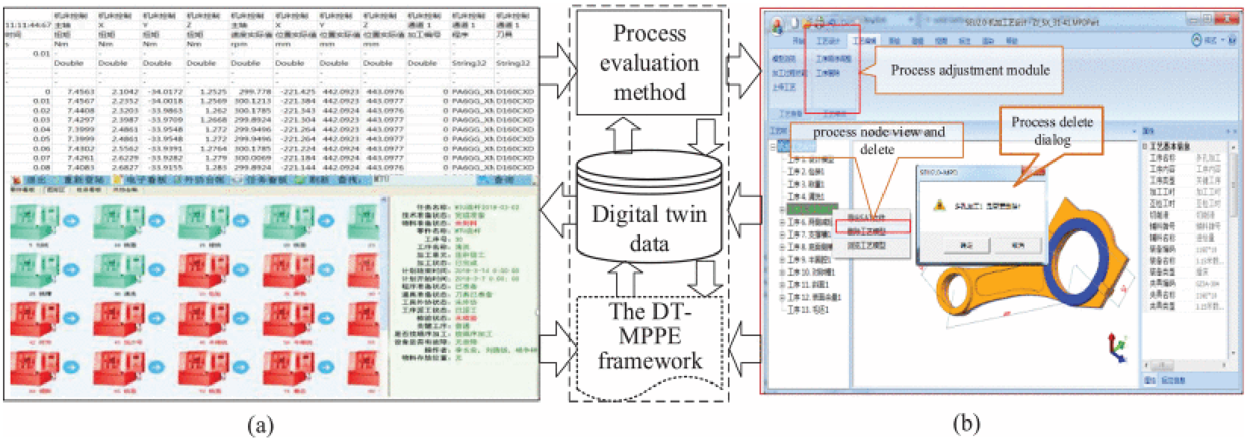

Figure 19: Evaluation of product and process quality and their interfaces with the digital twin (from [52])

Similarly as for production control, evaluation and optimisation can be done for the production planning process. When the behaviour and capabilities of the production stations in a factory are known, a digital twin of the production environment can assist to the production planning. Based on the station's capability data and simulations in a digital prototype of the factory, changes in the production planning can be suggested based on the current state of the machines. A defect in one machine may for example result in the rerouting of the products it needs to process to other machines based on their capability and availability. Another functionality could be to dynamically change the planning as a machine becomes available.

Predictive maintenance

There are different types of maintenance [55]. Currently maintenance to machines generally can be described as being reactive or preventive. Reactive maintenance occurs after a component breaks. As this happens unexpectedly, it will always result in unscheduled downtime. Preventive maintenance aims to reduce this type of downtime by describing maintenance and the replacement of components at set intervals. The main disadvantage of this type of maintenance is that components are replaced even though they might not be at their end of life. A third type of maintenance is predictive maintenance. Utilising models and (historic) machine data, a digital twinning application can be used to predict when a machine requires maintenance. The data gathered is used to calculate the remaining useful life (RUL) of the machine's components. Based on this indication, downtime can be planned in advance, and replacement parts can be ordered in time and only when needed. While a twin like this is powerful, current applications remains mostly limited to high-value equipment only [56]. This can be explained by the fact that in order to fabricate a twin for predictive maintenance, usually extensive knowledge of the functioning of the machine and its fault mechanisms is required. Even then the behaviour of a complex machine nearing a failure can be difficult to predict. New technological advancements in the fields of machine learning, AI, and FEM however can potentially account for this unknown behaviour. By gathering large amounts of data through various sensors, patterns can be identified over time which are related to component failure. At the moment this will require significant investments meaning it is not yet feasible to apply this tactic to lower value assets. Still, predictive maintenance for simpler applications and known failure behaviour is already in reach as demonstrated by the example shown in Figure 20. Here a digital twinning application was developed for determining the RUL of the blades of a gas turbine. It was known that the RUL of the blades was primarily influenced by the rotational speed of the turbine and the in- and outlet temperatures. Based on mathematical models these known parameters were translated to behaviour at the blade and then to a validated damage profile.

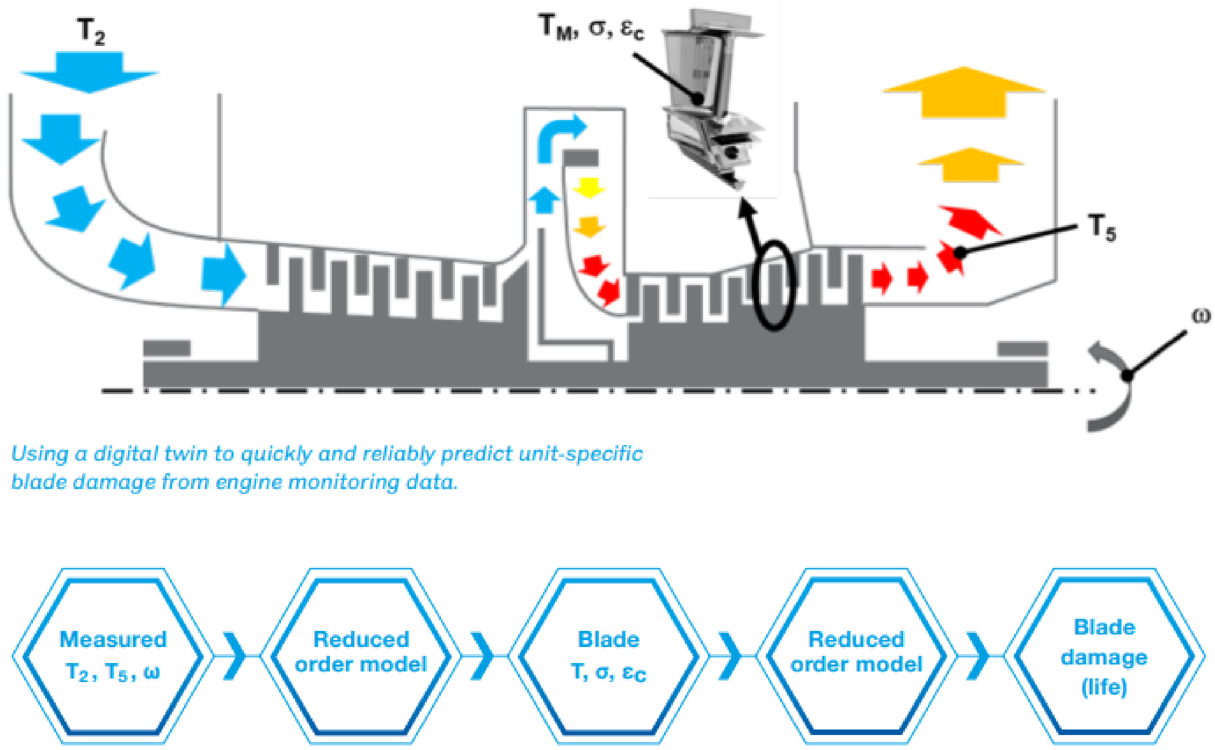

Figure 20: Situation and outline of the underlying models of a turbine blade's digital twin (from [26])

3 Requirements

This chapter outlines the requirement lists for the digital twinning development support that was defined in *2.4*. Separate lists have been created for both the required approach and the required tool. The approach should lead to the formulation of digital twinning applications that contain the characteristics as set out in *Digital Twinning*. The overview tool will be tailored to the outcomes of this approach and should provide a means of navigating their information content, this tool will be referred to as the digital twinning overview tool. The requirements are based on the contents of the *Analysis* chapter and have been expanded based on discussions with Delwi employees. From where the requirements were sourced is written between brackets behind each requirement. The requirements will be verified later in this thesis.

3.1 Requirements - Digital twinning approach

Below the functional requirements of the digital twinning approach, or workflow, have been set out. These requirements are verified at the end of *Blueprinting approach* and the workflow is validated in *Case Study*.

1. The approach should contain a formulation of the intended purpose of the digital twinning application. (*Section 2.2.5)*
2. The approach should describe the functionalities that are required of the digital twinning application. (*Delwi stakeholder interviews)*
3. The approach should contain an overview of the relevant stakeholders and perspectives (*Section 2.2.5)*
4. The approach should describe the required information output of the digital twin (*Section 2.2.3*)
5. The approach should describe the data that is required for the digital twin (*Section 2.2.3*)
6. The approach should promote the reuse of components of other digital twinning applications (*Section 2.2.4*)
7. The approach should allow for a distinction to be made between manual and automatic data flows (*Section 2.2.1*)
8. The approach should allow for the inclusion of existing data/information sources (*Section 2.2.3*)
9. The approach should provide guidance for the gradual development of the digital twinning application (*Section 2.3.2*)
10. The approach should allow for continuous adjustments to be made to its outcome (*Section 2.2.4 & 2.3.2*)
11. The approach should promote continuous evaluation of the digital twinning application (*Section 2.2.4*)

12. The outcomes of the approach should be understandable by the stakeholders involved in its execution (*Section 2.3.2*)
13. The approach should be applicable for any digital twin (*Section 1.3*)
14. The approach should be usable by any manufacturing SME (*Section 1.3*)

3.2 Requirements – Digital twinning overview tool

Below the functional requirements of the digital twinning overview tool have been set out. These requirements are verified at the end of *Digital twinning overview tool* and the tool is validated in *Case Study*. The requirements below will be expanded where necessary based on the outcomes and concepts that are presented in chapter 4 and 5.

1. The tool should show how information is used in a digital twinning application (*Section 2.2.4*)
2. The tool should be able to capture the overall digital twinning landscape of an organisation (*Section 2.2.3*)
3. The tool should show both direct and indirect relations within an organisation's digital twinning landscape (*Section 2.2.4*)
4. The tool should allow for the capture of the outcomes of the workflow (*Section 2.4)*
5. The tool should allow for filtering of its content (*Delwi stakeholder interviews)*
6. The tool should allow for easy navigation of its content (*Delwi stakeholder interviews)*
7. The tool should allow for changes to be made to its contents and functionality (*Section 2.4 and Delwi stakeholder interviews)*

4 Blueprinting approach

The first part of the digital twinning development support is an approach that deals with the initial formulation of a digital twinning application. The outcome of this approach is a representation of the application that contains its governing purpose, stakeholders involved, and the required functionalities, information, and data of the application. Additionally, the approach should allow for the definition of future iterations of applications even if some of their elements are currently unattainable by a company. As such, the goals of the approach are threefold: to define how a digital twinning application will translate data to value for its users, to provide a starting point for its development, and to provide the directions for future development and implementation of the application. The approach is therefore primarily meant to assist the actors responsible for the development of digital twinning within an organisation.

4.1 General structure

The starting point for the developed approach was the structure shown in Figure 21. It follows the different levels of the Advanced Manufacturing Landscape (Figure 11) aggregated by the 'Layers' dimension of the RAMI4.0 model (Figure 6). Moreover, it shows how the approach is governed by the intended purpose of the twinning application. As the purpose is being formulated, or shortly after, it is important to consider and consult the stakeholders that will interact with the twin. It is their perspective and expert knowledge that enables the creation of intelligence from information so that the application can achieve its purpose. Perspective here refers to the way in which the stakeholders interpret the information presented to them, this is influenced by their experience and intended use of the information content. Discussions with stakeholders can clarify which information and functionality is needed to come to a usable application. Finally, the necessary information that is derived from raw data about a physical asset, system, or process, to which relevant context is added. Context is the set of rules and relations that provide meaning to the data such that it can be interpreted by a stakeholder [34]. A digital twinning application consists of a physical- and digital domain component. Multiple of such applications can stem from a single purpose. Therefore, in Figure 21, the purpose is depicted separately from the physical-digital domain combination that makes up a digital twinning application.

The structure includes various 'black boxes' between each level. These 'black box' and 'data acquisition' blocks represent the methods that should enable each translation step in the digital twinning process. Effective digital twinning is only possible if each of these translation steps is possible and yields satisfactory results. Even so, not every required method might be known, possible, or available during initial formulation of a digital twinning application. In those cases, a black box-method containing the required functionality and interfaces will have to suffice to still be able to formulate the intended workings of the twin and to identify points of attention for future development.

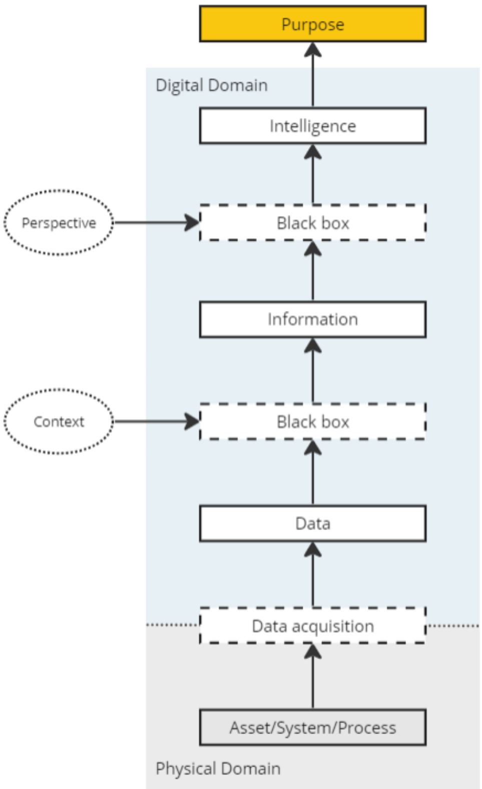

Figure 21: General structure for digital twinning

4.2 Modularity

The 'black boxes' or methods can be viewed as modules which prescribe the functioning of the digital twinning application. Constructing these applications in a modular fashion maintains their flexibility in terms of structure and content, encourages the reuse of elements of existing applications, and it necessitates a reproducible workflow for the creation of new digital twinning applications. In the general structure described in Figure 21, a module takes inputs and converts these into certain outputs. A module can entail a wide range of functionalities. Examples are modules representing a series of mathematical operators, prescribing certain sensors, or ones describing charts or software to convey information.

Modules can be interchanged, adjusted, removed, or added as the required functionality of a digital twinning application changes. A module can be interchanged by another module with (largely) the same functionality [57]. Following the structure above, that means that a module can be interchanged if the replacing module can take the same inputs and can yield the same outputs. This means that when e.g. a data acquisition module like a sensor will be replaced with a more accurate one, it should be checked if this will not lead to problems in existing applications. A sensor yielding a number output that is accurate to two decimal points might not directly be usable by a software component only expecting round numbers. In such cases a conversion method might have to be added to the application. Although the issue in the example above could likely be resolved with ease, a change of the receiving software component could be much less straightforward as it likely has much more interfaces that must be accounted for.

4.3 Workflow

Based on the previous sections, the approach should allow for the capture of stakeholders' perspectives on the information content of a digital twinning application. Simultaneously, the interfaces between the components of an application should be defined to allow its developers to make informed decisions about any changes they might want to make to its content. Following both requirements, the approach will make use of graphical representations of the applications' content and functioning. Such a format is often more comprehensible for dealing with complex patterns than e.g. text [58]. A graphical representation then captures the intended workings of a digital twinning application and can serve as a reference for stakeholders both during and after its development. While a general overview of an application can be used for discussions about the content of the application, it more importantly serves as a base from which to define the content of a first, short-term version of the application as well as the content of future, long-term iterations of the application. These different overviews of the digital twinning application's content will be referred to as blueprints in the remainder of this thesis. The approach of creating and updating them will be referred to as the blueprinting approach.

Now that the outcomes of the approach are defined, the workflow for the creation of these blueprints is presented. The workflow consists of a series of steps divided in two parts. The goal of the first part is to create the general blueprint of a digital twinning application (DTA). This general blueprint shows how data in the organisation will be used in relation to the defined functionalities of the DTA. The need of the DTA itself follows from a certain driving purpose. The goal of the second part of the workflow is to use the general blueprint to create a short-term and long-term blueprint of the DTA. These blueprints can serve as two ends of a roadmap. While the short-term blueprint can be used for initial development of the application, the long-term blueprint captures the intent for a future version of the application. The application's development trajectory can then be structured so that the gap between the two is gradually bridged.

The blueprinting workflow is visualised in Figure 22. The red and blue blocks represent the primary stakeholders that are involved in the process. The intended user is the stakeholder that will hold the most power over what should be included in the eventual DTA. The developer is the stakeholder responsible for the creation of the DTA. The arrows pointing away from the stakeholders indicate the steps in which they provide the main input. The output of the first steps are blocks to be used in block diagrams that graphically represent the functioning of the twinning application. It must be noted however that other forms of documenting the outcome of each step can be just as valid. The form used in this thesis should in no way be seen as prescribing the 'correct' form, in the end it is up to the users to determine what is most suitable and workable for them. It is advised however to stick to one form within a company in order to prevent unnecessary ambiguity stemming from stakeholders working in different ways. Each step of the workflow is explained in more detail below the figure.

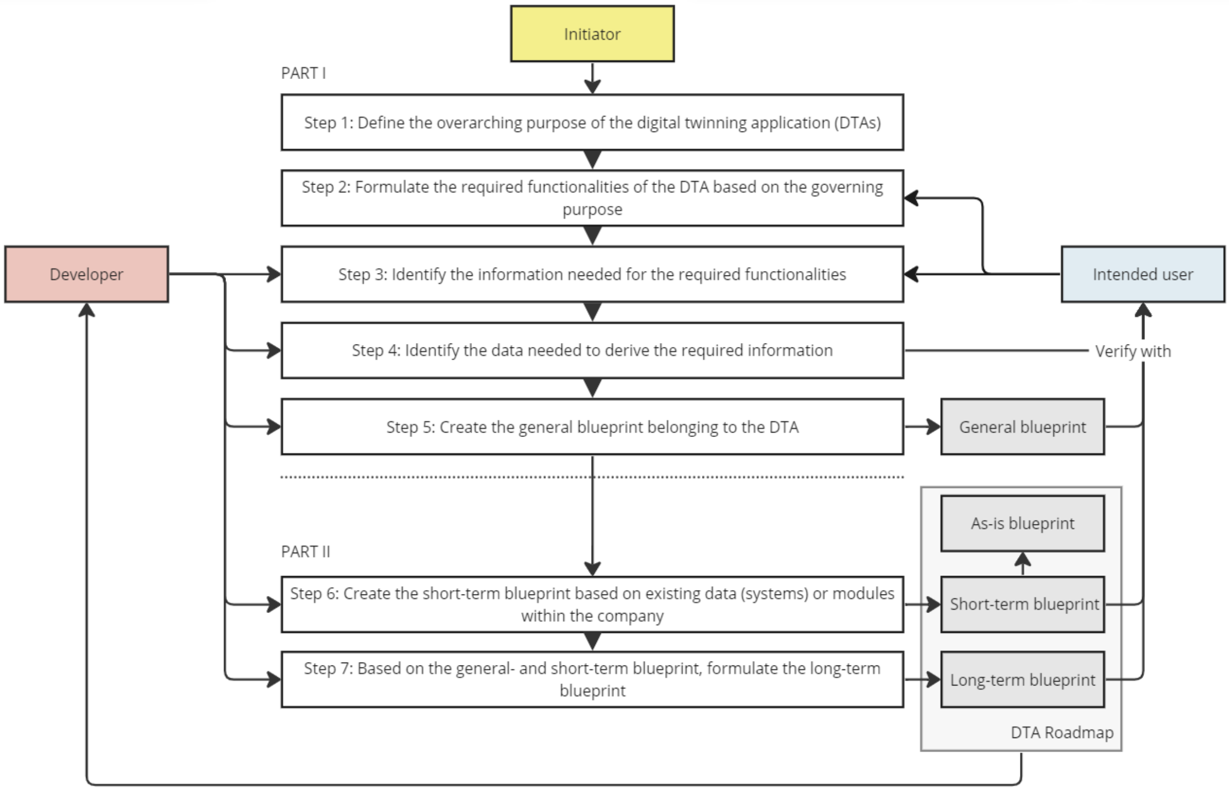

Figure 22: Blueprinting workflow

PART I – Translate a purpose to what information and data should be included by the DTA

Step 1: Define the overarching purpose of the digital twinning application (DTAs)

Each development cycle of a DTA starts with defining its purpose. This purpose can originate from various sources. It could be defined by management, arise from the company strategy, but also for example from wishes of individual stakeholders part of the factory ecosystem. In the workflow this source is referred to as the 'Initiator'. The purpose behind employing digital twinning will not always be specific, sometimes it will represent a more general need. In those cases it may be necessary to formulate subgoals that align with the overall purpose in order to better scope individual DTAs.

Step 2: Formulate the required functionalities of the DTA based on the governing purpose

The purpose will provide a general formulation for the intent of the application. This is however not ideal when discussing the goal of the DTA with other stakeholders involved in its development. Especially stakeholders that will directly interact with the tool will most likely express their wishes in terms of the functionalities that they require. These required functionalities will differ per stakeholder based on the perspective they have on the tool. Moreover, new ideas for the DTA that emerge during use will be in terms of new or changed functionality. As the DTA could have multiple stakeholders that will interact with it, this and the following steps should be carried out with each stakeholder to account for their unique perspectives on the DTA's purpose.

Step 3: Identify the information needed for the required functionalities

` This step also requires close collaboration with developer and the intended users of the DTA. Per functionality it is determined what information is needed.

Step 4: Identify the data needed to derive the required information

The required information is further split into its underlying data. This is done in cooperation with the intended users but will largely be determined by the developer of the DTA. This is because they will have the most knowledge about the development of data-driven applications. However, the proposed data foundation, how it is used to derive information, and the specifications of the data will need to be discussed with the user stakeholder. These users might have certain demands concerning for example the fidelity or format of the data that is gathered and used. These demands might not always be obvious to a developer that lacks the end user's expertise and knowledge.

Step 5: Create the general blueprint belonging to the DTA

The outputs of the previous steps are combined into a general blueprint of the DTA. 'General' here meaning that the blueprint does not consider the data and data systems already present in the organisation. Its primary function is to explicitly capture relevant expert knowledge and the preferred workings of its associated DTA. Considering the existing data foundation of the manufacturing environment might prove limiting in this regard. This step concludes part I of the workflow and its output is a general blueprint of an idealised version of the DTA. This blueprint serves as a reference for further development of the DTA, it serves as a base for discussions about the ideal working of the DTA. As stated earlier in this section, in this thesis the format used for the blueprint is that of a block diagram. Its structure is explained in more detail in section 4.4.

PART II – Create a roadmap for the development of the DTA

Step 6: Create the short-term blueprint based on existing data (systems) or modules within the company

Creating a functioning DTA requires investments and experience. Rather than spending time and effort in introducing a first time right DTA containing all previously defined functionality, it is better to start simple and gradually expand the tool. This also means that any changes to the intended functionality can be taken into account early and thus cheaply. The short-term blueprint maps a version of the general blueprint that is more tailored to the as-is situation in the company. The DTA takes modules, data, and data systems that are already available as its basis. This short-term blueprint will usually start relatively simple as compared to the general blueprint as not all required information is initially available to an acceptable degree. This means that certain functionalities or information will be approximated based on what is currently available. Once a DTA based on the short-term blueprint is realised, this blueprint becomes the as-is blueprint of the application. This as-is blueprint gives insights into the current workings of the DTA.

Step 7: Based on the general- and short-term blueprint, formulate the long-term blueprint

When comparing the short-term or as-is blueprint and the general blueprint, points of improvement can be identified that should be included in the DTA's further development. These may be missing functionalities, incomplete data, inaccessible data, missing modules, or other shortcomings. These aspects can, however, be included in the long-term blueprint. This blueprint is an expansion of the short-term blueprint and may also include modules and methods that are not yet available, not yet practical, or methods of which the exact functionality remains unknown (black box modules). Initial efforts by the company will be directed at achieving a working version of the DTA based on the short-term blueprint. However, future development efforts will be guided by the long-term blueprint. This blueprint captures what the DTA should ultimately contain. By comparing the current state of the DTA with the intended state captured in the long-term blueprint, it becomes possible to define the content of the next iteration of the DTA. Once this short-term version of the DTA has been realised, it becomes the as-is representation of the DTA and the cycle starts anew. This goes on until the as-is blueprint and the intended state captured in the long-term blueprint overlap. Of course, this does not mean that the development of the DTA is truly finished. Changing requirements regarding the application's functionality can always cause the as-is and long-term blueprint to no longer coincide. The as-is, short-term, and long-term blueprints together form a roadmap based on a general formulation of the DTA, this is visualised in Figure 23.

Step 7 concludes part II and the workflow as a whole. Together, the different blueprints serve as a reference for the discussion, development, implementation, and evaluation of a digital twinning application. Any changes in the purpose or intended functionality of a DTA will mean that the workflow must be followed again to incorporate these changes into its associated blueprints.

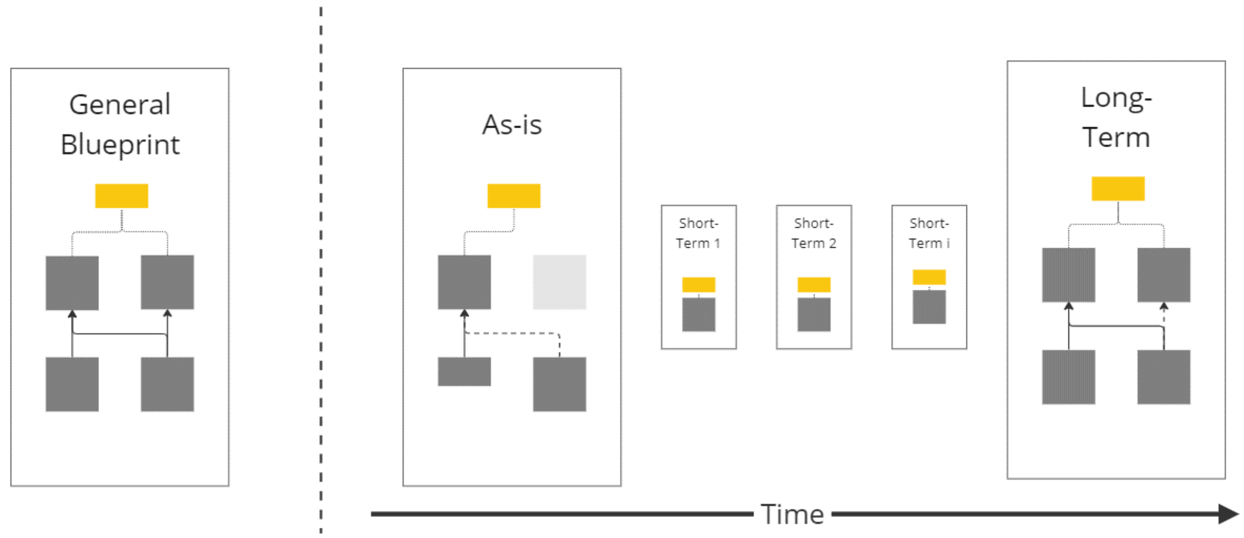

Figure 23: Roadmap structure of blueprints

4.4 Blueprint components

In this section the different building blocks that make up the blueprints are explained. The example blueprint in Figure 24 shows how these different building blocks together describe the workings of a DTA. Each component is explained in more detail below the figure. It also shows the difference between which blocks can be included in a general blueprint , in a short-term blueprint, and in a long-term blueprint.

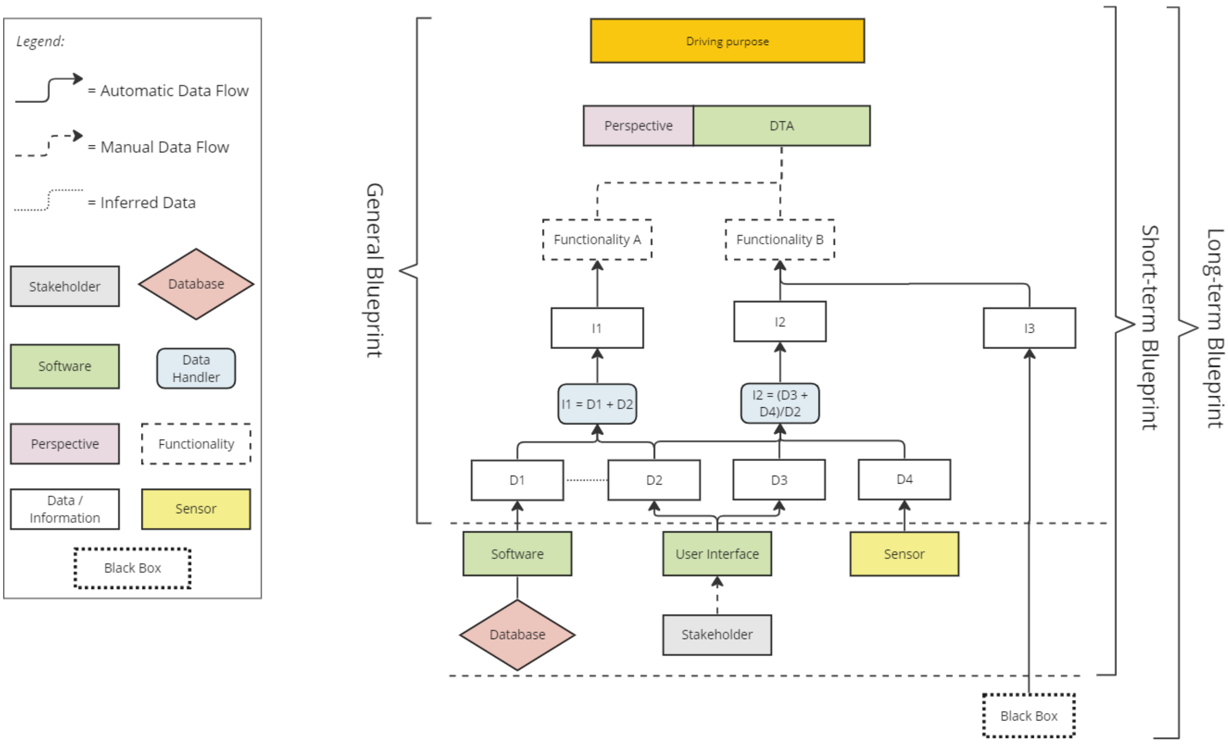

Figure 24: Example blueprint

Data flows

In the blueprints a distinction is made between different types of data flows. This distinction is based on the different levels of integration of digital twins, as explained in chapter 2.2. While data and information flows within software will largely be automated, acquisition of data can be a manual process. Also, legacy systems whose content is inaccessible to other (software) systems may necessitate a manual conversion step. By mapping the type of data flows it becomes possible to identify future points of improvement. Additionally, an 'inferred data' flow was added to represent how certain data used in a DTA might be inferred from other data. If a DTA for examples requires an order ID for one of its functions, this order ID can be linked to information regarding the suppliers or stock of its components via relations established in an ERP system. This inferred data can then be used to provide the required input for another functionality of the DTA.

Software

Software blocks represent the different software systems that play a role in the DTA. This can be the DTA itself but also systems that act as a source of data and information such as ERP, MES, and PDM systems. The example also includes a 'User Interface' software component. This represents the need for a system that allows a stakeholder to manually supply information to the DTA.

Perspective

The perspective block connected to the DTA shows from which perspective the blueprint is created. It shows the required functionalities and information for that specific stakeholder. A DTA might have to satisfy multiple perspectives, however rather than making all functionalities available to each stakeholder it is better to reason from individual perspectives. This reduces the risk of information overload and unnecessary complexity that hinders the DTA's usability.

Functionality

These blocks represent the functionalities that the main stakeholder requires of the DTA. Per functionality it can then be mapped which information is required to offer said functionality.

Stakeholder

This block will most commonly be used in conjunction with manual data flows. Although it may appear similar to the perspective block, they are different. The perspective block determines top-down what information is required for the DTA. The stakeholder block on the other hand is meant to indicate what stakeholders are involved in the acquisition of this information.

Data Handler

The data handler blocks show how data and information is used to create new information. These blocks represent how exactly the inputs for the DTA are transformed into information that is required for the DTA's functionalities. While this process is primarily determined by the application's developer these blocks can be useful to identify missing or unused information inputs in collaboration with the end user. Moreover, explicitly mapping the underlying functioning of the DTA allows future applications to include the same techniques.

Data/Information

These are the most basic blocks in the blueprint and represent the data and information that is used in the DTA. In each blueprint all of these blocks should either directly or indirectly feed into one or more of the defined functionalities. In both short-term and long-term blueprints, it should be possible to trace all of these blocks back to a source. This source is either a database, stakeholder input, or sensor. Normally, this data is transferred via a software component converting the data into an usable format.

Database

Database blocks represent the data repositories involved around a DTA. Existing software systems will often be built upon a database that tracks information over time. Also, some DTAs will create new information that needs to be stored. In the blueprints it is assumed that information retrieved or stored in database components remain available for future use. Of course, the data repositories to which they refer might have their own logic concerning how long certain data is stored.

Sensor

The sensor block can be used to map what data on a physical asset or system is created via sensors.

Black box

The last type of building block that can be used to in a blueprint is a black box. These type of blocks can be used for components of which the required interfaces (inputs and outputs) are known but for example not their source. These blocks allow for long-term blueprints to still include future functionality without these current feasibility or availability constraints. As digital twinning capabilities and possibilities within an organisation increase over time, these black boxes may be replaced with more specific building blocks.

4.5 Verification of blueprinting approach

In the section above, an approach was created to support manufacturing SMEs with the formulation, realisation, and evaluation of digital twinning applications. This was done by defining a series of steps, the actors involved, and the required outcomes of these steps. Via the workflow presented, a defined purpose for employing digital twinning is translated to three different graphical representations of a DTA. Using these blueprints, a roadmap can be created which guides the further development of the application. These blueprints are not static. Any desired changes in the eventual content of the application, can be incorporated by refollowing (parts of) the blueprinting workflow. Below the requirements set out in chapter *3.1* will be verified by relating them to the approach presented in this chapter.

1. **The approach should contain a formulation of the intended purpose of the digital twinning application.**
   This is included in the blueprints and as the first step of the workflow. This main purpose can stem from a variety of sources.

2. **The approach should describe the functionalities that are required of the digital twinning application.**
   This is included in the blueprints and as the second step of the workflow. Changes in the required functionality mean that the workflow will have to be followed again to incorporate this.

3. **The approach should contain an overview of the relevant stakeholders and perspectives.**
   This can be distilled from the perspectives and stakeholders included in the short- or long-term blueprints. The general blueprint is not suitable for this as it does not include information sources which mean stakeholders who supply information are excluded.

4. **The approach should describe the required information output of the digital twin.**
   Included in the blueprints and a result from step three of the workflow.

5. **The approach should describe the data that is required for the digital twin.**
   Included in the blueprints and a result from step four of the workflow.
6. **The approach should promote the reuse of components of other digital twinning applications.**
   While it is possible to recognise similar components and component structures (modules), their reuse is not actively promoted in the workflow. Instead, this would be up to the developer to check as they formulate the details of the blueprints. This requirement can however be satisfied by the tool that is to be designed in the next chapter, as this tool allows for filtering of the information captured in various blueprints. This can then be used to look for modules that might be reusable.

7. **The approach should allow for a distinction to be made between manual and automatic data flows.**
   This can be included in the blueprints.

8. **The approach should allow for the inclusion of existing data/information sources.**
   These can be incorporated in the short- or long-term blueprints. Especially the short-term blueprints are wont to include existing information sources.

9. **The approach should provide guidance for the gradual development of the digital twinning application.**
   By following the approach, a roadmap can be created that includes the as-is situation and an intended future state. From these two, intermediary stages for a DTA can be formulated.

10. **The approach should allow for continuous adjustments to be made to its outcome.**
    By refollowing the approach, changes can be incorporated into existing blueprints.

11. **The approach should promote continuous evaluation of the digital twinning application**
    This can be done every time a change is required that will alter the long-term blueprint. From here the as-is blueprint will have to be assessed again to formulate the contents of the next short-term iteration of the application.

12. **The outcomes of the approach should be understandable by the stakeholders involved in its execution**
    The evaluation of this requirement will follow from the results of the case studies presented in *Case Study*.

13. **The approach should be applicable for any digital twinning application**
    The approach allows for any type of information to be represented. As such the information needs of any DTA can be included. No matter how much of it is already known.

14. **The approach should be usable by any manufacturing SME**
    The approach is not tailored to any specific SME. Even the representation and elements shown in block diagram form can be changed depending on what works best for the approach's user.

5 Digital twinning overview tool

The second part of the digital twinning development support is a tool that allows an organisation to keep track of their digital twinning applications. The main inputs for this tool are the blueprints that are formulated through following the blueprint approach described in chapter 4. These blueprints provide a good overview of a DTA with limited functionalities and limited complexity. However, as time progresses and the DTAs become more complex, blueprints representing the entirety of a DTA will become difficult to navigate and interpret. Moreover, relations between multiple applications using the same inputs might become difficult to discern from separate blueprints. This unclarity of the dependencies within an organisation's digital twinning landscape will negatively affect an organisation's ability to make changes to their DTAs. If an application for example requires a new sensor to be installed it must be known what applications rely on the same sensor as even the process of replacing the sensor might already hinder their performance. Also, given the modular structure of digital twins (Figure 12) such effects can both directly and indirectly impact the functionalities of other DTAs. An aggregated overview can not only help prevent such problems, but it could also provide new insights concerning the development of digital twinning within a company. Having a joined overview of the data needs captured in the long-term blueprints could for example yield insights in which data acquisition projects should be prioritised, e.g. for redesign or optimisation.

This chapter will begin by providing additional details about the underlying concepts and structure of the digital twinning overview tool (DTOT). Following this, the main stakeholders together with their perspectives on the content of the tool, will be defined. Based on these sections, the required functionalities of the overview tool are formulated. This is then used as input for the creation of a prototype of the tool which is to be used during a case study at the case company.

5.1 Ontology structure

As explained in the introduction of this chapter, there is a need to define and document the relations between elements of different digital twinning applications. This can be done through the use of a semantic data model like an ontology [59, 60]. An ontology is a conceptualisation of a body of knowledge. This means that an ontology is an abstract, simplified representation of the world that is considered [61]. This representation contains elements, the relations between them, and any properties that are of interest. This basic structure is shown in Figure 25. The number of types of elements and types of relations can vary depending on what is to be represented by the ontology. A simple ontology could for example be made for the books in a bookcase. The elements, and properties that are then of interest are likely aspects like book titles, writers, publishers and genre of the book. An ontology representing a city on the other hand would quickly become much more complex to define. By defining the properties and relations between elements, it does however become possible to filter the captured information. Even a complex system such as a city can then be broken down into condensed, more manageable networks representing specific areas of interest.

Figure 25: Basic ontology structure

For the overview tool, the domain that should be represented by an ontology is that of digital twinning within an organisation. The blueprint structure defined in the previous chapter will be used to design the ontology behind the overview tool. These blueprints already provide a conceptual representation of DTAs and are therefore a suitable starting point for the definition of the ontology. The defined ontology structure will serve as a framework through which instances of digital twinning applications within the organisation can be described. These applications are built up of the components presented and explained in section 4.4. Hence, the same components can be found in the framework ontology shown in Figure 26. This ontology shows the possible elements, and the possible relations between them, that can together constitute a DTA. The name of the 'Data/Information' blocks found in the blueprints has here been shortened to 'Data'. The exact relations and elements that will be present in an instance of a DTA will depend on its application. Moreover, more basic elements or relations can be defined when needed. This ontology is flexible, like the blueprints and DTAs should be, to accommodate changing demands regarding its content. The same goes for any properties attributed to the elements and relations. For simplicity, the relations in the ontology are shown as being directional. However, each relation also has a corresponding reverse counterpart. For example, 'hasSource' implies an 'isSource' relation in the opposite direction. Also, the properties of the different components have been omitted from view.

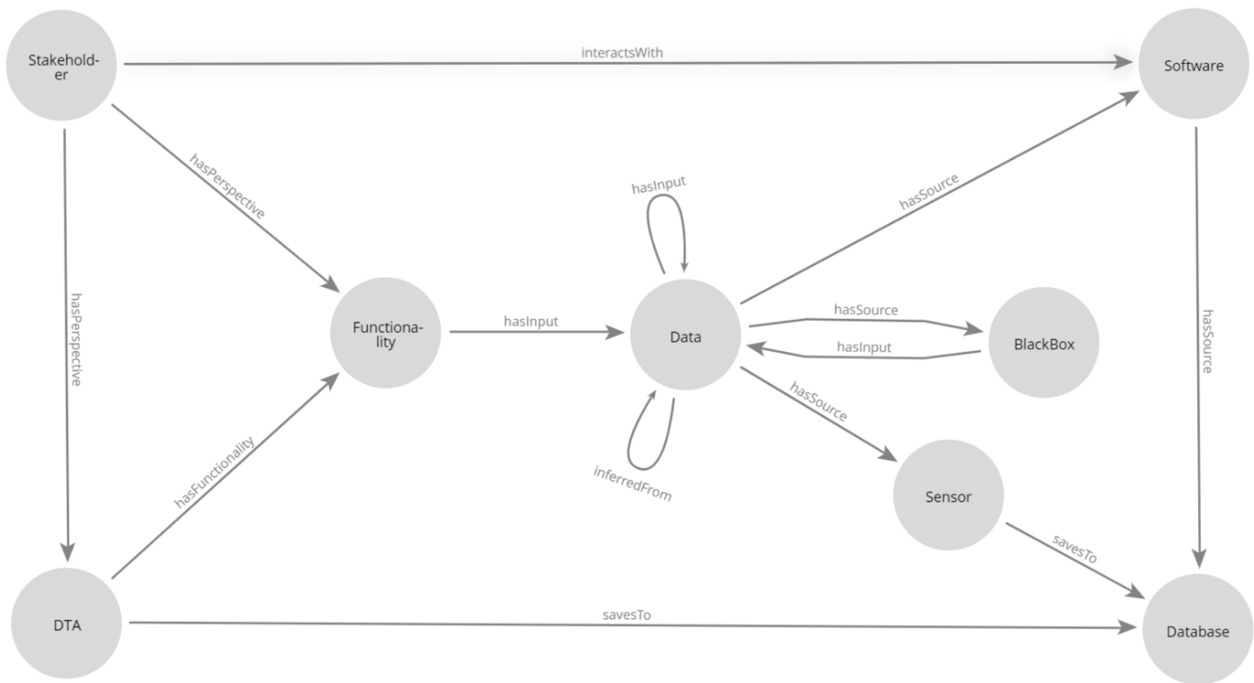

Figure 26: Framework ontology for DTAs

Any DTA blueprints that are made by an organisation can be expressed following the structure captured in the framework ontology shown in Figure 26. Through common elements in the resulting instantiations of the ontology, the information captured in different blueprints is linked together to form a semantic network. Two example blueprints have been represented in terms of the ontology framework set out above. These are shown in Figure 27, represented by structure A and B. Structure C shows how these instances together form a larger network representing the overall digital twinning landscape resulting from both blueprints. The elements shown in blue are the elements through which example structures A and B are connected. This network may expand as more functionalities are defined for DTA A and B, also the addition of another DTA with common elements would expand the network. A DTA added to this digital twinning knowledge base that does not have any elements in common could go on to form its own network for as long as none of their components overlap.

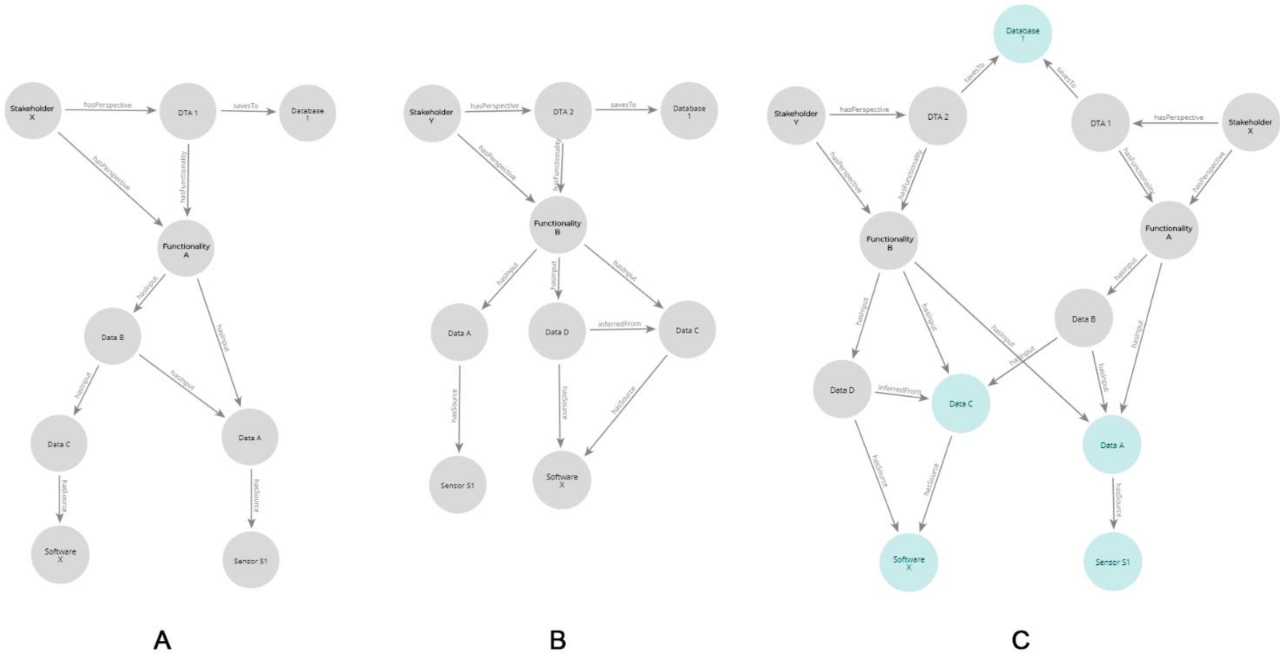

Figure 27: Examples of instanced ontology and resulting network (larger images can be found in Appendix 1)

5.2 Stakeholders

Within an organisation there are many stakeholders which might have an interest in their digital twinning landscape. Rather than going past each of them, two primary stakeholder are formulated together with their main interests concerning digital twinning within their organisation. It is expected that these two types of stakeholders will be present in every organisation, while the other types of stakeholders might differ. These common stakeholders are the developer of the digital twinning applications and management responsible for business decisions affecting the digital twinning applications. These stakeholders and their main interest will be used to determine the required functionalities of the tool. Interests of other stakeholders, that are not shared with the two stakeholders defined, can be included during future development of the tool and are left outside of the scope in the rest of this thesis.

Developer

The developer responsible for the development of digital twinning within an organisation will be the main user of the tool. As the developer works through the blueprinting approach, they will discuss and think out a large amount of different functionalities. As more DTAs are developed, more perspectives included, and their complexity increases, there is a high likelihood of functionalities or components overlapping. Rather than reinventing the wheel for every DTA, the DTOT should provide a base from which the developer can recognise elements and structures to reuse. By for example recognising a similar required functionality of a to be developed application and one defined in the DTOT, the developer could reuse the components that lead to said functionality. The DTOT thus becomes a base from which reusable modules can be recognised. At the same time the developer can assess what DTA's will be affected by e.g. a change in a data source like a sensor. The DTOT can present this information in a unified overview, eliminating the need for the developer to review each blueprint individually. These are just some examples of the type of analyses that the developer might want to do.

Management

Management will also have an interest in having an aggregated view of the organisation's digital twinning environment. This interest will however likely be from a more general perspective on how their choices might affect digital twinning applications. Decisions on any investments to enable digital twinning will be made by management. To this end, the aggregated view of digital twinning is useful to assess how much impact such a decision might have. One DTA requiring information that is currently unavailable due to a lack of sensors might not warrant an investment to be made to acquire such sensors. However, this might change if it appears that multiple DTAs can benefit from the introduction of these sensors. At the same time it can for example be useful to be able to examine the importance of a particular information source used by the DTAs. This would indicate what DTAs would need to be adjusted or what information should still be available after a change in the information source occurs such as a major update to e.g. the used ERP system.

5.3 Required functionalities of tool

In this section the requirements presented in chapter 3.2 will be translated to the required functionalities of the tool. This is done based on the blueprinting approach presented in *Blueprinting approach* and on the contents of *5.1* and *5.2*.

The required functionalities are set out below.

1. The tool should show how information is used in a digital twinning application (*Section 2.2.4*)
    a. The tool should show the information's source
    b. The tool should show the relations between different information 'blocks'
    c. The tool should show what information is used or required by a digital twinning application
    d. The tool should show the properties of an application's components
2. The tool should be able to capture the overall digital twinning landscape of an organisation (*Section 2.2.3*)
3. The tool should show both direct and indirect relations within an organisation's digital twinning landscape (*Section 2.2.4*)
4. The tool should allow for the capture of the outcomes of the workflow (*Section 2.4)*

   a. The tool should be able to show the as-is contents of a DTA
   b. The tool should be able to show the short-term contents of a DTA
   c. The tool should be able to show the long-term contents of a DTA
5. The tool should allow for filtering of its content (*Delwi stakeholder interviews)*
6. The tool should allow for easy navigation of its content (*Delwi stakeholder interviews)*
7. The tool should allow for changes to be made to its contents and functionality (*Section 2.4 and Delwi stakeholder interviews)*

5.4 Developed tool

Following the requirements, a tool is needed that allows for visualisation and navigation of an organisation's digital twinning landscape. Furthermore, interaction with the information content describing this landscape should be possible. Instead of creating a new tool or developing a mock-up that merely mimics the required functionality, it was opted to look for an off the shelf solution. There is plenty of software available to work with data structures such as the one described in Figure 26. In industry, networks built from instantiations of such data structures are often referred to as graph databases. For this thesis, the free edition of Neo4j AuraDB graph database software was used. This cloud based software provides the required functionality and flexibility upon which a first prototype of the DTOT could be built. Although some functionalities for interacting with the database are directly built in the software, more complex computations will need to be done using queries. Neo4j uses its own query language called Cypher to interact with the database's content. While querying via this Cypher language is very versatile, it might be difficult for users unfamiliar with the language. For that reason, some queries have been saved in the form of buttons to facilitate easier manipulation of the database's content. In practice, many of the operations that affect the stored and displayed information will be repetitive.

The example graphs A and B, shown in Figure 27, have been transferred to a database in Neo4j. The resulting digital twinning landscape will be used to illustrate some functionalities of the tool. In the next section, the main database manipulations through queries and the defined buttons will be explained. The buttons' functions have been based on the functionalities described in the previous section.

5.4.1 Database manipulations

The contents of a blueprint, or in this case example graph, can be added to the database using Cypher language. This thesis will not go into too much detail about how this language works. The basics will be however be explained as this gives an idea of how graphs can be created. Neo4j databases follow the same structure as visualised in Figure 25. The only difference being that in Neo4j, 'Elements' and 'Relations' are referred to as 'Nodes' and 'Relationships'. How the information captured in such a structure can be transferred to Neo4j is visualised in Figure 28.

Cypher: CREATE (:Node {ID: "Node1"})-[:hasRelationship]->(:Node {ID: "Node2"})

Figure 28: Cypher query and its result as a database graph

Through various Cypher queries like the one above, example structures A and B were added to the DTOT. The complete overview of the long-term digital twinning landscape could then be queried based on the properties assigned to the nodes and relationships. In Figure 29 the effects of two different buttons used to visualise the short-term (ST) and long-term (LT) views on application DTA 1's content are shown. From this overview it can be concluded that once this ST version of DTA 1 is realised, only the connection with Database 1 (brown circle) will still need to be implemented.

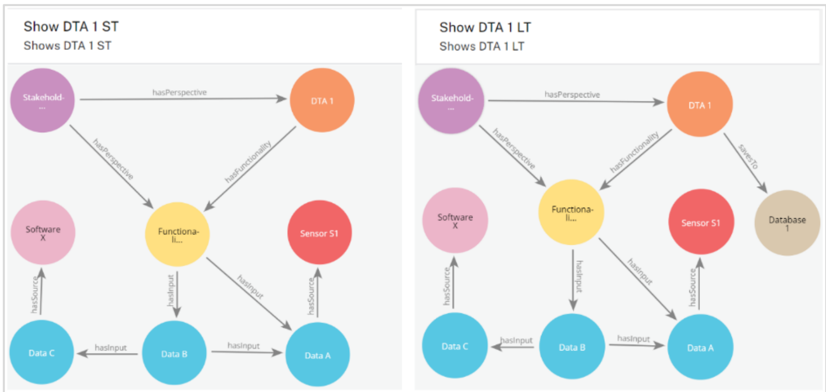

Figure 29: Effects of two buttons on the contents included in the overview

Figure 30 shows how the tool can also be used for filtering based on the properties of nodes. A filter is applied to only show the InfoData components that have a unit that is expressed in 'm/s'. A developer could use this to quickly find existing InfoData blocks that contain information regarding the speed of a certain object. This could be useful when the developer is busy creating a blueprint of a DTA for which it is also required to measure speed.

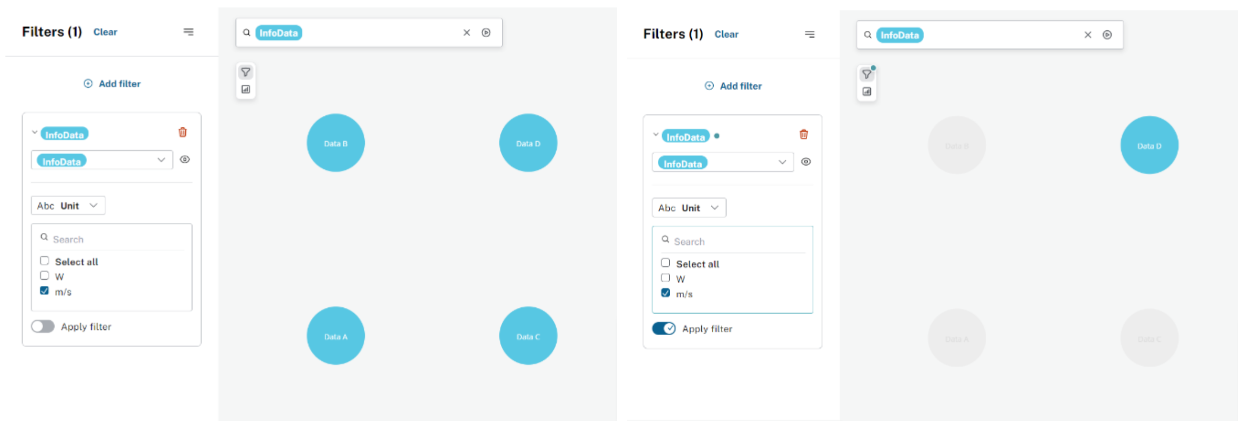

Figure 30: Filter function within the tool

In Figure 31 the overall digital twinning landscape example is shown. On the left the LT landscape is presented. On the right, all relationships not currently part of the as-is landscape of an organisation are filtered out (DTA 1 → Database 1 and Functionality 2 → Data A). From here it can be seen that in the as-is situation, 'Data C' and thus 'Software X' are the most critical component in the landscape as these are shared by both DTAs. A problem with either of these components and both DTAs will not function the way they are supposed to.

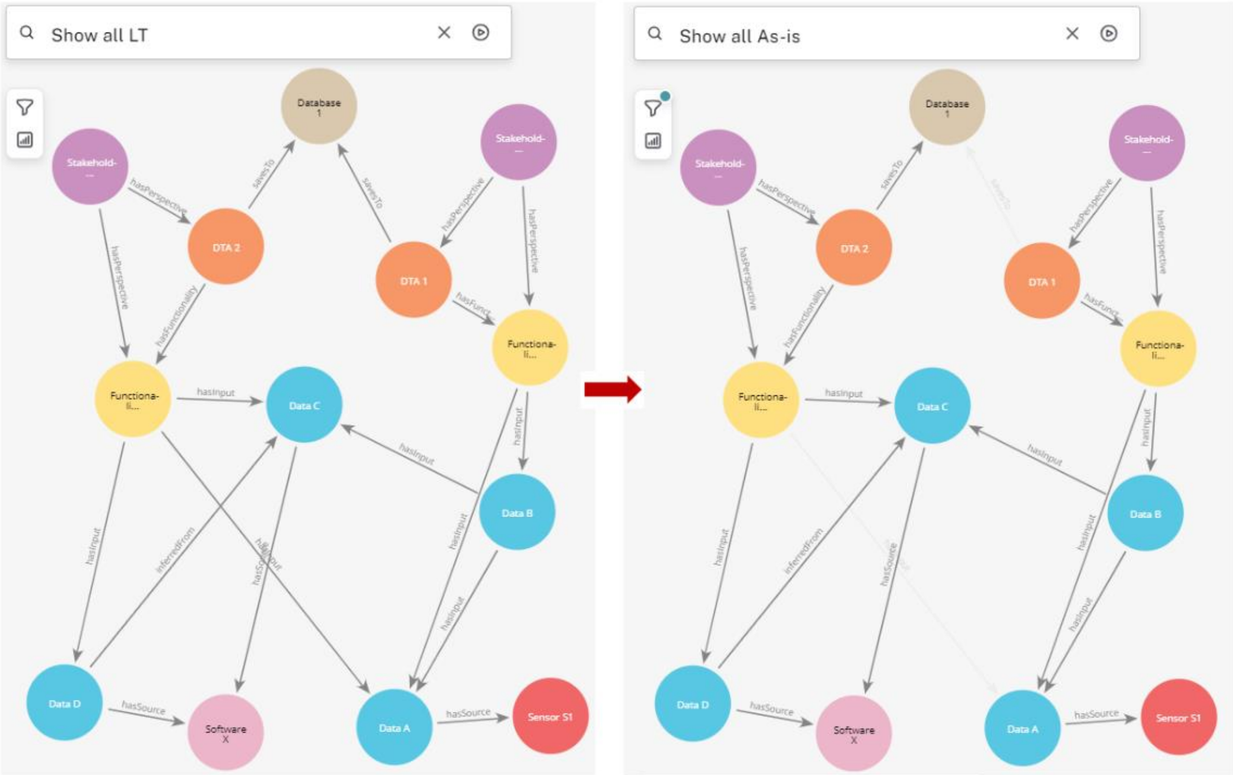

Figure 31: Comparison between a digital twinning landscape's long-term (LT) and as-is state

The last functionality that will be shown in this chapter is that of indirect relations. Even though these relations are not defined in the database, the DTOT allows for their visualisation by creating so called virtual relationships. Figure 32 shows how the tool can be used to directly relate a DTA to its source components. As an indirect relation exists via two different paths between DTA 1 and Sensor S1, two virtual relationship are shown. This could mean that the application is mostly dependant on the information yielded by the sensor.

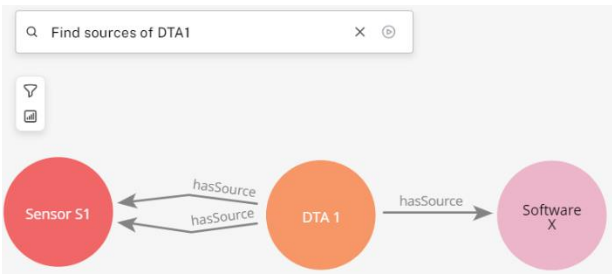

Figure 32: Indirect relationships visualised in the DTOT

There are many more functionalities embedded in the created DTOT. These will however not all be explained as this is not the focus of the thesis. Above some functionalities were explained to provide a sense of the versatility of the DTOT. The tool's overall content will be assessed by verifying its requirements.

5.5 Verification of DTOT

In this chapter the design behind a tool to review and query the overall digital twinning landscape within an organisation was explained. Such a tool can support stakeholders in their decision-making regarding digital twinning in an organisation. The first step in the design process was defining a framework ontology around which to structure the contents of the blueprints created in the blueprinting workflow. Based on this, two sample blueprints were created that could be used in the tool to verify if it contains the required functionalities. The expanded list of requirements that was defined in section *5.3* is used for verification below.

It is recommended that when other software is used for graph database manipulation, that the main functionalities are comparable to the ones shown in *5.4*.

1. **The tool should show how information is used in a digital twinning application**
    a. **The tool should show the information's source**
    This relation is defined in the short- and long-term blueprints which are used as the main input for the tool.
    b. **The tool should show the relations between different information 'blocks'**
    These relations are defined in the short- and long-term blueprints which are used as the main input for the tool.
    c. **The tool should show what information is used or required by a digital twinning application**
    These relations are defined in the short- and long-term blueprints which are used as the main input for the tool.
    d. **The tool should show the properties of an application's components**
    These properties can be viewed in the tool by clicking on the component of interest. They are not included in the main view window so as not to clutter the viewport.

    All sub requirements are met so it can be concluded that the DTOT meets the overall requirement.
2. **The tool should be able to capture the overall digital twinning landscape of an organisation**
    The tool can capture the as-is, short-term, and long-term state of an organisation's digital twinning landscape. Furthermore, a graph database like the one used in the tool can grow as more instances of blueprints are added.
3. **The tool should show both direct and indirect relations within an organisation's digital twinning landscape**
    Direct relations are one of the two main types of building blocks within a graph database. Indirect relations can also be inferred from the graph as was shown in section 5.4.1
4. **The tool should allow for the capture of the outcomes of the workflow**
    a. **The tool should be able to show the as-is contents of a DTA**
    This can be done through the definition of properties for the nodes and relationships in the tool. These allow for querying the as-is contents of a DTA.
    b. **The tool should be able to show the short-term contents of a DTA**
    This can be done through a similar approach as described at 4a.
    c. **The tool should be able to show the long-term contents of a DTA**

This can be done through a similar approach as described at 4a

All sub requirements are met. Furthermore, these functionalities were demonstrated in section 5.4.1.

5. **The tool should allow for filtering of its content**

   This is an inherent function of the software used to create the DTOT prototype. Furthermore, it was explained how this can be done through formulation of the appropriate queries.

6. **The tool should allow for easy navigation of its content**

   The software with which the tool was created allows for various means of traversing its content. Larger graphs will require the user to define queries in order to break down the graph in more manageable pieces. This requires the user to be able to learn and use the Cypher language.

7. **The tool should allow for changes to be made to its contents and functionality**

   The information captured within the DTOT can continuously be expanded. New ways of interacting with this information can be created using queries. Still, it might happen that a functionality is required that is not supported by the tool. In those cases it might be necessary to export the contents of the database and use another means of interacting with its content.

All in all, the prototype of the DTOT satisfies all set requirements. Some minor points of improvement could be formulated but the DTOT contains enough functionality to be able to validate it during the case study. This will be done in the next chapter, *Case Study*.

6 Case Study

In this chapter the case studies that were carried out at Machinefabriek DelwiGroenink are presented. Three case studies were carried out to assess the validity and usability of the blueprinting workflow and to see if its outcomes could indeed serve as a base for further development of individual DTAs. Additionally, one case study was conducted to evaluate the DTOT. The first section will explain the goals and setup of the different case studies and explains how they relate to one another. Each case study, and more importantly their results, are discussed in the remaining sections. The chapter concludes with a summary of the case study results.

6.1 Case study structure

The case studies were conducted with different stakeholders within DelwiGroenink. This was done to include multiple points of view on the designed digital twinning support. Some stakeholders might for example be more familiar with concepts related to digital twinning than others which could influence the way they perceive the blueprinting approach. Also, it was evaluated how the blueprinting approach could be integrated in Delwi's current practices for the introduction of new technologies to their manufacturing environment.

The case studies were divided into three phases. During first phase, the blueprinting approach was carried out with stakeholders from two different departments within the company. Their feedback on the approach could then be used to alter the blueprinting approach were necessary to better fit Delwi's way of working. In the second phase, the approach was again carried out with another stakeholder within Delwi to validate any changes made to the approach. The blueprints that resulted from these case study sessions were used in the third phase as input for the prototype of the DTOT. In this third and final phase, this tool was evaluated with a manager, who within Delwi would head digital twinning projects. The relation between the different case studies and their outputs is visualised in Figure 33.

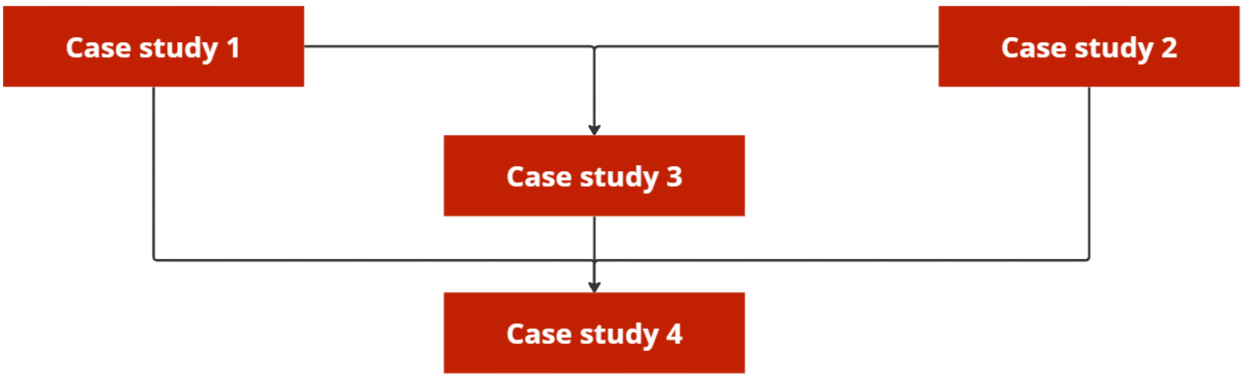

Figure 33: Relation between the different case studies

6.1.1 Goals and setup of case studies 1, 2, and 3

The goal of case studies 1, 2, and 3 was to validate the approach that was designed in *Blueprinting approach*. Furthermore, these sessions were used to receive feedback that could be used to improve the approach. The blueprinting approach is meant to be carried out over an extended period of time. This is both because defining and verifying the blueprints takes time, and because the approach is meant to be part of the continuous development cycle of a DTA. For these reasons, some concessions had to be made in order the validate the approach within the time scope of this thesis. First of all, it was decided to keep the defined DTAs relatively simple. This meant that the blueprints could be kept small and that verification of its contents could be done much more quickly. Secondly, it was decided to create mock-ups of the DTAs based on the blueprints. This was done to test the feasibility of using the blueprints to create applications that meet stakeholder expectations. Additionally, it facilitated basic discussions as if the application was already in use. Being able to connect the blueprints to the mock-up tools supported the stakeholders in their understanding of the blueprinting workflow. It should be noted that the writer took on the role of developer to guide the stakeholders through their first encounters with the blueprinting approach.

To explain, execute, and discuss the results of the blueprinting workflow, approximately 2.5 hours was needed per stakeholder. This time was divided over two different sessions. This time is excluding the creation of the mock-ups. Both sessions were accompanied by a semi-structured interview to guide the discussions. The topics and guiding questions of these interviews can be found in *Appendix 2*.

6.1.2 Goals and setup of case study 4

The goal of the last case study was to validate the prototype of the DTOT that was designed in *Digital twinning overview tool*. This was done together with the manager who would head digital twinning projects within Delwi to account for the management perspective on the tool's content. As stated in the previous section, the role of developer was taken on by the writer. The tool was, however, also discussed with a software engineer and automation engineer within the company. These employees would, like the manager, most likely be involved in digital twinning projects.

One session with the manager was necessary to explain, show, and discuss the DTOT. To guide the discussion, this session also made use of a semi-structured interview. See *Appendix 2* for the topics.

6.2 Blueprinting approach and DTOT applied at Delwi

The outcomes of using the designed digital twinning support at Delwi are presented in this section. These outcomes formed the basis for validation and discussions with Delwi employees.

6.2.1 Case study 1 – Delay tracker

The first case study was carried out together with a engineer from the manufacturing engineering department. During the first session, the overarching purpose used as a starting point was 'Improve feedback to and from the shopfloor'. This followed from Delwi's desire to get more insight in what is happening in their factory to make more accurate production forecasts. From here several ideas were formulated of potential applications that related to this purpose. For this case study, it was decided to look at a tool to track delays in the assembly department that resulted from faulty parts. This could then be used to get more accurate data of the effective time it actually takes to assemble a product. Furthermore, by tracking how often a faulty part occurs, it becomes possible to track supplier performance. After the rest of the required information and data was determined, the engineer was asked to define the functionality they preferred to see in a first version of the application. This concluded the first session. Based on this session the general blueprint depicted in Figure 34 was created. The legend shown in Figure 35 can be used to check what type of components the blocks represent.

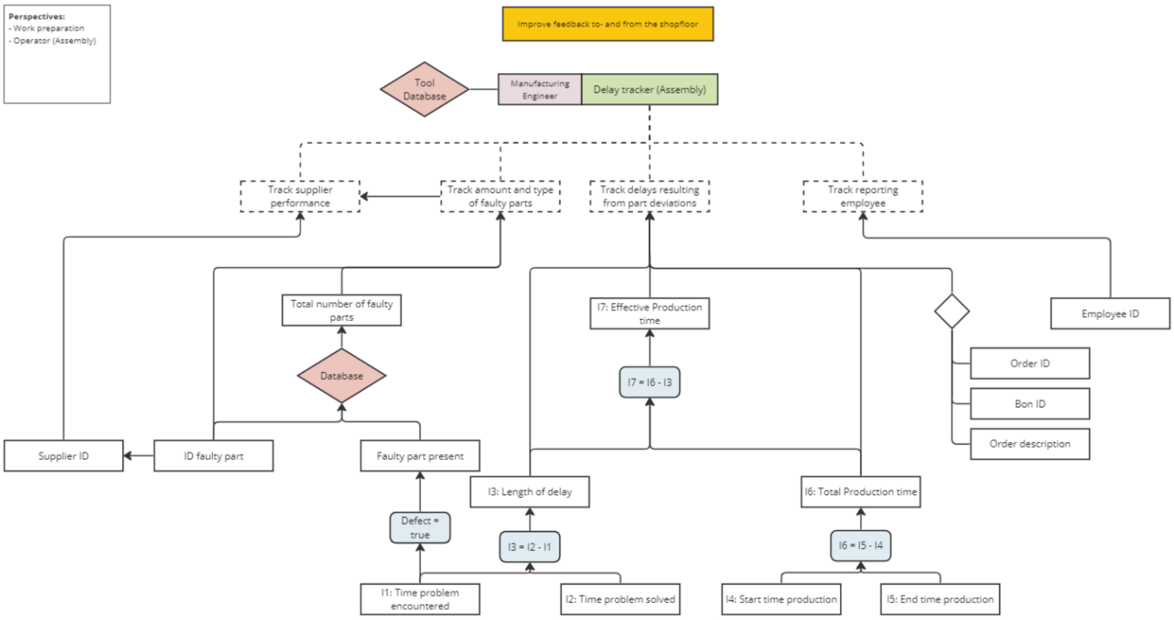

Figure 34: Delay tracker DTA - General blueprint

After its contents were verified with the manufacturing engineer, a first short- and long-term blueprint of the DTA were defined. These blueprints are shown in Figure 35 and Figure 36 respectively.

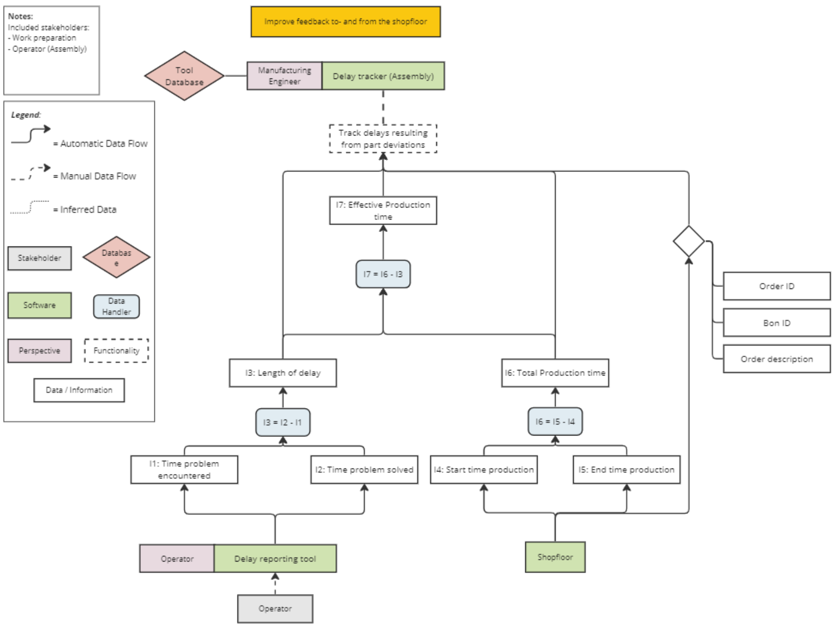

Figure 35: Delay tracker DTA - Short-term blueprint

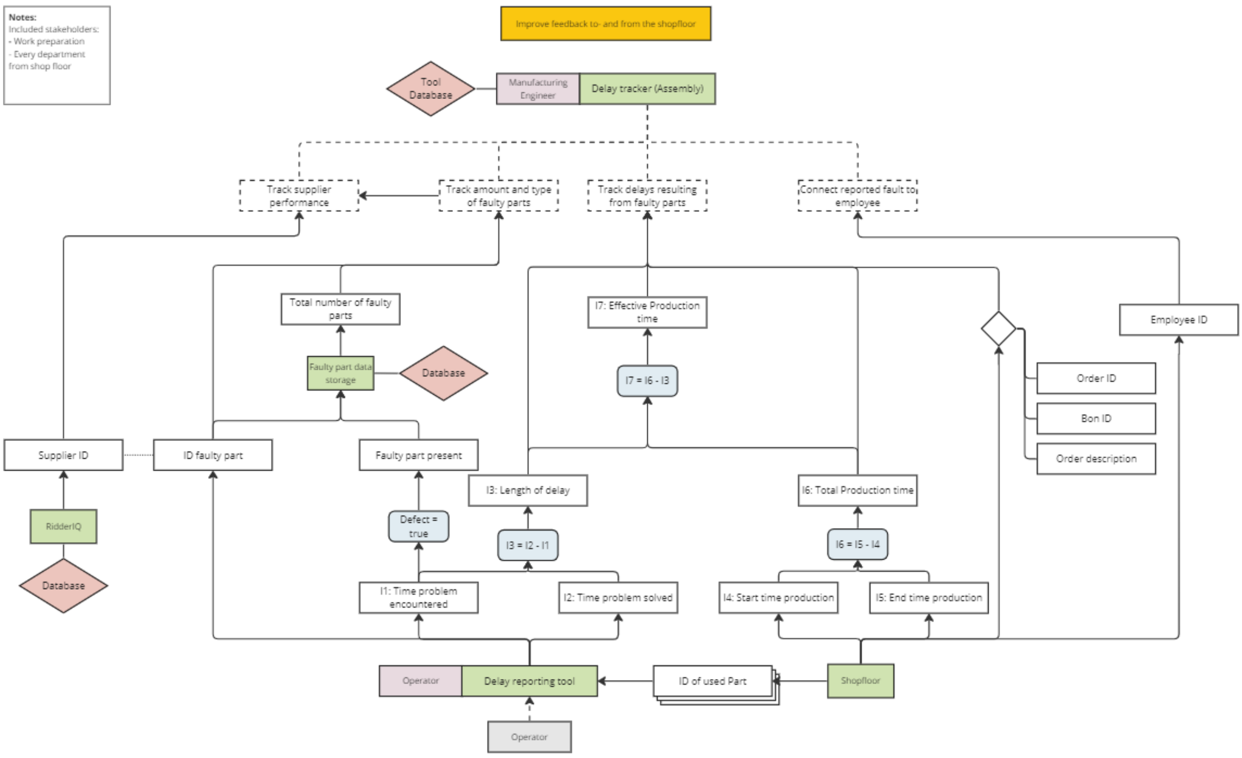

Figure 36: Delay tracker DTA - Long-term blueprint

Based on what is defined in the short- and long-term blueprints, a mock-up was created using Figma. This is a free tool often used for interface design prototypes since these prototypes can be expanded with some basic interactions to mimic their required functionality. A short-term and long-term version mock-up was created of the delay tracking DTA. Figure 37 shows some frames of the tool. The short- and long-term blueprints and the mock-up were verified and discussed in the second session.

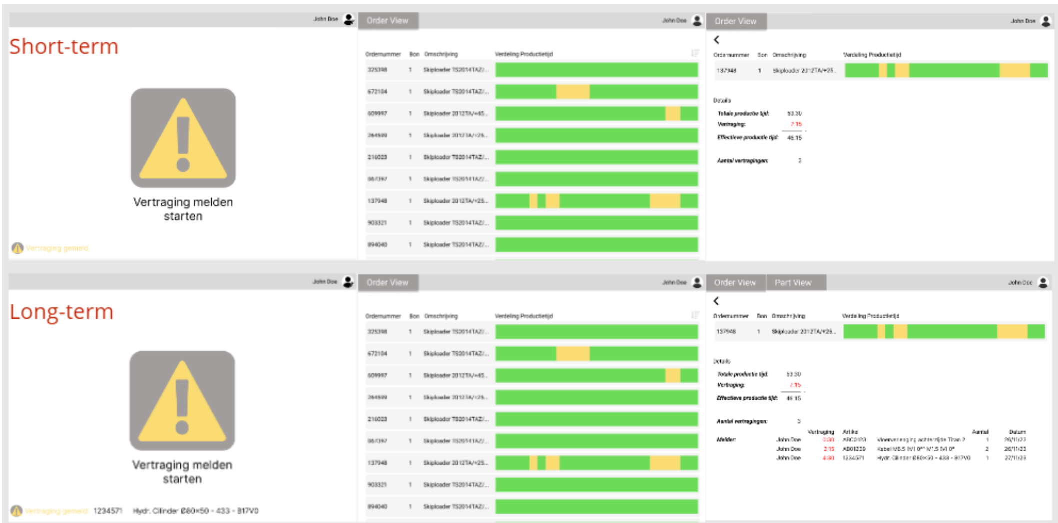

Figure 37: Three frames from the short-term (top) and the long-term (bottom) version of the delay tracking DTA

6.2.2 Case study 2 – VOCA/NACA validation

The second case study was done with the case company's business controller. The focus of this discussion session came to lie on an existing DTA. This was related to a dashboard that was used to assess the difference between the company's precalculated (VOCA) and post-calculated (NACA) costs. By walking through the blueprinting approach, it was possible to define how the system should work and how it functions in practice. This means that the largest focus came to lie on the as-is of the DTA. Mapping this entire DTA would however require a large understanding of its current relations to Delwi's digital infrastructure which was outside of the scope of this case study. No blueprints were therefore developed based on the outcomes of this case study. The participant did mention that they appreciated the method of mapping out the intended functionalities beforehand. They expected that the problem currently faced with the dashboard could have been recognised beforehand if this method was followed.

6.2.3 Case study 3 – Welding robot maintenance tool

The third case study was conducted together with an automation engineer. During this case study, the overarching purpose was 'Get more insights in machine status and performance'. Here the functionalities defined were for a DTA to track if maintenance is needed on one of the robot welding machines. Furthermore, the automation engineer wanted to be made aware of what part caused this warning. By monitoring the status of critical machine components, it could be possible to work towards predictive maintenance. The engineer also wanted the operators responsible for the robot's maintenance to be able to digitally see and log their maintenance operations. Currently, this is still done on paper. For this DTA, it proved more difficult to work from the required information to what data would be needed. Although not evident in the general blueprint (Figure 38), this issue will become apparent in the long-term blueprint. This concluded session one of this case study.

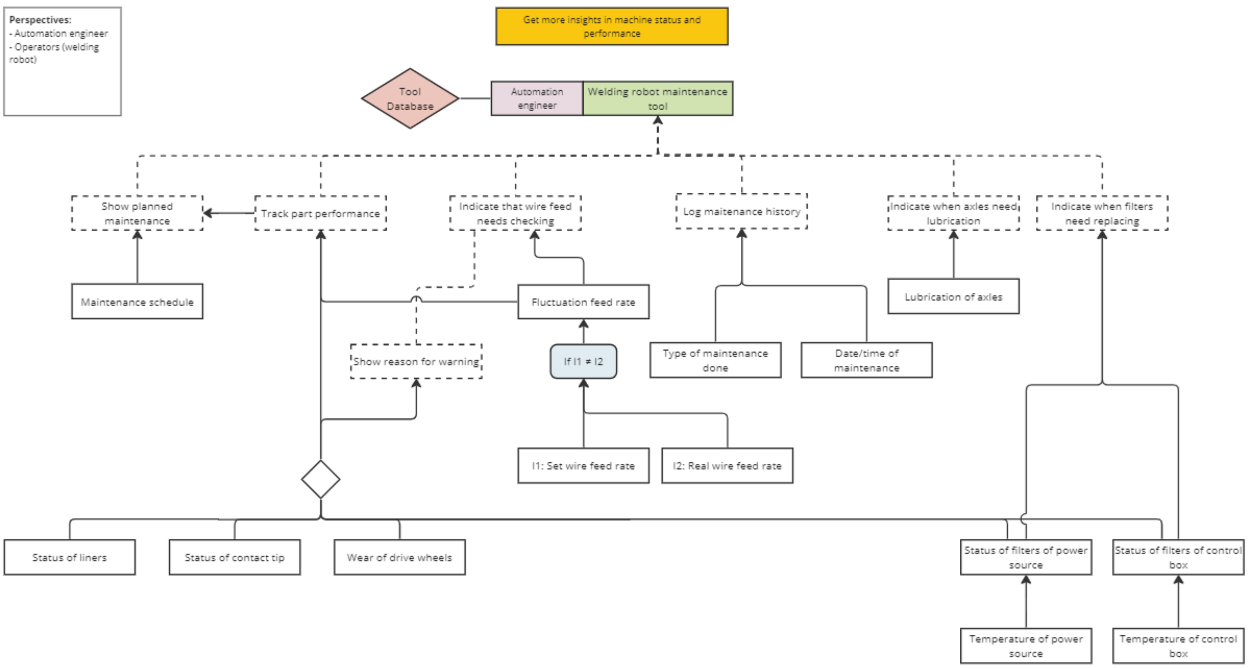

Figure 38: General blueprint of welding robot maintenance tool

Based on the contents captured in the general blueprint, the engineer could only point out one functionality that could likely be developed with Delwi's current technical knowledge and available information. Another functionality could potentially be partly achieved. The resulting DTA that could then be made in the relative short-term is represented by the blueprint shown in Figure 39.

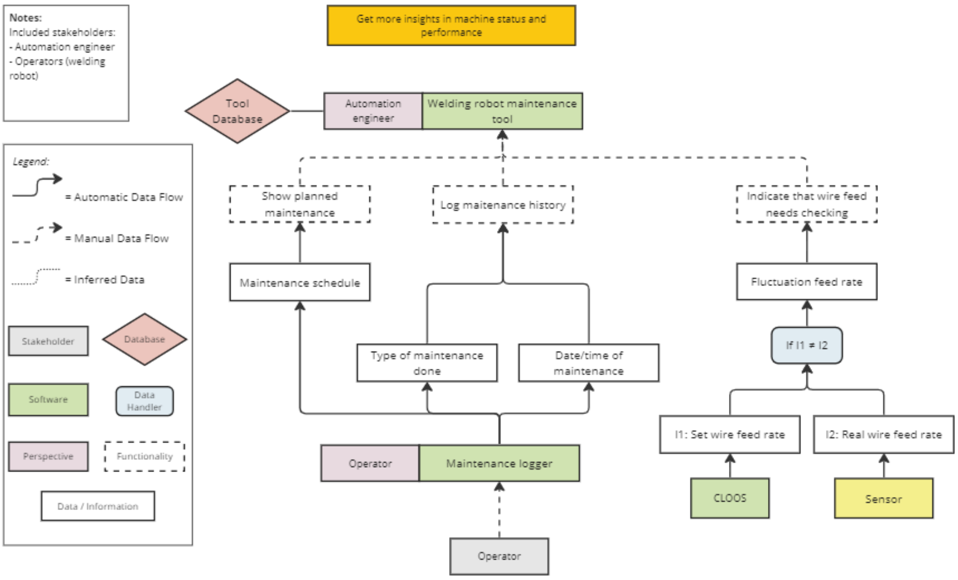

Figure 39: Short-term blueprint of welding robot maintenance tool

For developing the other functionalities, the blueprint still contains too many unknowns. This is represented by the many black box modules part of the long-term blueprint. The long-term blueprint is shown in Figure 40. From this blueprints it can be concluded that further research is needed to define how the required information can be created. Still the need is captured for future reference.

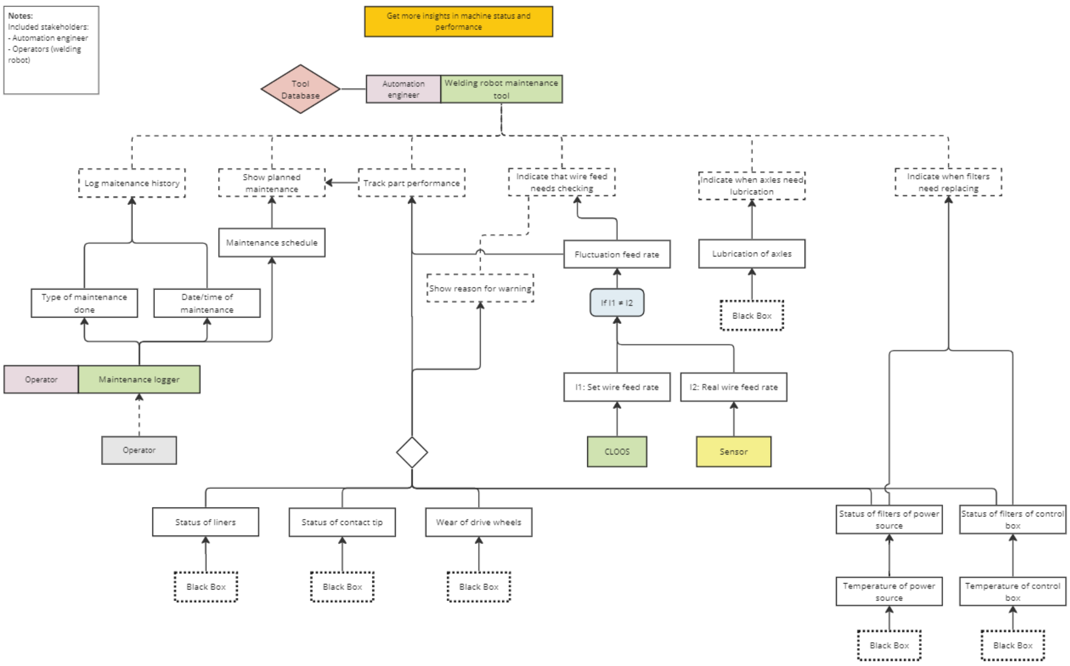

Figure 40: Long-term blueprint of welding robot maintenance tool

Figure 41 shows some frames from the created mock-up. The windows on the left show the view from the automation engineer. The windows on the right show the tool from the operator's point of view.

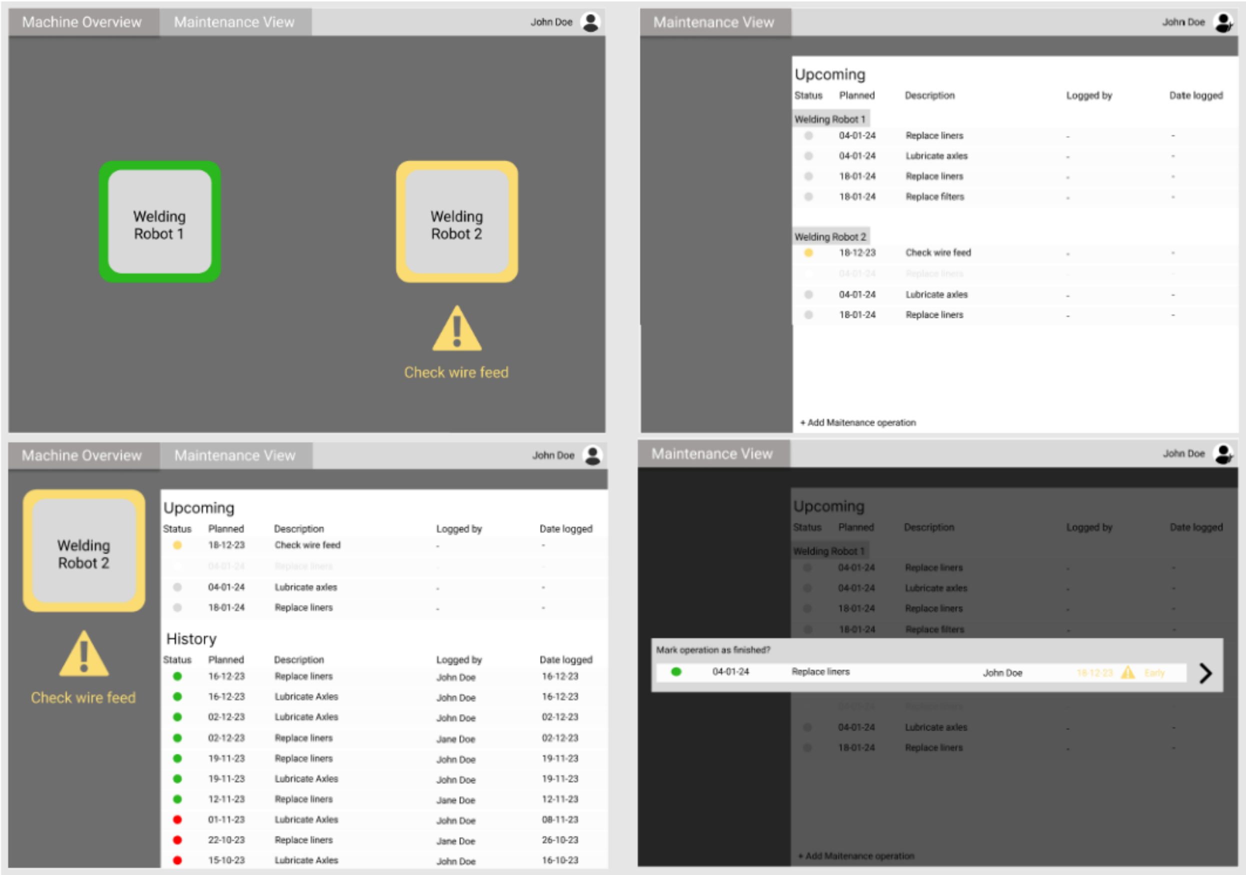

Figure 41: Frames from the welding robot maintenance tool

6.2.4 Case study 4 – Digital twinning overview tool

The different blueprints defined during case study 1, 2, and 3 were manually transferred to the DTOT. Together, they are taken to represent the overall digital twinning landscape in Delwi. The functionalities of the DTOT were explained and verified in *Digital twinning overview tool*. Its usability was however not yet validated with the potential users of the tool. The overall landscape used for this assessment is shown in Figure 42. The landscape shows the envisioned long-term state of this landscape. The tool is zoomed out to give a better overview of its total content. Still, this view could already be used for some general analysis. The two groups of connected nodes that can be recognised, represent the two DTA tools. Since they each form their own island, it can be inferred that they thus do not share any of their components.

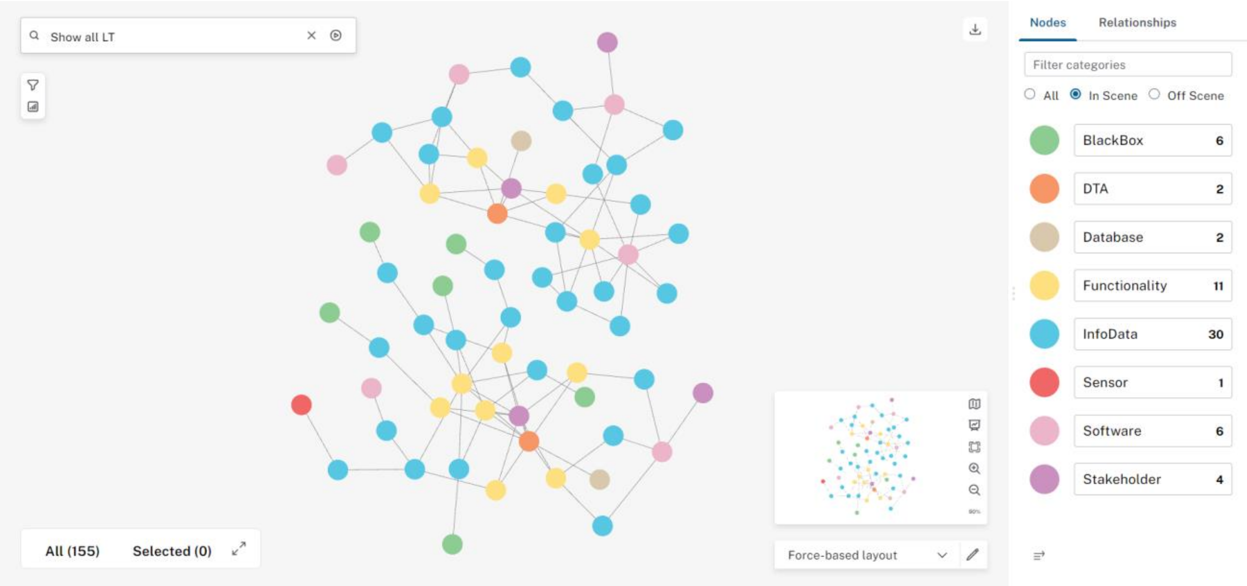

Figure 42: Long-term digital twinning landscape of DelwiGroenink

As can be seen, the information representing the different DTAs in a company can become complex very fast. Only two blueprints already introduce many relationships and nodes to the DTOT. This is why it is so important to be able to filter the view. Figure 43 is filtered to only include the parts of the DTAs that will be included in their first development cycles. This view is already much easier to grasp.

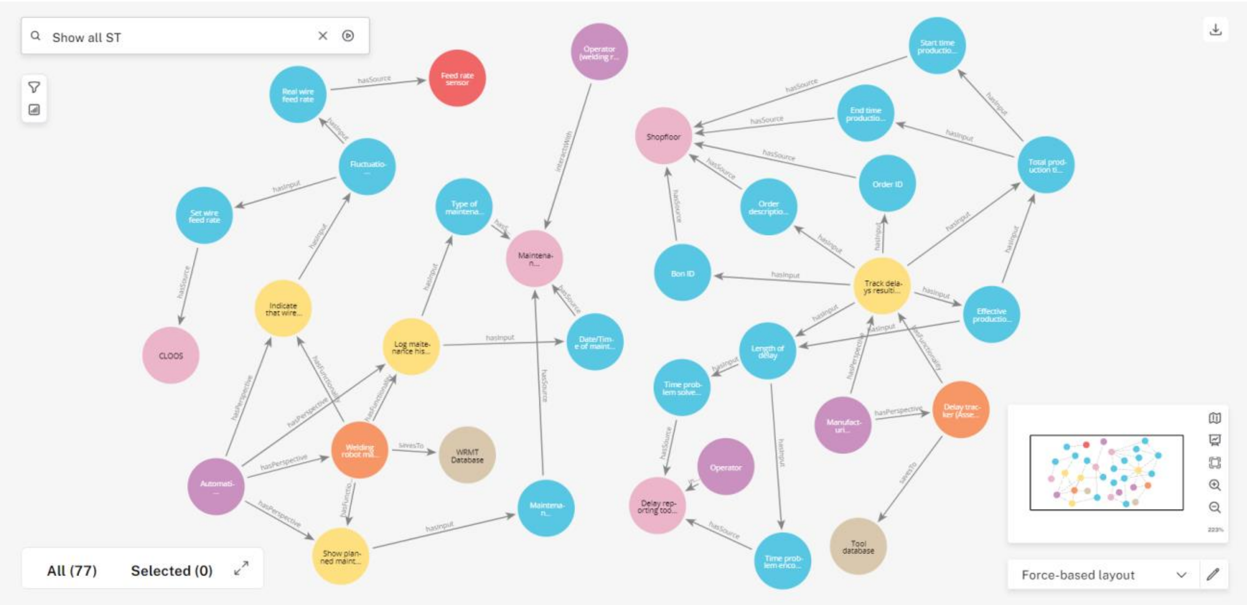

Figure 43: Short-term digital twinning landscape of DelwiGroenink

Figure 44 shows an analysis that was carried out during the validation session. The user wanted to see the dependencies that the DTAs had on their various sources. It can be seen that the delay tracking DTA has by far the most (indirect) dependencies with Shopfloor. The welding robot maintenance tool seems to rely most on the information captured in the maintenance logger software.

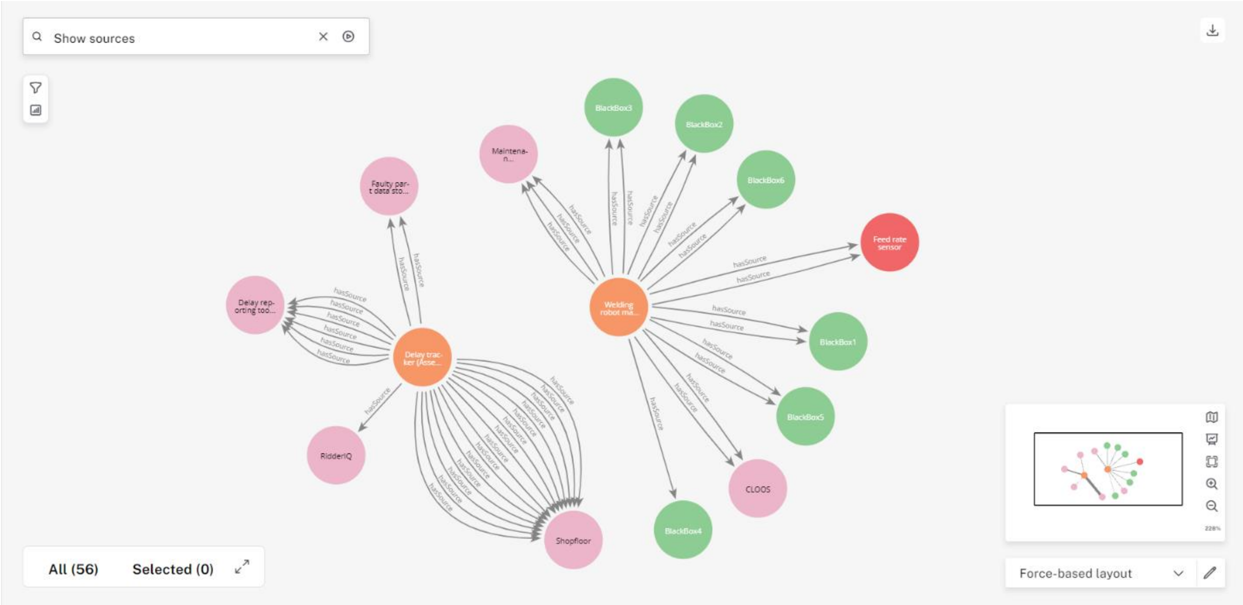

Figure 44: The DTAs with their source dependencies

All in all, the examples above give an idea of the capability of the DTOT. During the validation session various of such analyses were done and the manager was asked to interpret the results. It was also examined if the tool could account for analysis needs that naturally came up during the discussion of the DTOT.

6.3 Conclusion

The goal of the case studies was to validate the blueprinting approach and the digital twinning overview tool (DTOT). The various blueprints, mock-ups, and prototype DTOT described in *6.2* were used to assess the validity of the designed digital twinning support. Additionally, the stakeholder that were involved in the case studies were interviewed and asked about their opinion on the approach and tool. The results and conclusions of these sessions are discussed in the remainder of this chapter.

6.3.1 Blueprinting approach

The blueprinting approach was carried out together with three different stakeholders divided over as many case studies. In two of the case studies, the approach resulted in the first elements of a roadmap that could be used to support the further development of their associated DTAs. Although these DTAs were kept limited in complexity and scope, they provided the users with a good understanding of the different steps set out in the approach. The blueprints were perceived as clear and provided a solid foundation from which to discuss the DTA's information contents and intended functionality. Especially when coupled with the mock-ups, the participants understood how the contents captured in the blueprints and roadmap would translate into actual DTAs. During the case study sessions, it became evident that most ideas for required functionalities were linked to the existing digital landscape and issues within the company. Participants indicated that this made it easier to understand and work through the approach. Including more complex information and functionalities in the DTA was expected to become easier once more experience was built up with using the approach. The participants stated that they thought both the as-is and the long-term blueprint to be of equal value for the development of a DTA. While the long-term blueprint could indeed guide future development efforts, the as-is could function as a reference for error-tracing. Any malfunctions occurring in the realised DTA could then be traced back using the as-is blueprint as a guide. All in all, the participants agreed that development projects for DTAs could benefit from following the blueprinting approach to explicitly capture their information needs. It was indicated that during blueprint verification, it is important to verify the properties of the information blocks, such as formatting, units, and data latency, to ensure their correctness and acceptability.

6.3.2 Digital twinning overview tool (DTOT)

The prototype made in Neo4j functioned as a proof of concept of the DTOT. The tool was primarily discussed with the manager that would head digital twinning projects within Delwi. It was shown how the tool could capture the contents of the different blueprints and how it could be used for various filtering and analyses purposes. The manager indicated that they thought this was a good way to represent and discuss the different dimensions of the company's digital twinning landscape. Moreover, the ability to filter and query the information was appreciated. The amount of clicking and scrolling of doing so was however deemed a bit too much. Nevertheless, the manager indicated that having such a tool would provide a solid foundation for making decisions regarding the development of DTAs within the organisation.

7 Conclusion

In this chapter, the content of this thesis will be related to the aims stated in *Problem definition*. This is done by summarising the main outcomes of the analysis, the proposed digital twinning support tools, and the results of the case studies. The aims of this thesis were stated as follows:

"... to identify how manufacturing SMEs can create value through digitalisation of their manufacturing environment and how this value, once realised, can be maintained."

The thesis started off by exploring the concept of an increasingly digitalised manufacturing environment. Such a manufacturing environment was related to the broader notion of Industry 4.0. This involved identifying the main drivers for, and capabilities of, an Industry 4.0 manufacturing environment. Such an environment is characterised by a high degree of digitalisation and interconnectivity between its actors. Early versions of these environments will offer better visibility into what is happening within the environment. As the technologies associated with Industry 4.0 mature, this visibility capability can be expanded with predictive or even adaptive capabilities. These different capabilities could yield all kind of benefits and solutions to problems that are currently faced by manufacturing companies. This does however require these companies to approach their transition towards a digitalised manufacturing environment in a structured manner. The second part of the analysis therefore focussed on a concept to structure this digitalisation transition so that it can offer value. It was shown how the data of physical assets could be captured in their digital counterparts, the digital twin. A purposeful application of the data and information captured in this twin can be ensured through digital twinning. This involves reasoning from the value that is pursued, towards what should be captured in the digital twin, instead of the other way around. The analysis concluded by discussing the main challenges that hinder manufacturing SMEs in the introduction of digital twinning applications (DTAs) to their manufacturing environments.

From the analysis, the required support for manufacturing SMEs to start and keep benefiting from digital twinning was defined. Firstly, support was required to translate a defined purpose into a DTA's information needs. Furthermore, a tool was required to function as a knowledge base for an organisation's digital twinning development efforts. The chapters following the analysis focussed on the design of these supporting tools. The outcome of the first part was the blueprinting approach. This approach can be followed to define what information is needed to reach the functionalities required of the DTA. The outcomes of the blueprinting approach can furthermore be used as inputs for a roadmap to guide future development efforts. The second support that was defined, was the digital twinning overview tool (DTOT). This tool can be used to capture the different blueprints that are created through following the blueprinting approach. By first formatting the blueprints through a defined ontology, it becomes possible to visualise and analyse how the different DTAs relate to each other. The DTOT can even be used to view the current and the intended future states of the organisation's digital twinning landscape.

The designed digital twinning development support was validated through various case studies that were carried out at the case company of DelwiGroenink. It was concluded from these case studies that both the approach and the tool met their requirements. Their combined use can thus support manufacturing SMEs in their strive towards reaping the benefits and value that an increasingly digitalised manufacturing environment has to offer. Both now, and in the future.

8 Discussion

The evolution of the manufacturing industry towards Industry 4.0 practices, digitalisation levels, and capabilities is an ongoing process. It involves many technologies that are continuously being developed, often at a rapid pace. On one hand, this offers many opportunities for the development of DTAs. Sensors, data storage, information processing systems, and various means of interacting with the data captured in digital twins are becoming cheaper and more accessible. Digital twinning is thus carried out in an increasingly volatile environment. The development support presented in this thesis, assumes a gradual, human-centred transition towards Smart Industry. In the past year however, there has been a surge in machine learning and generative AI tools. For instance, ChatGPT was launched shortly before the start of this thesis. Although these systems are not yet used to build DTAs, this is theoretically possible. In such cases it will often be unclear how exactly the data and information within the application are derived. These applications would therefore be difficult to capture in the blueprinting approach. In such cases, companies will have to reconsider their approach to the process of digital twinning. However, it is unlikely that this will be necessary anytime soon. For that reason, it is expected that the digital twinning development support presented in this thesis will remain applicable for the foreseeable future.

The blueprinting approach and DTOT that were designed during this thesis have been applied at one manufacturing SME. Since both the approach and the DTOT were constructed there, it is possible that the employees' ability to use the tools was influenced by earlier discussions on the topics involved, providing them with pre-knowledge necessary to use the approach and DTOT. Also, the degree of technical knowledge and the knowledge and understanding about the concept of digital twinning may vary greatly between companies. This might impact a company’s ability to work with the supporting tools.

In *Acceptance of digital twinning in manufacturing SMEs* it was explained how DTAs will first need to be accepted in a company before they can start yielding value. The same holds for the blueprinting approach and DTOT. The DTOT can support the company to get a grasp of their digital twinning landscape, based on the outcomes of the approach. This does require a leading role of these tools in the overall development process. If their value is not recognised or accepted by the company, their value will deteriorate quickly. This is especially true for the DTOT. If development efforts for a DTA are not based on the outcomes of the blueprints, or if the as-is, short-term, or long-term state captured in de DTOT are not updated as changes are made to their respective blueprints, a mismatch in information will occur. The DTOT then no longer accurately reflects the company’s digital twinning landscape. As a result, it becomes an untrustworthy and incomplete base for decision-making. This in turn can have a negative impact on the acceptance of the tool, and so a downwards spiral begins. Aligning the contents of the DTOT with the real-life situation is always possible but can prove very tiresome when the mismatch is large.

Finally, the designed digital twinning support was created specifically for manufacturing SMEs. However, the theoretical basis upon which the support was created will largely be the same for other types of companies. Even MNEs or sole proprietors might therefore find (parts of) the supporting tools useful.

9 Recommendations

The tools that were introduced in this thesis are meant to support organisations in the development of digital twinning applications. The designed blueprinting approach and DTOT were tested out at one case company. Although these supporting tools should be applicable for any manufacturing SME, this would be good to validate this with actual tests. In addition, this would allow for common analysis needs to be identified which could then be translated to integral functionalities which should be preset in the DTOT. Furthermore, the blueprinting approach was only applied to relatively simple DTAs with limited functionalities. This was necessary given the time scope of this assignment. It would however be interesting to examine how the blueprinting approach is used in a larger project which involves multiple stakeholder perspectives of what should be captured in the DTA. This would likely include more sessions to work through the sessions which each stakeholder individually and then with them together to combine insights and ideas about the defined DTA. Moreover, it should be checked if and how the blueprint could be split into multiple smaller blueprints so that they can maintain their function of supporting discussions. Concerning the translation of the blueprints to the DTOT, it might be worth exploring if these can be automated. This could involve developing a tool that can automatically define the type of components and relationships between them based on a created blueprint. Currently, this requires an extensive amount of manual labour that is prone to errors.

If Delwi, the case company, is going to make use of the blueprinting approach and the DTOT, it is recommended to start with simpler projects and to use the approach to capture existing DTAs in the company. This will help to build an overview of the current state of the company's digital twinning landscape. From there, it will then be possible to identify future development directions. Before this is done however, the case company should research how the approach and DTOT should be integrated into their existing work practices and organisation structure. This step is critical to prevent the problems mentioned in the discussion. This is also a broader recommendation for future research. The DTOT and blueprinting approach should be attributed a leading role in the development projects of DTAs. This means that it should be examined what changes should be made to existing practices, or it should be checked what changes should be made to the approach and DTOT to facilitate their integration in an organisation. This would also be a good time to include the perspectives, of other stakeholders than the developer and management, on what functionalities should be included in the DTOT. A potential future functionality for the DTOT that can already be defined is that of allowing a user to see previous versions of the digital twinning landscape. While the primary focus of the DTOT is to support working from an as-is to a to-be situation, a has-been view might also provide useful insights in certain situations. E.g. when a user wants to analyse changes that have been made to a DTA over time. When the functionality of assessing historical database versions would be added however, it must be ensured that users cannot accidently base their decisions on outdated information.

Finally, there is a recommendation for the structure and elements of the blueprint and its associated ontology framework. These have both been repeated for reference on the next page in Figure 45 and Figure 46. Based on the capabilities and levels of integration that were discussed in *Digital twin*, a DTA can also have a driving influence on the physical environment. This aspect was however not included in the scope of the current blueprints and ontology. A digital twin that has a third level of integration with its physical counterpart, can influence the physical asset via various actuators. Adding these actuators and on which physical asset they work, are points of improvement of the framework ontology and blueprint structure. Given the modular structure of both however, these elements could be easily added when necessary.

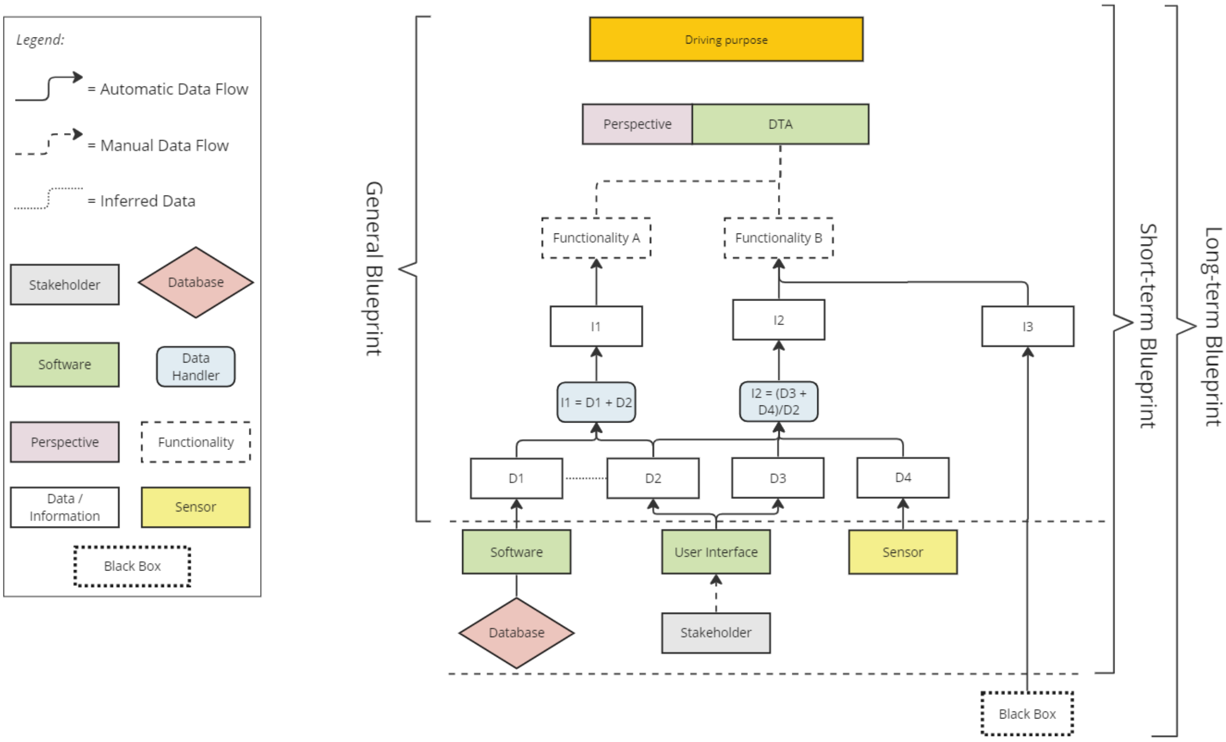

Figure 45: Basic blueprint structure

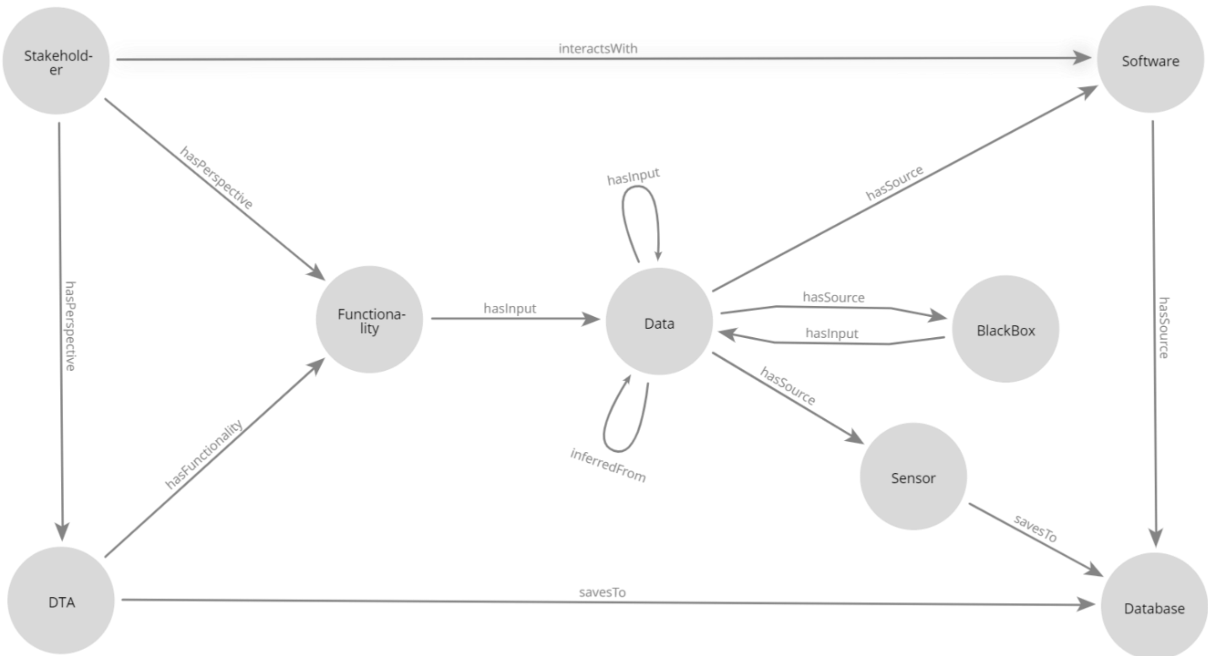

Figure 46: framework ontology based on the basic blueprint structure

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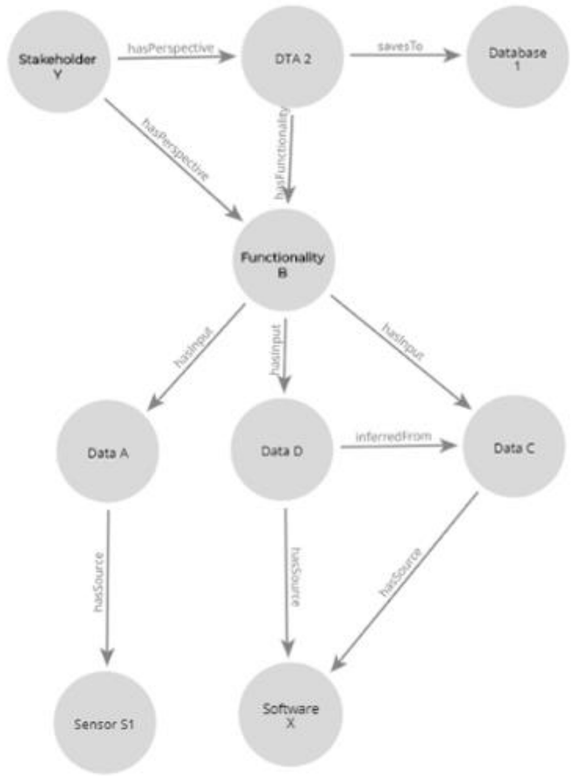
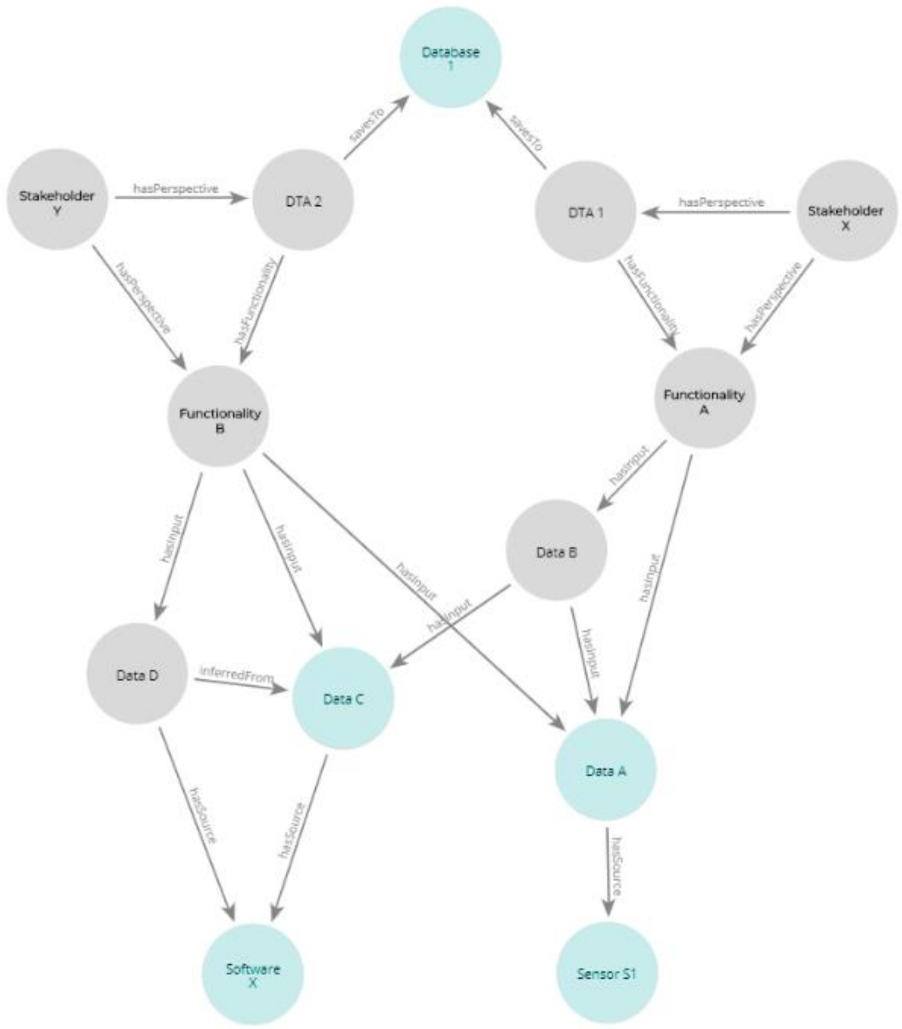
Appendices

Appendix 1

A



B


Database 1
savesTo
savesTo
Stakeholder Y
hasPerspective
DTA 2
DTA 1
hasPerspective
Stakeholder X
hasPerspective
hasFunctionality
hasFunctionality
hasPerspective
Functionality B
Functionality A
hasInput
hasInput
hasInput
hasInput
Data B
hasInput
hasInput
hasInput
Data D
inferredFrom
Data C
Data A
hasSource
hasSource
hasSource
Software X
Sensor S1

C

Appendix 2

The interview plan for the semi-structured interviews that were part of the case studies is set out below. The questions included were mainly there to steer the discussion sessions were necessary.

Introduction

- Explanation of thesis topic
- Explanation of session structure
- Ask permission for audio recording

Information of participant

- How long have you worked at Delwi?
- What is your role?
- What is your background (study/previous experience)?

General

- How familiar are you with digitalisation within industry?
- How do you think digitalisation will affect your work?
- What projects did you work on involving the introduction of new technologies to Delwi?

Blueprinting approach

- Explanation of blueprinting workflow
- How was it to go through the different steps?
- Do you think the blueprints give a good impression of the information needs/use?
- Do you think the blueprints will stay useful?
- Do you think this approach could be integrated at Delwi?
- Any input?

Mock-up

- Revisit blueprints
- Did the mock-up contain the functionality you expected?
- Would you alter the blueprints now that you have seen the mock-ups?
- Do you have ideas for other DTAs?

DTOT

- Is the tool understandable?
- Are the required functionalities there?
- Would you think the tool can be of added value to Delwi?