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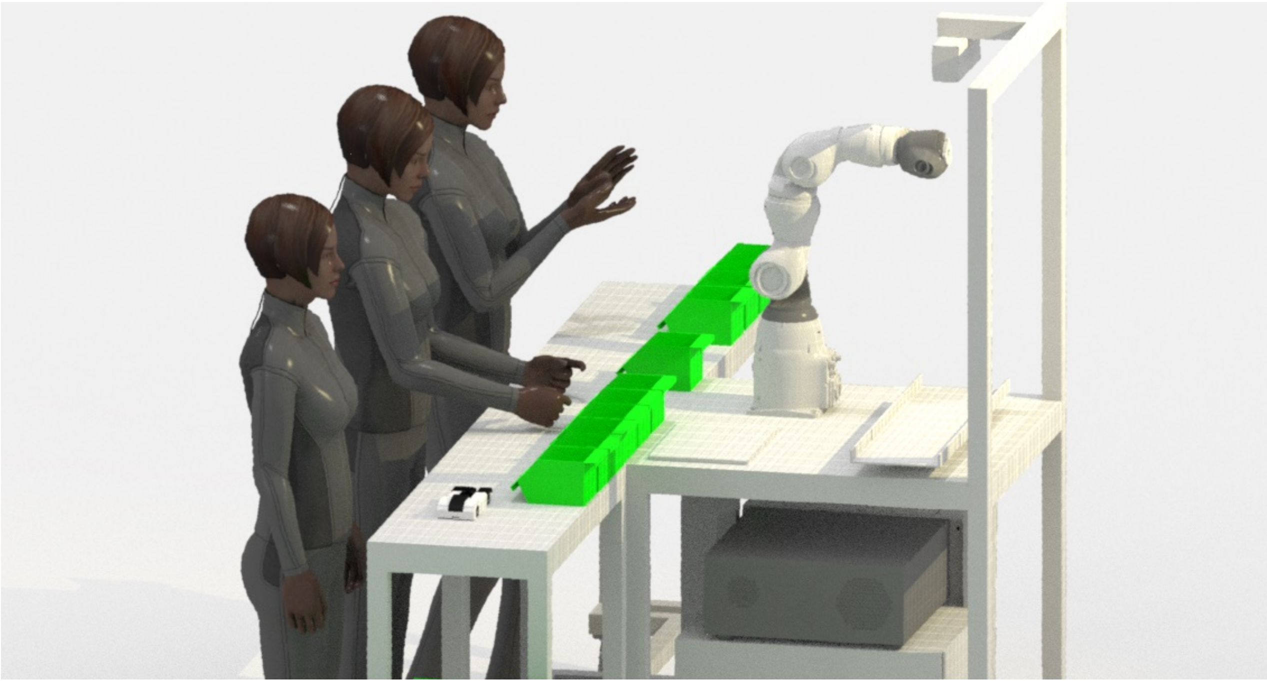

Towards a Digital Twin for the Smart Factory

An evaluation of the concept and technology of a digital twin

Master's thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020
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Cover: Rendition of the virtual model of the Vera Smart Factory created in 3DEXPERIENCE.

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Abstract

The concept of digital twins is a popular subject within the production industry and during the last couple of years it has been expanding with the help of Industry 4.0. This thesis evaluates the concept and the technology behind digital twins for the smart factory. It examines the different definitions of a digital twin, how far the technology has come, and what is required by small and medium-sized companies in the production industry to implement and create digital twins. A case study was conducted to increase the understanding of the creation process for digital twins which together with a literature study and interviews have been used to answer the research questions formulated in this thesis. It was found out that the digital twin is a complex concept still in an early stage of its maturity with divided opinions among different professions and academia of how it should be defined. A compiled definition of digital twins within the production industry is proposed together with an estimation of the technology's readiness level, as well as guidelines for implementing and creating a digital twin for small and medium-sized companies within the production industry.

Keywords: digital twin, digital twin manufacturing, digital twin shop-floor, virtual commissioning, virtual twin, smart manufacturing, smart factory.

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Jimmy Ek & Tobias Norman Hult
Gothenburg, June 2020

Contents

Glossary

Computer Integrated Manufacturing (CIM) - A manufacturing approach which uses computers to control production processes. Allows individual processes to exchange information.
Cyber-Physical System (CPS) - The connection between physical systems and virtual systems which is controlled by computer-based algorithms. Hardware and software can interact with one another in different contexts.
Design Reaserch Methodology (DRM) - A product development methodology with focus on design. It is a general concept for realizing and developing the design process.
Internet of Things (IoT) - A network of data transfer for computing equipment without human interaction.
Industrial Internet of Things (IIoT) - Internet of Things with industrial applications for data collection, data transfer, and data analysis.
Product Lifecycle Mangement (PLM) - The management of a product during different phases of its life.
Programmable Logic Controller (PLC) - A computer designed for the control of industrial manufacturing or production processes. For example robots or assembly lines.
Shop-floor - The space in a factory where people work with machines.
Small and Medium-Sized Company - Companies with a lower amount of employees, usually between 10-250 people.
Technology Readiness Level (TRL) - Is a set of indicators for determining the maturity level for different technologies.
Virtual Commissioning (VC) - The process of deploying a virtual factory before, or in parallel with, the deployment of the physical factory.

List of Figures

List of Tables

1
Introduction

In this chapter the relevant background for this thesis will be presented followed by the purpose and research questions. The chapter ends with the thesis' delimitations and its structure.

Digital twins are predicted to be an increasingly more used technology for industrial organizations in the future according to NEC (2020). The possibilities are endless, ranging from virtual models of products and processes, complete shop-floors in manufacturing and production, to smart cities, and even the human body (NEC, 2020). Imagine a digital twin of the human body which can analyze exactly what would happen if you ate something, how many minutes of your life you lose when smoking a cigarette, or when you are expected to get a heart attack. Or a digital twin of a production company's shop-floor which can predict exactly when a robot's bearing needs to be replaced, while planning for maintenance or changing the workload between the stations so there is no down time. A smart city with autonomous cars where everything communicates to minimize traffic queues while the traffic flow can be seen in real time and cars that presents a risk and needs service for various reasons can be highlighted.

Creating complex networks of digital twins which can gather relevant data regarding almost anything is probably something that the not so distant future holds for humankind. Being able to virtually analyze a unique product's properties on a molecular level, analyze production processes to optimize robots, workflow, or ergonomics, simulate infrastructure or air quality in cities, or knowing what would happen to the body if consuming specific food, may seem like a dream to many people. This technology has however been expanding rapidly over the last couple of years. More and more companies offer solutions for digital twins within different areas and for various industries. But creating these complex systems is anything but easy. A tremendous amount of resources are needed ranging from people, money, and time, to smart components, sensors, servers, and processing power which at the same time needs to be compatible in order to communicate with each other.

1.1 Project Background

This thesis is written in collaboration with Smarta Fabriker and Dassault Systèmes.

Smarta Fabriker is a government funded project in Sweden which aims at increasing and building knowledge in technology within manufacturing and production for students and companies within the engineering and industrial sector with focus on digital applications (Smarta Fabriker, 2020a). They have small-scale production cells which works as demonstrators. These demonstrators range from automation processes, robotics, flexible and collaborative production where humans and robots work together, to production in virtual reality.

This thesis will work together with Smarta Fabriker's demonstrator for flexible and collaborative production. It is called the Vera Smart Factory and assembles a small-scale Lego truck called Vera which is a representation of Volvo Truck's electric and autonomous concept truck with the same name (see Volvo Trucks (2020)). The production cell aims at simulating a real production line by using this miniature Lego truck which can be seen in figure 1.1.

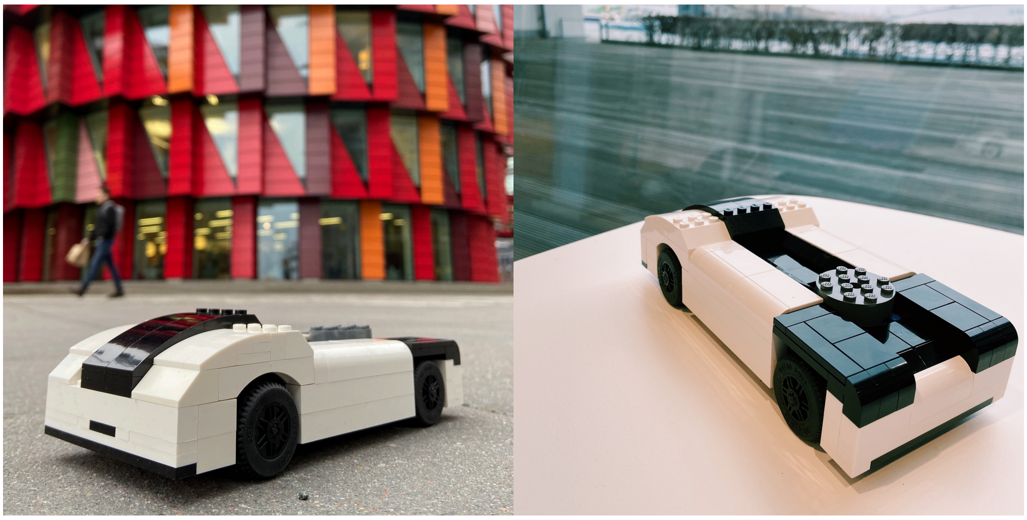

Figure 1.1: The Lego Vera truck.

The Lego truck consist of several variants and configurations where there are different variants for the rims, the body, the motor, and the battery packs. This is because the production line is supposed to be able simulate a real factory with variant and change management.

The production line consists of three assembly stations where each station has manual assembly and can be assisted by a collaborative robot. The robot can be moved to each station to prevent bottlenecks and to assist the worker at the respective station. The robot cell used in the production line is the ABB IRB 14050 Single-Arm YuMi collaborative robot (see ABB (2018)).

Figure 1.2: The production cell for the Vera Smart Factory.

During previous years, other theses have been conducted at Smarta Fabriker to develop their smart factory and to spread knowledge regarding manufacturing and future technologies (Smarta Fabriker, 2020b). For their new production cell, the Vera Smart Factory, they want a digital twin to support the physical production cell with decision making and to be used for visualization purposes. As a partner to Smarta Fabriker, Dassault Systèmes will provide their business platform 3DEXPERIENCE to support the creation of the digital twin.

The meaning of a digital twin and the purpose of using it varies a lot between industries and in which area it is used in. The central aspect concept studies and papers agree on is the vast amount of possibilities that come with digital twins and how they can be used to benefit companies, both on a functional level and on an organizational level. The knowledge behind digital twins are more common in larger companies with larger production where more resources are put into the development of this type of technology. Small and medium sized-companies with 10-250 employees with smaller production, similar to the production cell of the Vera Smart Factory, are not as familiar with digital twins and do not have the same resources or knowledge regarding digital twins as larger companies do.

Today there is no concrete outline for the concept of digital twins, its maturity, or the implementation and creation of digital twins. This thesis therefore has the aim to fill this gap by creating a digital twin as a case study to understand how a digital twin can be implemented and created for small and medium-sized companies within the production industry.

1.2 Purpose and Research Questions

The purpose of this thesis is to investigate how a digital twin can be implemented and created for small and medium-sized companies within the production industry.

The following research questions have been derived to reach the purpose of the thesis.

1. What is the definition of a digital twin?
2. What level of maturity has the technology behind digital twins reached?
3. How can small and medium-sized companies work towards implementing and creating a digital twin?

To support the purpose and to answer the research questions, a digital twin of the Vera Smart Factory is going to be created as a case study to enhance the understanding of what is needed regarding information and practice to create a digital twin. Furthermore, in-depth research will be done to outline the concept of digital twins and the technology by using the Design Research Methodology presented by Blessing and Chakrabarti (2009).

1.3 Delimitations

The time frame for this thesis is planned to proceed during 20 weeks with start in late January and finish in early June of 2020.

The created virtual model will not be used to test programmable logic controllers or robot code and the accuracy will not be validated with regards to the physical model. Furthermore, the realization of how Industry 4.0 will be executed in practice with regard to integration between physical and virtual models will not be examined.

The thesis is limited to evaluate how a digital twin of a production system can be created and will therefore not evaluate the production system itself. This means that the digital twin will show how it can be used for optimization purposes, although optimization of the production line will not be made.

Due to unforeseen events during this project, namely the COVID-19 outbreak which affect both industry and schools, the amount of interviews has been limited. And thus, may not reflect the majority of small and medium-sized companies' view on digital twins accurately.

1.4 Thesis Structure

The layout of the thesis is presented as follows.

2 Frame of Reference
This chapter presents the theoretical framework used in this thesis and is divided into digitalization, sustainable production and work methodology.
3 Methodology
Chapter three presents the methodology and work procedures used during this thesis. The chapter presents the research method, data collection process and how the case study was conducted. The chapter ends with a section about method criticism.
4 Results
In this chapter the results of the most notable areas from the interviews are presented along with the case study of the created digital twin
5 Discussion
In this chapter a comparison between the literature and interviews is made together with the experience gained from case study in order to answer the research questions. The chapter ends with a discussion about the ethical and sustainability dilemmas with digital twins and the need for future research in different areas.
6 Conclusion
This chapter presents the concluding statements regarding the findings in this thesis to fulfill the purpose of how small and medium-sized companies within the production industry can implement and create digital twins.

2
Frame of Reference

The following chapter describes the theoretical framework used in this thesis.

2.1 Digitalization

The evolution of digitalization dates back several decades and has in recent times become a widely spread term. It characterizes how it is possible to transform current business processes using IT and digital technology. Digitalization provides the opportunity to optimize the coordination between different business processes in a more efficient manner (Verhoef et al., 2019). In the industrial sector it can be seen that more and more companies try to achieve competitive advantage by making manufacturing and production more effective and sustainable with the use of IT and digital technologies (Cenamor, Sjödin, & Parida, 2017; Ignat, 2017).

According to Rosen, von Wichert, Lo, and Bettenhausen (2015), during the 1960's the use of digital systems and simulations were limited in terms of only the experts of specific areas had access to it. After 1985, simulation tools had become the basic tool to answer engineering questions, for example simulation of fluid dynamics. Later on in the 2000's it had grown even further and simulation allowed a more complex approach to multi-level systems. During the last couple of years a new term has been adopted, known as the *Digital Twin* with the purpose of connecting the entire life cycle of products, processes, and systems as seamlessly as possible with collection, storage, and usage of relevant data (Rosen et al., 2015).

2.1.1 Smart Manufacturing

With the introduction of microelectronic and robotic technologies in the 1960s, the third industrial revolution has been expanding, resulting in a massive boost of automated processes together with the usage of computer-integrated manufacturing (CIM) (Stock, Obenaus, Kunz, & Kohl, 2018). CIM offers the possibility to increase manufacturing flexibility, changeover, and speed by connecting tools, robots, and automated devices into a collective platform which is dependent on the integration of networks, connections, information processing, and control systems (Lei & Goldhar, 1991). Introducing Industry 4.0, the so-called fourth industrial revolution, takes this one step further with focus on value creation by digitalization of manufacturing and production processes. A visualization of this can be seen in figure 2.1. Cyber-physical systems (CPS), are networks consisting of hardware and software components, which are used to monitor, control, and coordinate these components. Linking systems like these together with each other creates another network called Internet of Things (IoT). By linking together resources, services, and humans in real-time with the use of CPS and IoT, Industry 4.0 aim for maintaining competitiveness in the future (Stock et al., 2018).

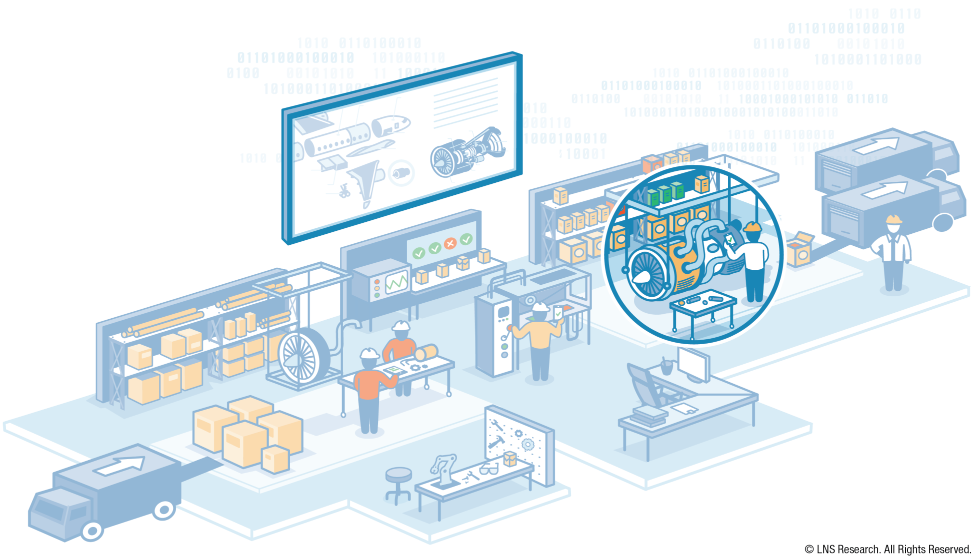

Figure 2.1: Visualization of a shop-floor using digitalization in a production process.
Source: (Hughes, 2018) Reprinted with permission.

According to Lichtblau et al. (2015), successful implementation of Industry 4.0 enables the smart factory with a highly automated production environment in which the production systems and logistics systems largely organize themselves without human interaction. The smart factory relies on the CPS according to Lichtblau et al. (2015) which creates the link between the physical and virtual models through the usage of IoT. Furthermore, through smart gathering, storage and processing of data, and by implementing Industry 4.0 the smart factory can be provided with resources and information more efficiently. The large amount of data and information of real-time data, cross-enterprise collaboration between production systems, information systems, and people, is analyzed and used for decision making models (Lichtblau et al., 2015).

Veza, Mladineo, and Gjeldum (2015) states that with smart factories, products that are uniquely identifiable can be produced and that this type of factory allow individual customer requirements to be met and one-off products can be produced and seen as profitable. During the manufacturing process the products can be located at all times which means that the products know their own history, current status and alternative route to achieve their target state (Veza et al., 2015).

A smart factory can be summarized by these three definitions according to Veza et al. (2015).

– "Production of smart personalized products."
– "Product and service are integrated into single extended product."
– "High level of collaboration through production networks."

According to Schuh, Anderl, Gausemeier, ten Hompel, and Wahlster (2017) the value creation potential of Industry 4.0 is estimated to be around 100-150 billion euros for the German economy over the next couple of years, although this may not be realizable because the concrete benefits of Industry 4.0 is mostly not acknowledged by companies. The Federal Ministry for Economic Affair and Energy highlighted this in a study which identified the lack of transparency regarding the benefits as the biggest difficulty for introducing Industry 4.0, which was mostly applicable to small and medium-sized companies (Schuh et al., 2017). According to Müller, Buliga, and Voigt (2018) large companies actively pursue Industry 4.0, but the attitudes of small and medium-sized companies towards Industry 4.0 vary widely.

The increasing competitive market makes it important for companies to have faster and better decision making. Decisions are often intuitive instead of basing them on concrete facts. One of the main potentials of Industry 4.0 is to "accelerate corporate decision-making and adaptation processes" (Schuh et al., 2017). Schuh et al. (2017) also define Industry 4.0 as "real-time, high data volume, multilateral communication and interconnectedness between CPS and people." Real-time data in big volumes at affordable prices which is available across an organization can enable faster decision-making processes by increasing the understanding of how things are related. In essence, making an organization more agile is a key enabler for introducing Industry 4.0 (Schuh et al., 2017).

One specific technology which has been on the uprise the last couple of years is the digital twin which can be directly linked to the quote above by Schuh et al. (2017). The capabilities of the digital twin have been limited mostly because the needed amount of data to process, computing power, storage and bandwidth costs have simply been to high. This has however changed in recent years and may lead to the development necessary for combining information technology and operations technology, i.e. creating more complex digital twins (Parrott & Warshaw, 2017).

To be able to reach smart manufacturing for shop-floors in manufacturing, it is important to reach convergence between the physical and virtual models. A digital twin for shop-floors enables this and is a crucial step towards smart manufacturing. (Tao & Zhang, 2017)

2.1.2 Virtual Commissioning

Virtual commissioning is an approach for testing and optimizing a virtual model of an automated system with a programmable logic controller (PLC) (Ahrens, Richter, Hehenberger, & Reinhart, 2019; Lechler, Fischer, Metzner, Mayr, & Franke, 2019). To support a physical commissioning of a production process, virtual commissioning can be used to reduce the risk of design flaws and collision between components, reduce lead times from start to finish, and validate the behaviour of the physical system (Lechler et al., 2019).

With virtual commissioning the behaviour of the physical entities are simulated in a virtual model. The behaviour should be as close as possible to the real world to ensure best results, which means that the virtual model should consist of the mechanical, geometric, kinematic, and logic properties as of the real system. This facilitates the validation of the PLC and enables a smoother implementation of the physical system. (Schamp et al., 2019)

2.1.3 Digital Twin

The concept of digital twins first came to light by Grieves in 2003 during his course on Product Lifecycle Management (PLM) at the University of Michigan (Grieves, 2015; Wang, 2020). Grieves definition had at this time only a three-dimensional conceptual framework which included the physical model, the virtual model and the connection between the two. It was not until 2012 when NASA and the U.S. Air Force released their definition of a digital twin for space vehicles the understanding was accepted and has since then been the foundation for researchers and industry in evolving new definitions of digital twins (Tao, Zhang, & Nee, 2019). NASA's definition says the following: "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin." (Glaessgen & Stargel, 2012).

Most definitions define a digital twin as a virtual representation that interacts with the physical object throughout its life cycle and provides intelligence for evaluation, optimization and prediction (Tao, Zhang, & Nee, 2019). The definitions focus on both the physical and virtual sides as well as the connection between, which are the essential elements in the digital twin's three-dimension framework according to Grieves (2015). Tao, Zhang, and Nee (2019) proposes an extended five-dimension definition, adding data and services to Grieves three-dimensional definition. This definition fuse both the physical and virtual model with data for more accurate and comprehensive information and also capture the functions of digital twins regarding detection, judgement and prediction (Tao, Zhang, & Nee, 2019).

LNS Research define the digital twin in a straightforward approach where they say: "A Digital Twin is an executable virtual model of a physical thing or system." (Hughes, 2018). They say that a physical thing or system has definable attributes which the digital twin characterizes in a virtual environment. Furthermore, a complete digital twin would have the ability to simulate every possible parameter of a physical product, system, or process (Hughes, 2018).

According to Parrott and Warshaw (2017) a digital twin can be visualized as a combination of five components which are sensors, data, integration, analytics, and actuators. The sensors recover data from operations in the physical world. The data is accumulated with data from other organizational systems. Different sensors then transmit this data and integrates it between the virtual and physical model. The data is analyzed and used for the actuators if a response is justified, which can start a specific operation in the physical environment (Parrott & Warshaw, 2017).

Grieves and Vickers propose the following definition, "the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin." (Grieves & Vickers, 2017). Tao, Sui, et al. (2019) opinion about digital twins is the following: "digital twin is a real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them" (Tao, Sui, et al., 2019).

According to Kritzinger, Karner, Traar, Henjes, and Sihn (2018) there is no common definition of digital twins because there is a variety of focus areas of different disciplines for digital twins. The literature review by Kritzinger et al. (2018) shows that the development of digital twins still is at its infancy and a lot of papers about digital twins are on concept studies. Negri, Fumagalli, and Macchi (2017) concur to this and mention in their literature review that there is a need for more research on digital twins.

Although there are various understandings of digital twins, Tao, Zhang, and Nee (2019) says that among researchers in academia and practitioners in the industry, models, data, connections, and services play the most important role in the digital twin and can be seen as its core. According to Qi et al. (2019) the definition by NASA and the U.S Air Force is one of the most accepted at this time.

As for today the value and importance of digital twins are increasing in organizations and more investments and resources are put into the development and deployment of digital twins. The capabilities will keep evolving along with the possibilities of generating more value for companies and it will play an important role in the industry for the integration and fusion between the physical and virtual world (Tao, Zhang, & Nee, 2019). With new technology in manufacturing, a new era of smart manufacturing has arrived according to Tao, Sui, et al. (2019). At this time the development process of the connection between the virtual and physical world impede the application of digital twins within manufacturing because the advancement of the connection has not reached the same advancement as the virtual and physical models (Tao, Sui, et al., 2019).

LNS Research anticipates that the financing for digital twins will grow over the coming years and has listed their prediction on initial budgets from companies for this type of technology which can be seen in 2.2 (Hughes, 2018).

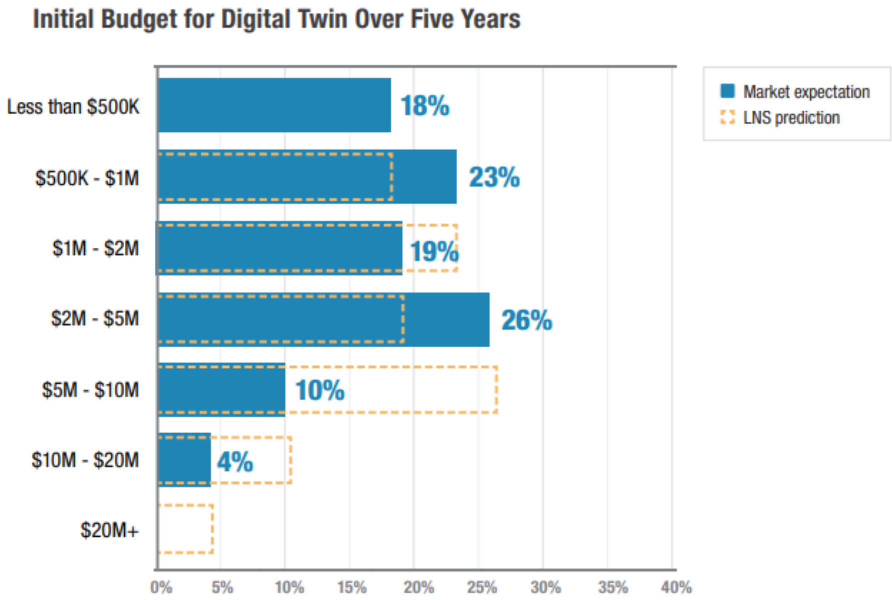

Figure 2.2: Market expectation and LNS Research's prediction for initial investments of digital twins.
Source: (Hughes, 2018) Reprinted with permission.

Hughes (2018) at LNS Research states that companies overall are very enthusiastic with their expectations on return on investment and 60% of the companies anticipate a full pay-back in only a year. They say that companies with a longer vision have a higher chance of success when it comes to implementing digital twins, where over a timeline of five years 75% of the companies anticipate to make a 10-100% return on investment (Hughes, 2018).

2.1.4 Digital Twin Shop-Floors

There are many areas of application for digital twins throughout a product's life cycle. Some digital twins are more developed than others regarding the exchange and interaction of information and communication. In the following section different models of digital twin shop-floors will be reviewed to get a better understanding of how researchers and industry classify digital twins. Figure 2.3 shows a simplified view of a physical production line with a virtual counterpart.

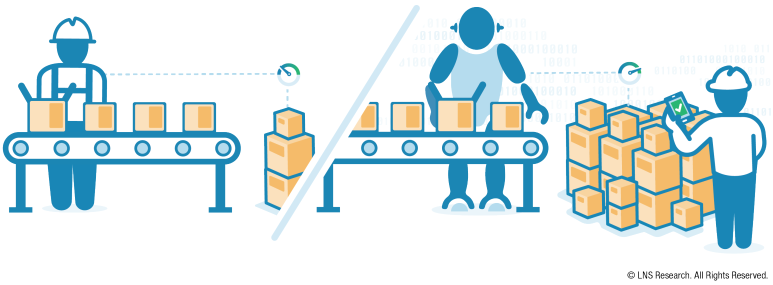

Figure 2.3: Simplified view of a physical production line with a virtual counterpart. **Source:** (Hughes, 2018) Reprinted with permission.

Digital twins are characterized by the linkage between the virtual and physical world which enables communication and interaction to benefit both models (Tao, Sui, et al., 2019). This can be connected to what Grieves (2015) proposed in his three-dimensional model where the physical and virtual models go side by side during a product's life cycle. By using a virtual model that can record changes from the physical model, optimizations, predictions and recommendations can be done for the physical model's behaviour and then be adjusted in real time (Tao, Zhang, & Nee, 2019; Negri et al., 2017). At the same time, the virtual model can be adjusted to be more factual and to better represent the real state of the physical model (Tao, Sui, et al., 2019; Negri et al., 2017). The physical model can at the end use simulations done by the virtual model get the "ideal behaviour" (Tao, Zhang, & Nee, 2019).

Tao and Zhang (2017) have in their article about digital twin shop-floors visualized the convergence between the physical and virtual models in perspective of their evolution, see figure 2.4. The first stage consist of the physical model of the shop-floor which lacks the means of information exchange and therefore solely rely on the physical model, which lead to low efficiency and accuracy. The second stage consist of a virtual model that acts as a copy and augments the physical model. In this stage, there is no communication or interaction between the models but information gained from either of the models can be used to do changes in the other model manually. The third stage consist of a virtual and physical model that interacts with each other. In this stage the models can communicate with each other automatically and information gained from the physical model can be used as input for the virtual model to do simulations, optimizations, and predictions to later be used in the physical model. All the information and interactions are made available through sensors, IoT and other communication technologies. The fourth and final stage consist of the two models that merge. In this stage the interaction between the models is greater which means that the models will be able to communicate in real-time. For this to happen technologies such as sensors and data processing must evolve and become more advanced. (Tao & Zhang, 2017)

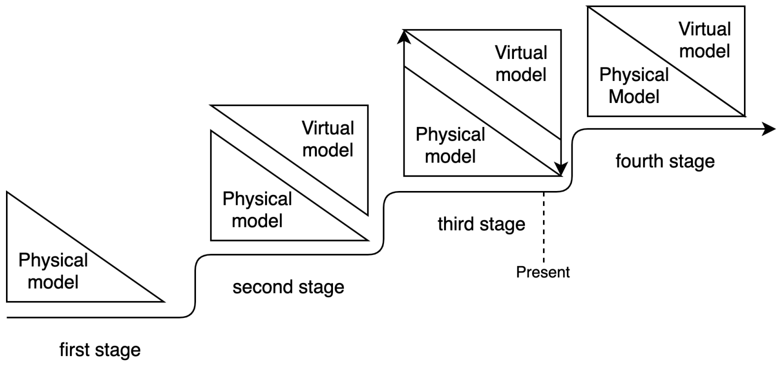

Figure 2.4: Map visualizing the evolution of a digital twin.

The information exchange between the virtual and physical models can be in different directions depending on the definition of a digital twin. Kritzinger et al. (2018) proposes a digital twin classification dividing digital twins in three sub-categories depending on the data exchange and level of integration between the virtual and physical model, see figure 2.5. The first category is the “Digital Model“ where there is only manual data exchange in both directions between the physical and virtual models. In the second category, the “Digital Shadow“, there is manual data flow between the virtual model to the physical model and automatic data flow between the physical model and the virtual model. In the third category, the “Digital Twin“, there is automatic data flow in both directions between the models.

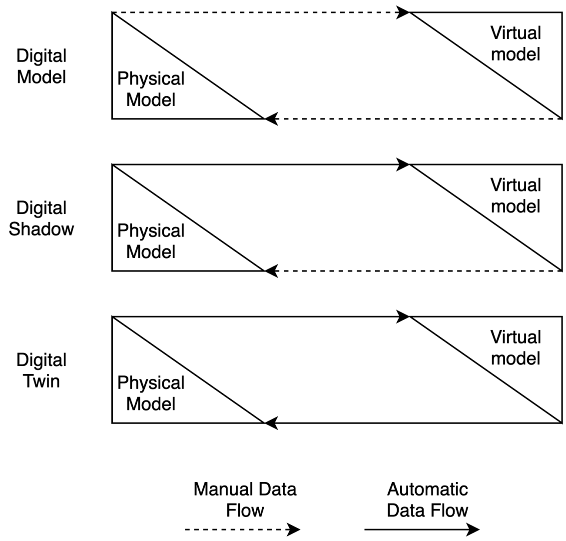

Figure 2.5: Visualization of the data flow between the physical and virtual models.

What differs the “Digital Twin“ from what Kritzinger et al. (2018) mention as the “Digital Model“ and the “Digital Shadow“ is according to Negri et al. (2017) the inclusion of real time synchronization with the physical model. This allows the digital twin to be updated and as exact as possible to the physical model and at the same time optimize it.

Tao, Zhang, and Nee (2019) propose the concept of a digital twin shop-floor to reach the convergence between the physical and virtual shop-floor. The concept divide the digital twin shop-floor into five dimensions; *Physical Shop-floor*, *Virtual Shop-floor*, *Shop-floor Service System*, *Shop-floor Digital Twin Data*, and *Connections* which can be seen in figure 2.6. According to Tao, Zhang, and Nee (2019) the most important aspect of the concept is to keep the physical and virtual models updated and optimized by each other by fusing data to one another consistently to get a coexisting virtual model that is as exact and important as the physical model. Tao, Sui, et al. (2019) states that by dual-optimization, the virtual shop-floor can record the performance and history of the physical shop-floor to make optimizations and predictions for the physical shop-floor. The physical shop-floor can at the same time provide the virtual shop-floor with properties for behavior and rules to keep it updated when changes are made in the physical shop-floor.

According to Tao, Zhang, and Nee (2019), The Shop-floor Digital Twin Data collect output data from the Virtual Shop-floor, Physical Shop-floor and Shop-floor Service System where the data is merged together and used as information to enhance the production. The Shop-floor Service System is used to manage the services needed for the evolution and operation of the Virtual Shop-floor and also to support the management and control of the Physical Shop-floor.

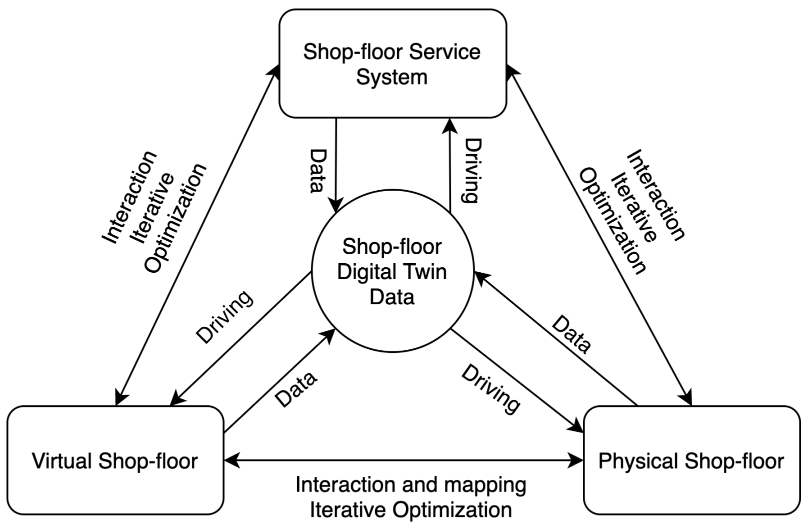

Figure 2.6: The concept of a Digital Twin Shop Floor.
Source: (Tao, Zhang, & Nee, 2019)

Tao, Zhang, and Nee (2019) also states that the Physical Shop-floor sends output data to the Virtual Shop-floor which then evaluates the accuracy according to the predefined process and then sends feedback with possible changes. Furthermore, the Shop-floor Service System is used to support normal activities of the Virtual Shop-floor and to keep track of services needed for the Physical Shop-floor. The services needed for the Physical Shop-floor are first tested on the Virtual Shop-floor, thereof the iterative interaction between the Shop-floor Service System and the Virtual Shop-floor. The iterative optimization between the Physical shop-floor and the Shop-floor Service System is there to facilitate the Physical Shop-floor with services that has been tested in the Virtual Shop-floor to optimize the production (Tao, Zhang, & Nee, 2019).

2.1.5 Areas of Usage for a Digital Twin

According to SEEBO (2019) a digital twin can be used to analyze the collected data from IoT otherwise fixed in different machines and equipment. This process can be very helpful to engineering, quality, and maintenance teams. The digital twin also allows for evaluation of production decisions, visualization of products' performance or usage of actual people in real-time, remote access to machines and equipment, connection of separate processes or systems, troubleshooting, and control over complex systems (SEEBO, 2019). Within maintenance a digital twin can be used as a predictive process instead of a reactive, thus reducing the need to disturb the production or switch parts unnecessarily. From a quality perspective it can help with identifying the root-cause of quality problems and defects. It can also help when simulating optimization of processes where the production can continue without disturbance (SEEBO, 2019).

LNS Research has conducted an inquiry across the world and interviewed over 300 executives within different industries about digital twins, how it is used in practice, and what they want to accomplish (Hughes, 2018). Companies within discrete manufacturing, batch production, and process production were interviewed and research showed that of the conducted interviews 47% had already implemented digital twins or were in a pilot stage, while 20% had planned for digital twins within the next 1-3 years, whereas 25% had no plans on using digital twins. Of those who did not have any plans for digital twins 45% do not know what it is, 45% said it is not relevant for their industry, and 10% believe it has no value. These numbers are presented in figure 2.7. What they also found interesting is that companies using PLM and IoT systems are more enthusiastic regarding digital twins. However, it is not stated what kind of digital twin with regards to the different definitions the interviewed companies were implementing or planning on implementing.

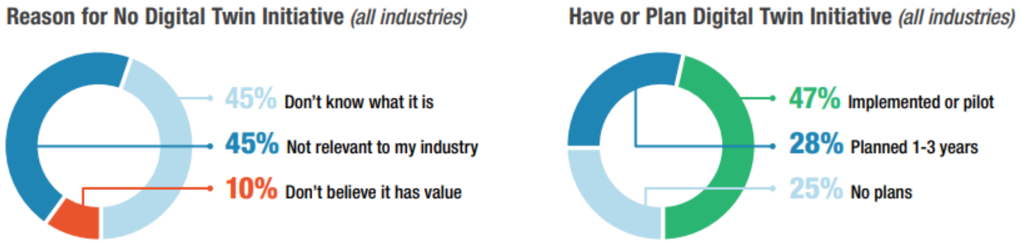

Figure 2.7: Implementation of digital twins within different production and manufacturing industries.
Source: (Hughes, 2018) Reprinted with permission.

Among the discrete manufacturers interviewed by LNS Research the most important use cases for digital twins are to improve product quality, reduce manufacturing costs, reduce unplanned down time, increase output, and ensure safe manufacturing (Hughes, 2018), which can be seen in figure 2.8.

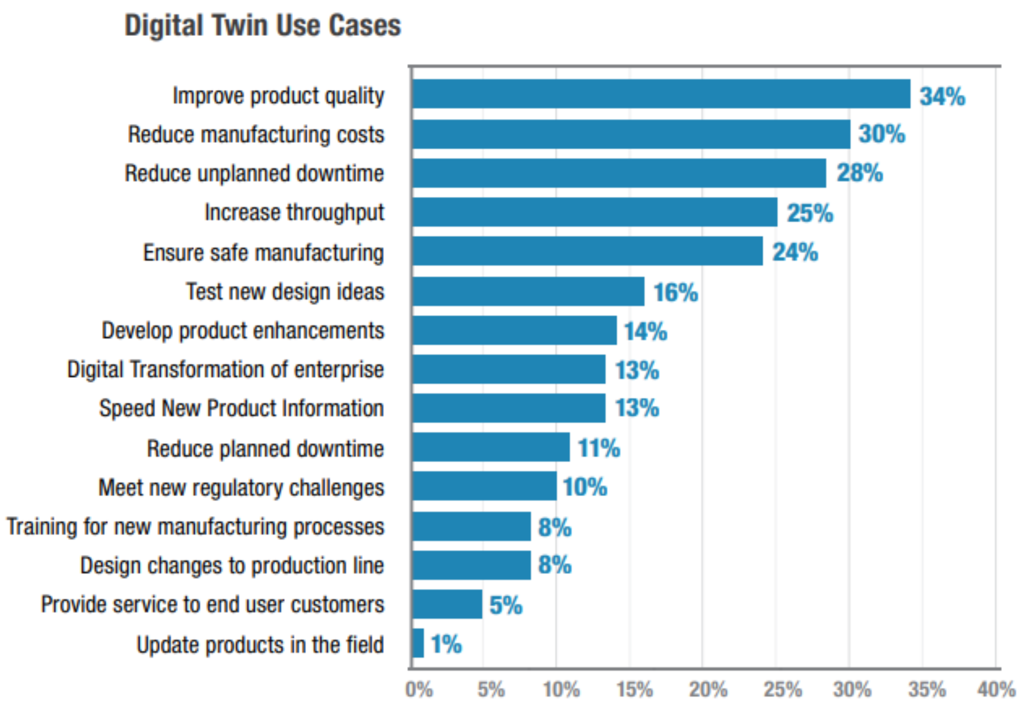

Figure 2.8: Important use cases for a digital twin among discrete manufacturers.
Source: (Hughes, 2018) Reprinted with permission.

According to Qi et al. (2019) there is a strong desire for small and medium-sized companies to incorporate a digital twin to their businesses but the complexity and lack of knowledge in these types of technologies hinders them on pursuing a digital twin. Although, companies are starting to realize the importance of service integrated products which have become a big part of today's society (Tao & Qi, 2019) and also a big part of the digital twin (Qi et al., 2019). The service integration consist of application services, third-party services and operation services (Qi et al., 2019). The application services help the customer of the digital twin to do simulations and optimizations, the third-party services are the tools for the creation process of the digital twin concerning data services and knowledge services and the operation services provide the customer with platform services and model building (Qi et al., 2019).

2.1.6 Working Towards a Digital Twin

As mentioned previously there are a wide range of applications and use cases for digital twins. To work towards digital twins there are according to Parrott and Warshaw (2017) and SEEBO (2019) certain phases that are important to consider during the implementation and creation process. First of all it is important to *imagine* the benefits and purpose of implementing a digital twin in the company. By *identifying and selecting* a pilot project that have high chances of being successful and can create the most amount of value, the pilot project can generate knowledgeable information for the continued work. During the *piloting/implementation*, the creation of the digital twin is done in iterations with focus on the creation process and return on investments. Lessons learned from the previous phase are then used to *industrialize* the pilot project with the use of established tools and techniques to make the digital twin mature enough to be expanded. The opportunities identified and established in previous phases are then used to *scale* the digital twin to a larger part of the company. Lastly the return of investment is analyzed and monitored and changes are made to optimize the digital twin to the specified purpose.

Tao, Sui, et al. (2019) highlights six steps that are important to consider during the creation process of a digital twin. The steps can be followed in sequence or concurrently to fit the specific work procedure at the specific company. The first step includes building a virtual model of the physical one by using modeling technologies such as computer-aided design to get the elements, behaviors, and rules modeled in the virtual environment. The next step is to process and integrate data from the physical model into the virtual model. The third step includes simulating the virtual model with tools such as virtual reality to analyze the product design and behaviour. The fourth step includes usage of the simulated behaviors to optimize the physical product. In the fifth step the real-time connection between the models is created by technologies such as network communication. In the sixth step data from various sources are collected by the help of IoT to enhance the virtual model.

2.2 Sustainable Production

The industrial value creation has its standpoint from a sustainable perspective which can be divided into economic, social, and environmental sustainability, also known as the three-pillar model (Stock et al., 2018). Sustainable Development was first characterized in the Brundtland Report (The World Commission on Environment and Development, WCED, 1987) and has since been adopted in United Nations' Agenda 2030 (General Assembly resolution 70/1, 2015) which includes 17 goals in order to accomplish sustainable development. However the sustainable development is a challenging area and the goals are mostly treated as a framework and support for the implementation of Industry 4.0 and different decisions and actions. The framework can be organized into principles related to efficiency, consistency, sufficiency, and participation (Stock et al., 2018).

Sustainable production, which is related to sustainable development (Veleva, Hart, Greiner, & Crumbley, 2001), has been defined by Lowell Center for Sustainable Production as, "Sustainable Production is the creation of goods and services using processes and systems that are: Non-polluting; Conserving of energy and natural resources; Economically viable; Safe and healthful for workers, communities, and consumers; Socially and creatively rewarding for all working people" (UMass Lowell, 2020). The term sustainable production appeared in 1992 when the United Nations Conference on Environment and Development established that the pattern of consumption and production is a considerable factor on the global environment (Veleva et al., 2001; Veleva & Ellenbecker, 2001).

Veleva and Ellenbecker (2001) propose the implementation of a set of indicators for sustainable production (ISPs) in order to address six essential aspects of sustainable production which are energy and material use, natural environment, social justice and community development, economic performance, workers, and products (Veleva & Ellenbecker, 2001). The ISPs are mainly used to increase awareness and understanding, support decision-making, and to measure progress (Veleva et al., 2001). However, only implementing a set of ISPs is not sufficient without knowing what to do with them. What is important to measure, who should measure it, and how it will be measured are key questions to be answered before implementing any new indicators. Otherwise, the risk of drowning in useless, incomplete, or incomparable data is substantial (Veleva & Ellenbecker, 2001).

With Industry 4.0 there is a way of bringing in new equipment with the latest features, but Industry 4.0 also enables the convenience of upgrading existing equipment by retrofitting them with different sensors, industrial internet of things (IIoT) systems, and custom software. This gives old equipment new capabilities and can be implemented in the Industry 4.0 trend. It is an efficient way of reducing costs instead of purchasing newer machines and gives the possibility to measure and monitor energy consumption for example (Ardanza, Moreno, Álvaro Segura, de la Cruz, & Aguinaga, 2019). This can provide a way for introducing a more sustainable factory, and potentially a first step to create a digital twin of the shop-floor.

2.3 Work Methodology

The following section presents the methodology and tools used in this thesis.

2.3.1 Design Research Methodology

Design Research Methodology (DRM) is used as a framework for producing a successful product by using theories and models, and validating the information obtained with different methods and tools (Blessing & Chakrabarti, 2009). The framework for DRM can be seen in figure 2.9.

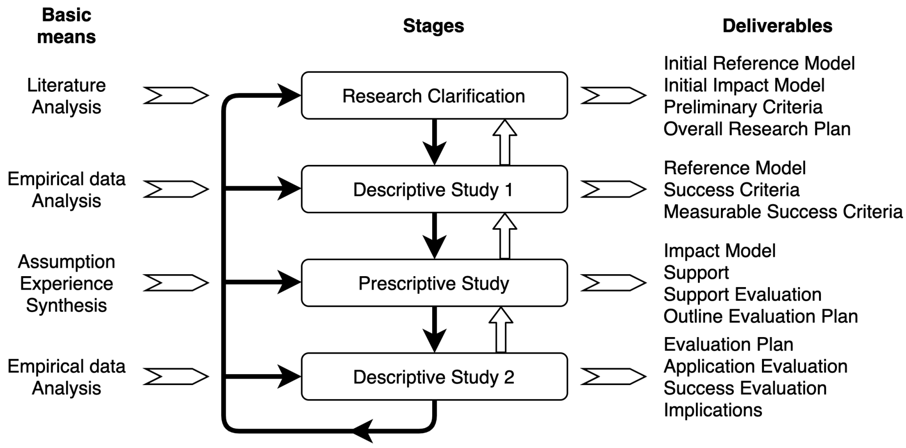

Figure 2.9: The work procedure for Design Research Methodology.
Source: (Blessing & Chakrabarti, 2009)

The stages seen in figure 2.9 are according to Blessing and Chakrabarti (2009) used in a concurrent approach and there is no specified way of working with these. A project can begin in any of the four stages and may only cover some of them. The arrows show the process flow and implies that it is an iterative methodology where each stage can be revisited for further research (Blessing & Chakrabarti, 2009).

In the first stage, *Research Clarification*, the goal is to determine the purpose with the project, research questions, what is to be examined, and what to achieve. The second stage, *Descriptive Study 1*, is used to expand the knowledge of the success factors for the project and its situation. This is done by conducting literature studies, exploratory interviews, and observations with an empirical approach. The *Prescriptive Study* stage is where support for the final stage is developed. It is done by addressing the presented success factors, creating models, and establish plans for assessing gathered data in order to progress with the project. In the last stage, *Descriptive Study 2*, the findings in the previous stages are evaluated, the impact of the created models are identified, and suggestions for improvements are made. (Blessing & Chakrabarti, 2009)

2.3.2 Technology level

The following section present tools and methods to divide the technology advancement of digital twins into different levels and to visualize the advancement of the technology.

The growth and anticipation of a specific technology can be visualized with a Gartner Hype Cycle, see figure 2.10 (Gartner, 2020). It is divided into five stages which are:

1. The technology trigger which is the start of an emerging technology. This stage consist mainly of theories about the technology and the interest is rising.
2. Peak of inflated expectations where reports about the technology's accomplishments and possibilities has caused the expectations to grow even more.
3. Trough of disillusionment is when the technology has failed to generate promising results and the expectations and interest takes a downturn.
4. The slope of enlightenment is when the technology has had time to evolve and is better understood as to how it can be an asset to companies.
5. Plateau of productivity is when the technology really start to generate return on investment and more and more companies follow in its footsteps.

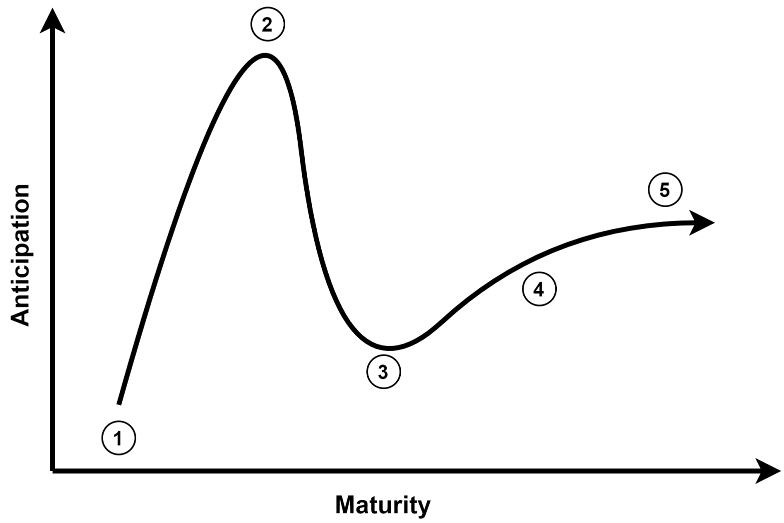

Figure 2.10: Visualization of a technology's maturity with a Gartner Hype Cycle.

Gartner has highlighted digital twins as an emerging technology at the top of the peak of inflated expectations, i.e. number 2 in figure 2.10, with the expectation of reaching its plateau in 5-10 years (Walker & Panetta, 2018).

A technology's maturity over time can be visualized with an S-curve which can be seen in figure 2.11. In the first stage, new technology is in its infancy and has not yet reached the level of performance required for it to be profitable or useful. Over time the technology will grow and its performance improves, this is the second stage. In the mature stage the curve begin to stagnate and the technology reaches its performance limit where it can not provide any better results. In the last stage the technology has aged to a point where new technology is needed to continue to increase performance. (Ulrich & Eppinger, 2011)

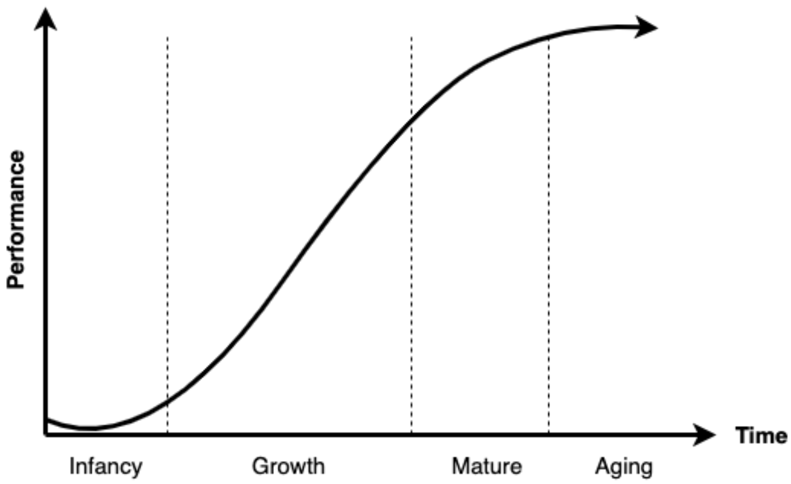

Figure 2.11: Visualization of a technology's growth over time as an S-curve.

The S-curve can be used in combination with a methodology called technology readiness level (TRL) which is used to determine where on the S-curve a technology is located. TRL is also used to explain what is required of a technology in terms of capabilities and resources during the various stages of its development (NASA, 2017). There are nine levels of technology readiness as defined by NASA (2017) and these are presented below:

- TRL 1 is the introduction of scientific research for the specific technology.
- TRL 2 is when essential functions of the technology can be tested based on the data discovered.
- TRL 3 is the research and design phase where analytical and laboratory research is conducted to verify that the technology is feasible.
- TRL 4 is when various components are tested together.
- TRL 5 is when the technology is established to be functional and requires more real-life testing.
- TRL 6 is when a prototype of the technology exists which functions as a practical model.
- TRL 7 is when the prototype requires testing in real-life surroundings.
- TRL 8 is when the technology has come so far that it is ready to be implemented into existing systems.
- TRL 9 is when the technology has been proved to work in a live scenario.

2.3.3 Applied Software for Creating a Digital Twin

Dasasult Systèmes and *3DEXPERIENCE* offer a business platform which ties together Dassault's standalone software and can create connectivity across an entire company (Dassault Systèmes, 2020a). From collaborative applications between roles and functions, 3D modeling applications for products and components, 3D layouts applications for plants and factories with the possibility to simulate robotics, ergonomics, factory flow, and more, to analysis applications. Together with these applications they have libraries with finished 3D models and machines from partners and manufacturers.

Delmia Digital Manufacturing is one of the software available in 3DEXPERIENCE and offer industries and service providers with solutions for connecting the virtual and physical world (Dassault Systèmes, 2020b). It can be used to collaborate, model layouts and processes, optimize, and perform simulations. Delmia Digital Manufacturing consist of a number of different applications ranging from the creation of manufacturing bill of materials (MBoM) structures, process planning, plant layout design, factory flow simulation, to more specific simulation applications such as ergonomics evaluation, robotic programming, robotic simulation, robotic optimization, work instructions, and work plan publications just to name a few.

2.3.4 Alternative Software for Creating a Digital Twin

The varying complexity of digital twins can require different software for the creation of virtual models and to manage the exchange of data between the physical and virtual models. Depending on the complexity and what is required regarding different parameters, there are several companies with various software and tools for creating feasible solutions depending on the purpose and scope. The software from different providers may vary regarding what is possible to achieve, but the aim for all of these are similar. To create digital solutions for organizations in order to be more efficient, effective, productive, and support decision makers across multiple functions. The following software providers are examples of companies who can offer different solutions for specific cases with various purposes and complexity.

Two of the most well-known companies are Siemens and PTC who offers similar possibilities as Dassault Systèmes with their respective business platforms.

Siemens's Teamcenter, which is a PLM system, work with connectivity trough out the whole organization by increasing the control of data and processes (Siemens, 2020b). Together with COMOS and MindSphere they offer the possibility of process designing, integrated automation, 3D plant designing, and workflow management and creating systems of this with the use of IoT (Siemens, 2020a, 2020c).

PTC uses their PLM software Windchill for easier integration across different functions across an organization and offer management capabilities in areas such as product data, Bill of Materials (BoM), change and configuration, quality, and manufacturing and process planning (PTC, 2020b). Together with their IoT platform

ThingWorx it is possible to connect processes for increased functionality and flexibility (PTC, 2020a). They offer solutions for connecting, building, analyzing, managing, and experiencing processes in a 3D environment.

There are also software providers working more towards virtual commissioning such as ABB, Visual Components, and ANSYS, and offer solutions for this but does not offer the integration of an entire organization in the same way as Dassault Systèmes, Siemens, or PTC.

ABB's software RobotStudio gives the possibility of working with offline programming and simulations for robotics (ABB, 2020). By working in 3D environments of a shop-floor the user can perform optimization without disturbing the physical production which can reduce the risk and cost, accelerate the start-up, decrease change-over time, and increase productivity.

Visual Components is working with manufacturing design and planning of 3D environments of factory floors and their processes (Visual Components, 2020). With their software Visual Components 4.2 they offer solutions regarding virtual commissioning and include tools for plant layout configuration, process planning, robotics, and component modeling. With this kind of virtual commissioning it is possible to create the factory layout as wanted, test robotic behaviour, analyze the factory flow of products and processes, and apply changes and optimizations before the physical factory is built. This helps with detection of problems at an early stage instead of changing them later when the process is much more costly. Visual Components Experience also offer the possibility of working in the created 3D environment using VR.

ANSYS offer different tools for modeling, simulating, and analyzing systems in a virtual environment (ANSYS, 2020b), together with the possibility to create, test, and experience these systems virtually in real-time with their VREXPEREINCE platform. They also offer solutions for connection and management of business processes and data in a cloud environment (ANSYS, 2020a).

Furthermore, using virtual 3D models for testing and training in virtual and augmented reality is also something that is being used more and more. In this area there are companies rising with their gaming platforms such as Unity who can provide an immersive 3D experience even in a production environment. However, these programs are even more limited in terms of simulation and integration capabilities.

Unity, widely known in the gaming and animation communities also offer solutions for the engineering and manufacturing sector (Unity, 2020). With Unity it is possible to create 3D environments for products and systems. By using virtual reality (VR) and augmented reality (AR) these 3D environments become more immersive and can be used to interact with the systems in real time. This kind of virtual models present the opportunity to train and educate operators or maintenance personnel in a virtual environment before the physical system is up and running. It also gives access to test virtual prototypes for various reasons without having to invest in costly physical prototypes.

Then there are companies who focus more on the flow, storage and management of data instead of using virtual models in 3D. Such a company is *General Electric* (GE). They provide companies with their Predix Platform which gives the possibility of connecting information technology data and operations technology data together with industrial applications into an IIoT platform for monitoring, analyzing, processing, and management of the data (GE, 2020).

These companies and software providers show that there are tools available which gives the possibility to create virtual models and take steps towards using digital twins. However, the tools available have not been evaluated to see how complex the models or the digital twins can be. It is only shown that there are several companies working to make it possible. Depending on what kind of solution is needed, it is required to set up a strategy for what to achieve, how to do it, and investigate which software that can help execute the strategy in the best way.

3
Methodology

The following chapter present the methodology and work procedures used during this thesis. The chapter presents the research method, data collection process and how the case study was conducted.

3.1 Procedure

This thesis examined the concept of digital twins, evaluated the technology readiness level, and analyzed how digital twins can be implemented and created within the production industry. A key factor in this thesis was to tie all these areas together. To fulfill the research purpose, the Design Research Methodology was used and can be seen in figure 3.1. The project had an iterative approach which made it possible to revisit each stage when new information was obtained to not bypass important data.

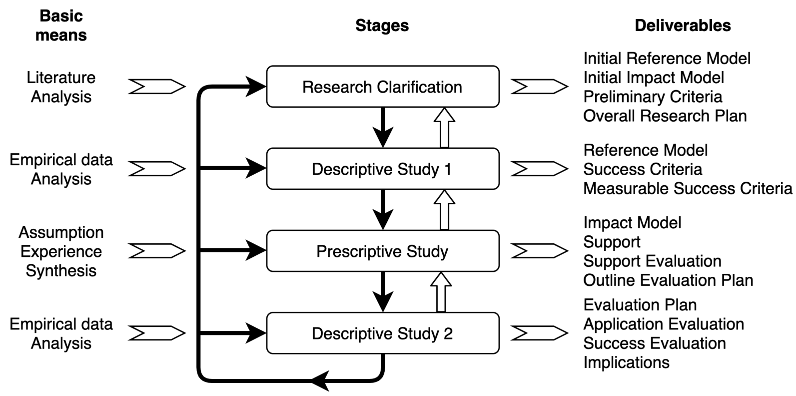

Figure 3.1: The work procedure for Design Research Methodology.
Source: (Blessing & Chakrabarti, 2009)

First, basic information was gathered on the concept of digital twins and what this project's purpose is. Then, more fundamental information regarding how the technology is defined and used was obtained. It was also investigated where on the market the technology behind digital twins is together with the technology's readiness level and how it can be used for different purposes within the production industry. The research process was an iterative and contemplative process which made the literature study widen as information was learnt during interviews and vice versa.

The information gained from literature was used as input to develop and create the digital twin which was done in parallel with the continued research. By creating a digital twin as a case study more insight was gathered on what is possible for smaller companies regarding the creation of a digital twin. To understand how different customers vision digital twins and to see what is available today, interviews were conducted to be used for a market research and to understand what different customer's want from this type of technology.

By using the understanding from the literature study as input for the interviews, the qualitative data from the interviews were then used to expand the literature study.

To create an outline for the concept of digital twins, different definitions and models were analyzed in order to propose a unanimous definition together with an evaluation of the technology's maturity. The evaluation of the technology's maturity was visualized by using an S-curve and assessing the technology readiness level. This was done based on the information gathered from the literature study and the interviews. To understand the implementation and creation process for a digital twin a case study was made to complement the literature and the interviews.

With the starting point in DRM, and how this project has evolved, a more detailed view of the exact procedure and how the four stages in DRM have been used can be seen in figure 3.2.

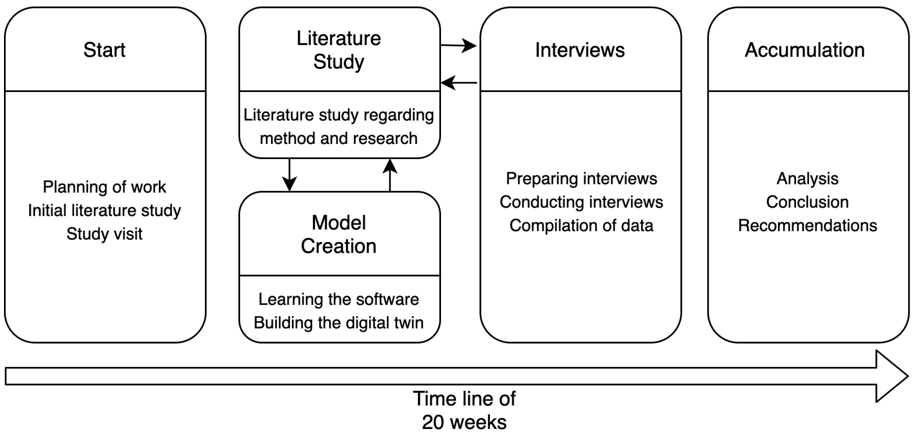

Figure 3.2: Map of the project's procedure.

3.2 Initial Work

In order to get a better understanding of the research field the investigation started with a literature study to understand what types of digital twins are available and how researchers and industry define a digital twin. To get more insight of how far research has come and to better understand the market, two exploratory interviews were conducted, see table 3.1, together with a study visit at Stena Industry Innovation Lab to get insight of how an organization can work towards digitalization in manufacturing. Information gathered here was used to increase the area of interesting and relevant information which was used to widen the research.

Table 3.1: List of initial interviews performed. More information about the interviewees can be found in appendix A.

Name	Title	Company
Johan Sahlström	Industry Process Consultant	Dassault Systèmes
Rikard Söderberg	Professor in Product and Production Development	Chalmers

3.3 Data Collection

Data from both primary and secondary sources were used in the study. The primary data was collected through interviews of exploratory and semi-structured nature. Data from secondary sources were collected from articles and reports by using the search engines Google Scholar, Chalmers Library Database, and Google.

3.3.1 Literature Study

The literature study has been a continuous part during the research process where the initial literature study set the basis for upcoming research studies. The literature study expanded when new knowledge came to light during the research itself and after the conducted interviews. By using an iterative approach, the knowledge could be added to complete missing information during the investigation process to enhance the most important information.

The literature study was conducted to gain knowledge regarding Industry 4.0, industrial digitalization and digital twins. The main areas that have been focused on is digitalization, digital twins for production (shop-floor), sustainability, challenges with digital twins and what kind of resources are needed for creating one. By using search words such as digital twin, digital twin manufacturing, virtual commissioning, smart manufacturing and combining these terms, searches for relevant articles and papers were made.

3.3.2 Interview Study

The interview study consisted of qualitative, semi-structured interviews to get a better understanding of how companies in the production industry define a digital twin, and how they use this type of technology. The combination of integrating interviews with the literature were done because of the lack of defined theories regarding digital twins in this area. This made the qualitative approach suitable to obtain different companies' understanding of digital twins and compare it to the literature.

Interview methodology

The interviews were conducted with a semi-structured format with predefined questions and topics that the interviewee could then talk freely about. Depending on the scope of the answers follow up questions were asked to pinpoint the answers to the defined questions which according to Adams (2015) is the benefit of using a semi-structured interview. Because the area of knowledge regarding digital twins is wide the approach of using this type of interview was suitable to not miss out on interesting information.

Interviews

In order to gain a better insight how the technology of digital twins are used within the production industry and how different companies work with virtual models, four interviews were conducted with four different small and medium-sized companies, see table 3.2.

Table 3.2: List of interviewed people during the interview study.

Name	Title	Company	Category
Johan Bengtsson & Greta Braun	Project leaders	Smarta Fabriker	User
Bernt Henriksen	Senior automation and production specialist	Robotdalen	Solution provider
Samuel Lindholm	Technical manager	Elektroautomatik	Solution provider
Håkan Törnqvist	Head of production	Emerson	User

A list of the interviewees along with their background and role can be found in appendix A.

The interviews consisted mainly of questions regarding the points below and the full questionnaire can be found in appendix B.

- How do different companies use virtual models and simulation software?
- What is the definition of a digital twin?
- What is needed of a company to use a digital twin to its fullest potential?
- What is required of the technology to be beneficial in terms of decision making, and the resources necessary for creating virtual models and keeping them updated?

The interviews were supported by audio recordings in those cases the interviewee was fine with it, and notes were also taken during the interviews. Each interview followed the same predefined questionnaire and started with a brief introduction of the authors and the thesis.

3.3.3 Data Analysis

The collected information from the interviews together with the literature review set the foundation for outlining the definitions of digital twins according to how different companies define and use digital twins. The information was also used as input to map the technology level of digital twins. Furthermore, it was analyzed by comparing the literature to the interviews in an iterative approach during the research process.

3.4 Case Study – Creating the Digital Twin

The software used in this thesis to create a digital twin of the Vera Smart Factory was Dassault Systèmes' 3DEXPERIENCE and more specifically Delmia Digital Manufacturing. The applications used have been focused on creating the manufacturing bill of materials (MBoM), planning of the process, designing the plant layout, and simulating the factory flow. This creation was designed as a case study to be used as support for comparing the experience gained to that of a smaller company without the potential resources needed for processes like this.

To create the digital twin for the Smart Vera Factory the steps seen in figure 3.3 were followed.

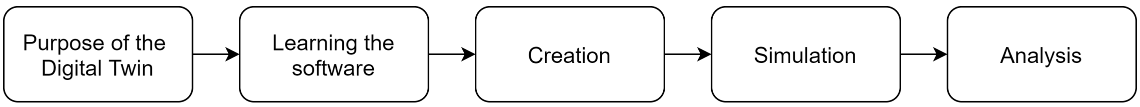

Figure 3.3: Steps taken to create a digital twin for the Smart Vera Factory.

The first step was to frame the *purpose of the digital twin* from Smarta Fabriker's and Dassault Systèmes' perspectives. The second step was to *learn the software* 3DEXPERIENCE and Delmia Digital Manufacturing to be able to create a digital twin. The third step was the actual *creation of the digital twin.* The fourth step was to complete a specific *simulation of the digital twin.* The fifth and final stage was to *analyze* the results from the simulation.

The utilization of the tools in 3DEXPERIENCE were used as preferred by the authors and can be one in numerous different ways. It is mostly up to personal preferences of how to utilize the existing tools to do the steps necessary in the software.

The process of creating the digital twin for the Vera Smart Factory was later used as a basis for the proposed work procedure of implementing and creating a digital twin.

3.5 Method Criticism

The methods used in the thesis have been chosen for the purpose of answering the research questions and to fulfill the thesis purpose. However, some parts could have been improved to provide more thorough and detailed information.

The literature research could have been extended and more articles could have been investigated to get a more thorough literature review on the concept of digital twins. However, due to the delimitations of this thesis, certain areas were not of interest for further, more detailed research.

Because of the relatively few interviews conducted, the result will not reflect all small and medium-sized companies' view or usage of digital twins. The result did on the other hand show how the knowledge of digital twins vary which also can be seen in the literature. For better representation of small and medium-sized companies, the amount of interviews should have been expanded.

The method and software used to create the digital twin of the Vera Smart Factory could be done in another way and with another software. By redoing the model with other software and with another methodology, the result could be different.

4 Results

In this chapter the results of the most notable areas from the interviews are presented along with the case study of the created digital twin.

4.1 Views on Defining a Digital Twin

According to B. Henriksen, senior automation and production specialist at Robotdalen (personal communication, April 21, 2020) and S. Lindholm, technical manager at Elektroautomatik (personal communication, April 23, 2020) the concept of digital twins is difficult to define since there are no known companies working with this kind of technology on a level which is considered a digital twin. However, according to R. Söderberg, professor in product and production development (personal communication, February 27, 2020) a digital twin is in essence some kind of online simulation in real-time with the purpose of optimizing different aspects. Lindholm on the other hand does not necessarily see the real-time exchange of information as a necessity of digital twin, but see the importance in that models, logic and physics are as accurate and identical to the physical model as possible which also is agreed upon by J. Bengtsson and G. Braun, project leaders at Smarta Fabriker (personal communication, April 6, 2020).

J. Sahlström, Industry Process Consultant at Dassault Systèmes (personal communication, mars 15, 2020), define digital twins in two different categories which can be seen in figure 4.1. The first type of digital twin, DT-1 involves the virtual model, the physical model and the short data loop. The second type of digital twin, DT-2 involves the historic data loop and stored data as well as the previous mentioned. The short data loop contains initial production data from the physical model which is used in the virtual model to enhance the production. Data is collected and transferred manually from the physical model to the virtual model to be used to perform test and optimizations. All tests should be able to be done on the virtual model because it is supposed to be as accurate as the physical model and act as a virtual master to the physical model. No changes are supposed to be performed on the physical model before being tested in the virtual model. The DT-2 model use stored data to make predictions and optimizations by using real-time exchange of data enabled by Industry 4.0 such as, IoT, CPS, and different production systems.

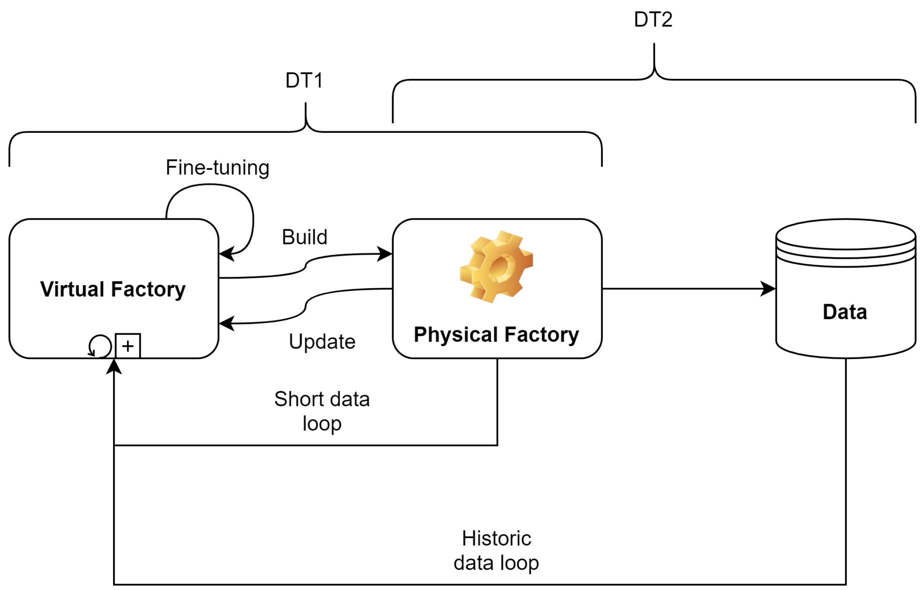

Figure 4.1: Industry Process Consultant's, at Dassault Systèmes, view of a digital twin.

4.2 Towards the Usage of a Digital Twin

According to S. Lindholm, technical manager at Elektroautomatik (personal communication, April 23, 2020) and B. Henriksen, senior automation and production specialist at Robotdalen (personal communication, April 21, 2020), the main area of usage of virtual models are in the area of virtual commissioning. By doing virtual commissioning a virtual model of the production line can be created to test and optimize the layout and configuration, program robots offline, and even explore the 3D environment in VR to obtain early feedback from operators or maintenance personnel. Henriksen also highlights some advantages of doing virtual commissioning. The deployment of the physical process can be done quicker, board members who may not have the required technical skills can more easily make decisions when presented with a virtual 3D environment, and tests can be done without affecting the real production.

The advantages of virtual commissioning is something J. Bengtsson and G. Braun, project leaders at Smarta Fabriker (personal communication, April 6, 2020) agree on. The way they look at how digital twins should be used are to test different scenarios in a virtual environment where problems can be detected, validate that the geometry is correct, and see that the system works. Virtual models are also used to show how different solutions of robot cells, which according to B. Henriksen, senior automation and production specialist at Robotdalen (personal communication, April 21, 2020) is a necessity to be able to sell the solution to a customer.

In addition to this, it is according to S. Lindholm, technical manager at Elektroautomatik (personal communication, April 23, 2020) easier to obtain early feedback and make changes early in the process when using virtual models and unlimited amount of testing can be done in the virtual model. This can lead to decrease of cost in travelling expenses, risks can be decreased, and by working in parallel the lead times from start to finish can be reduced.

H. Törnqvist, head of production at Emerson (personal communication, April 21, 2020), mention digital twins as something they are not pursuing anytime soon because of their relatively straightforward production which focus mostly on on-time delivery for their customers. Even though digital twins are not something they are considering at the moment because of the rather uncomplicated production with more important low hanging fruit in other areas. Törnqvist highlights the curiosity for simulation tools for their production to get continuous feedback in their systems and the tools for calculating capacity, cycle times, and workload balancing. As of now, their work with digitalization consist mostly of traceability in their business and production systems.

Aspects of digital twins Smarta Fabriker highlights as important to work towards are according to J. Bengtsson and G. Braun, project leaders at Smarta Fabriker (personal communication, April 6, 2020) the possibility to enable them to work with sustainability, provide easy communication with different stakeholders, and to optimize the shop-floor. It is important that the digital twin is accurate enough so it can replace the need for meetings at the physical shop-floor and to be able to visualize the physical shop-floor in real-time. The digital twin should also be able to validate that geometry is correct, test signals and code, provide a support for decision making regarding sustainability aspects and to import production data to the digital twin to achieve a closed loop between the physical and virtual model.

For H. Törnqvist, head of production at Emerson (personal communication, April 21, 2020) to work towards implementing a digital twin for their production it would require higher maturity as a company regarding the technology behind digital twins. The complexity behind new software to create digital twins is what worries him and the need of having to invest large amount of time before gaining return on investment. Törnqvist see interest in starting with more simple software to enable them to get early and easy victories and pay back on their investments before having to go deeper into a certain software. However, according to S. Lindholm, technical manager at Elektroautomatik (personal communication, April 23, 2020), simpler programs with low threshold often just enable visualization of factory flows and are not used for optimization or decision making.

4.3 Technology Level of Digital Twins

The technology of digital twins has not come further because of one reason according to S. Lindholm, technical manager at Elektroautomatik (personal communication, April 23, 2020) which has to do with that there is no proper standardization between software, hardware, and suppliers. To be able to create the best possible virtual models today it is very important to use compatible software and hardware to get the most out of it. When using third-party software there is always the need for reconfiguration or recompiling which takes more time, and the result may vary a lot. In order to be able to create as good digital twins as possible in the future, standards within interfaces, programming, blueprints, how it works, how it is connected, what kind of components there are, kinematics, logic, and file formats are needed (S. Lindholm, personal communication, April 23, 2020).

When standardization eventually are set, then suppliers and manufacturers must also implement these standards and use them which can take several years. R. Söderberg, professor in product and production development (personal communication, February 27, 2020) agree and states that the standardization between software and hardware is a big issue, but still believes that digital twins will be the future and in order to implement an ultimate digital twin, traceability of every single component is needed. Söderberg also states that in general the industry can be quite slow, especially when going from something that works to something that is more uncertain, and to take this decision some kind of requirement from management would be necessary.

According to S. Lindholm, technical manager at Elektroautomatik (personal communication April 23, 2020) some physics of robots and machines today are complex and sometimes impossible to simulate with virtual models but newer machines and new technology have higher possibilities to manage this. The use of older machines and equipment can be hard to combine with virtual models. J. Bengtsson and G. Braun, project leaders at Smarta Fabriker (personal communication, April 6, 2020) believes that the two biggest problems with the technology of digital twins is the sharing of data between companies because of secrecy and the difficulty to simulate human interaction in the models.

4.4 Implementation of a Digital Twin

The technology of digital twins is being used more and more according to B. Henriksen, senior automation and production specialist at Robotdalen (personal communication, April 21, 2020), but there is quite a high threshold before implementing it because of the many parameters to set up. According to R. Söderberg, professor in product and production development (personal communication, February 27, 2020), for a company to rely on simulations of this kind a certain maturity must be reached. He states that people tend to rely more on themselves to do optimizations, even if it takes a couple of weeks longer.

Creating virtual models is time consuming and the complexity of the models can vary widely. According to S. Lindholm, technical manager at Elektroautomatik (personal communication April 23, 2020) it is important to decide why a virtual model is needed and the purpose of having it, what it is supposed to be used for and for how long. Lindholm also mentions the importance in deciding if the physical or the virtual model is the "real" model, more specifically which model that follows the other. Elektroautomatik, usually spend 1-2 weeks only on creating the virtual models (S. Lindholm, technical manager at Elektroautomatik, personal communication, April 23, 2020), and B. Henriksen, senior automation and production specialist at Robotdalen (personal communication, April 21, 2020) states that they spend up to 200 hours on a pretty advanced model, besides the time to gather the data necessary for creating it.

According to B. Henriksen, senior automation and production specialist at Robotdalen (personal communication, April 21, 2020), producing companies, especially small and medium-sized companies, may not have the capacity or competence required to create virtual models on their own, which create the need for a production engineer. Many companies do not have time play around with the physical models and test programming code for robots when the production line is running which also creates the need for a virtual model (B. Henriksen personal communication, April 21, 2020). S. Lindholm, technical manager at Elektroautomatik (personal communication April 23, 2020) concurs to this and states that for the most part, their customers do not have the competence required to know what to ask for or to do it themselves and those who do know what they want, would rather want virtual commissioning with a certain scope rather than a complete digital twin.

S. Lindholm, technical manager at Elektroautomatik (personal communication April 23, 2020) mentions that they use software intended for the hardware they are using and not any third-party software available on the market where all information and data can be used, because that kind of software does not work as well as the original software. The downside with the use of multiple software is the need for maintenance of the virtual models when updates are needed on software and the many files needed for each model can be tedious to manage. Other problems and obstacles that can occur during the implementation process of a virtual model is according to J. Bengtsson and G. Braun, project leaders at Smarta Fabriker (personal communication, April 6, 2020) the implementation and testing of the PLC, and problems with keeping the virtual models updated to the physical models.

4.5 Case Study - Creating a Digital Twin

The Vera Smart Factory at Smarta Fabriker is a flexible and collaborative demonstrator with three workstations and one robot station in front of the workstations. The robot in this demonstrator is a flexible and collaborative robot from ABB called IRB 14050 Single-Arm YuMi. The robot station can be moved between the workstations and help the workers to reduce the risk of bottlenecks. The layout of the Vera Smart Factory can be seen in figure 4.2.

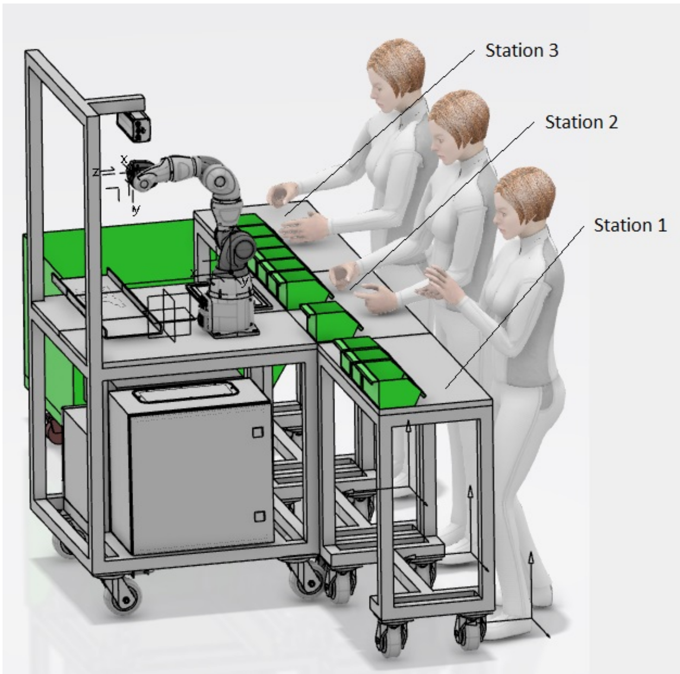

Figure 4.2: Layout of the Vera Smart Factory production cell.

The following sections present the result of the created digital twin for the Vera Smart Factory and the process behind it. Certain steps have been taken to develop and create the digital twin in 3DEXPERIENCE which are explained in the way the authors have proceeded. As it was presented in section 3.4 this process was designed as a case study for supporting the evaluation of a creation process like this in smaller companies. The steps followed for creating the digital twin for the Vera Smart Factory can be seen again in figure 4.3.

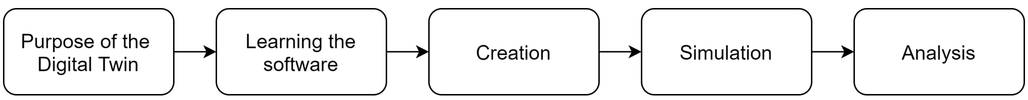

Figure 4.3: Steps taken to create a digital twin for the Smart Vera Factory.

4.5.1 Purpose of the Digital Twin

The purpose with this digital twin of the Vera Smart Factory is first of all to gain a better understanding for the implementation and creation process of digital twins. Secondly it is to be used by Smarta Fabriker to present together with their demonstrator what a digital twin can be used for and how it can provide various possibilities for the production industry.

4.5.2 Learning the Software

Before starting the development of the digital twin for the Smart Vera Factory, understanding how to use 3DEXPERIENCE was essential. Different courses within the software were done to obtain basic knowledge of the different applications that was going to be used. These courses were indeed basic and did not fulfill every aspect of what was needed to be done in developing the digital twin. Therefore, as the work continued, different people within Dassault Systèmes had to be asked for help to understand various issues which appeared. All questions could not be answered by people at the office in Gothenburg so a Delmia Digital Manufacturing industry consultant expert in Germany was contacted for help with the development.

4.5.3 Creation

By defining a *PPR context* in 3DEXPERIENCE, which stand for product, process and resource, all of the physical model's aspects could be defined in the virtual model. The product which in this case is the Lego Vera truck was defined as the product, the process is how the truck is going to be assembled by different operations and tools, and the resources are the different parts of the production system such as the tables, robot, and manikins that do the operations of the assembly.

In the creation of the digital twin, six different applications were used. These were;

1. Assembly Design
2. Manufactured Item Definition
3. Process Planning
4. Plant Layout Design
5. Robot Simulation
6. Factory Flow Simulation

In *Assembly Design* the virtual Lego Vera truck was assembled. With *Manufactured Item Definition* a manufacturing bill of materials (MBoM) was created. *Process Planning* was used to define different operations for each station and determine the product flow for each part of the Lego Vera truck. For designing the layout of the virtual Vera Smart Factory *Plant Layout Design* was used to position every resource in the correct way. *Robot Simulation* was used to define movement for the robot. In *Factory Flow Simulation* it was defined where in the virtual Vera Smart Factory each operation takes place.

Vera Truck

Table 4.1 show the parts of the Lego Vera truck and the quantity for each part. The body, the wheels, the batteries, and the motor also come in different variants. However, in this model, only one variant has been taken into consideration.

Table 4.1: List of the parts included in the Lego Vera truck.

Lego Vera Truck Parts	Quantity
Body	1
Trailer Fastener	1
Chassis	1
Wheel	4
Front Fastener	2
Rear Fastener	2
Battery Plate	2
Battery cell	4
Rail	2
Motor Plate	1
Motor	1

All parts had to be assembled in the application *Assembly Design* before continuing with creating the digital twin. The assembled Lego Vera truck can be seen in figure 4.4.

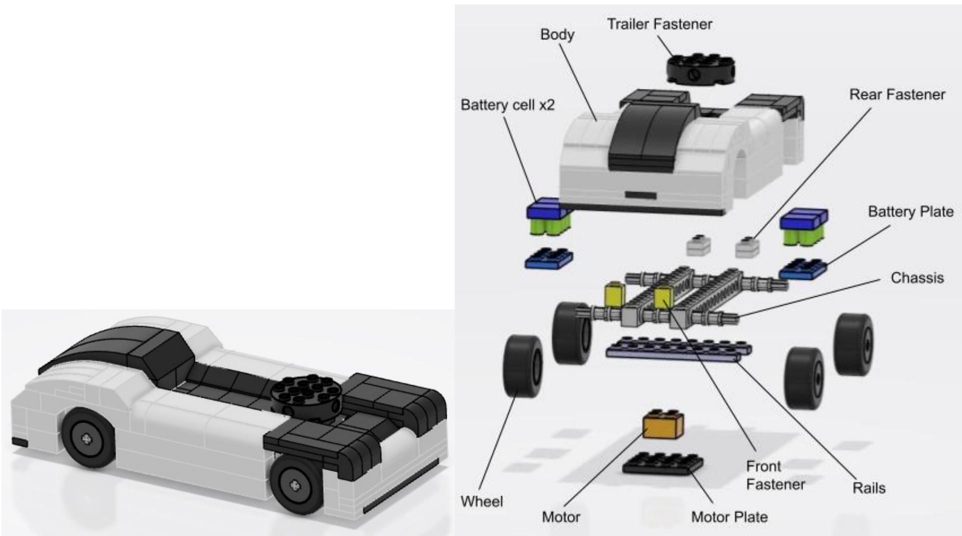

Figure 4.4: 3D view the Lego Vera truck with its different components.

As it can be seen in figure 4.4 the truck consist of the chassis where four wheels, four fasteners (two for the front and two for the back), one motor with a plate, four battery cells (two for each side) with one plate each side, the rails, the body, and the trailer fastener are all assembled together.

Manufactured Item Definition

In the next step of the creation process a manufacturing bill of materials (MBoM) was created which contained all the parts of the specific variant of the Lego Vera truck. The MBoM was created in an application called *Manufactured Item Definition*. The MBoM was created in a 3D-view which can be seen in figure 4.5.

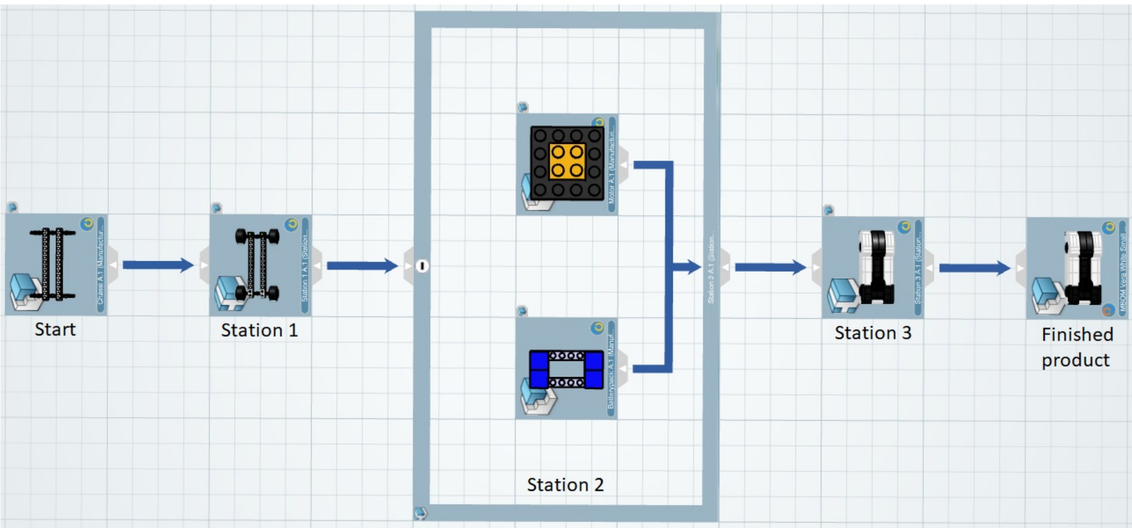

Figure 4.5: 3D view of the Manufacturing Bill of Materials for the Lego Vera truck. Each station consist only of the parts necessary for the respective assembly operation.

The structure of the MBoM was created by defining a start and end position, these are called *manufacturing assemblies*. The start is the chassis, and the end is the finished product. Between these, there were three *installations* inserted, one for each station. Station 1 consist of the wheels and the fasteners. In station 2, there are two different sub-assemblies being assembled and installed on the chassis. Because of this, two separate manufacturing assemblies were created in this installation, which are the motor and the battery pack. Station 3 consist of the last parts which are the body and the trailer fastener.

The MBoM viewed in 3D can also be visualized in a tree structure which is presented in figure 4.6.

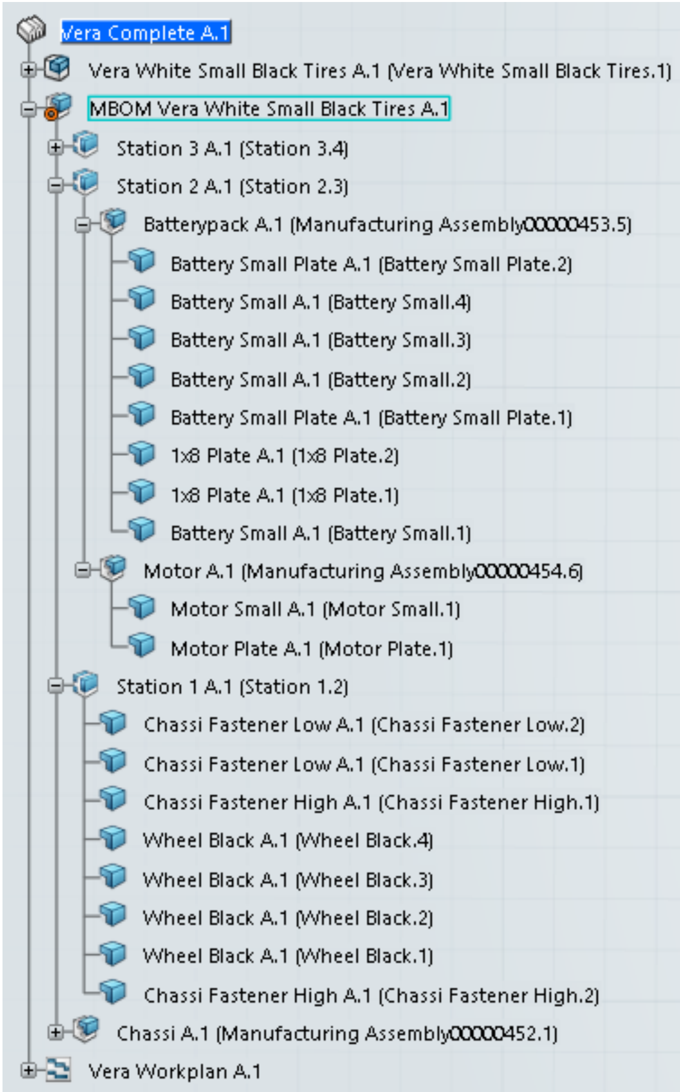

Figure 4.6: The tree structure of the Manufacturing Bill of Materials for the Lego Vera truck.

Process Planning

When the MBoM had been constructed it was time to decide the product flow and in which order components and assemblies come together. This was done in an application called *Process Planning*. In this step, five so-called workplan systems were defined. One for the whole production cell, one for station 1, two for station 2, and one for station 3. Each system represent one station or assembly process in the physical production. The overview of these systems can be seen in figure 4.7. The arrows pointing from one system to another determine the flow for which parts or assemblies that are needed at the next station.

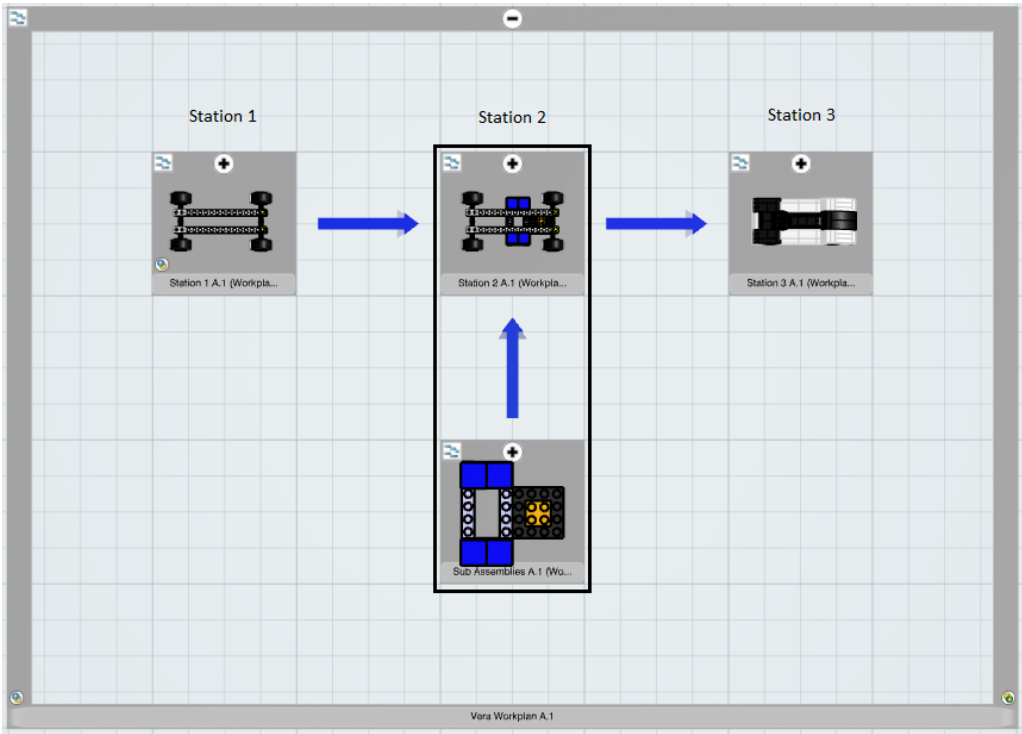

Figure 4.7: Overview of the process plan for the Vera Smart Factory.

At station 1 the worker takes the chassis and install one wheel at a time. Then the worker install the fasteners one at a time before sending the assembly to the next station. This process can be seen in figure 4.8. The reason for having two different operations for the wheels and the fasteners is because in the physical Vera Smart Factory the robot is able to move and assist the worker at each station. So in order to make changes more simple in the process plan, if the robot were to be moved, two operations were defined such that the product flow (the arrows) can be changed accordingly.

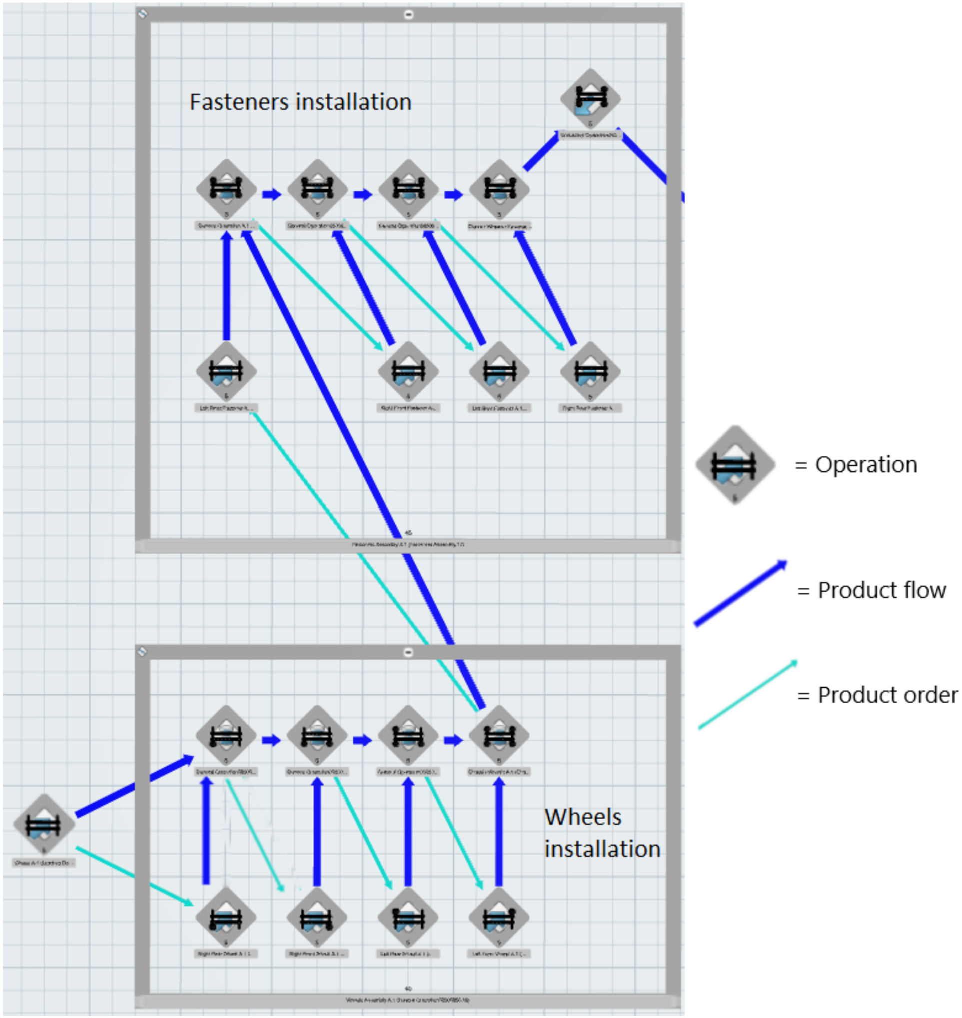

Figure 4.8: Overview of the process plan for station 1 where the wheels are installed and followed by the front and rear fasteners.

The dark blue arrows determine the flow for the parts that are to be assembled, while the light blue arrows determine in which order the parts are assembled. For example, first the worker takes the chassis, and then install one wheel at a time onto the chassis. For the next step, the worker takes the output, which is the chassis with the wheels, and install the fasteners. In essence, the light blue arrows display that in order to install the fasteners, the chassis with wheels need to be finished. The complete assembly of chassis, wheels, and fasteners is then the input for station 2. This principle of product flow applies to all the three stations.

The structure for station 2 looks different in the process plan because of the two sub-assemblies, the motor and the battery pack. These are assembled at the same time by the worker and the robot. At station 2 the worker therefore need the chassis assembly with wheels and fasteners together with the completed sub-assemblies before being able to install them on the chassis. The motor is installed and followed by the the battery pack which can be seen in figure 4.9.

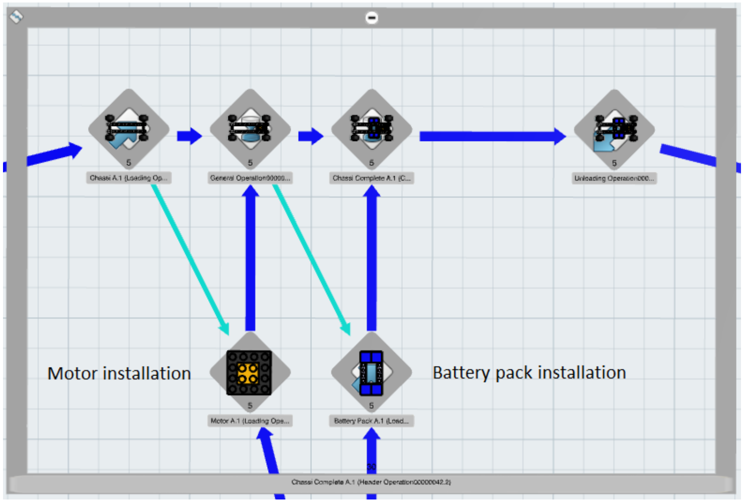

Figure 4.9: Overview of the process plan for station 2 where the motor and the battery pack are installed.

Figure 4.10 show the operations for the sub-assemblies where the worker assembles the motor at the same time as the robot assembles the battery pack.

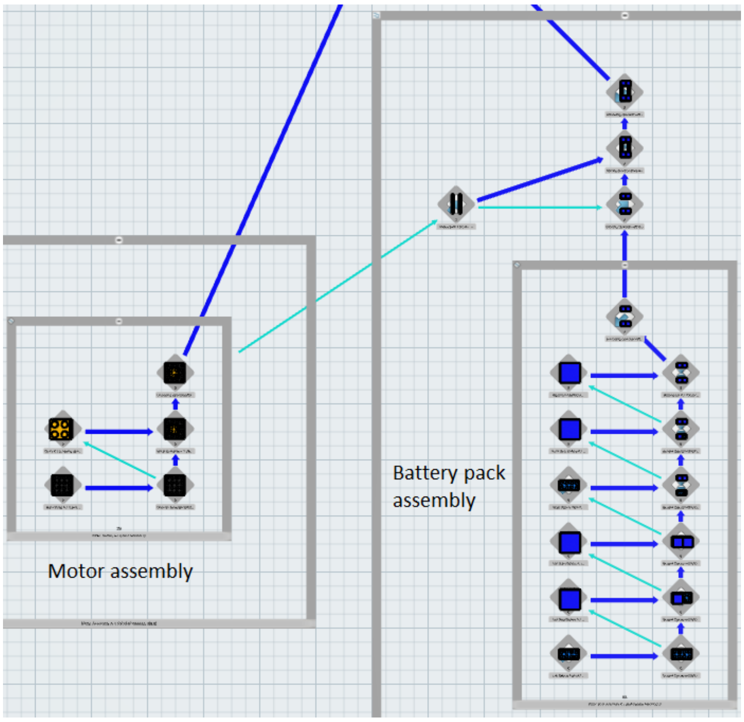

Figure 4.10: Overview of the process plan for station 2 where the motor and the battery pack are assembled at the same time.

When station 2 has completed the assembly of the chassis with the motor and battery pack it is sent to station 3 where the worker install the body onto the chassis followed by the trailer fastener. This process can be seen in figure 4.11.

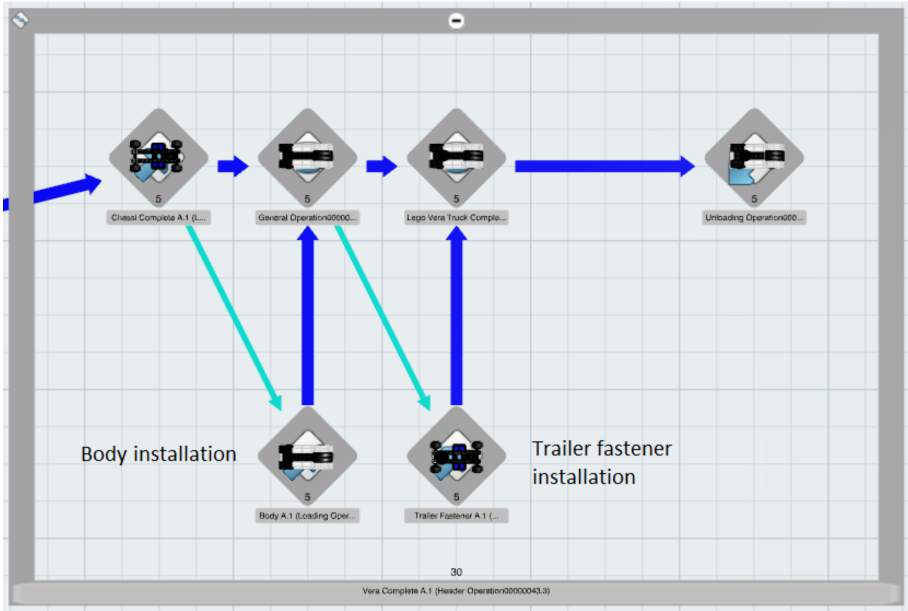

Figure 4.11: Overview of the process plan for station 3 where the body and the trailer fastener are installed.

In figure 4.12 the overview of the process plan can be seen as a Gantt chart. The chart is used to give an overview over the entire process plan and gives a more detailed view over how the different operations are connected. It shows the lead time for every operation and installation and in which order each station can start with the respective work. As it can be seen, the Gannt chart is displayed with a waterfall effect which implies that an operation is performed after the preceding one. What it also shows is that station 1 and station 2 can begin the respective assembly at the same time without having to wait for previous parts to be finished. Whereas station 3 has to wait for both station 1 and station 2 to finish before starting.

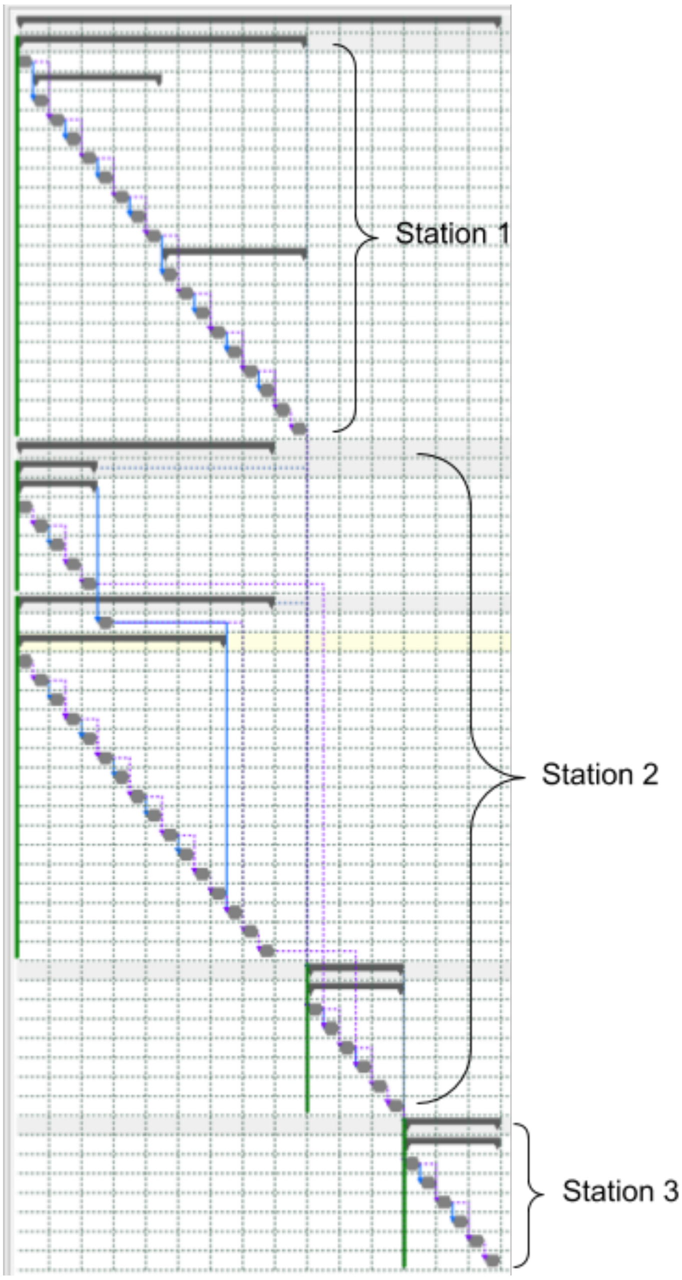

Figure 4.12: Overview of the process plan visualized with a Gantt chart to show how all the operations are connected.

The process plan was made in a similar way as the MBoM where all the different parts were assigned to the respective system or operation where the parts are used.

This process plan laid the ground for the next step where the product was introduced to the virtual factory consisting of the assembly stations, robots, and manikins. The structure of the process plan can also be reused for other product variants with the same structure and product flow so that this procedure does not need to be done from scratch again for similar products.

Plant Layout Design

In the application *Plant Layout Design* the virtual factory was modeled using the parts designed by Smarta Fabriker. The robot was a workaround because it did not exist in any of Dassault Systèmes' product libraries so it had to be manually adjusted with working joints. However, it does not have the correct kinematics or logic with regard to the real robot.

The tables of the three workstations were defined as working resources, which enable them to be used for analyzes in the application *Factory Flow Simulation*. Because of the geometry of the robot station a new working resource had to created and positioned on top of the robot station. The three manikins were placed at the three work stations to be used as working resources to be able to do operations. Storage bins and a containers were imported from the library to be used as storage resources.

All objects were then placed the way they are in the physical model in order to be able to simulate different scenarios as close to reality as possible. The layout for this production cell can be seen in figure 4.13.

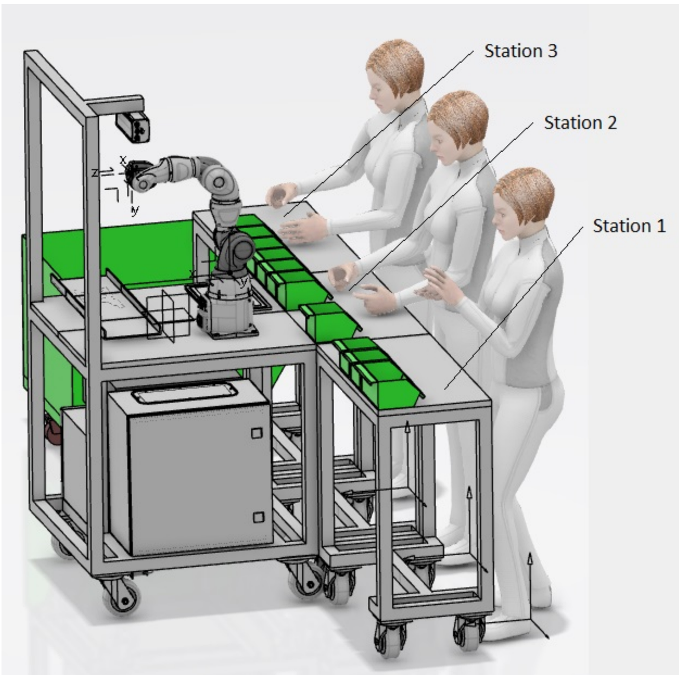

Figure 4.13: Overview of the production cell layout.

Robot Simulation

To get the preferred robot behavior in the simulation, the positions of the robot had to be defined but no robot code was used to define its movements. In 2020X version of 3DEXPERIENCE it was also not possible to use simulations created in the *Robot Simulation* application to be used in factory flow simulation. A workaround was therefore made to define movements of the robot in the virtual model.

In the *Robot Simulation* application all positions for when the robot pick up or drop a Lego brick were defined. These positions were then used in the *Factory Flow Simulation* application to visualize the movements of the robot.

Factory Flow Simulation

In the application *Factory Flow Simulation* the product flow in the virtual model was defined. Figure 4.14 display different spheres with a flow between them. The spheres furthest away are called in-zones and define where different parts come in to the cell. The spheres in the green boxes represent buffer zones and are connected with the respective in-zone. There are also product zones in front of the manikins which is where the actual assembly takes place. To the far right in the figure is the dispatch zone, where the completed assembly goes in order to make it ready for storage or delivery.

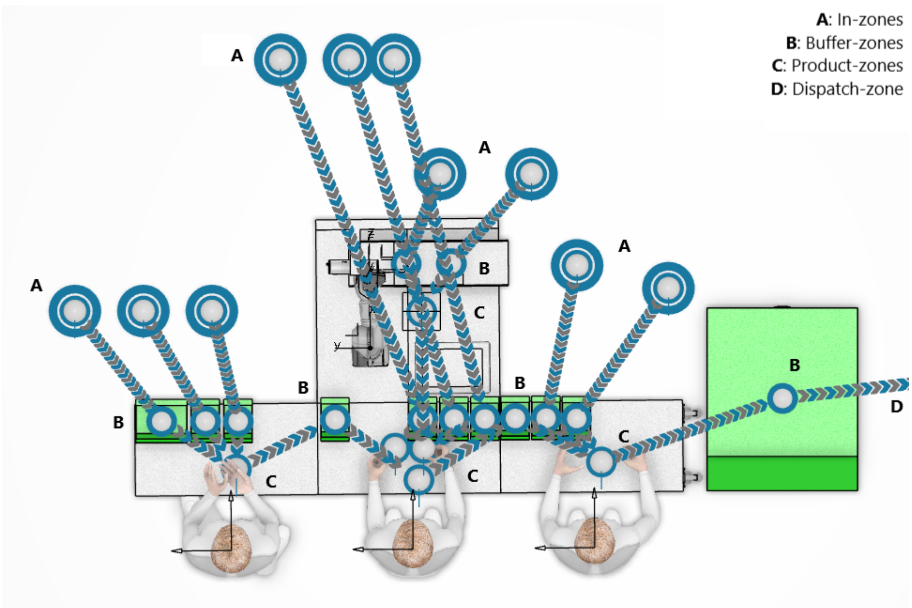

Figure 4.14: The factory flow process viewed from above. The letters describe the type of zone each sphere represent

The robot was defined as a resource to the robot station to be able to perform the operations assigned to that station. To get the robot to move in the simulation, the positions of the robot defined in the *Robot Simulation* application was applied in *Factory Flow Simulation*. This was done by allocating the robot to a so-called resource pool containing the pre-defined positions. The robot could then be selected to perform specific operations assigned to the robot station.

Figure 4.15 gives an angled view of how the different in-zones, buffer zones and product zones are connected to each other.

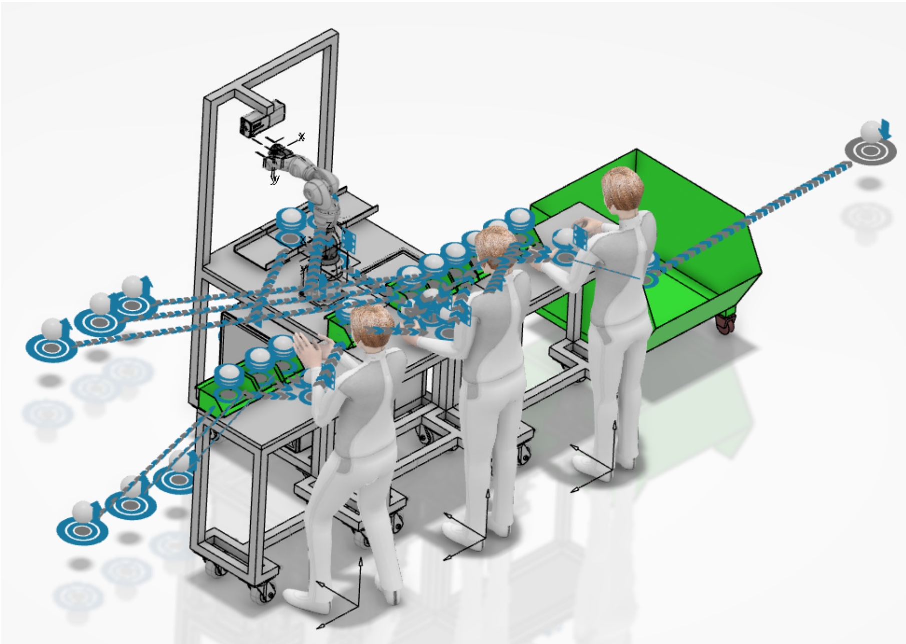

Figure 4.15: The factory flow process viewed from an angle.

4.5.4 Simulation

In *Factory Flow Simulation* it is also possible to simulate and analyze different scenarios. By defining lead times for each station and assembly, an evaluation of the workload can be done to see the utilization and performance for each station, worker, or robot.

The lead times for each operation in the simulation were set to five seconds in order to get a result which can show interesting numbers. The simulation ran for 1000 seconds with a warm-up time of 100 seconds which concluded in 9-10 finished Lego Vera trucks. The cycle times for each station can be seen in table 4.2.

Table 4.2: Cycle times for each station during the simulation.

System	Count	Cycle Time (Seconds)		
		Min	Max	Avg
Station 1	9	90	90	90
Station 2	10	90	127	95.329
Robot station	9	92.365	92.365	92.365
Station 3	10	90	159.058	98.606

4.5.5 Analysis

The utilization for each station can be seen in table 4.3 where it shows that for station 1 the utilization rate was at 89,4%, for station 2 it was 65,3%, for the robot station it was 65%, and for station 3 it was 33,3%. These numbers depend on that the workload has not been balanced and the lead times for each operation does not match the lead times of the physical production cell. But it gives the insight that in order to increase the utilization for each station the lead times have to change, as well as balancing the workload between the stations so that each worker do not have to wait for the previous assembly to be finished.

Table 4.3: Distribution of the processing time, wait time, and utilization for each station.

System	Products				State Times (Seconds)		Average Processing Time (Seconds)	Average Requirement Time (Seconds)	Utilization (%)
	Input	Produced	Consumed	Output	Processing	Wait for Input (s)			
Station 1	79	72	144	9	805	95	5	0	89.444
Station 2	54	48	97	10	587.954	312.046	5	6.625	65.328
Robot station	53	54	99	9	584.992	315.008	5	1.859	64.999
Station 3	30	20	40	10	300	600	5	9.801	33.333

During the 1000 second simulation the bottlenecks for each station could be seen in real-time. Figure 4.16 show the average percentage of bottlenecks after the simulation had finished. In this simulation it can be seen that there is no bottleneck for station 1. On the other stations where there actually were a small amount of bottlenecks during the whole simulation it can be seen that for station 2 there was an average bottleneck of 7,24%, for the robot it was 1,46%, for the robot station it was 1,20%, and for station 3 it was 3,33%. The reason that worker 3 is also visible in this graph is because it has a movement included in the operation and it is not a valid result with regard to the other workers since they have not been programmed to move. In essence, the bottleneck for worker 3 can be disregarded.

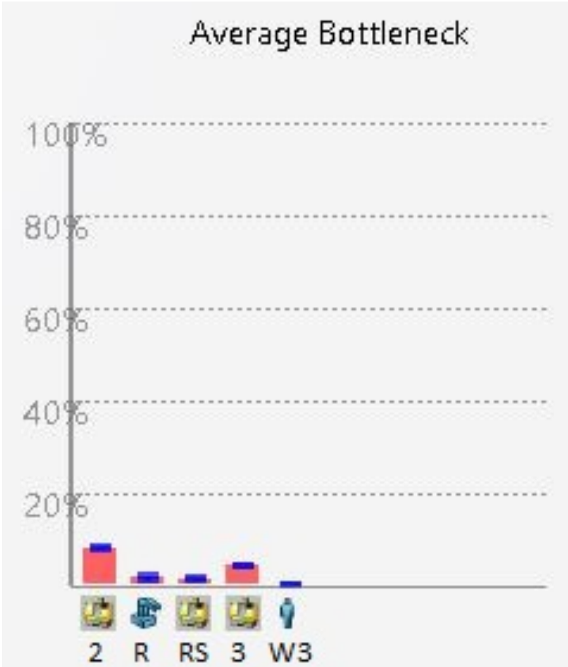

Figure 4.16: Distribution of bottlenecks over the production cell.

By analyzing these results it can be understood in an early stage that the workload must be balanced in order to achieve the best possible productivity and utilization across the different stations. Together with the bottlenecks it can also be concluded that how the assembly is put together affect the production cell and would require change.

Alternative Simulation Options

This model can be used to simulate and analyze a wide variety of different parameters in order to optimize it. Although this has not been done in this project, it is nonetheless important features for digital twins in order to be as exact and precise as possible with regards to their physical counterpart.

In table 4.4 a few different simulation applications and their area of usage are listed in order to present what more can be done.

Table 4.4: List of different applications for simulation and evaluation.

Application	**Area of Usage**
Ergonomics Evaluation	Evaluation of workers' ergonomics for their defined motions.
Material Definition	Defining materials and their properties for different parts used in the model
Robot Programming	Programming of robots to define their behavior and motion.
Robot Simulation	Simulation of the robots movement to evaluate reach and potential collision issues.
Robot Optimization	Optimization of robots for better fit in the model.
Time-Motion Study	Analyzing the complexity of operations and compute operation times.
Work Instructions	Create work instructions for operations the workers perform.
Work Plan Publication	Publish the work plan with instructions and make it accessible for relevant parties.

5

Discussion

In the following chapter a comparison between the literature and interviews is made together with the experience gained from the case study in order to answer the research questions. The chapter ends with a discussion about the ethical and sustainability dilemmas with digital twins and the need for future research in different areas.

5.1 Definition of a Digital Twin

The definition of a digital twin is discussed widely within industries and in research and no standard has been set regarding what type of virtual model should be called a digital twin. The difference between virtual models used for virtual commissioning to other types of virtual models used for simulations seem to be called digital twins for some and for others not.

What can be agreed on by both researchers and industry is that the digital twin should consist of a physical model, a virtual model and a connection between the two. How this connection is managed in practice and what it should include is however not defined. Some want to include real-time interaction between the models and some do not see the need of this for a digital twin to be useful. The reason behind including real-time optimization could have to do with the revolution of Industry 4.0 which can make this happen in the near future with the use of IoT, CPS, and other systems which gather and manages data.

The created model for the Vera Smart Factory is not a digital twin but instead a virtual representation of the physical system. It would instead be called a virtual model of the production cell. It does not meet the requirements for a digital twin since it does not contain some of the important parameters such as correct kinematics and logic for neither the robot or manikins. Furthermore, it is not integrated in any way to the physical production cell, and it does not support a real-time data connection. Although the model can be used for supporting decision making in various ways, and may be a first stage in order to develop a digital twin, it can not be called a digital twin as previously explained.

The proposed concept of digital twin shop-floor by Tao and Zhang (2017) is a good way to visualize how advanced a certain virtual model is. By comparing the created virtual model of the Vera Smart Factory to figure 5.1 conclusions can be drawn to what is there and what is missing for it to be a digital twin. The virtual model is managed through a service system, in this case the 3DEXPERIENCE platform, where interaction and optimizations of the model is managed manually. The physical model does not have any interaction with the virtual counterpart or to the service system. The virtual model, physical model and the service system are not connected to any kind of data system that manages the data. The physical model together with the created virtual model is not a digital twin according to Kritzinger et al. (2018) either because there is no automatic data flow between the physical and virtual model.

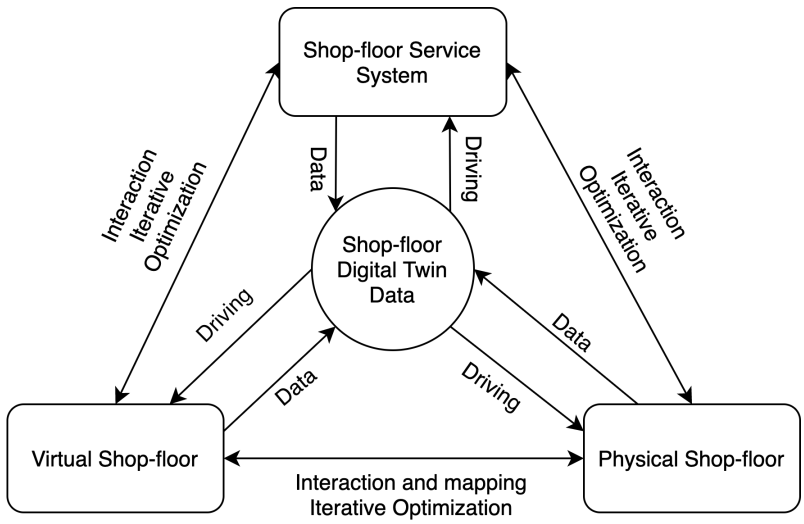

Figure 5.1: The concept of a Digital Twin Shop Floor.
Source: (Tao, Zhang, & Nee, 2019)

Even though the opinions are fragmented regarding the definition of digital twins, the following definition is proposed to compile the most important aspects for digital twins used in the production industry.

A digital twin is constructed by a physical and a virtual counterpart constantly optimized by each other where the interaction and communication of data between the counterparts is processed in real-time to simulate, optimize, and predict the behavior of the physical production system.

By comparing the definitions presented in section 2 it can be seen that they present different factors and are either very simplistic or very detailed and complex. Because of this, the definition presented above is considered suitable since it presents the most important factors of a digital twin without being too vague or too complex.

5.2 Maturity Level of Digital Twins

Depending on how digital twins are defined, the maturity level of them varies. Virtual models used for virtual commissioning that some would regard as digital twins have a high maturity, but digital twins defined as proposed above has not reached a high level of maturity.

The knowledge of digital twins are, as with the definition, fragmented which can be seen when talking to people within different industries with different roles. The knowledge is widespread among researchers and practitioners, especially those who work with virtual commissioning. However, as stated in the interviews, smaller companies within production do not really have the resources to familiarize themselves with digital twins. While they may have interest for the technology, resources are limited and since the concept of digital twins is such an extensive area, there are many obstacles to overcome before realizing and being able to properly use digital twins. There are often more important things to pursue before directing the focus to a technology which is still in an early stage where there are high risks and many uncertainties.

Gartner highlighted digital twins at the top of the peak of inflated expectations in the Gartner Hype Cycle with the expectation of reaching its plateau of productivity in 5-10 years (Walker & Panetta, 2018). If this is accurate, the technology still has a long way to go. As it can be seen in the literature and the interviews conducted, the knowledge and definition of digital twins is implicitly divided. As it was presented by Tao and Zhang (2017) in section 2.1.4, the evolution of digital twins is still in the third stage and to reach the fourth stage technologies such as sensors and data processing have to evolve. Based on this, Gartner's prediction may very well be correct. Even though no concrete information about the technology readiness level for digital twins were found for this thesis, an estimation of the technology readiness level for digital twins is proposed and placed in an S-curve.

Most of the research regarding digital twins is in a conceptual stage with few exceptions for live testing. While virtual commissioning has been proved to work, and the interviews are evidence for this, the authors believe virtual commissioning has reached TRL 9. However, since it does not align with the definition of a digital twin previously presented it is not considered. For digital twins the readiness level was estimated to be somewhere in the range of TRL 4-5 where various components have been tested together and the technology is established to be functional but requires more real-life testing before it is proven to work in live scenarios.

This puts the technology of digital twins still in its infancy stage on the S-curve, which can be seen in figure 5.2 and before it has been proved to work in live scenarios it does not meet the requirements for the second stage of growth.

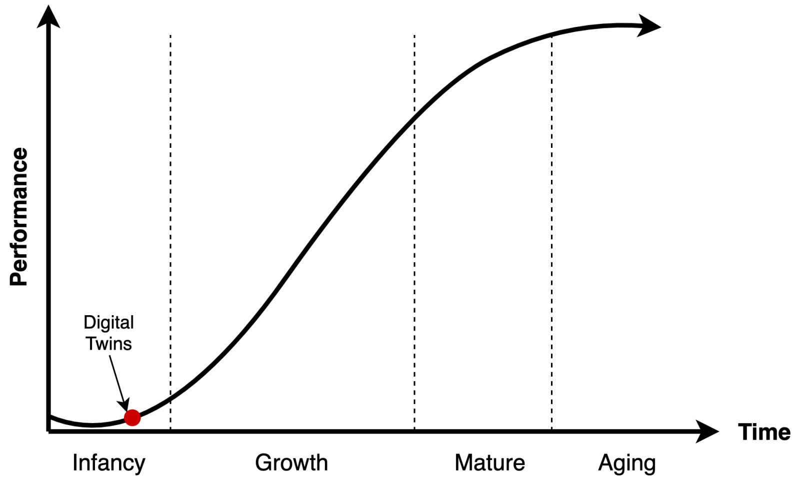

Figure 5.2: Visualization of where the digital twin technology is today in the S-curve according to the authors.

While it is no doubt that digital twins will be used for various purposes across many industries, it still has a long way to go before the possibilities outshine the complexity of implementing and creating digital twins.

5.3 Implementation and Creation of a Digital Twin

As it was found out in the literature study and the interviews there are many possibilities digital twins can offer as well as where they can be used. The results from the interviews focused mainly on virtual commissioning which can be used to test and optimize the layout and configuration of the system, program robots offline, and explore the virtual environment in 3D. These advantages can result in faster deployment of a physical system, support decision making, and optimizing the system without interfering with the real production. This is supported by a digital twin as well with even more possibilities presented in the literature. For example the compilation of digital twin use cases done by LNS Research in section 2.1.5 where they highlighted the most important possibilities of a digital twin within discrete manufacturing such as product quality improvements, cost reduction for manufacturing, or reduction of unplanned downtime. This compilation gives insight to the vast amount of possibilities and business drivers a digital twin can offer. However during the implementation process of a digital twin it is important to know the reason why it is necessary and what it is going to be used for. Because of the complexity of creating virtual models that represent the physical world, it is also important to consider how accurate the model is supposed to be. Will it just be used as a representation of the physical model or is it going to be used for optimization where it is important that the data is as close to the physical model as possible? While the benefits and possibilities of using a digital twin may seem like a great way to gain competitive advantage it will most likely create more problems than it solves without a realizable strategy for implementing it.

What was understood when creating the virtual model of the Vera Smart Factory is the sheer amount of time needed for creations like this. While the authors were not familiar with neither the software used or the concept of digital twins in general at first, the experience can be compared to that of a smaller company without resources to tackle issues like these. It is estimated that the total amount of work for creating the virtual model of the Vera Smart Factory was around 200 hours. This includes starting from scratch and learning the software, overcoming different issues appearing throughout the process, and consulting with experts in order to achieve proper results. The created model is not highly complex when comparing it to other models created for virtual commissioning for example, but it is useful to highlight the complexity when more parameters are introduced such as robot programming, ergonomics, optimization, and integration between the physical and virtual environments.

The importance of service integrated products has become an important part of today's society and the digital twin. In the proposed concept of the digital twin shop floor presented by Tao, Zhang, and Nee (2019) in section 2.1.4 the service system of the shop floor is included in the digital twin. Third-party services and consulting firms may in the future play a big part in helping small and medium-sized companies to implement and create a digital twin for their production in case they do not possess the competence or resources required. It can be compared to that of leasing a car where maintenance and different services are included in the leasing contract. In the same way, during the "subscription" of a digital twin the creation, maintenance, and updating is managed by a third-party.

Together with the literature, the interviews, and the case study it was realized that the implementation and creation process of a digital twin can be summarized in six steps which can be seen in figure 5.3. The first two steps in this process are considered the implementation stage whereas the last four steps is considered the actual creation of the digital twin. The created model for the Vera Smart Factory include the first three steps which are envision, selection, and creation. These three steps are also confirmed by the technical lead at Elektroautomatik and how they work with virtual commissioning. Thus, the authors propose this process when implementing and creating a digital twin. While larger companies may already possess the knowledge necessary for implementing and creating digital twins, smaller companies can benefit from having a concrete process like this to highlight the important steps needed in order to establish a feasible vision and strategy.

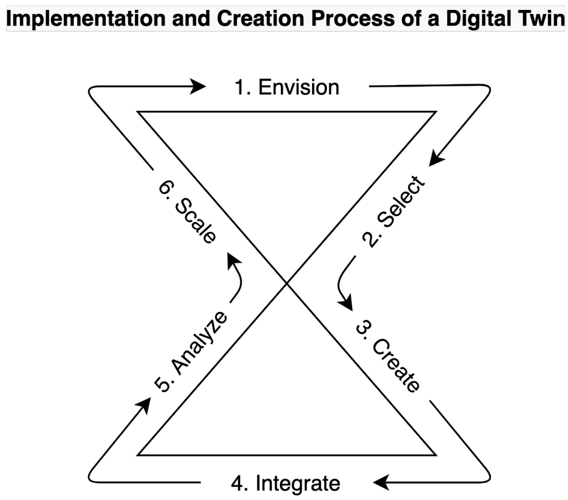

Figure 5.3: Steps to consider when creating a digital twin.

Envision is the first step of the process and is where the scope and purpose is determined for the digital twin. The second step, *selection*, is to define how it will be used and select the necessary parameters for the specific purpose. The *creation* step is the actual creation of the virtual model. In this step geometry, physics, behavior and rules are added from the physical model. *Integrating* the virtual model is when the connection between the physical system and the digital model is done with sensors to enable a data connection in real-time. Then the digital twin is *analyzed* regarding its accuracy to the physical model and used for simulation, optimization, and prediction of the physical system. The last step is where the digital twin can be *scaled* to increase the scope and add more parameters to cover more instances of the production.

5.4 Ethical and Sustainability Aspects Regarding Digital Twins

The treated aspects in this thesis are the social, environmental, and economical impacts a digital twin can have. The digital twin created in this thesis will however not have a direct impact on these aspects but future developments of this type of products may.

Digital twins increase the need for sensors and surveillance of different systems for the virtual model to be as accurate as possible to the physical model. This will affect peoples integrity around each created system and data stored must be managed in an ethical and secure way. Other social aspects that can be affected by the creation and implementation of digital twins within the production industry is in the work sector. Digital twins may in the future reduce the need for maintenance personnel thanks to condition-based and predictive maintenance, or replacing line workers because of more automated and autonomous processes in the production.

Because the digital twin can be capable of controlling and managing most systems and processes it can lead to an excess of the workforce. The surplus of workers can on the other hand receive new responsibilities to maintain and control the digital twin.

Using digital twins can have positive effects on both economical factors in a company as well as the environmental factors. With a digital twin a company within the production industry can increase the efficiency of their logistics and maintenance for example. Thus having more control over material consumption, enabling condition based maintenance, and reducing costs and environmental impacts for these. A digital twin also gives the possibility for working remotely which can reduce travel expenses and the environmental impact of transportation.

As presented in section 2.2, retrofitting old equipment with sensors and connecting it to IIoT systems can reduce the costs instead of investing in new expensive equipment, and gives the opportunity to measure energy consumption for example. The importance of what to measure, who should measure it, and how it will be measured is also highlighted in order implement technology like this in a feasible and efficient manner.

5.5 Further Research

The technology of virtual models are constantly evolving and new products and technologies are making the transfer of data between the physical and virtual world possible with higher speed and accuracy. Today there are no standardization's regarding software and hardware used for virtual models or how the processing and transfer of data is managed. Future work should include an investigation of possible methods and procedures for standardization of virtual models and the technologies behind them.

Furthermore, to get a more realistic view on digital twins, continued work regarding this thesis can include improvements of the virtual model of the Vera Smart Factory regarding geometry, kinematics, logic, and lead times as well as a validation of the accuracy. How the integration between the physical model and the virtual model can be done together with the integration of service systems for continuous data flow and management is also something worth investigating.

6
Conclusion

This chapter presents the concluding statements regarding the findings in this thesis to fulfill the purpose of how small and medium-sized companies within the production industry can implement and create digital twins.

The thesis has evaluated the concept and technology of digital twins in order to answer the following research questions.

1. What is the definition of a digital twin?
2. What level of maturity has the technology behind digital twins reached?
3. How can small and medium-sized companies work towards implementing and creating a digital twin?

It was found out that today there are no standards regarding the definition of digital twins. In academia and industry the definitions vary widely without any real evidence for who is right and who is not. Because of this, the following definition of digital twins in the production industry has been proposed in an attempt to compile the most important aspects of a digital twin:

A digital twin is constructed by a physical and a virtual counterpart constantly optimized by each other where the interaction and communication of data between the counterparts is processed in real-time to simulate, optimize, and predict the behavior of the physical production system.

It was stated by the interviewees that they do not know of any company working with digital twins on such a level described in this thesis, and most of the work done today is in the area of virtual commissioning. Together with the literature review which shows that the knowledge and opinions of digital twins is divided it is believed that digital twins have a long way to go before becoming an everyday technology. Because of this it can be considered that the complexity and low maturity of digital twins makes it more difficult to implement and create a digital twin as of today, especially for small or medium-sized companies within the production industry.

The technology readiness level for digital twins has therefore been estimated to be around TRL 4-5 and more real life testing is required for it to be proven to work. This positions the technology in its infancy on the S-curve but is still expected to grow and become the go-to technology for producing companies in the future.

The Vera Smart Factory is a small-scale production cell demonstrator at Smarta Fabriker which is a government funded project in Sweden. A virtual model of the Vera Smart Factory was created which did not have an established real-time connection of data to the Vera Smart Factory. Because of this it was not considered a digital twin. This model was combined with literature research and interview studies to establish guidelines for implementing and creating a digital twin for small and medium-sized companies within the production industry. To highlight the importance of a strategy and to guide small and medium-sized companies within the production industry, a six step process has been proposed that involve; *envision, selection, creating, integrating, analyzing and scaling*, which can be seen in figure 6.1.

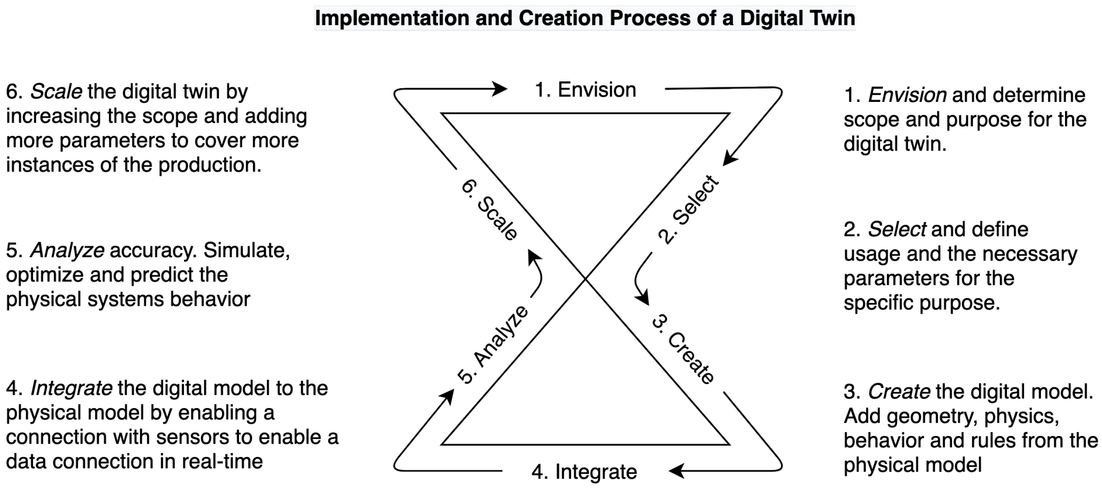

Figure 6.1: Guidelines for implementing and creating a digital twin.

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A
Interviewees

In the following appendix information about the interviewees are presented.

Rikard Söderberg is the head of the department of Industrial Sciences and Materials at Chalmers University of Technology and professor in product and production development. He was interviewed about Industry 4.0, digitalization and digital twins in order to gain more knowledge of what it is, how the research works, and how companies react to this type of technology.

STENA Industry Innovation Laboratory (SII Lab) is a part of Chalmers University of Technology and aims at offering digital solutions and demonstrators for the Swedish industry to test and use in training. They were visited to see how they work with digitalization, what kind of software they use, and how they can connect their work between education and industry.

Johan Sahlström, Industry Process Consultant and Senior Manager at Dassault Systèmes has several years of experience working with Volvo Group within variant and change management. He was interviewed about digital twins in general and what could be expected in the future.

Johan Bengtsson and Greta Braun, project leaders at Smarta Fabriker were interviewed to see how smaller companies can work toward digitalization and how smart factories can be used. They were also asked about what their purpose with a digital twin would be.

Håkan Törnqvist, head of production at Emerson Automation Solutions in Mölnlycke, Sweden, was interviewed about digitalization in production, how they work with digitalizaton at Emerson, their thoughts about digital twins, and what may be the driving factor for them to pursue this kind of technology. Emerson Automation Solutions in Mölnlycke, Sweden, produces radar based measurement instruments for tank gauging (Emerson, 2020) and has roughly 250 employees.

Bernt Henriksen, senior automation and production specialist at Robotdalen in Västerås, Sweden, was interviewed about how they work with virtual commissioning, which kind of companies and industries they work with, how the market looks like from a solution provider's perspective, and digital twins in general. Robotdalen provide companies with solutions for increased productivity with focus on robotics and automation. Virtual commissioning is one thing they work with and can offer different analyses for automation, pre-studies, simulations and support with deployment (Robotdalen, 2020).

Samuel Lindholm, technical manager at Elektroautomatik in Skövde, Sweden, was interviewed about the advantages of virtual commissioning, how they work with it, how the market looks like from their perspective, and resources needed to work with virtual commissioning, and digital twins in general. Elektroautomatik provides customer specific solutions for virtual commissioning, robotic programming, and simulation, with preparation, development, construction, and deployment (Elektroautomatik, 2020).

B
Interview Questions

In the following appendix the questions asked during the conducted interviews are presented. Some of the questions are specific for different companies or for different persons interviewed.

Questions directed toward a research perspective about digital twins:

– Is it okay to record this conversation and refer to what you say in our thesis?
– What is your role?
– How does the development of digital twins look like, mainly toward manufacturing and production?
– How can a digital twin contribute to a more efficient production/manufacturing?
– What is needed by a digital twin to ensure it fulfill ones requirements?
– What problems do you see with a digital twin?
– What makes the implementation of digital twins difficult?
– Which companies is on the forefront when it comes to digitalization and digital twins?
– How does it look like within research about digital twins?
– What is needed by companies in terms of resources to implement digital twins?
– What is the main reason to use a digital twin?
– How do you see on the development of digital twins the coming years?

Questions directed toward working with digital twins:

– Is it okay to record this conversation and refer to what you say in our thesis?
– What is your role?
– How do you work toward digitalization?
– What steps have you taken to increase the productivity/efficiency of your production with digital tools or software?
– What do hope to get out of the digitalization?
– What resources do you possess to drive the digital development within your organization?
– Do you use some kind of digital twin?
– What kind of problems have you encountered when implementing a digital twin or virtual models of your systems?
– What are your goals with a digital twin, how can it help your way of working?
– What do you think the development of digital twins can lead to within the production industry?
– What is missing today for you to use a digital twin?

- What is your experience with how the market react to this type of technology?
- What kind of companies are you working with?
- What do your customers mainly want to get help with?
- What kind of software do you use to create virtual models, simulate, and analyze these?

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