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THE DIGITAL TWIN AS A PART OF THE MANUFACTURING EXECUTION SYSTEM AND AUTOMATION INTEGRATION

Master of Science Thesis
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Examiners: Professor Minna Lanz and
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ABSTRACT

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The Digital Twin as a part of the manufacturing execution system and automation integration
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The Digital Twin is an emerging technology that has gained a lot of interest in both academia and industry. It is under wide research in many fields and manufacturing is one of those. This thesis aimed to find the most important applications, advantages, and challenges of the Digital Twin usage in the manufacturing field.

Effective Digital Twin use requires suitable integration with other systems such as MES and automation. One main goal was to identify potential integration architectures and implement an example integration between the Digital Twin, MES, and automation. The possible effects of the Digital Twin on integration were also investigated.

To identify the Digital Twin applications, advantages and challenges a literature review was conducted. The same literature review was used as a base material for the integration case study to identify different integration architectures. One integration example was implemented with Siemens software.

Based on the literature review, some of the main Digital Twin applications were monitoring, maintenance and optimisation. These can lead to benefits such as increased flexibility and predictability which can lead to cost savings in the production. The most significant challenge was the lack of the Digital Twin standardisation. This was also the root reason for many other challenges.

From the literature, only two different integration architectures were found. The integration case study was done based on the more common architecture. In this case study, the Digital Shadow level of the integration was achieved. No major issues were found in integrating or adding the Digital Twin as part of the MES and automation connection.

Keywords: Digital Twin, MES, automation, integration, manufacturing

TIIVISTELMÄ

Heikki Toivo
Digitaalinen kaksonen osana tuotannonohjausjärjestelmän ja automaation välistä integraatiota
Tampereen yliopisto
Konetekniikan diplomi-insinöörin tutkinto-ohjelma
Diplomityö
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Digitaalinen kaksonen on nouseva teknologia, joka on herättänyt paljon kiinnostusta sekä tiedemaailmassa että teollisuudessa. Sitä tutkitaan laajasti monilla aloilla, joista valmistus on yksi niistä. Tämän opinnäytetyön tavoitteena oli löytää digitaaliseen kaksosen käytön tärkeimmät käyttökohteet, edut ja haasteet valmistavassa teollisuudessa.

Tehokas digitaalisen kaksosen käyttö edellyttää sopivaa integrointia muiden järjestelmien kanssa, kuten MES:n ja automaation. Toisena päätavoitteena oli tunnistaa mahdolliset integraatioarkkitehtuurit ja toteuttaa esimerkki integraatio digitaalisen kaksosen, MES:n ja automaation välillä. Myös digitaalisen kaksosen mahdollisia vaikutuksia integraatioon tutkittiin.

Digitaalisen kaksosen sovellusten, etujen ja haasteiden tunnistamiseksi suoritettiin kirjallisuuskatsaus. Samaa kirjallisuuskatsausta käytettiin esimerkki integraation toteutuksen pohjamateriaalina erilaisten integraatioarkkitehtuurien tunnistamiseksi. Yksi integraatioesimerkki toteutettiin Siemens-ohjelmistoilla.

Kirjallisuuskatsauksen perusteella tärkeimpiä digitaalisen kaksosen käyttökohteita olivat valvonta, ylläpito ja optimointi. Nämä voivat johtaa etuihin, kuten joustavuuden ja ennustettavuuden lisääntymiseen, jotka voivat johtaa kustannussäästöihin tuotannossa. Haasteiden kannalta tärkein oli digitaalisen kaksosen standardoinnin puute. Tämä oli juurisyy myös moniin muihin haasteisiin.

Kirjallisuudesta löytyi vain kaksi erilaista integraatioarkkitehtuuria. Integraation esimerkki toteutus tehtiin yleisemmän arkkitehtuurin pohjalta. Tässä toteutuksessa saavutettiin digitaalisen varjon taso integraatiossa. Merkittäviä ongelmia digitaalisen kaksosen integroinnissa tai lisäämisessä osaksi MES:n ja automaation yhteyttä ei löytynyt.

Avainsanat: Digitaalinen kaksonen, MES, automaatio, integraatio, valmistus

PREFACE

I would like to thank the Ideal GRP for offering this opportunity to do my master’s thesis in this interesting topic. It will be interesting to see where the Digital Twins will evolve in the future.

Great thanks to Markus Ranta for guiding and supporting me throughout the thesis writing process. I got the support when needed and it was nice to discuss the potential thesis topics and then choose the ones which seemed the most interesting.

Thank you Hasse Nylund and Minna Lanz for acting as examiners of my thesis. The feedback I received was very valuable and it helped me to improve my thesis. Many of these things I would not have noticed myself.

Finally, I would like to thank Essi for supporting me during this thesis and proofreading my entire thesis, it must have been an interesting experience.

In Tampere, on 21 October 2022

Heikki Toivo

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AR	Augmented Reality
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
DM	Digital Model
DS	Digital Shadow
DT	Digital Twin
ERP	Enterprise Resource Planning
EX DS	Execution Discrete
EX FN	Execution Foundation
I4.0	Industry 4.0
IEC	International Electrotechnical Commission
ISA	International Society of Automation
ISA-95	Standard that defines the functions between the operational control level systems and enterprise level systems
IIoT	Industrial Internet of Things
IoT	Internet of Things
MES	Manufacturing Execution Systems
MOM	Manufacturing Operations Management
MQTT	Message Queue Telemetry Transport
OPC UA	Open Platform Communications Unified Architecture
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
PS	Plant Simulation
RQ	Research Question
VC	Virtual Commissioning
VR	Virtual Reality
WOO	Work Order Operation

1. INTRODUCTION

Increased customer demands and global markets have set the manufacturing companies in a position where they must change the ways they work and improve their performance. Future manufacturing lines should be able to handle greater and faster variation of the new products and product variants (Novák et al., 2020). Lattanzi et al. (2021) have mentioned mass-customised products, shorter time to market goals and highly competitive global markets as the main reasons why manufacturing companies must find ways to improve their production. Increased flexibility and ability to react changes in the real-time are potential ways to increase the production performance.

Industry 4.0 (I4.0), also known by the names smart industry or smart manufacturing, means the fourth industrial revolution which is currently chancing the manufacturing industry. It is increasing the number of digital solutions in the manufacturing industry and replacing the old systems by the new digital ones. One important step towards digitalisation and Industry 4.0 is the use of a Manufacturing Execution System (MES).

One important aspect to achieve Industry 4.0 goals is the seamless integration between different devices and systems. Advanced digital technologies have enabled the easier integration of interconnected intelligent components (Negri et al., 2017; Kritzinger et al., 2018). However, at the same time Tao et al. (2019) mentions the integration of the physical and virtual worlds to be a key challenge for the smart manufacturing.

A fairly new technological innovation, especially in the manufacturing field, is seen as a potential solution to achieve this integration between the physical and virtual worlds. This technology is called Digital Twin (DT). It is mentioned to play a key role towards smart manufacturing (Kritzinger et al., 2018; Tao et al., 2019; Corallo et al., 2021; Onaji et al., 2022). According to Lattanzi et al. (2021) the Digital Twin is seen as a one of the most interesting innovation trends. The research and advisory company Gartner has named the Digital Twin among the top 10 strategic technology trends for a three years a row in 2017, 2018 and 2019 (Gartner, 2016, 2017, 2018). This identified importance of the DT is the key reason why it is at the main role of this thesis.

1.1 Research Problem and Objective

The Digital Twin has got a lot of interest in both academia and industry in past few years. This increased interest is easy to understand because it is seen as a key technology to achieve Industry 4.0 goals. It is true that the Digital Twin has a huge potential in the manufacturing industry, but it also has its challenges and a lot of open questions. These lead to the first two main research questions (RQs) which are the following:

RQ1. What are the potential applications of the Digital Twin and what value can these bring?

RQ2. What are the current major challenges for companies in the Digital Twin implementations?

As mentioned, the integration between different systems and between physical and virtual worlds is one of the most important aspects of the Industry 4.0. An especially important part of the integration is the vertical integration between systems in the different hierarchical levels. This vertical integration between the MES and the shop floor level leads to the third main research question of this thesis:

RQ3. How to add the Digital Twin as a part of the MES and automation integration?

The integration between the MES and automation systems is quite common in many manufacturing companies. However, implementations of the Digital Twin in the manufacturing industry are very scarce. This opens the need for the fourth research question which is:

RQ4. How does the Digital Twin affect the MES and automation integration?

All these questions work together to consider whether it is beneficial to implement the Digital Twin in today's manufacturing plants at its current maturity level. How the DT should be implemented together with the MES and automation systems is discussed and suitable implementation methods are proposed.

The goal of the thesis was to identify the DT potential and its potential challenges in the manufacturing industry. The aim was to consider these in the level where these can be used to support potential Digital Twin projects in the future. From the point of view of the integration, the main goal was to implement a working integration between MES, automation, and the DT. This was aimed to do at least the Digital Shadow level.

1.2 Research Methods

To answer the proposed research questions three main research methods were used. These were a literature review, an interview, and a demo case implementation. All these together form a view of whether the DT should be implemented in the industry and how it should be included as a part of the MES and automation integration. Overall view of the research structure of this thesis is shown in Figure 1.

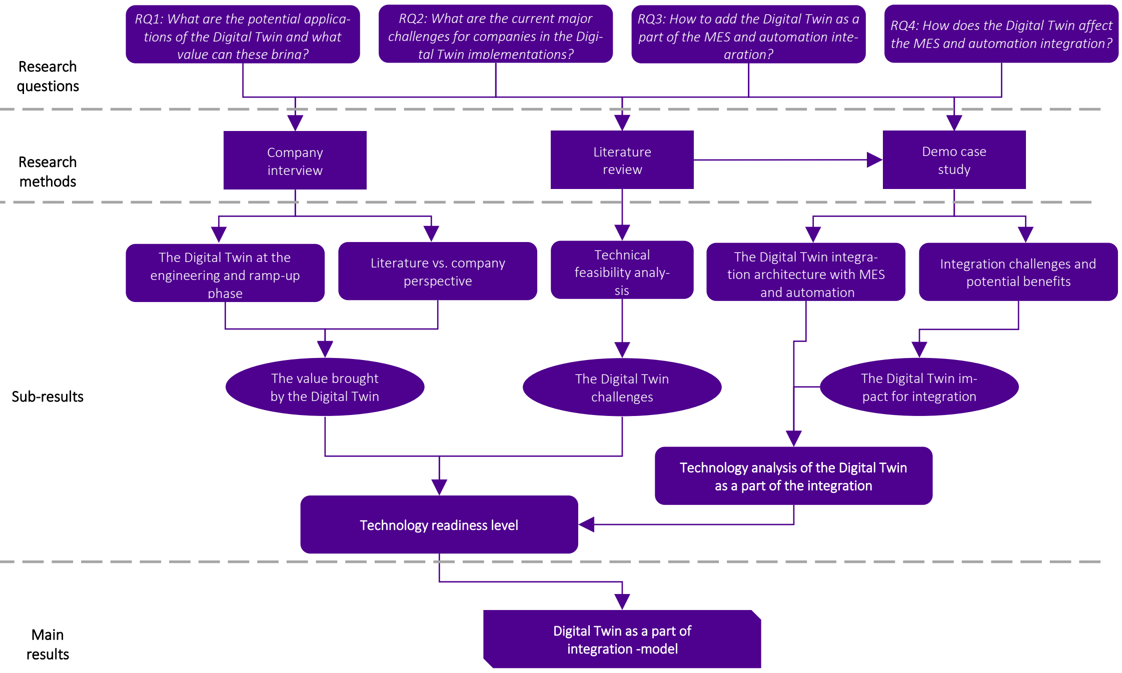

Figure 1: Thesis research structure

The literature review is used to create theoretical background understanding about the Digital Twin in manufacturing industry. Also, other integration related theories are introduced. The literature review material consists of scientific articles and books acquired from several different databases. Many articles in the literature review mentioned the DT research being very active for approximately past five years. Very active research means that the older results can become outdated quite quickly. Therefore, an effort was made to keep the articles and materials collected from the literature as relevant as possible by favouring the newer available material. The articles used in the literature review were chosen manually based on the abstract and overview of the article. Then the selected articles were read through, and the suitable ones were used in this thesis.

For the research questions RQ1 and RQ2 the literature review was the main material to form the answer. The interview was also used to support the material findings from the literature review. This interview was done with the Information Solutions Manager of a one Finnish company. The main goal of this interview was to get the real industrial company perspective on the possible use and benefits of the DT, as well as on the challenges. The conducted interview was a semi-structured interview with a predetermined theme around the Digital Twin. The semi-structured form with the clear theme was selected because it would allow interviewee to give new viewpoints for the interviewer (Routio, 2007). In this thesis context, this was seen as an important advantage. The semi-structured interview is also suitable for the topics when there is not enough knowledge for the interviewer to ask the exact questions (Routio, 2007). This was also seen as an advantage of the semi-structured interview.

The literature review gave a good background for the research questions RQ3 and RQ4. In addition, for the findings from the literature, a demonstration case example was implemented. In this case study, the integration between the MES, the DT and automation were implemented. This demo case aimed to support the findings from the literature but also to find potential issues and open new questions related for the integration.

1.3 Scope and Structure of the Thesis

Nowadays almost anything can have the Digital Twin. The Digital Twin can be almost any physical thing such as a human, a car, and a water system (Autiosalo et al., 2021). Qi et al. (2021) mention there being the DT applications for example in healthcare, smart cities, construction, automobile, aerospace, and manufacturing. In this thesis, the Digital Twin is discussed only in the manufacturing industry environment. More precisely limited to the production systems only. In this thesis, the term Digital Twin is mostly used to mean the physical production system or a part of it and its virtual counterpart. Since this thesis focuses on the integration between different layers and systems the detail levels of the Digital Twin structure will not be discussed.

Another important aspect to consider about the thesis scope is the automation pyramid and different system levels. The automation pyramid is shown in Figure 2. In this thesis, the focus is on the planning level and below to the control and field levels. This leaves out the higher-level business planning systems such as Enterprise Resource Planning (ERP) -systems from this thesis. This thesis also completely excludes the horizontal integration between different systems at the same level and focuses only to the MES to automation vertical integration and connection.

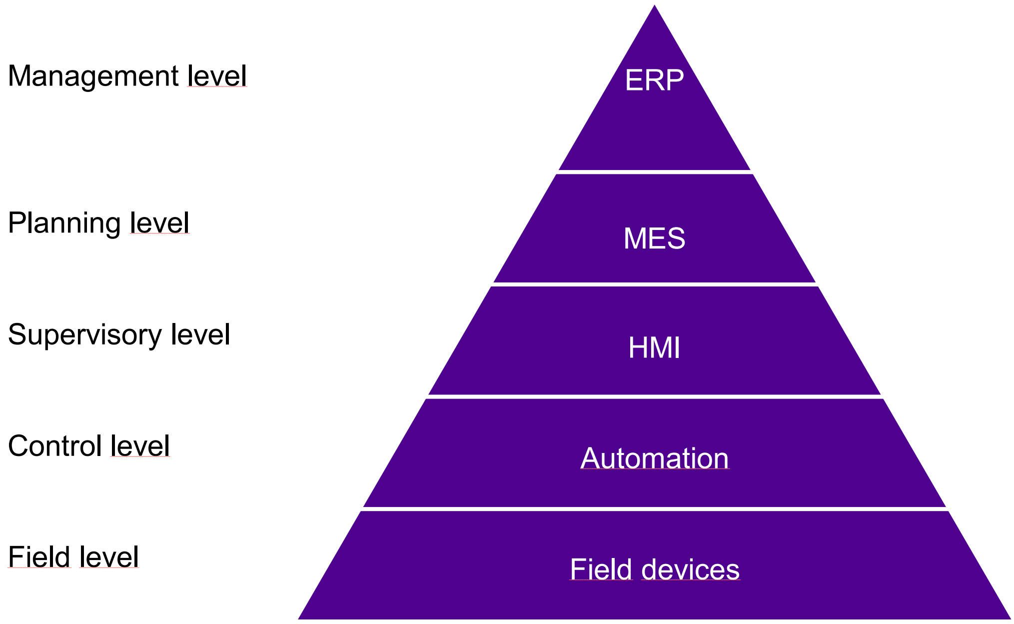

Figure 2: Automation pyramid (based on International Electrotechnical Commission, 2013; Martinez et al., 2021)

Appropriate communication protocols are necessary to transfer information correctly between different systems. Multiple different communication protocols exist. In this thesis, the used communication protocol will be the Open Platform Communications (OPC) Unified Architecture (UA). The choice of the OPC UA to be the used communication protocol was already made before starting this thesis. Therefore, any comparison between different communication protocols or the OPC UA suitability analysis for the MES and automation integration with the Digital Twin are not performed. All the used software has readiness to use the OPC UA for data transfer which makes it very suitable communication protocol for this purpose.

This thesis is divided into multiple main chapters. The results of the literature review will be discussed in chapter 2. In the chapter 2 subchapters 2.5, 2.6 and 2.7 potential applications, benefits and challenges are introduced and discussed. Next in chapter 3, the implementation of the MES-Automation-DT integration is presented. In chapters 4 and 5, the results are presented and discussed. Finally, in chapter 6 the final summary is drawn.

2. LITERATURE REVIEW

To correctly understand the possibilities of the Digital Twin for the manufacturing industry it is important to understand what the Digital Twin is. This also helps to understand the limitations and challenges which the Digital Twin might have. In this chapter, the theoretical background of the Digital Twin is presented. This chapter also includes the literature review findings on the DT applications, advantages, and challenges.

This thesis is not only about the Digital Twin but also its integration with other important systems to achieve the full potential of the Digital Twin. When talking about the integration, the ISA-95 model is the basis for understanding it and its importance. At first, the ISA-95 model is introduced. Manufacturing Execution Systems and automation and those integration are also introduced in this chapter.

2.1 ISA-95 / IEC 62264 Standard

ISA-95 also ANSI/ISA-95 is an international standard of the International Society of Automation (ISA). International Electrotechnical Commission (IEC) has also made standard IEC 62264 which is based on the ISA-95 standard. The purpose of the ISA-95 / IEC 62264 is to provide standard terminology and a coherent set of concepts and models to help integrating business logistics into the manufacturing. By this, it aims to improve communication between systems in different levels and make integration simpler at a lower cost. (International Electrotechnical Commission, 2013; Jaskó et al., 2020) ISA-95 defines a five-level functional hierarchy where the different levels go from zero to four. According to IEC (2013) these five functional hierarchy levels of ISA-95 are the following:

- Level 0. Physical production processes
- Level 1. Sensing and manipulating the physical processes
- Level 2. Monitoring and controlling the physical processes
- Level 3. Activities to maintain and coordinate the processes, production data collection
- Level 4. Business-related activities to manage a manufacturing organization

All these levels of the functional hierarchy are shown in Figure 3 with additional information.

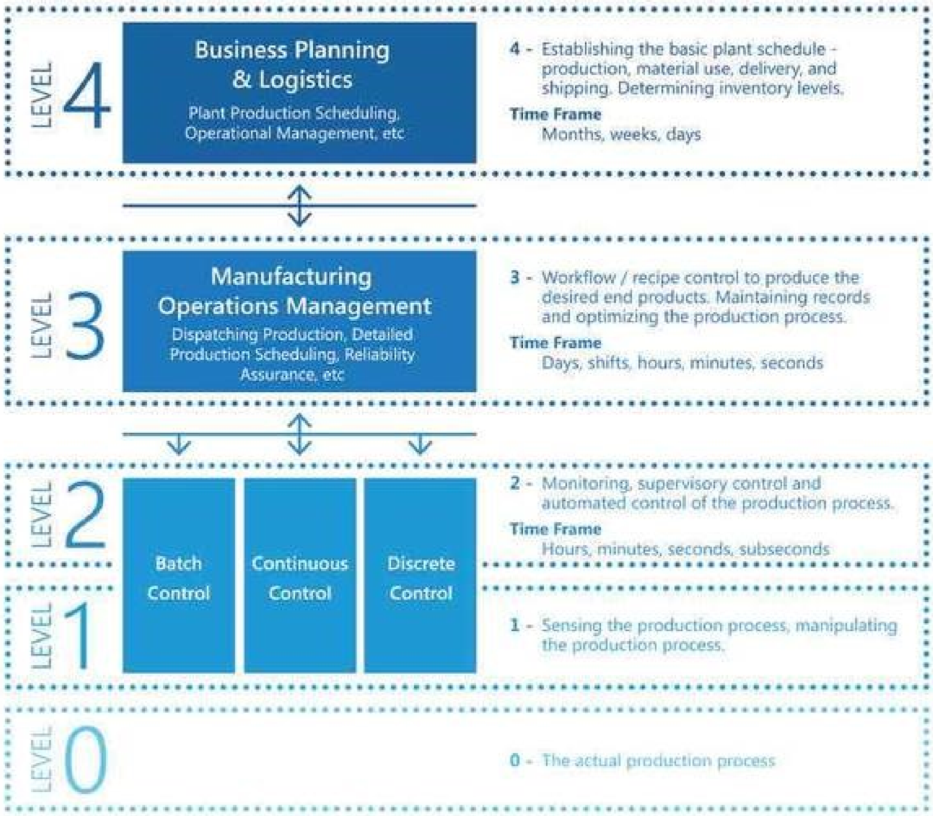

Figure 3: ISA-95 levels of functional hierarchy (Almada-Lobo, 2015)

In many production systems different production equipment is controlled automatically. Looking at Figure 3 it means the level 3 integration with the levels 2 and 1. ISA (2022) defines the automation as: "the creation and application of technology to monitor and control the production and delivery of products and services." It includes wide selection of different technologies such as robots and expert systems, process measurement and control, sensors, and wireless applications.

This automation layer and automatic control is nowadays performed in many factories by Programmable Logic Controllers (PLCs) (Langmann and Rojas-Pena, 2016; Cavalieri and Salafia, 2020). Those are in the layer 2 in the Figure 3. The usage of the PLCs, for example the programming languages, are determined more in detail in the standard IEC 61131 (2003). Because the PLCs or industrial control in general do not fall within the scope of this thesis, those will not be discussed further.

Figure 4 illustrates alternative form of the ISA-95 based functional hierarchy with the typical company information systems, ERP and MES. Same Figure 4 also illustrates well the different time frames between different layers as well as the information scope and detail levels.

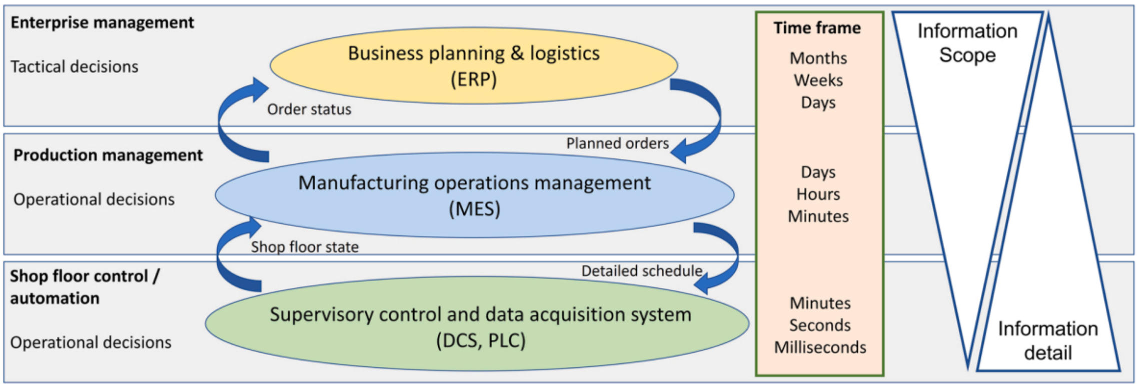

Figure 4: Information and management systems for planning and control (Rolon and Martinez, 2012; Shojaeinasab et al., 2022)

This thesis scope in the Figure 4 lies between two bottom layers, production management and shop floor control / automation.

2.2 Manufacturing Execution Systems

The Enterprise Resource Planning systems are systems which are designed for the overall management of companies at a higher level (Fatima et al., 2020). The ERP systems give a good overview of what is going on and how the company performs. Due to the focus on that higher level management, the ERP systems lack of a good integration to the shop floor level (Fatima et al., 2020). The ERP systems also lack a good real-time production level information (Mantravadi and Møller, 2019).

Since the mid-1990s manufacturing companies have begun to recognise the need to fill the gap between the higher management level and the lower shop floor level. Suitable solution to fill this gap was found, the Manufacturing Execution System or usually shortly MES. The MES is a company information system which is designed for the shop floor level management. This includes execution, monitoring and reporting of factory floor operations in a real-time. (Mantravadi and Møller, 2019; Fatima et al., 2020; Jaskó et al., 2020) It is also the information system located closest to the shop floor level (Salvadorinho and Teixeira, 2020).

The MES has eleven main functions which are defined by MESA International (1997):

1. Operation planning/details
2. Allocation of resources and status
3. Distribution of production units
4. Document control
5. Product tracking and genealogy
6. Performance analysis
7. Work Management
8. Maintenance Management
9. Process Management
10. Quality Management
11. Data Collection

The MES is used to collect data about the production processes in a real-time and that data is used to check if the production plan and its implementation matches (Fatima et al., 2020). This provides a better opportunity to detect possible anomalies in the production processes. The MES also allows quality control of processes and products (Fatima et al., 2020). This is an important thing for the production quality.

The requirements for the MES have increased and are still increasing because of the manufacturing digitalisation and Industry 4.0. The MES is moving from its traditional role as an executive middle-ware software towards much wider vision as an enabler of interoperability between different operation layers in the modern Cyber-Physical Production Systems (CPPS). (Jaskó et al., 2020; Beregi et al., 2021) Jaskó et al. (2020) define the Cyber-Physical Systems (CPS) as an objects with a specific computing capability and embedded software. Whereas the term Cyber-Physical Production Systems is related to the manufacturing equipment, for example sensors and actuators, and it has a completely integrated intelligent network which knows its own status, capabilities and possible configurations (Jaskó et al., 2020). Shortly the CPS can mean any system linking virtual and physical worlds together, whereas the CPPS focuses on the production systems with that similar link.

The CPS and CPPS set the new requirements for the MES. In Industry 4.0 environment the Cyber-Physical Systems will generate remarkable data flows and the MES must be able to handle those. The MES should connect them seamlessly, securely, and reliably to enable highly automated intelligent solutions. (Jaskó et al., 2020)

The changing manufacturing field also requires changes from the MES. Beregi et al. (2021) mention that the typical MES functions will still stay as important as before even the architecture of the MES would change. One important new role that the MES must adapt to is the coordination of the horizontal and the vertical integration (Jaskó et al., 2020). Future factories must have smooth data flow between all the enterprise layers; company management layer, production management layer and control / automation layer.

Companies have traditionally been using customised information systems for the shop floor level and manufacturing data have been collected for example in the different Excel spreadsheets (Mantravadi and Møller, 2019). With the globalised markets and increasing customer demands, the manufacturing companies have been forced to find more effective ways to manage manufacturing processes. The MES aims to automate the data collection and eliminate the manual paperwork (Mantravadi and Møller, 2019). The MES is also capable of providing the real-time production data to increase transparency which can improve production system performance (Mantravadi and Møller, 2019).

2.3 Systems Integration

In the chapter 2.1 ISA-95 / IEC 62264 Standard the relation between different levels of the automation pyramid were discussed. Improving and simplifying integration opportunities was mentioned as one of its goals. In this chapter, the importance of this integration and some typical characteristics of it will be discussed. Especially the interest will be towards the future manufacturing systems and the requirements which those set for the integration.

The integration between different systems and ISA-95 layers is an important step towards the smart manufacturing and Industry 4.0 goals. In the I4.0 different devices and systems should be seamlessly integrated with each other to achieve continuous data flow. (Negri et al., 2017) According to Chen et al. (2020) the first step is to integrate hardware and software and allow communication between these. This would allow communication between software and software, and hardware and software (Chen et al., 2020).

There exist two types of the integration that can be done between different systems, horizontal and vertical integration. The horizontal integration aims to link multiple machines, equipment or units at the same ISA-95 level (Kagermann et al., 2013; Werr, 2014) Whereas the vertical integration's main goal is to integrate all the logical layers of the organisation. Starting from the shop floor level at the bottom to all the way up to the whole enterprise level. It aims to allow a transparent and easy data flow up and down between layers which helps to make strategic and tactical decisions. (Jaskó et al., 2020) The horizontal and vertical integration are illustrated in Figure 5.

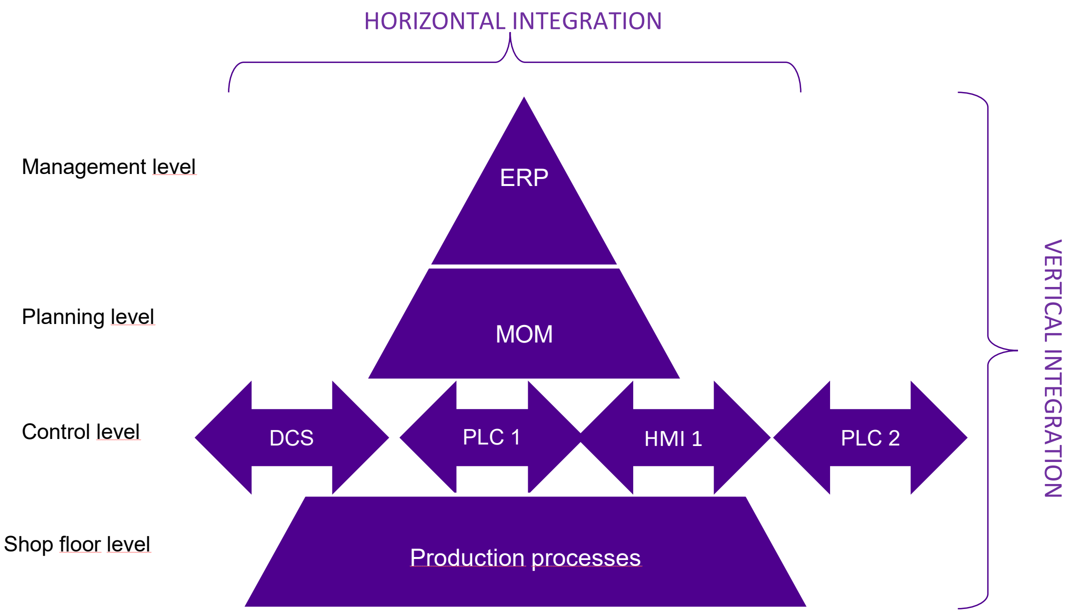

Figure 5: Horizontal and vertical integration

According to Beregi et al. (2021) Industrial Internet of Things (IIoT) with sensors and CPPS generate a lot of data and correct vertical integration is the way to ensure effective data flows. Jaskó et al. (2020) also mention that proper integration between ERP, MES and the shop floor increases flexibility, agility, efficiency and quality of the manufacturing processes. The same idea is also supported by Mantravadi and Møller (2019) in their article pointing out that the transparent and easy data flow and smooth collaboration between all the enterprise layers is a must have for the future manufacturing industry. Chen et al. (2020) support this idea by mentioning that the smart factory and Industry 4.0 require both horizontal and vertical integration. It is easy to see that the MES will play an important role as an enabler of this integration in the future manufacturing (Jaskó et al., 2020).

Cimino et al. (2019) mention that the most of the companies are using traditional manufacturing machines. This leads in a typical hierarchical ISA-95 based automation pyramid where the sequence of the operations is controlled by the MES. This makes it more difficult to implement and integrate the DT as a part of the traditional MES-based equipment. (Cimino et al., 2019) This makes the integration part an important to consider when discussing about the DT.

The proper integration into both vertical and horizontal directions require suitable communication protocols. Many different possibilities exist in that area such as MTConnect, Message Queue Telemetry Transport (MQTT) and OPC UA (González et al., 2019). This thesis scope is limited only for the use of the OPC UA technology.

The OPC UA is a platform independent service-oriented architecture for the secure and reliable interchange of data in the industrial automation area (OPC Foundation, 2022). It is developed by OPC Foundation. Beregi et al. (2021) mention in their article that the OPC UA is not only a communication and transportation protocol. It is a more complex information modelling technology (Beregi et al., 2021). It is mentioned to be one of the most promising solutions to lead the standardisation and system integration in the industrial applications (González et al., 2019).

The OPC UA is mentioned as the core technology for the I4.0 (Novák and Vyskočil, 2022). Liu et al. (2022) mention the OPC UA being designed for the cross machine communication which makes it good for an applications where different machines must communicate such as the DT. The OPC UA is also mentioned as a suitable communication protocol for the data transfer between the DT and other systems in multiple articles (Azarmipour et al., 2020; Jaskó et al., 2020; Negri et al., 2020). Cimino et al. (2019) mention in their review article that the OPC UA is one of the most used communication protocols in the DT implementations. These mentioned things support the use of the OPC UA as the DT communication protocol.

2.4 Digital Twin in Manufacturing

The manufacturing is a process which aims to turn different materials into goods as optimally as possible. It requires different resources such as people, capital, processes, systems, and enterprises to deliver end-products with an added value to the markets. (Beregi et al., 2021) A concept called Digital Twin appears frequently when it comes to future manufacturing systems. This concept is discussed further below.

History of the twinning can be seen to start as a part of the NASA’s (National Aeronautics and Space Administration) Apollo program in 1960s when NASA introduced a concept about the twin. At that time, the twin was a physical equivalent of the spacecraft being sent into the space. They manufactured two identical spacecrafts which a one was sent into the space while the another was kept on the Earth. The twin version on the Earth was used to simulate the conditions in the space and observe the potential impacts of these to the actual spacecraft. (Rosen et al., 2015; Ashtari Talkhestani et al., 2019; Prarthana et al., 2021; Liu et al., 2022)

As can be seen, the idea behind the twin is older than it might be expected. At the same time, it is quite easy to understand why this kind of twinning has not become more popular. It is quite expensive to build even a one complete complex system not to mention building two of them (Modoni et al., 2019; Prarthana et al., 2021). Still nowadays physical twins are used, one good example is the Iron Bird which is used in the aircraft industry (Rosen et al., 2015; Airbus Industries, 2017). But more developed computation and simulation technologies have moved the twins from the physical worlds more into the virtual environments towards the Digital Twins (Rosen et al., 2015; Prarthana et al., 2021).

There is a wide consensus in the literature that the concept of the Digital Twin was first introduced by Michael Grieves. In 2003, he taught a Product Lifecycle Management (PLM) related course at the University of Michigan where he introduced this DT concept. (Grieves, 2014; Grieves and Vickers, 2017; Tao et al., 2019; Neto et al., 2020) This concept had all the elements of the Digital Twin namely real space, digital space and data and information connection between the real and virtual spaces (Grieves, 2014; Grieves and Vickers, 2017; Atalay et al., 2021). This concept is illustrated in Figure 6.

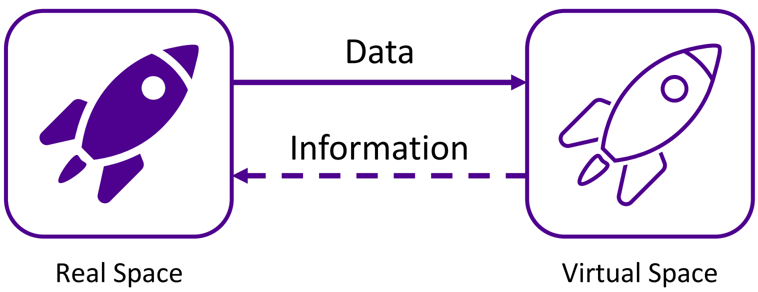

Figure 6: The Digital Twin concept of Grieves (based on Grieves, 2014)

Even the idea behind the Digital Twin was introduced in 2003, the first definition for the Digital Twin appeared in 2010. It was in the draft and then in the final version of the NASA’s (Shafto et al., 2010) Modelling, Simulation, Information Technology & Processing Roadmap in 2010 (Negri et al., 2017). During that time, the interest and research towards the DT was still quite weak (Tao et al., 2019). The real interest towards the

Digital Twin started after Grieves (2014) published his whitepaper about the Digital Twin in 2014 because it explained potentials and applications of the DT (Tao et al., 2019; Neto et al., 2020).

The original idea of the Digital Twin was to mirror the products and it spread from the aerospace sector (Negri et al., 2017; Kritzinger et al., 2018). According to Kritzinger et al. (2018) the original idea of the DT does not limit it only to the product stage but it also allows it to widen into the process stage too. Negri et al. (2017) mention that the first time the term Digital Twin appeared in the manufacturing context was in 2013. In that time Lee et al. (2013) determined the DT to be a virtual representation of the production resources and not only a products. This set the term Digital Twin in a manufacturing environment which this thesis also concentrates on. In this area, the term Digital Twin is not even a decade old but it is mentioned to be one of the most promising DT application fields (Cimino et al., 2019). The Digital Twin is mentioned to be one of the main concepts of the I4.0 and the smart manufacturing (Negri et al., 2017; Tao et al., 2019; Onaji et al., 2022). As a result, there is a widespread interest in the Digital Twin in manufacturing, and a lot of research and publications have been done. The simplified DT timeline showing the main milestones mentioned in this thesis is shown in Figure 7.

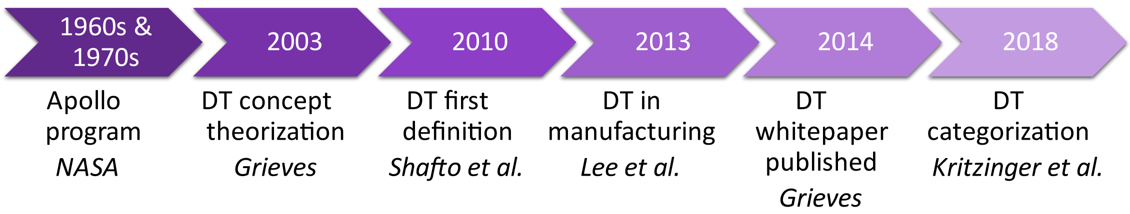

Figure 7: The Digital Twin timeline

Although the Digital Twin is a topic of widespread interest in both academia and industry, it does not seem to have one clear definition. This allegation is also supported by many scientific articles, all of which state that the DT does not have a single formal definition (Negri et al., 2017; Kritzinger et al., 2018; Ashtari Talkhestani et al., 2019; Cimino et al., 2019; Liu et al., 2022). Despite this, the common consensus is that the DT can be seen as a CPS and it has at least three main components (Rosen et al., 2015; Liu et al., 2022):

- self-aware physical system enabled by sensors,
- real-time updated virtual model using available data,
- communication method which connects all the components of the physical and virtual systems.

Those are the same three main components which Grieves (2014) already introduced in 2003; real space, digital space and connection of data and information between real and virtual spaces (Grieves and Vickers, 2017). Based on this three piece structure, Atalay et al. (2021) have proposed the following components into the manufacturing context:

- real physical production system,
- its virtual counterpart, and
- data flow between these two systems.

Above the Digital Twin was determined to be a Cyber-Physical System itself. Autiosalo (2018), Ashtari Talkhestani (2019) and Lu et al. (2020) define the Digital Twin as meaning only the cyber part of the CPS which still needs the physical system to be mirrored. The Digital Twin has similarities to CPSs and Internet of Things (IoT), but it is someway different and complimentary to them as Lattanzi et al. (2021) mention. Therefore, it is not clear what is exactly the relation of the DT and CPS but somehow those are interconnected. It depends on the definition of how these things can be seen. For this thesis context, it is not important if the Digital Twin can be seen as a whole CPS or just a part of it.

There exists also a more general definition for the Digital Twin in the literature which does not take CPS into account at all. This kind of more general definition is the definition which characterises the Digital Twin considered in this thesis. One such a definition of the Digital Twin in manufacturing context is given by Negri et al. (2017) based for the Garretti et al. (2012) article: "*The DT consists of a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behaviour of the production system at each life cycle phase in real time*."

This definition can be shortened and condensed into the following sentence which kind of description is found in most of the reviewed articles. The Digital Twin is meant to be a virtual and computerised representation of the physical system which is deeply linked into the whole system for the real-time data synchronisation (Negri et al., 2017; Cimino et al., 2019; Ashtari Talkhestani et al., 2019; Atalay et al., 2021; Autiosalo et al., 2021; Liu et al., 2022).

This real-time data synchronisation from the sensed data on the shop floor is possible by modern IoT and I4.0 technologies such as sensors (Negri et al., 2017; Liu et al., 2022). This allows the virtual version of the system to be updated autonomously based on the current state of the real system (Liu et al., 2022). This real-time data synchronisation makes it possible to perform real-time optimisation, decision making, monitoring and predictive maintenance tasks (Negri et al., 2017; Atalay et al., 2021). Beyond the real-time data usage, the Digital Twin can be used also to forecast and estimate system future conditions (Atalay et al., 2021).

The definitions above mention the connection between the physical and virtual worlds. It is still quite unclear what kind of data transfer there is happening and in which directions. Kritzinger et al. (2018) tackled that problem and made a literature review about the Digital Twins in manufacturing in 2018. They concluded that there is no clear definition for the term Digital Twin and that there is no common consensus what the term DT really means as was already explained above. Therefore, they proposed the categorisation of the Digital Twins based on the level of the data integration between physical and virtual worlds. The proposed subcategories for the Digital Twins are show in Figure 8 (Kritzinger et al., 2018) and introduced below:

- Digital Model (DM)
    - In the Digital Model, there does not exist any automated data flow between physical and digital worlds. Changes in the physical world do not have any direct effect for the digital world and vice versa.
- Digital Shadow (DS)
    - In the Digital Shadow, there exist one-way automated data flow from physical world to digital world. Changes in the physical world changes the state of the digital world, but not vice versa.
- Digital Twin (DT)
    - In the Digital Twin, the physical and virtual worlds are fully integrated. There exist automated data flow in both directions. Changes in the physical world changes the state of the digital world and vice versa.

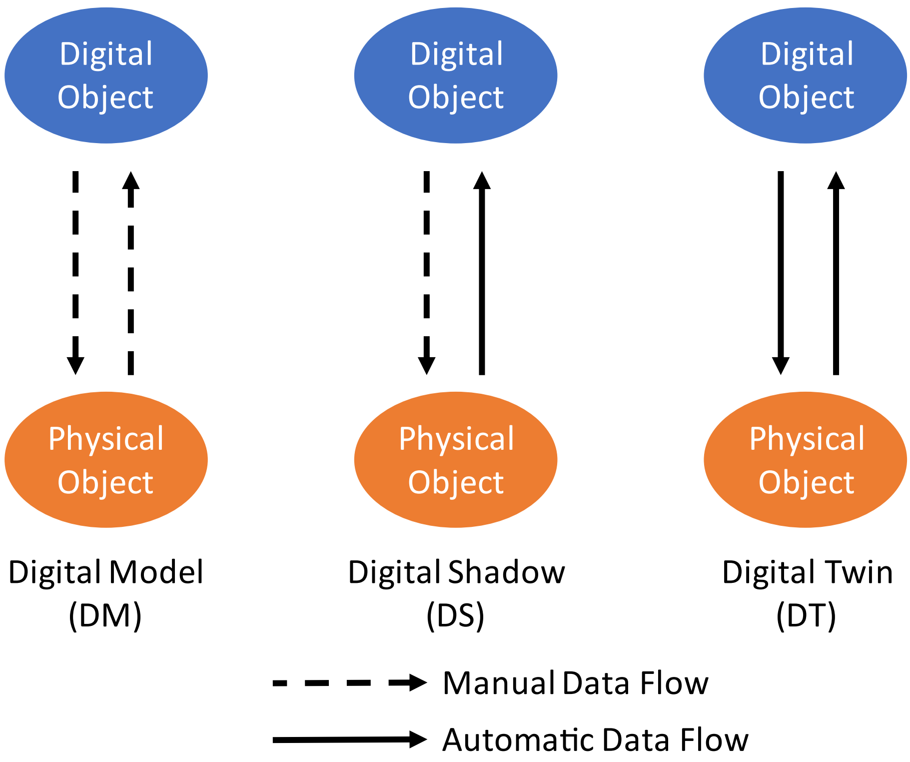

Figure 8: Level of data integration (based on Kritzinger et al., 2018; Lattanzi et al., 2021)

This categorisation of the Digital Twins proposed by Kritzinger et al. (2018) is very widely accepted in the literature with over 700 citations in the Scopus database in the September 2022. Liu et al. (2022) reviewed many review articles and mentioned that the DTs are commonly classified into these three categories based on the communication directions between physical and virtual worlds as proposed by Kritzinger et al. (2018). Here are a few of the articles used in this thesis that are referring to and using that categorisation of Kritzinger et al. (2018): (Cimino et al., 2019), (Atalay et al., 2021), (Lattanzi et al., 2021), (Rolle et al., 2021), (Onaji et al., 2022) and (Savolainen and Knudsen, 2022).

In this thesis, the proposed classification of the Digital Twins by Kritzinger et al. (2018) will be followed as it is done widely in the other literature too. The generic term Digital Twin will be used to mean any of these three subclasses the DM, the DS, or the real DT. In cases where it is necessary to distinguish the type of the Digital Twin used, it will be made clear in the text which type of the Digital Twin this case is suitable for. Also, the term “real Digital Twin” will be used to mean the Kritzinger et al. (2018) defined Digital Twin.

It is also important to mention that there is a big difference in how common each subcategory of the DT is (Kritzinger et al., 2018; Cimino et al., 2019; Liu et al., 2022). The most common are the two simplest versions, the Digital Model and the Digital Shadow (Kritzinger et al., 2018; Cimino et al., 2019; Liu et al., 2022). The most complex category of the Digital Twins, the real Digital Twin, is mentioned in the literature to be very rare (Kritzinger et al., 2018; Liu et al., 2022). Kritzinger et al. (2018) also pointed out that the term Digital Twin is widely used as a synonym for the Digital Model and the Digital Shadow which makes this classification by the integration level more difficult.

As can be seen, the term Digital Twin does not have a one clear definition which makes the review of the literature more challenging. Use of the term Digital Twin in the scientific literature varies. In addition to this, the DT also lacks standardisation (Ashtari Talkhestani et al., 2019; Liu et al., 2022; Onaji et al., 2022). Therefore, multiple different implementation methods with different characteristics exists (Ashtari Talkhestani et al., 2019; Liu et al., 2022; Onaji et al., 2022).

Atalay et al. (2021) described in their article how the fully functioning DT should work. First, it gets the real-life data from the physical system and transfers it into the virtual model. This digital version of the system then performs the calculations and simulations using the data which can be updated near real-time. Virtual model provides the results based on the real-time data which can then be used to make decisions or predict the state of the physical system in future. Physical system can then be updated automatically or manually based on the results. Then the loop can start from the beginning. This kind of loop should be continuous for the fully functional DT. (Atalay et al., 2021) There it is easy to see that the Digital Twin is much more than only a pure data. It has algorithms and predetermined actions to make it intelligent (Rosen et al., 2015; Kritzinger et al., 2018). Therefore, the DT is seen as an enabler to improve the real systems performance by using the information from the virtual system (Rolle et al., 2021).

The real Digital Twin must have a bidirectional communication, physical-to-virtual and virtual-to-physical. In this the virtual model is able to control the physical system using the control data even without human intervention (Ashtari Talkhestani et al., 2019; Cimino et al., 2019; Lattanzi et al., 2021; Liu et al., 2022). Ashtari Talkhestani et al. (2019) have introduced the concept of the Intelligent Digital Twin in their article. This Intelligent Digital Twin uses Artificial Intelligence (AI) which makes it possible to make decisions based on the data and simulations. Based on these decisions, the virtual part of the real Digital Twin can control the actual physical system. (Ashtari Talkhestani et al., 2019)

The simulation aspect is an important part of the Digital Twin so it should not be ignored. According Tao et al. (2019) modelling and simulation are the core of the DT implementations. The DT can be seen as an environment that supports various simulation tasks or even as the simulation itself that is synchronised in near real-time with the physical world (Cimino et al., 2019). It has also been mentioned as a next-generation simulation technology where it can serve in the design evaluation and validation purposes before realising the physical system (Rosen et al., 2015; Tao et al., 2019; Lattanzi et al., 2021; Savolainen and Knudsen, 2022). Ashtari Talkhestani et al. (2019) also mention that this simulation feature of the DT for the production system can make the system easily and quickly reconfigurable when different scenarios can be analysed before implementation. At the same time, it is important to mention that the DT is more than only a simulation (Singh et al., 2018; Ashtari Talkhestani et al., 2019). Onaji et al. (2022) have defined the three DT features which differentiate it from the simulation model and these are the following:

- Real-time data exchange
- Interaction and convergence
- Self-development

A lot of material about the DT is available in the research literature. Despite this the material of the DT from the real industrial environment is quite limited. Practical case examples are mentioned to be rare, especially for the real Digital Twin, in manufacturing industry (Kritzinger et al., 2018; Fuller et al., 2020; Perno et al., 2022). Bambura et al. (2020) also mention that there is a lack of real-life DT case implementations in the literature. Whereas, many frameworks and concepts have been presented in the literature (Bambura et al., 2020). Modoni et al. (2019) mention the DT diffusion still being quite small. Lu et al. (2020) and Lattanzi et al. (2021) mentioned in their review articles that the most of the DT research made in the field of manufacturing is conceptual work and real use-case implementations are still at early stage. Therefore, there might be some limitations to the identified applications, advantages, and challenges which are discussed below.

2.5 Digital Twin Applications in Manufacturing

The DT has many applications at different areas of manufacturing. Most common applications focus on the shop floor manufacturing activities and manufacturing in general which includes for example monitoring and management. (Ashtari Talkhestani et al., 2019; Cimino et al., 2019; Atalay et al., 2021). In this chapter, the most common uses of the DT in the field of the manufacturing are introduced. Then in the following subchapters the potential benefits and common challenges of the DTs usage in these applications are introduced. The main goal of this and following two chapters is to answer why companies should implement the Digital Twins in their production and what challenges should be considered when planning the DT implementations.

The DT applications are mainly identified from the literature. There are several great review articles that are focusing for the DT applications, benefits, and challenges. Cimino et al. (2019) mention manufacturing area as a one of the most promising fields for the successful implementation of the Digital Twins and to benefit from its use. They have identified multiple potential applications of the DT in their review article. Modoni et al. (2019) have done a literature review where they have identified potential DT usages in the manufacturing. Bambura et al. (2020) have identified multiple different potential applications for the Digital Twin in their article where they have implemented the DT to the engine block manufacturing process. Neto et al. (2020) have identified multiple drivers for the Digital Twin implementations from the literature and expert interviews. The drivers are the reasons which lead the companies to launch and complete the DT related projects (Neto et al., 2020). Liu et al. (2022) have made a survey of the DT implementations. They mention the Digital Twin still being an emerging technology which has both potential and challenges.

In addition to the literature review, one interview was made. It aimed to get the real industrial perspective of the DT's current state in the industry. This interview took place at the beginning of July 2022 when the company was building its new production plant. They have been using simulation models actively and were planning to transform those simulation models to the DT during the plant operation phase. This led to them being selected for the interview to get potentially different and new points of views for the DT related things. After the literature review and interview some key application categories were identified. All of these have the potential to benefit from the use of the Digital Twin. The main identified DT applications in manufacturing industry are the following:

1. Monitoring
2. Optimisation
3. Maintenance
4. Simulation
5. Virtual commissioning
6. Training

Those are also presented in Table 1 which also includes some of the references where that application is mentioned. It is also good to notice that the Digital Twin applications are not only limited for the operational stage of the manufacturing system, those can also be used for example at the engineering phase (Ashtari Talkhestani et al., 2019).

Table 1: Applications table

Application	References
Monitoring	(Qi and Tao, 2018; Cimino et al., 2019; Modoni et al., 2019; Tao et al., 2019; Bambura et al., 2020; Fuller et al., 2020; Rasheed et al., 2020; Prarthana et al., 2021; Rathore et al., 2021; Onaji et al., 2022)
Optimisation	(Negri et al., 2017; Qi and Tao, 2018; Ashtari Talkhestani et al., 2019; Cimino et al., 2019; He et al., 2019; Modoni et al., 2019; Zhang et al., 2019; Bambura et al., 2020; Novák et al., 2020; Rasheed et al., 2020; Prarthana et al., 2021; Rathore et al., 2021; Gulewicz, 2022; Onaji et al., 2022)
Maintenance	(Negri et al., 2017; Qi and Tao, 2018; Ashtari Talkhestani et al., 2019; Cimino et al., 2019; He et al., 2019; Neto et al., 2020; Rasheed et al., 2020; Rathore et al., 2021; Gulewicz, 2022)
Simulation	(Negri et al., 2017; Modoni et al., 2019; Bambura et al., 2020; Barbieri et al., 2021; Fuller et al., 2020; Löcklin et al., 2020; Onaji et al., 2022)
Virtual commissioning	(Negri et al., 2017; Ashtari Talkhestani et al., 2019; Modoni et al., 2019; Löcklin et al., 2020; Barbieri et al., 2021; Prarthana et al., 2021)
Training	(Modoni et al., 2019; Neto et al., 2020; Yang et al., 2022)

Monitoring

The real-time process monitoring, and remote monitoring are one of the potential uses of the Digital Twin. The remote monitoring enables the monitoring and observation of the different processes of the production system without being physically on site. (Qi and Tao, 2018; Cimino et al., 2019; Tao et al., 2019; Bambura et al., 2020; Rasheed et al., 2020; Prarthana et al., 2021; Rathore et al., 2021; Onaji et al., 2022) This potential of the DT for the monitoring purposes was also brought up in the interview. One good potential usage for the remote monitoring would be a similar situation as during COVID-19, when there was a desire to keep social contacts as a minimum. Another case where this would be beneficial is a hazardous process or a phase of process where on-site monitoring is not possible, and it is safer to do it remotely.

One important potential of the DT at the monitoring use is the visualisation capabilities (Qi and Tao, 2018). The DTs can also be used to visualise the real-time status which can be helpful when used to monitoring the manufacturing processes (Tao et al., 2019). Visualisation can be used to underline important information which can help for example in the detection of deviations. In many cases, the DT virtual models contain three-dimensional dynamic models (Qi and Tao, 2018). According to Qi and Tao (2018) this takes the visualisation of the current state of the production to the next level compared to traditional static tools.

The Digital Twin's real-time monitoring feature opens up more potential applications for the DT. Fuller et al. (2020) mention the DT potential to show the real-time status and performance of the machines which enables better and earlier identification of potential issues. Modoni et al. (2019) mention that the real-time monitoring enables better decision making about maintenance strategies and early detection of possible errors. Tao et al. (2019) mention the DT virtual models to be able to analyse, evaluate and optimise production using the real-time data coming from the physical system. They also mention that these capabilities require the use of AI algorithms (Tao et al., 2019).

The real-time data collection and monitoring is possible for both the Digital Shadow and the real Digital Twin. This feature can be considered as a backbone of the Digital Twin since almost all the following applications are based on the real-time data collection. To get the full benefits of those applications, it requires in many cases the bidirectional autonomous data flow. As we know it is possible only for the real Digital Twin.

Optimisation

Real-time data collection opens opportunities for the process optimisation. This is one application where the Digital Twin is seen to have a significant potential in the manufacturing industry (Rosen et al., 2015; Negri et al., 2017; Ashtari Talkhestani et al., 2019; Cimino et al., 2019; Rasheed et al., 2020; Prarthana et al., 2021; Rathore et al., 2021; Onaji et al., 2022). In the interview the information solutions manager mentioned the optimisation as a one potential usage of the DT, but it was not the main application where they intended to use it. Using the Digital Twin in optimisation can lead to several improvements in the production and these will be discussed later.

One way to optimise is to collect data from the physical world, and then compare it to the plans. If the plans and the reality differ, the DT can be used to find out reasons and optimise the production. Another approach for the optimisation is that the virtual part of the Digital Twin is used to simulate and evaluate different production schedules to find the optimal performance for a specific situation. (Qi and Tao, 2018).

Autonomous production optimisation is only possible if the DT has the closed loop between physical and virtual worlds. This can only be realised with the real Digital Twin. The feedback ability from the virtual to the real world can be used for the autonomous decision making in the real world. With these decisions the system performance can be optimised. (Modoni et al., 2019) One example of this is the robot movement optimisation (Huynh et al., 2019).

Bambura et al. (2020) mention the bottleneck detection and diagnosis to be one of the key applications of the Digital Twin. Gulewicz (2022) has also identified it as a one of the potential uses of the DT. Bottlenecks have a distinct impact for the system performance (Bambura et al., 2020). If the throughput time can be shortened without making compromises on another productivity meters, it is beneficial for the manufacturing companies. Therefore, it is important to detect these bottlenecks. In a case study of the Bambura et al. (2020), they have implemented a real-time bottleneck detection as a part of the DT. In this case, the actual bottleneck was located at a different point in the production system than it was first expected (Bambura et al., 2020). This example clearly shows the potential advantages which the Digital Twin can bring over the traditional simulation and other methods. The case study showed promising results of the DT to work as a real-time optimisation tool as Bambura et al. (2020) mention.

Maintenance

Novák et al. (2020) mention the continuously running DT to be an efficient tool in case of an unexpected event to reschedule the production. These unexpected events can be for example manufacturing equipment failures. Better situation would be to avoid these failures completely. The Digital Twin has been identified as a useful tool for predictive maintenance which aims to do the maintenance before equipment failures (Negri et al., 2017; Ashtari Talkhestani et al., 2019; Cimino et al., 2019; Neto et al., 2020; Gulewicz, 2022).

The Digital Twin has one main benefit over the traditional monitoring tools in the context of the maintenance. The real-time data gathering capabilities can be used to predict potential failures of the manufacturing equipment. This real-time data is analysed with intelligent analysing algorithms to detect potential anomalies in the equipment behaviour.

Using this information, the maintenance plans can be rescheduled to optimise the maintenance times and avoid failures. (Rasheed et al., 2020)

Qi and Tao (2018) mention the historical data use possibilities of the Digital Twin as a suitable for predicting the failures and estimating the maintenance needs. He et al. (2019) proposed the Digital Twin in a process industry which enable automated decision and optimisation when a failure occurs. The proposed Digital Twin was able to detect failures and optimise the production based on it. The same system was able to be used for general process monitoring and diagnosis using the collected data. (He et al., 2019) Neto et al. (2020) have identified the smart fault detection and predictive maintenance bring clear benefits to the manufacturing industry.

Simulation

The DT offers a possibility to perform simulations where it is possible to test different production programs and configurations. The data collection allows use of the historical data in the simulations. (Modoni et al., 2019; Onaji et al., 2022) More important than historical data usage is the potential of using the real-time data in the simulation (Bambura et al., 2020; Fuller et al., 2020). Traditional simulation models do not have this capability for the real-time data usage, which can be useful for the prediction and learning purposes (Fuller et al., 2020). This capability can also be used to compare modelled and real system behaviour (Löcklin et al., 2020). The noticed differentiations between those two can be solved using the DT optimisation algorithms.

An important difference between traditional simulation and the DT is in the flow of the data. In the traditional simulation there does not exist any automated data flow between physical and virtual worlds. In the real Digital Twin, the data flow is bidirectional and automated. This allows the real-time data usage, and the simulation results can be directly used to optimise the real system. This increases the system’s capability to adapt to unexcepted situations. (Negri et al., 2017; Barbieri et al., 2021) Therefore, the DT is much more than only a traditional simulation model (Ashtari Talkhestani et al., 2019).

Virtual Commissioning

One potential application for the Digital Twin is Virtual Commissioning (VC) (Negri et al., 2017; Ashtari Talkhestani et al., 2019; Löcklin et al., 2020; Prarthana et al., 2021). In this case, it is important to notice that the physical system may not exist yet, so the DT cannot be the real Digital Twin or the Digital Shadow. VC applications are mainly limited to the Digital Model level of the integration.

In VC, the DT can be used to replace the missing components. The system may not be built yet or may be under the maintenance when the DT is used for Virtual Commissioning. (Löcklin et al., 2020) During the design phase, a lot of time and other resources can be saved by simulating. The DT as a part of VC can be seen as a one possible way to solve potential issues existing in the new system configurations. (Prarthana et al., 2021) It can be used to validate and verify changes before implementing these into the real physical system (Modoni et al., 2019; Barbieri et al., 2021; Prarthana et al., 2021). Ashtari Talkhestani et al. (2019) proposed industrial robot and control unit offline programming and VC as a one potential way to use the Digital Twins.

Löcklin et al. (2020) have made a literature review about the DTs and VC. The results show that the DT has been used successfully in verification and validation purposes (Löcklin et al., 2020). Prarthana et al. (2021) mention that by using the DT in Virtual Commissioning approximately 25 % of the total manufacturing time can be saved in discrete manufacturing field. Therefore, the DT can be seen as a suitable tool for efficient verification and validation processes. The DT also has a lot of other capabilities so its use should not be limited only for the virtual commissioning or the simulation (Löcklin et al., 2020).

In the interview, it was revealed that the product manufactured by the company is unique in the world which means that its production process is also unique. This means that the factory they are now building is also quite unique. This makes the system commissioning and ramp-up phases even more critical and challenging than usual. They have been and are using multiple simulation models to model and test different things during the design and production phases. This is a great example of VC and simulation results have already shown significant benefits for the company. In the interview, it was mentioned that more obvious benefits can be expected later in the ramp-up phase. They also have a vision that after the design, Virtual Commissioning and ramp-up phases, the used simulation models can be run parallel with the real systems. The simulation model is then transformed to the Digital Twin. This vision of the company is a great example of how the simulation and the Digital Twin can be used during all the phases of the production system's lifecycle. It is also an example how the models for the VC can be used later for other applications.

Training

The DT can be used for teaching and learning. The NASA's physical twin was meant to be used for training purposes. Similarly the DT together with AR/VR technologies can be used for teaching and training purposes. (Modoni et al., 2019; Yang et al., 2022) According to Neto et al. (2020) the employee training is seen as a one beneficial application of the Digital Twin. This training and learning ability can be used for training new employees for the manufacturing process tasks without being in the real manufacturing environment. This can save time from training in the actual manufacturing environment which leads to the cost savings.

2.6 Digital Twin Advantages in Manufacturing

The Digital Twin has several applications in the manufacturing industry. In all these the DT has advantages over traditional methods used for these applications and purposes. Next these potential benefits are introduced and discussed.

As it was mentioned, there is a lack of the real industrial case implementations of the Digital Twins. This made finding the real use case advantages really challenging. Therefore, most of the identified benefits of the DT do not come from the real industrial cases. These are more from conceptual DT works and laboratory implementations. Some of the potential applications and benefits of the DT can only be achieved by using the Digital Shadows and the real Digital Twins. Achieving the DT full potential and all its potential advantages requires the fully synchronised bidirectional communication between physical and virtual worlds. This means that the implementation of the real Digital Twin opens up many advantages over the DM and the DS (Modoni et al., 2019).

Some review articles were found that listed the potential benefits of the DT. Modoni et al. (2019) have done a literature review where they have identified multiple benefits but also challenges which need to be tackled before all the potential benefits can be achieved. Perno et al. (2022) have made a review about the Digital Twins in the process industry where they identified both benefits and challenges.

One important driver for the DT implementations is the need for the higher production flexibility (Neto et al., 2020; Rasheed et al., 2020). Neto et al. (2020) have identified this driver from both expert interviews and literature. The flexibility is listed as a one of the main advantages of the Digital Twin in several papers (Kockmann, 2019; Tao et al., 2019; Zhang et al., 2021). This production flexibility can mean a larger selection of product variants or the ability to dynamically reschedule production if needed (Neto et al., 2020). Neto et al. (2020) have identified multiple works which have been using this dynamic rescheduling to increase flexibility. Novák et al. (2020) mention that the DT with the Artificial Intelligence leads to more flexible and efficient manufacturing processes.

The potential decentralisation of the production is one of the identified advantages of the DT. The DT enables the decentralisation of the production systems controls which opens up a new level for the flexibility of automation systems. (Modoni et al., 2019) This can lead to flatten the typical automation pyramid which can lead to more distributed automation solutions (Ciavotta et al., 2017).

Increased system reliability is one important benefit of using the DT (Tao et al., 2019; Negri et al., 2020). The DT increases integration and feedback between equipment in the production system which leads to increased reliability and performance (Fuller et al., 2020). The increase in performance is especially linked to the Artificial Intelligence algorithms which can make the DTs intelligent (Fuller et al., 2020).

The increased predictability of the system is one of the advantages of the DT (Feofanov and Baranov, 2019; Rasheed et al., 2020). It is closely linked to the use of the Digital Twin in the predictive maintenance which was discussed above. According to Tao et al. (2019) the DT enables manufacturing industry to make more accurate predictions, rational decision, and informed plans.

The DT is highly integrated, and it has continuous data flows that allow the system to be more transparent. This increased transparency is one possible benefit of the DT implementation (Feofanov and Baranov, 2019; Neto et al., 2020). The increased transparency can be beneficial to both internal groups and different external stakeholders (Zhang et al., 2019; Neto et al., 2020).

An important advantage of the Digital Twin is the possibility to collect data from the different equipment and sources and combine these into a single entity in the Digital Twin model (Cimino et al., 2019; Prarthana et al., 2021). This can help in the real-time monitoring and decision making because all the important data is integrated into a single system (Prarthana et al., 2021). Cimino et al. (2019) have identified the possibility for the real-time storage and analysis of the data generated by the production. By using the DT, historical data can be stored and used later for analysis. This storage and use of historical data is typically not possible with the current MES which only shows the current situation at the certain moment. (Cimino et al., 2019) All these make the data management easier.

The Digital Twin can help to increase understanding of the data relationships and data consistency of the real system. Modelling and using the DT can help to understand the different relationships in the real factory and its data flows. These can increase awareness of the real system. (Modoni et al., 2019; Prarthana et al., 2021)

All the previously mentioned advantages can together lead to one important goal of the manufacturing industry, reducing the costs. Compared to the Physical Twin, the Digital Twin has a clear cost advantage. It has lower implementation cost because of the virtual modelling (Modoni et al., 2019). The use of the Digital Twin has been identified to produce cost savings (Kockmann, 2019; Modoni et al., 2019; Neto et al., 2020; Prarthana et al., 2021). Neto et al. (2020) have mentioned that the reduction in the production costs is mainly due to smart fault detection and predictive maintenance which highlights the importance of the DT in the maintenance applications. All the identified advantages are collected in Table 2 with the references.

Table 2: Benefits table

Benefit	References
Flexibility	(Ashtari Talkhestani et al., 2019; Kockmann, 2019; Modoni et al., 2019; Tao et al., 2019; Neto et al., 2020; Novák et al., 2020; Rasheed et al., 2020; Zhang et al., 2021)
Reliability	(Tao et al., 2019; Fuller et al., 2020; Negri et al., 2020)
Predictability	(Feofanov and Baranov, 2019; Neto et al., 2020)
Transparency	(Feofanov and Baranov, 2019; Neto et al., 2020; Zhang et al., 2021)
Data management	(Cimino et al., 2019; Prarthana et al., 2021)
System understanding	(Modoni et al., 2019; Prarthana et al., 2021)
Production cost reduction	(Modoni et al., 2019; Kockmann, 2019; Neto et al., 2020; Prarthana et al., 2021)

The final important note is that the benefits of the DT usage are not only limited to the single product, part of the factory or only one part of factory’s lifecycle. The DT has possibilities at all stages and scales. (Modoni et al., 2019; Rathore et al., 2021) Mainly, current applications that provide the benefits listed above focus on the design, pre-process, and process phases (Ashtari Talkhestani et al., 2019; Modoni et al., 2019).

2.7 Digital Twin Challenges in Manufacturing

Lattanzi et al. (2021) mention the Digital Twin and its core technologies still being in a rather early stage. They have also stated that the widespread implementation of the DT in the industry seems quite unrealistic right now. Qi et al. (2021) mention that the DT is far from the potential it could offer. It is a complex system and reaching its full potential requires a long-term process (Qi et al., 2021). Savolainen and Knudsen (2022) mention that the reality of the DT still being more of a master spreadsheet with manual inputs from different sources and with nice 3D animations. Perno et al. (2022) have stated that the DT has a huge hype, but a companies are facing a significant challenges at the DT implementation process. The reasons above make this chapter especially important when considering the DT implementations. Many of these challenges can also be found in other DT application environments in addition to the manufacturing industry.

One important aspect to consider when discussing the Digital Twin challenges is whether it relates to the Digital Model, the Digital Shadow, or the real Digital Twin. The level of the integration can eliminate or add certain challenges. Related to this, Cimino et al. (2019) mention that the majority of the applications reviewed in their article do not have a connection from the digital world to the physical world control system. This sets most of the reviewed applications to the Digital Shadow category. This means that these are unable to utilise the full potential which the real Digital Twin can offer. This limitation to the Digital Shadow stage without virtual-to-physical connection excludes for example automated process optimisation. (Cimino et al., 2019) Many of the challenges introduced can be found in DTs at any level of integration. In many cases when the level of integration increases, also increases the complexity of the system which can make it more difficult to overcome these challenges.

Modoni et al. (2019) mention that most of the challenges are related to the nature of the DT. It is a complicated system in a space with many dimensions. It requires integrated multi-physics, multi-domain, multiscale modelling technology and very high synchronisation and detail level between physical and virtual worlds. (Modoni et al., 2019) Fuller et al. (2020) pointed out that the DT building and operating environment is very heterogeneous which sets its own challenges.

The introduced challenges were identified during the literature review. Singh et al. (2018) have identified some of the key challenges of the Digital Twin in their article regarding high value manufacturing which includes for example aerospace, automotive and power generation sectors. Fuller et al. (2020) have made a good review about the Digital Twin enabling technologies, challenges, and open research topics. They mention that the DT will be mainly used with IoT and AI technologies which leads to sharing many similar challenges. Neto et al. (2020) have identified multiple barriers for the Digital Twin implementations from the literature and expert interviews. Atalay et al. (2021) have made a literature review about the Digital Twins in the manufacturing. They have mentioned several different challenges and open research questions related to the DT implementations.

After identifying the most typical challenges associated with the Digital Twin implementations these were classified into nine main categories. All these categories are presented in more detail below. The main categories are following:

1. Standardisation
2. IT infrastructure
3. Modelling
4. Data
5. Connectivity and communication
6. Privacy and security
7. Organisation and people
8. Cost
9. Technology immaturity

The identified challenge categories are collected in Table 3. It also contains some of the references that have mentioned that specific challenge category.

Table 3: Identified challenges

Challenge	References
Standardisation	(Autiosalo, 2018; Singh et al., 2018; Modoni et al., 2019; Tao et al., 2019; Ala-Laurinaho et al., 2020; Bambura et al., 2020; Fuller et al., 2020; Neto et al., 2020; Atalay et al., 2021; Lattanzi et al., 2021; Liu et al., 2022; Onaji et al., 2022; Perno et al., 2022)
IT infrastructure	(Tao and Zhang, 2017; Neto et al., 2020; Fuller et al., 2020; Atalay et al., 2021; Lattanzi et al., 2021; Prarthana et al., 2021; Gulewicz, 2022; Perno et al., 2022)
Modelling	(Tao and Zhang, 2017; Singh et al., 2018; Modoni et al., 2019; Tao et al., 2019; Rasheed et al., 2020; Atalay et al., 2021; Lattanzi et al., 2021; Prarthana et al., 2021; Liu et al., 2022; Onaji et al., 2022; Perno et al., 2022)
Data	(Tao and Zhang, 2017; Modoni et al., 2019; Singh et al., 2018; Tao et al., 2019; Fuller et al., 2020; Rasheed et al., 2020; Atalay et al., 2021; Prarthana et al., 2021; Onaji et al., 2022; Perno et al., 2022)
Connectivity and communication	(Tao and Zhang, 2017; Singh et al., 2018; Modoni et al., 2019; Tao et al., 2019; Bambura et al., 2020; Fuller et al., 2020; Neto et al., 2020; Rasheed et al., 2020; Redelinghuys et al., 2020; Lattanzi et al., 2021; Prarthana et al., 2021; Liu et al., 2022; Perno et al., 2022)
Privacy and security	(Tao and Zhang, 2017; Singh et al., 2018; Modoni et al., 2019; Tao et al., 2019; Fuller et al., 2020; Rasheed et al., 2020; Atalay et al., 2021; Prarthana et al., 2021; Perno et al., 2022)
Organisation and people	(Singh et al., 2018; Fuller et al., 2020; Neto et al., 2020; Rasheed et al., 2020; Gulewicz, 2022; Liu et al., 2022; Onaji et al., 2022; Perno et al., 2022)
Cost	(Singh et al., 2018; Fuller et al., 2020; Neto et al., 2020; Atalay et al., 2021; Lattanzi et al., 2021)
Technology immaturity	(Fuller et al., 2020; Neto et al., 2020)

Standardisation

One of the key challenges for the Digital Twin is the lack of standardisation (Singh et al., 2018; Ala-Laurinaho et al., 2020; Bambura et al., 2020; Fuller et al., 2020; Neto et al., 2020; Atalay et al., 2021; Autiosalo et al., 2021; Liu et al., 2022). It is the most mentioned challenge in the DT literature. Therefore, it can be considered the most important one.

The definition variability of the DT is the challenge which is closely related to standardisation (Fuller et al., 2020; Atalay et al., 2021; Liu et al., 2022). The unclear definition of the DT can lead to misconceptions (Fuller et al., 2020; Liu et al., 2022). Liu et al. (2022) mention that many implementations without bidirectional communication are stated as the Digital Twins, even though the real Digital Twin requires this bidirectional data flow. This is the problem that Kritzinger et al. (2018) began to investigate and proposed the classification introduced earlier.

Another standardisation related challenge is the interoperability (Fuller et al., 2020; Atalay et al., 2021; Liu et al., 2022). The standardisation would enable interoperability and applicability between different devices, sectors, and organisations (Fuller et al., 2020; Neto et al., 2020; Lattanzi et al., 2021). In particular, the need for the standardisation of the connection and communication protocols is identified in multiple articles (Tao et al., 2019; Fuller et al., 2020; Lattanzi et al., 2021; Onaji et al., 2022). A bidirectional constant, reliable and standardised data flow is needed to connect the different parts of the DT together to get the full benefits of the Digital Twin (Fuller et al., 2020; Atalay et al., 2021; Lattanzi et al., 2021). Without the standardisation this can be a difficult to achieve if there are various different ways to implement the connections (Fuller et al., 2020).

The missing general implementation framework is an important part of the standardisation challenge and it is identified in many articles (Tao et al., 2019; Bambura et al., 2020; Fuller et al., 2020; Autiosalo et al., 2021). Without the clear standardisation, the DT implementations can vary, making it difficult for users to understand these (Fuller et al., 2020). The different implementation methods of the DTs can also lead to situations where the different DTs are unable to communicate with each other and operate on different platforms and environments (Ala-Laurinaho et al., 2020; Autiosalo et al., 2021; Liu et al., 2022).

These issues could be possible to tackle with a proper Digital Twin standardisation defining the implementation frameworks and the used communication protocols. It would enable easier seamless integration between the different DTs. This would allow more scalable and modular Digital Twin implementations. This scalability and modularity would be beneficial in situations where the DTs from multiple sources are wanted to combine into a one larger system entity. (Liu et al., 2022) Singh et al. (2018) have also mentioned the scalability of the DT systems. Savolainen and Knudsen (2022) have emphasised the importance of the modularity for the Digital Twin structure. The scalability and modularity would allow easy scaling of the DT systems to the different sizes and different levels of complexity regarding to the needs. (Singh et al., 2018). Ala-Laurinaho et al. (2020) have mentioned that building the DT from the different software blocks or systems allows flexibility because the DT structure can be modified according to the needs. One possible example of the needed modularity and scalability would be the Digital Twin models offered by several different production device vendors, which would then be combined into a single entity to model a specific plant.

IT infrastructure

Technological infrastructure and interfaces are setting challenges for the DT implementations. These performance issues are related to hardware and software limitations. (Neto et al., 2020; Atalay et al., 2021; Prarthana et al., 2021; Gulewicz, 2022; Perno et al., 2022). Fuller et al. (2020) mention the IT infrastructure limiting the IoT growth. The DT sets requirements for the IoT and especially for the sensors (Fuller et al., 2020).

Efficient usage of the Digital Twin needs easy data flow between the physical and virtual worlds. A continuous bidirectional data connection between physical and virtual spaces is needed for the real-time applications such as the real-time monitoring. (Tao and Zhang, 2017; Perno et al., 2022) This sets specific requirements for physical components, software and network components (Tao and Zhang, 2017; Atalay et al., 2021). The DT also requires enough performance for AI, data analytics and IoT, which requires enough computing power from both hardware and software. The challenge is not the difficulty of finding good enough IT infrastructure but its installation and operation costs. (Fuller et al., 2020) Perno et al. (2022) have also mentioned achieving this continuous data flow between the physical and virtual worlds to be very challenging with the current systems. Therefore, some IT infrastructure upgrades may be needed before implementing the DT.

Computational speed becomes an important aspect when the virtual model is not only meant to model the physical world. The DT is expected to model the physical world dynamically in near real-time. There will always be some delay between the physical and virtual worlds but how much that delay will be and how much delay is allowed are still an open questions. (Lattanzi et al., 2021) These will probably depend on the requirements set for the Digital Twin and its goals. The important factor for that will be the used IT infrastructure.

It is possible to perform simulations and tests using the data collected by the DT. This is only possible with suitable software tools that support this type of modelling and simulation. (Modoni et al., 2019) Similarly there are also requirements for other tools and software. These requirements depend on the goals and purpose of the DT.

Modelling

The detail level of the DT virtual model is a one important aspect to consider before implementing the Digital Twin (Lattanzi et al., 2021; Liu et al., 2022). The DT is intended to be as precise and realistic model of the physical world as possible to be able to perform accurate simulations and evaluations. This may require very detailed virtual models of the manufacturing systems. (Modoni et al., 2019) A highly accurate model can lead to a large number of sensors and measurement devices needed, resulting in a huge number of different signals and data. This can be difficult to handle properly. (Lattanzi et al., 2021) Also the very detailed synchronisation process paired with the high sampling frequency can be very costly which is seen to be a one barrier for the Digital Twin implementations (Modoni et al., 2019).

Developing precise, trustworthy, and up-to-date models of the complex production systems can be challenging (Tao and Zhang, 2017; Atalay et al., 2021; Perno et al., 2022). Lee at al. (2019) mention that developing a very accurate model can require a lot of time and it will need a lot of computational capabilities. This can lead to trade-offs between time and resource investments and the DT accuracy (Perno et al., 2022). Too simplified Digital Twin model can lead to not utilising the full potential of the DT (Lattanzi et al., 2021). Therefore, it is important to find the right balance between the detail level of the DT and the synchronisation process and the costs. The DT must still bring enough value to the company so that it can achieve the goals set for the DT. (Ezhilarasu et al., 2019; Modoni et al., 2019; Rolle et al., 2019).

Tao and Zhang (2017) mention the important point that the virtual model is always some form of simplification of the real system. There will always be some contradictions between physical system and virtual models. How to identify and handle those contradictions between different worlds is an important issue to consider before the DT implementation. (Tao and Zhang, 2017)

If the Digital Twin is meant to be used for early detection and prediction of potential failures, those should also be modelled in the virtual world. Therefore, those potential failures must be known in advance. This can be one limiting factor in the DT implementation. (Lattanzi et al., 2021) Prarthana et al. (2021) mention that it may not be possible to implement all the functions and actions of the physical system into the DT virtual model.

Uncertainties in the Digital Twin models and unresolved uncertainties in prediction of complex systems are identified as a one important challenge (Singh et al., 2018; Onaji et al., 2022). Variations and inconsistencies between the physical and virtual worlds may be due to distractions and uncertainties in the physical world or inaccuracies in the modelling of the virtual world (Lattanzi et al., 2021; Prarthana et al., 2021). Onaji et al. (2022) mention that the every complex system is unique and there exist variabilities that are unique for that system. Even if the behaviour of the machine is well known when operating independently, its performance and behaviour can be very different as a part of the complex system (Onaji et al., 2022). According to Singh et al. (2018) the complex environment requires even more complex systems and models to be able to deal with these uncertainties. Atalay et al. (2021) mention the complexity of production parameters to be a reason which increases the complexity of the already complex digital models. Overall, this high and multi-dimensional complexity of the Digital Twin virtual models can lead to different estimations and presumptions (Onaji et al., 2022).

Data

The data is an important part of the Digital Twin operation and performance. The amount of IoT and IIoT have significantly increased. All of those collect a lot of data and the challenge is to ensure the efficient flow and use of that data. This challenge becomes more obvious in the Big Data environment. (Fuller et al., 2020) Modoni et al. (2019) have mentioned many of the DT's data challenges to be typical for the Big Data as well. Therefore, the data and Big Data related challenges show a very important role as challenges for the Digital Twin implementations (Singh et al., 2018). The data Velocity and the data Volume have been identified as two important Big Data challenges for the Digital Twin (Modoni et al., 2019; Rasheed et al., 2020). The data Velocity is about how fast the new data is generated. The issue with the data Velocity is how to handle all this real-time data. For historical data, the data Volume becomes an issue because it increases throughout the entire plant lifecycle. (Modoni et al., 2019)

Another main challenges of the DT and data are data variety, managing big data, data management systems and data storage (Singh et al., 2018; Rasheed et al., 2020; Onaji et al., 2022). One important challenge especially related to the Digital Twin is the data gathering from different sources (Tao et al., 2019; Onaji et al., 2022). Singh et al. (2018) pointed out that the amount of information during the manufacturing lifecycle of a product is huge and it is complex, and these make it difficult to manage it with a single system like the DT.

The data must be high quality, structured and constant for the optimal DT performance (Prarthana et al., 2021; Perno et al., 2022). That is not always the case as the data can be collected and stored in multiple different locations from where it should be correctly transferred to the virtual world at the moment it is needed (Prarthana et al., 2021; Onaji et al., 2022). This data collected from both physical and virtual sources and stored in different locations can lead to non-heterogeneous data which causes its own issues (Onaji et al., 2022). Therefore, the data used must be properly pre-processed to ensure its efficient use (Fuller et al., 2020). This requires the right choice of appropriate tools, software, and algorithms.

Real-time monitoring capabilities are needed for many Digital Twin applications which set the requirements for the data flow (Modoni et al., 2019). Data accuracy and reliability are important factors in terms of sufficient Digital Twin performance. Incorrect data or incorrect data analysis can cause issues between physical and virtual models. This is one challenge where the solution should be found before the DT implementations can widespread. (Fuller et al., 2020; Atalay et al., 2021; Perno et al., 2022)

Connectivity and communication

IoT related communication and connectivity is one major challenge to overcome before the Digital Twin can be fully implemented. This is especially important if the DT is used for the real-time monitoring or optimisation because these need the real-time data. A single modern manufacturing process could have many sensors and IoT devices and the Digital Twin implementation could require even more of those. This large number of sensors makes a significant challenge when those all should be connected at the same time. Power outages, software errors and ongoing deployment errors are the things affecting the connections negatively. A single faulty sensor can have a significant negative impact on the Digital Twin performance. That is why this connectivity challenge should be solved before implementing the Digital Twin. (Fuller et al., 2020)

The Digital Twin is supposed to be tightly integrated system that includes both virtual and physical parts (Singh et al., 2018; Tao et al., 2019). Tao et al. (2019) mention that without the suitable communication between different DT parts it can cause complex problems. The effective implementation of the cyber-physical connection is a key challenge for the DT. The missing universal framework for this purpose is one of the main issues and it is strongly related to the standardisation challenges. (Tao and Zhang, 2017; Tao et al., 2019) This tight integration also requires suitable integration between different technology domains. For example, suitable data handling and processing algorithms are needed. (Lattanzi et al., 2021)

The data is necessity for the DT and proper implementation of the communication is the mandatory to ensure the correct data flow. Compromises and cost saving in this area can lead to faulty or lost data. This can cause issues in the DT performance. (Prarthana et al., 2021) Therefore, the integration and communication between different parts of the system and organisation is one important challenge. (Fuller et al., 2020; Neto et al., 2020; Lattanzi et al., 2021; Perno et al., 2022) Especially connecting the DT to the shop floor level has been found to be challenging (Modoni et al., 2019). This same challenge is also identified in other articles. These mention linking and communicating between the physical and virtual worlds as one of the main challenges for the DT. (Onaji et al., 2022) Another challenge is how to distribute intelligence and data through the factory floor. If all the data is sent to the one main DT it can cause issues by increasing transmission times and reducing network availability. (Modoni et al., 2019)

Rolle et al. (2021) mention that there exist a lot of “non-smart” legacy devices in the real manufacturing plants. Those are the devices without the modern smart features such as networking capabilities or data processing possibilities. Integrating those legacy devices and systems together with the new modern ones and becoming a part of the Digital Twin is one of the main challenges of the domain integration (Rolle et al., 2019; Fuller et al., 2020; Lattanzi et al., 2021; Perno et al., 2022). Integrating existing and new systems can cause high investment costs which makes these investments unsustainable. Also integrating the different parts of the existing or new system together is identified as a challenge. (Perno et al., 2022) A suitable solution to overcome the interface compatibility issues between different software applications does not yet exist. Also, there is not yet a suitable solution which would allow fully automated synchronisation between different domains. (Lattanzi et al., 2021) These make this challenge even more important to consider before the Digital Twin implementation.

Bambura et al. (2020) have identified in their article data collection issues related to latencies. In their DT evaluation phase, some data collection point signal has shown latencies in the connections. This caused the incorrect data information to be written which caused missing actions in the database. Same kind of issues with latencies are identified in multiple another articles (Rasheed et al., 2020; Redelinghuys et al., 2020; Lattanzi et al., 2021; Perno et al., 2022).

Privacy and security

For many modern technologies, the data privacy and security issues are major challenges (Singh et al., 2018; Fuller et al., 2020; Atalay et al., 2021; Perno et al., 2022). The Digital Twin is a part of the digital transformation of the industry which makes those cyber-security and data security issues also challenges for the Digital Twin implementations (Tao and Zhang, 2017; Tao et al., 2019; Fuller et al., 2020; Rasheed et al., 2020; Atalay et al., 2021). Many of the security issues are related to the cyber-physical form of the DT. This cyber-physical interconnection makes the DTs and production systems open not only for the physical threats but also for the cyber threats. (Tao et al., 2019)

The data transferred between different units of the Digital Twin could contain sensitive production information which could be a valuable target for criminals. This data can even have some personal data which has its own laws and regulations. (Fuller et al., 2020) Hence, it is important to find suitable ways and methods to handle all this data when implementing the Digital Twin and its data flows (Fuller et al., 2020; Prarthana et al., 2021). Atalay et al. (2021) mention the DT to be still a novel and immature technology which makes these issues even more important to consider.

Organisation and people

Organisational issues are mentioned to be one of the Digital Twin implementation challenges. It means all the internal challenges which companies have to face when dealing with a new technologies such as the DT. (Perno et al., 2022) The Digital Twin requires correct integration not only with the different devices and software but also in the entire organisation where it is used. Neto et al. (2020) have identified the organizational culture and strategy things as a one of the possible barriers for the Digital Twin implementations. In an organisation with department silos and high resistance to the change, the implementation of any new technologies is much harder than in a well-integrated organisation with a high motivation to change. (Neto et al., 2020)

People and competence can also be one important barrier to the new technology implementation (Onaji et al., 2022). People's missing knowledge and general resistance to the change can be seen as barriers for the DT implementations (Neto et al., 2020; Gulewicz, 2022; Onaji et al., 2022). One root issue of the people's missing knowledge may be the speed which technology is evolving. Employees and managers cannot adopt the new technology at the same pace. (Neto et al., 2020)

Trust issues may not be the first thing that comes to mind when dealing with the challenges of data analytics or the Digital Twin. It is mentioned to be a one important challenge that needs to be overcome before wider implementations of the Digital Twins. Trust issues occur with all new technologies, especially if those are not properly understood. This issue can be seen coming both from organisational and user level. (Fuller et al., 2020) This can lead to issues when a properly trained AI algorithm suggests some improvements to the production, but due to a lack of trust, the human will not accept those. In this case, all the potential offered by AI and the DT is not used. One suitable way to overcome this challenge is to verify for the users that the Digital Twin is performing properly (Fuller et al., 2020).

One issue with data analytics, AI, IoT or any new technology can be the high expectations which might not be realistic. Some people may think that using AI algorithms will solve all the problems and instantly save time and money. When it comes to the IoT, the users might not fully understand what the IoT devices can do or how to properly use them. This misuse can lead to other challenges such as security issues which can lead to bigger problems and increase more trust issues. Like the previous ones, the expectations for the Digital Twin can be unrealistic. It is important to make potential users aware of the possibilities and limitations of the Digital Twin. The reality is that these technologies are still quite new and there is not enough knowledge yet. So, not all potential benefits and limitations are known yet. If these expectations are unrealistic, it can slow down the implementations of the Digital Twins. (Fuller et al., 2020)

Increasing digitalisation and use of the digital tools require more human-machine integration. The Digital Twins can also increase this closer cooperation between humans and machines. Appropriate use of this requires effective and rapid communication ways to ensure seamless operation between these two. (Onaji et al., 2022) The interviewed company also mentioned people as one of the biggest challenges. This challenge is related to the humans as a part of the digital manufacturing and human-machine integration. The DT must be kept actively up-to-date especially if it is wanted to use for the real-time operations. This is especially important for the real Digital Twin which can automatically send data and commands to the production.

Human interactions can be seen as a challenge for the development of the DT. There is still a lot of manual work performed in the shop floor and human actions cannot be precisely monitored or be predicted. This could cause challenges for the DT performance if something unpredicted happens. Also, in the CPPS all the devices are meant to communicate and operate with each other. There may not be much space for the human decision making. If it is wanted as a part of the system, the system must wait for the human inputs at predetermined points. (Singh et al., 2018) Another human interaction challenge is the data collection from the manual operations. This potentially important data from the manual production operations must be transferred to the Digital Twin and hopefully in near real-time. This usually requires an employee to enter the data into some system. As the interviewed company mentioned, this should be a seamless part of the normal work operations to be done correctly.

Another important aspect of human interaction with the DT is the suitable Human Machine Interfaces (HMIs) to ensure proper integration of humans with the DT systems. Also, the Digital Twins are still at early phase and contain many complex and high-technical solutions. When those are implemented in the real industrial environments some of the users are not as technically oriented as the developers. This also requires suitable communication ways between humans and machines such as the suitable HMI. (Rasheed et al., 2020; Liu et al., 2022) The suitable HMI should also be so easy to use that it will not cause too much resistance among the employees.

Cost

The cost-benefit analysis is one important factor in the Digital Twin implementation. Before the Digital Twin is implemented it should be guaranteed to bring economic and financial benefits to the manufacturing. Dissemination and widespread application of the Digital Twin can only happen if it is shown to bring tangible and significant benefits to the financial side of the business. (Lattanzi et al., 2021)

Cost and time are mentioned as challenges for the Digital Twin implementations. Developing and maintaining the DT requires time which increases costs. (Singh et al., 2018; Abusohyon et al., 2021) Neto et al. (2020) mention there are challenges in measuring the potential benefits of the Digital Twin projects. This is supported by Atalay et al. (2021) who mention that the Digital Twin investment and deployment costs are still quite high. Singh et al. (2018) mention that the DT is better known for its complicated challenges than for its benefits. In Gulewicz (2022) interviews, the high implementation costs were identified as the most important barrier to the DT implementation. These all are important factors slowing down the implementations of the DTs in the manufacturing industry (Neto et al., 2020; Atalay et al., 2021).

Technology immaturity

The novelty and immaturity of different technologies is a common factor in many of the challenges identified above. For example, the Artificial Intelligence and other analytics technologies are some of the potential key components enabling the DT (Fuller et al., 2020). At the same time, Fuller et al. (2020) mention that AI itself needs further research and its potential applications in the Digital Twin usage are still an open question. Similarly, Neto et al. (2020) have identified the technology immaturity, especially in the analytics technology, to be one key barrier in the DT implementations. These analytic technologies are especially needed for the autonomous control of the real production system. The immaturity of these technologies cause unreliability which can cause risks to the operation of the DT (Neto et al., 2020; Gulewicz, 2022). Unreliability and risk are good reasons for many companies to delay the implementation of the Digital Twins.

The challenges related to the immaturity of technology were also identified in the interview. The company has a vision about the DT to MES connection that would be needed to achieve the real Digital Twin. This Implementation of the real Digital Twin was mentioned to require intelligence. Since the real DT can have an ability to control the process without human supervision, it must have some algorithms and intelligence. There are not ready-made solutions available and as was mentioned above, the AI itself is still its infancy. Therefore, the AI with the DT is even further from the maturity. Development and building up the necessary intelligence require time and resources. This may be one major barrier to overcome in a full transformation from the DS to the true DT.

3. MES-AUTOMATION-DIGITAL TWIN INTEGRATION CASE STUDY

The development of the digital technologies has made it easier to integrate the different systems. At the same time the connectivity and communication are mentioned to be one of the key challenges of the DT. It is one of the things which are slowing down the DT implementations and the rise of the smart manufacturing. Overcoming this challenge is therefore important.

There are many articles and literature about the architecture of the Digital Twin itself. Those consider how the Digital Twin should be built to achieve different goals and in a such a way that it can be integrated with different systems. In this thesis, the interest is in the integration between the DT and other systems and not in the DT implementation itself. Therefore, there is no discussion of how the DT should be constructed or how it works. This chapter only covers the integration between the MES, automation systems and the Digital Twin. One integration example using mainly Siemens software is presented and discussed.

3.1 Digital Twin as a Part of the Integration

According to Kritzinger et al. (2018) the Digital Twin can be categorised into three different types based on the data integration level. These three types are the Digital Model, the Digital Shadow and the Digital Twin (Kritzinger et al., 2018). These were introduced and discussed in detail in chapter 2.4. When discussing the DT integration, it is important to remember the differences between these three types.

There are several requirements when integrating the DT with other systems. One important aspect is the communication between different DT parts as was mentioned in the challenges chapter. It gets more complex depending on the number of the automatic data flows between the virtual and physical worlds.

The integration requirements of the real DT implementation are different from the DM. In the DM there are only manual data flows between the physical and digital worlds which does not require any integration with the different systems. Thus, the DM can be very close to typical simulation models, and therefore it is not discussed further in this chapter. By adding an automated data collection from the real world and the possible bidirectional synchronisation with the real system, the DS or the DT is achieved. This difference and transformation are illustrated in Figure 9. First there is just the DM. When the solid arrows are added, the DS is achieved and when the dashed lines are added, the real DT is achieved.

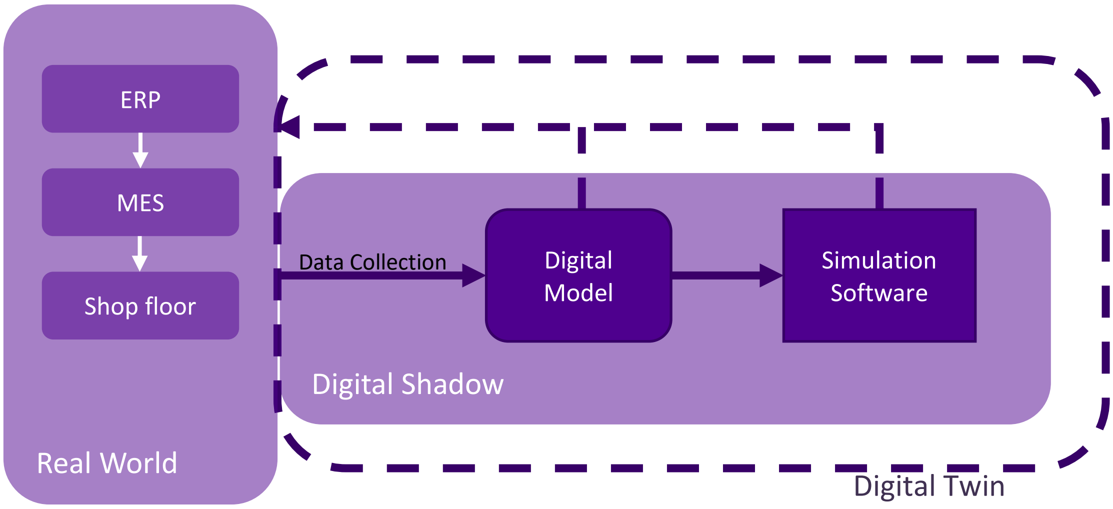

Figure 9: The Digital Model to the Digital Twin transition

As can be seen from the Figure 9, the number of the arrows increase when transforming from the DM to the DS and then to the real DT. The DM does not have any automatic data flows thus it does not require integration. The DS and the real DT require integration with other systems so in this chapter the focus will be in these two.

3.2 Implementation Software

The Digital Twin creation requires suitable software. In many cases, the Digital Twin virtual part may be recognised as a nice 3D model of the system, but it does not have to be. Many DT applications do not require any visual presentation. On the other hand, some applications need that 3D visualisation. As Kaarlela et al. (2022) mention the DT implementation software requirements depend on multiple things such as the type of modelled system, goals of the DT and the data transmission.

In this thesis, one integration example was implemented using the Siemens software. The main software used to structure the DT are TIA Portal, PLCSIM Advanced and Tecnomatix Plant Simulation (PS). The overall structure of these software forming the DT is shown in Figure 10. The Siemens Opcenter Execution Discrete (EX DS) version 3.3 is used in the integration as the MES to control the DT.

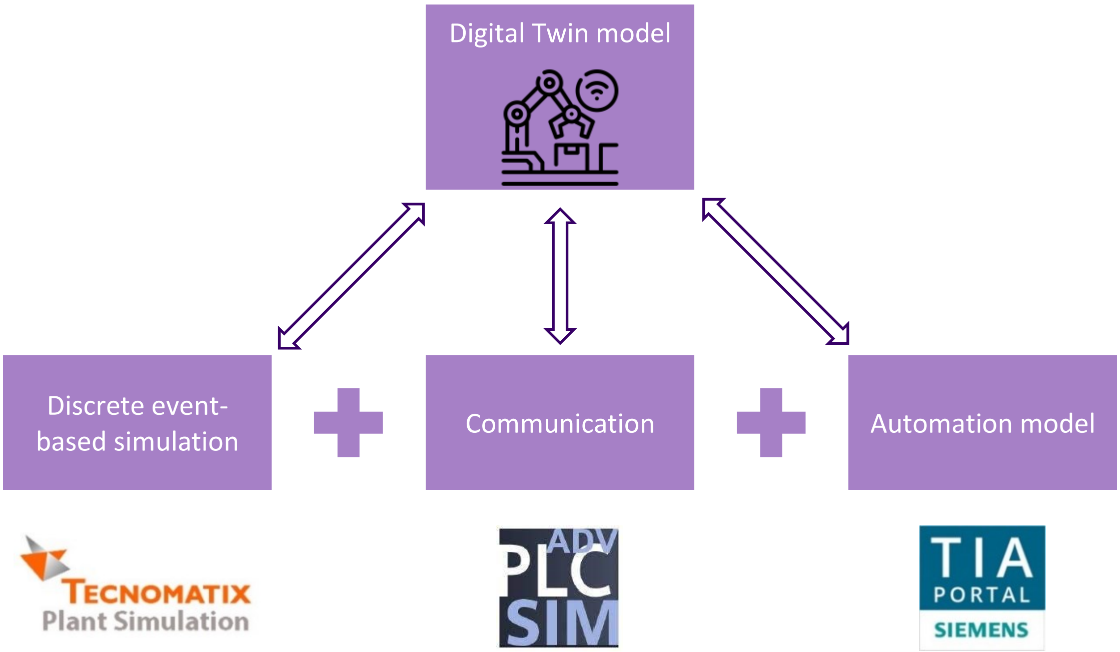

Figure 10: Software structure for the Digital Twin architecture

The Opcenter is a Manufacturing Operations Management (MOM) solution production family developed by Siemens. It offers multiple different software systems for the different purposes such as Opcenter Execution Semiconductor or Opcenter Execution Pharma. The software used in this thesis is the Opcenter Execution Discrete, which is a MES solution for discrete manufacturing needs. (Siemens Software, 2022a) The used version is 3.3 which has been released in 2020. The latest version of the Opcenter EX DS was released in August 2022 and its version name is 2207. Therefore, the version of Opcenter used may be outdated for some functions and details compared to later releases.

Siemens TIA Portal and PLCSIM Advanced are used in the automation control side. The PLCSIM Advanced is a PLC emulation software. It is designed for Virtual Commissioning purposes with the hardware (Ružarovský and Skýpala, 2022). The PLCSIM Advanced can also be seen as the Digital Twin of the PLC itself. The PLCSIM Advanced allows simulation of the virtual PLC without the requirement of the real hardware. (Jeon and Schuesslbauer, 2020) Therefore, it is in two roles in this thesis, it works as the DT itself and is also a part of the structure of another DT. This is an example of how the different DTs together can form a larger DT. This can be the case in the future when the different individual machine DTs together form the DT of the system.

TIA Portal is the software which is used for the PLC programming and in this thesis it was used together with the PLC emulator. (Ružarovský and Skýpala, 2022) In this thesis, the TIA Portal was not used very much. All the needed PLC codes were ready determined and already uploaded to the virtual PLCs. The TIA Portal was mainly used to identify some needed OPC UA tags and other information.

The final part of the Figure 10 is the simulation model which is in this case Tecnomatix Plant Simulation and version 16.0. Onaji et al. (2022) mention the Plant Simulation as a suitable software for the Digital Twinning because it has 3D visualisation capabilities and the OPC UA interface. They mention the real-time supervision, monitoring, and physical system visualisation as possible DT applications where the Plant Simulation can be used.

The Plant Simulation is a discrete-event simulation software which can be used to simulate, visualise, analyse, and optimise systems performance (Siemens Software, 2022b). A discrete-event simulation consists of a series of separate events and their occurrence times in the simulation. The execution of any event can result in the execution of any number of events at subsequent timestamps. (Lin, 2000) Another form of the simulation is continuous simulation where the variables are constantly changing.

The Plant Simulation uses an object-oriented simulation modelling method (Bambura et al., 2020). In the object-oriented simulation environment, the simulation model is built from different graphical objects which each contains its typical characteristics and functions. It is meant to simplify building and understanding of the simulation model without the necessary knowledge of programming languages. (Yalcin and Namballa, 2005; Bambura et al., 2020) The Plant Simulation also has its own programming language SimTalk which can be used to expand the modelling and control capabilities of the simulation if needed.

In this thesis integration example, the different parts of the system were located into different PCs. For example, the PLCSIM Advanced and TIA Portal were in one PC and the Plant Simulation model was in another. These were communicating between each other using the OPC UA connection. This makes this implementation closer to the real industrial case. In the real industrial environment, the different parts of the DT would be located into different devices and cloud platforms.

The used software in this thesis form only one integration example between different systems. It is important to notice that the used software can be replaced by another one and the integration architecture itself will not change. However, how the different software is integrated with each other would probably change in that case.

3.3 Integration Architecture

The integration architectures are important part of the integration process between MES, automation, and the DT. For the case study integration of this thesis, the integration architectures found in the literature were evaluated and analysed. Based on these, a suitable integration architecture is formed for the integration case study later.

Most of the DT literature focuses on the building and operation of the DT. There was not that much literature available on the integration architectures, but a few good examples were found. In most of these, the integration is implemented between the DT, the shop floor control level and production management such as MES level. These are the same systems which are used in this thesis integration case study. These integration architectures found in the literature are discussed below.

Azarmipour et al. (2020) have proposed an integration architecture for the DT-based optimisation with the MES and process control systems. In this framework, the MES controls the process control level. The DT optimisation runs parallel with the MES and control levels and has the real-time status information. The results of the DT simulation are sent to the MES which utilises these before sending these to the control level for the implementation. (Azarmipour et al., 2020) This feedback link from the DT to the MES makes this case the real Digital Twin.

Negri et al. (2020) have proposed the MES-integrated Digital Twin framework. In their integration architecture the commands come from the MES to the field devices. The DT updates its status based on the sensor values from the field devices. At this point, a special intelligence layer makes decisions based on the sensor values and the DT status. If a predefined unexpected situation occurs, the DT sends feedback to the MES. This DT to the MES feedback connection is implemented in the MES integration layer which is located in the same simulation environment as the DT. In this framework, the DT runs parallel with the physical system.

In Barbieri et al. (2021) Digital Twin framework, the digital model synchronisation with the real production process is controlled by the PLC. In their integration architecture, the Microsoft Excel works as the MES that sends the production sequence to the PLC. The PLC sends the current production process status information to the DT. Using that data, the DT updates its models to mirror the real system.

Barbieri et al. (2021) have also implemented a rescheduling algorithm as a part of the DT used to automatically reschedule production in a case of the machine breakdowns. If the machine breakdown occurs, it sends a signal to the PLC. The PLC delivers information to the DT. As a part of the DT, the specific scheduling algorithm is implemented.

A machine breakdown signal from the PLC to the DT triggers this specific algorithm which calculates the new production schedule based on the current system state. (Barbieri et al., 2021)

At Guo et al. (2021) framework, the MES sends the production order information to the control systems. Control systems control the physical equipment and the Digital Twin updates itself based on the physical system. In this framework, the DT runs parallel with the physical system and uses the real-time data collected by sensors for the optimisation. (Guo et al., 2021) This architecture has the feedback loop from the virtual world to physical, so it is the real DT.

In Onaji et al. (2022) proposed DT architecture, the MES is connected directly to the physical system. The physical system is connected into the DT via specific communication link layer which uses the OPC UA connection. Their implementation is at least the DS, but their article does not clearly state whether there is bidirectional communication between the physical and virtual worlds or not.

All the previously discussed integration architectures share multiple similarities. All of them contain some type of the MES which sends signals to the PLC or other production controlling system. The DT status is updated based on the data coming from the physical system. The Digital Twin therefore runs in parallel with the physical system. Four of the proposed integration architectures also have the feedback link from the DT to the MES making these implementations the real Digital Twins.

Novák et al. (2020) and Novák and Vyskočil (2022) have proposed very similar integration architecture compared to the previous ones, but it has also a one clear difference. They have made an implementation of the real Digital Twin with AI-based production planning component. Both the physical and the virtual systems are controller by the MES via OPC UA. When the MES sends the control signals to the physical world the digital model simultaneously updates itself based on these signals. (Novák et al., 2020) The real Digital Twin status is attained by a data signal from the DT to the production planner module. This production planner module is connected to the MES.

This framework has a slight difference in how the Digital Twin status is updated compared to the other five architectures discussed earlier. One issue with the proposed framework by Novák et al. (2020) and Novák and Vyskočil (2022) may be the synchronisation issues between the real and digital worlds. The same signal from the MES is sent to both systems at the same time. If there is an issue in the physical system that makes it impossible to execute the command sent by the MES, it can cause a situation where the digital model has already updated itself based on this MES signal, even though that action has not happened in the real world. In this case, the situations may arise where the status of the physical and the virtual systems are different. This can lead to big problems because the integration and communication challenges are very important issues related to DTs.

One similar feature between all the introduced integration architectures is the implementation of the certain integration layer from the DT to the MES. Based on the literature review and other online research, it seems that there are no easy and ready-made solutions available for establishing a feedback connection from the DT to the MES. This depends on the used MES and other software, but currently the connection from the DT to the MES seems to require some special layer implementation to be successful. This may be an important challenge to overcome before the real Digital Twin implementations can become widespread in the industry.

3.4 Implementing Digital Twin as a Part of the Integration

In the chapter above, the different DT integration architectures were introduced. Five of them had very similar structure. Only one of the introduced architectures had a small difference compared to the others in terms of updating the virtual model. In this chapter, a suitable integration architecture to interconnect the DT, the MES and automation is proposed. It is highly based on these five integration architectures proposed above where the MES sends signals to the PLC and then the PLC updates the DT.

In this thesis, only one integration example was implemented using the previously described software. Also, the implementations and the test were performed only in the virtual environment. The used PLC was only a virtual PLC which was run at PLCSIM Advanced software. Similarly, any real physical systems controlled by the PLC did not exist, but only a digital model implemented in the Plant Simulation was operated. The virtual PLC run in the PLCSIM Advanced operates and performs almost like a real physical one. Therefore, the integration architecture and its operation would not be very different if implemented with the real physical systems.

The DT integration architecture between the DT, the MES and the PLC can be easily divided into several main integration parts. In each of these, one integration is implemented. In the first part, the MES is connected to the automation, in this case to the PLC. In the second part, the PLC is connected to DT, which is typically a suitable simulation software. These two integrations form the Digital Shadow. In the case of the real Digital Twin, one additional integration is required. It is the connection from the DT to the real physical system. In the reviewed integration architectures, this is achieved by connecting the DT to the MES. The following subchapters discuss the creation of the integration architecture of the demo case using the proposed division. The background and starting points of the demo case are first introduced in the next subchapter.

3.4.1 Integration Task Background

This thesis is a part of the multinational project Machinaide. Machinaide aims to define how the industrial ecosystems will work together in the future. The different machines and plants create a local ecosystem and Machinaide aims to connect these ecosystems. The Digital Twins are an important part of building this connection. (Machinaide, 2022)

Finnish partners together form a one of these ecosystems. Its focus is on the Aalto Industrial Internet Campus where it has two main parts in this Machinaide project context. These are the smart crane called Ilmatar and the virtual grinding machine. Both machines have their own Digital Twins. The Plant Simulation model of the crane and the virtual grinding machine in the Aalto Industrial Internet Campus have been build and it is shown in Figure 11. This thesis mainly focuses around the Ilmatar crane and its integration.

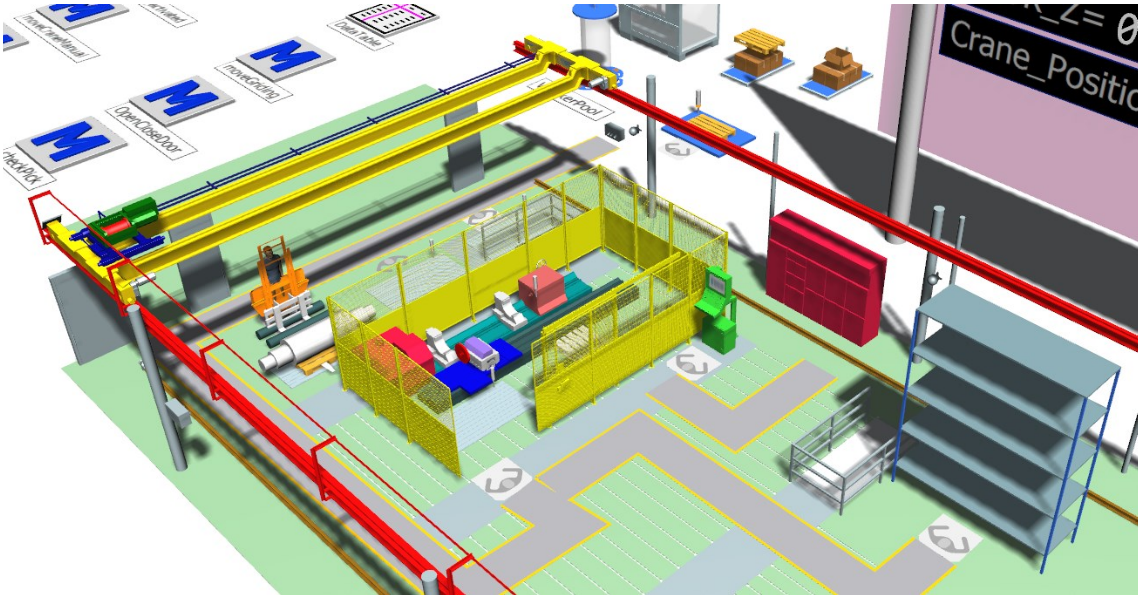

Figure 11: Plant Simulation model with the crane and virtual grinding machine

The aim of the thesis is to implement a suitable integration with the Plant Simulation model where the overhead crane is controlled using the MES. The material to be processed is a large metal roll and the crane's task is to move the roll to and from the virtual grinding machine on the factory. The crane's process steps are shown in Figure 12.

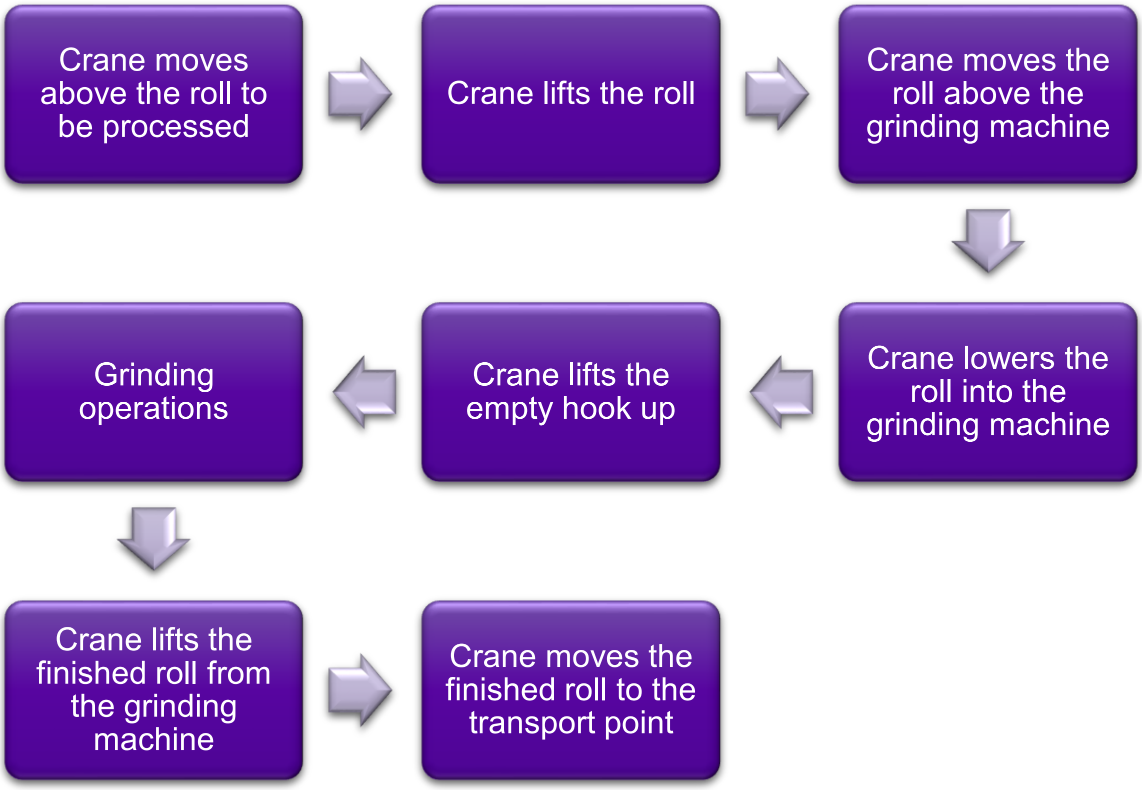

Figure 12: Crane process diagram

It can be seen from the Figure 12 that the whole process can be divided into three main parts: moving the roll to the grinding machine, grinding operations, and moving the finished roll from the grinding machine.

3.4.2 MES and PLC Integration

The suitable integration architecture implementation begins with the MES and the PLC integration. This type of integration is not only necessary for the Digital Twin implementations. The integration between the MES and the PLCs or other automation control systems is utilised in many different industrial applications. One example could be the automated control of the production using the MES. The MES can be used to send automatic control signals to the manufacturing equipment.

The commonness of this type of integration makes its implementation easier. The Siemens Opcenter, and probably many other MES software, have easy and ready-made interfaces to make connection to the PLCs. In the Opcenter this is done by the OPC UA connection. Modern PLCs such as SIMATIC S7-1500 -series have built-in OPC UA server capabilities that makes the connecting simpler. With the older legacy PLCs, the MES connection may require additional components and software, but this is not covered in this thesis.

In this thesis demo case, the integration has been implemented between two software, the Opcenter and the PLCSIM Advanced. Matrikon OPC UA Explorer is also used to support the integration process. The Matrikon OPC UA Explorer is an OPC UA client software provided by Matrikon, and it can be used to show OPC UA items values (MatrikonOPC, 2022). The Matrikon OPC UA software data view window is shown in Figure 13. In this integration process, it is used to show and write the OPC UA item values to facilitate the connection verification and testing.

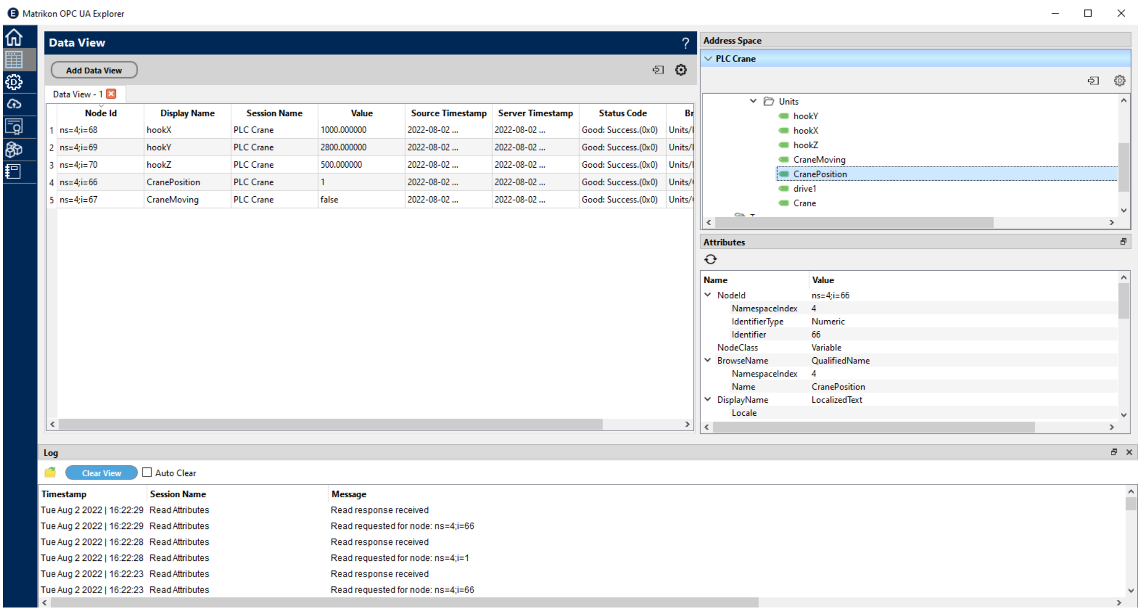

Figure 13: Matrikon OPC UA Explorer view

The first part of the integration process is the PLC. In this case, the virtual PLC determined in the PLCSIM Advanced. Creating a new PLC instance in the PLCSIM Advanced starts by selecting the correct connection mode. There exist three different connection modes and these are: local instance via Softbus, local instance via TCP/IP, and distributed instance over TCP/IP. The local instance via TCP/IP is used in this case because it allows the use of the OPC UA protocol. This communication mode is accessed by using the PLCSIM Virtual Ethernet Adapter in the PLCSIM Advanced. This communication mode is illustrated in Figure 14. The configured PLCs of the crane and the virtual grinding machine in the PLCSIM Advanced are show in Figure 15.

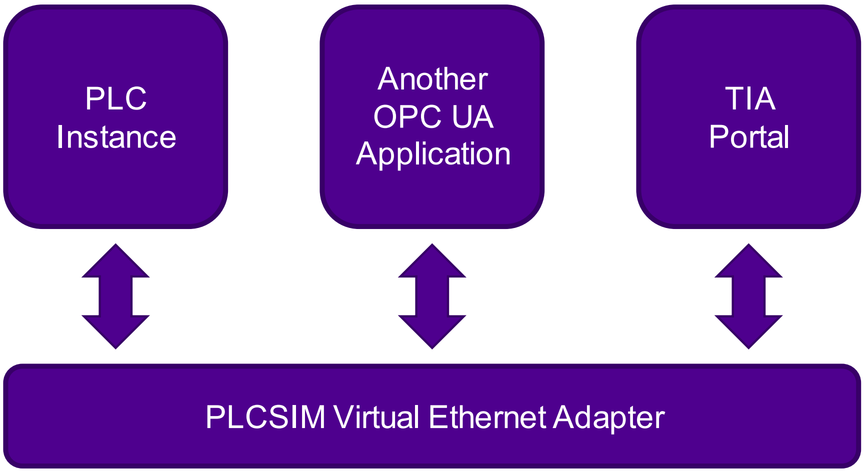

Figure 14: PLCSIM Advanced virtual Ethernet Adapter communication (based on Elting, 2021)

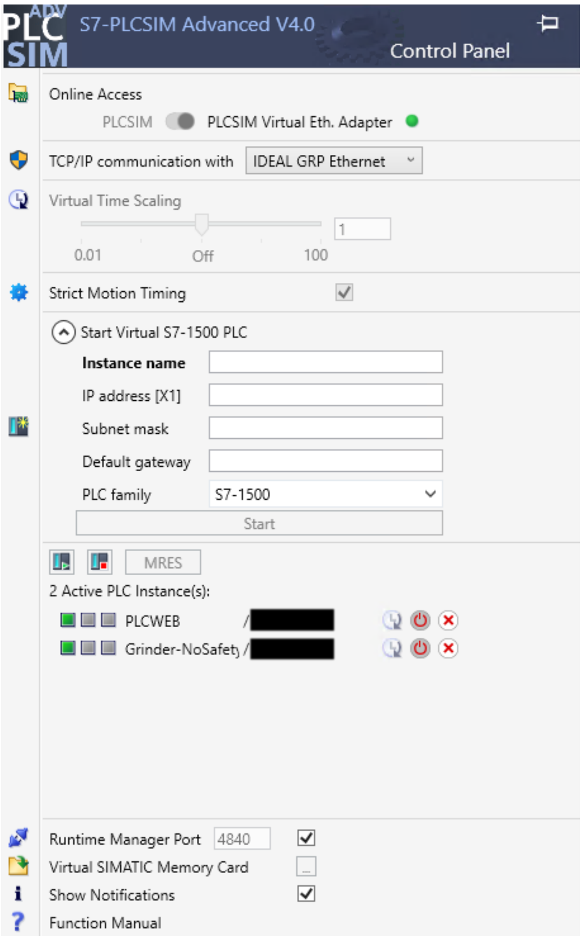

Figure 15: Configured PLCs in the PLCSIM Advanced

Once the new PLC instance is configured and created it still requires code to be able to perform its predefined tasks. The PLC coding is performed in the TIA Portal and the code is uploaded to the PLC either in the real hardware or as in this case in the virtual one. The used PLC code for the crane was a test code implemented especially for Machinaide project purposes and it was not provided by the crane manufacturer. This test code was already implemented before this thesis so there was no need for the PLC coding during this thesis. When the code is uploaded into the virtual PLC, it should be set into the run mode, so it is ready for the use. Figure 16 shows a preview of the TIA portal with a part of the PLC program code and the PLC Tags. It also shows the PLCSIM Advanced configured and running alongside the TIA Portal.

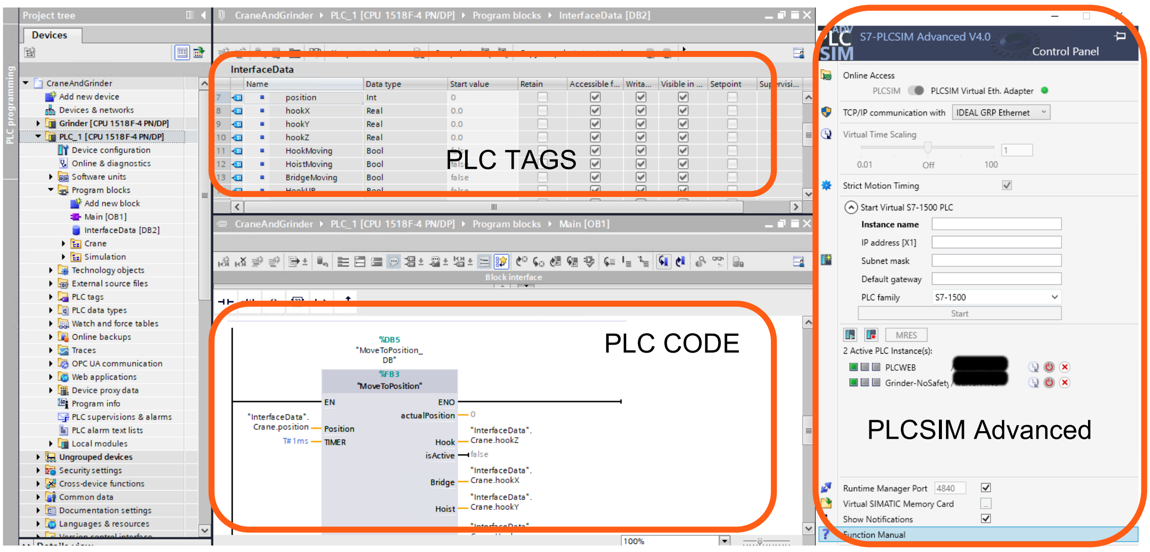

Figure 16: TIA Portal program with PLC Tags and PLCSIM Advanced

After setting the virtual PLC and the PLCSIM Advanced, it was time to integrate the Opcenter and the PLC. The Opcenter has an Automation Gateway App that is used to communicate with low-level control systems such as the plant PLCs. The Automation Gateway is used to configure and manage the automation connections. The process for the Automation Gateway App configuration is shown in Figure 17.

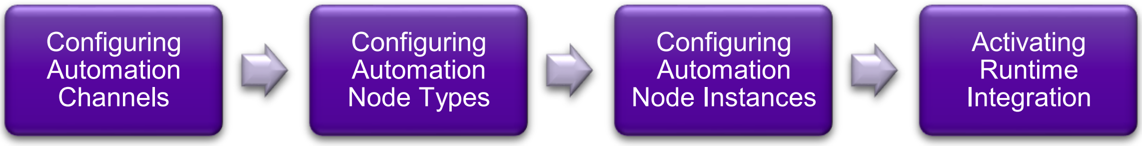

Figure 17: Automation configuration workflow (based on Siemens AG, 2020a)

As can be seen from the Figure 17, the configuration process begins from the Automation Channel configuration. In the used Opcenter EX DS version 3.3 has two possible automation channel types, OPC UA and S7. S7 is meant to communicate with the S7 PLC family but this communication method is not supported since Opcenter Execution Foundation (FN) 4.0 release (Siemens AG, 2020a). In this demo case, the OPC UA connection is used so the OPC UA Automation Channel is chosen.

In this integration case, only the demo environments and systems in the company's internal network are used. Therefore, there was not set security policy for the OPC UA connection. For the real industrial use cases, the security policy usage is highly recommended. There are three possible security policy options available: basic128Rsa15, basic256 and basic256Sha256 (Siemens AG, 2020a). The details and usage of these security policies are not discussed further in this thesis.

Next in the Figure 17 is the Automation Node Types configuration. These are structured sets of data which can be linked to the automation layer. Node Type structures can represent for example equipment types, machines or tools at the abstract level and contain the Automation Parameters. (Siemens AG, 2020a) In this case, one Automation Node Type was determined for the crane. An important part of the Automation Node Types is the Automation Parameters. In this case, five different parameters were determined. These are shown in Table 4 and Figure 18.

Table 4: Automation Node Type Parameters

Parameter Id	Data type	Default Value
CraneMoving	Bool	False
CraneWantedPosition	Int	0
HookX	Real	0
HookY	Real	0
HookZ	Real	0

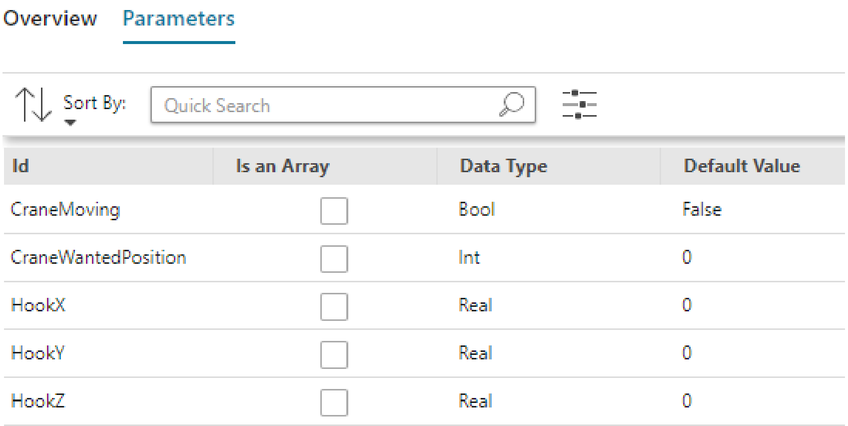

Figure 18: Automation Node Type Parameters in the Opcenter

Automation Parameters have the information needed to execute read and write operations of the automation data (Siemens AG, 2020a). In the Table 4, the Parameter Id is the unique identifier set for the Automation parameter in the Opcenter. The data type defines the set data type for the Parameter. The Default value is the set default value for the Parameter in the defined data type. There are also multiple other configurable Parameter attributes, but these presented in the Table 4 are the most relevant for this thesis purpose.

The Automation Node Instances are based on the Automation Node Types. These are meant to represent the real-world plant objectives and enable the data transfer with the field level. (Siemens AG, 2020a) An important part of the Automation Node Instance configuration is setting the Automation Parameter attributes. In this, the determined Automation Parameters will be linked to the specific parameters of the field device. In the

OPC UA context every entity is called as a node, and it has its own unique NodeId. Each Automation Parameter in the Opcenter is linked to one NodeId. In this way, it is possible to read and write PLC parameter values on the field level.

After all the previous necessary configuration steps have been performed and those status are set to approved, it is time for the last step in the Figure 17. The activation operation is required to deploy all the configurations and transfer them to the Automation Gateway Server to allow usage of those in the Automation Gateway App. Both Automation Channel and Automation Node Types and Instances must be activated. (Siemens AG, 2020a)

After successful activation, it is possible to read and write the values of the determined PLC parameters through the Opcenter Automation Gateway App. When the connection works and the parameters between the PLC and the Opcenter are set correctly, it is time to find out how to automatically control the PLC using the MES. This configuration procedure is discussed in next subchapter.

3.4.3 MES Semi-Automated Control Configuration

During the integration implementation of the demo case, no suitable way to achieve fully automated crane process control via the MES was found. Multiple Opcenter manuals about configuration and usage, as well as examination of the available Siemens training and support materials, were unable to provide a solution for this issue. The best answer found was that it is not possible with the current Opcenter EX DS 3.3 without additional Opcenter Connect MOM software. Opcenter Connect MOM would allow automated message transfer between the Opcenter MES and the shop floor level.

Thus, the process control was formed as automated as possible with the available systems and software. It is called a semi-automated process control because the movements of the crane require manual starting and completing of different Work Order Operations (WOOs) to complete the entire process cycle. The semi-automated control of the crane is possible to achieve with the Setpoints which are used to set specific values for the previously defined Automation Node Instances. These Setpoints and values are linked to the defined Process Operations, and these are transferred to the shop floor level by the Signal Rules. This Opcenter to shop floor integration framework is shown in Figure 19.

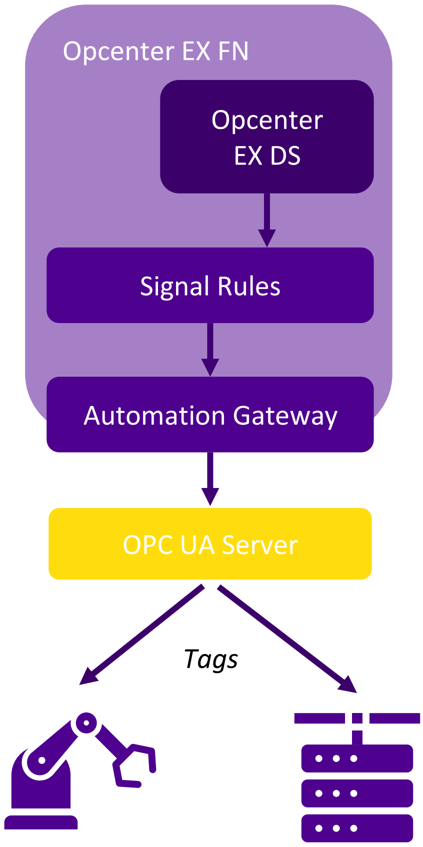

Figure 19: Shop floor integration framework

The first step is to define the different Setpoints. The Setpoints are used to drive the behaviour of a specific Machine or a Tool at the runtime. This will eliminate the need for the manual adjustments. The Setpoint values are transferred to the shop floor level via two Signal Rules. These two rules are *OnTransmitEquipmentSetPointSignalRule* for the Equipment and *OnTransmitToolSetPointSignalRule* for the Tools. Both of the Signal Rules must be imported, approved, and deployed before these can be used. (Siemens AG, 2020b).

The used PLC code was predetermined and has 12 predefined crane positions which are used to move the crane to desired positions. The code was not changed during this thesis. Figure 20 contains screenshot of the TIA Portal showing the defined crane positions. Each of these crane positions contain information about the crane hook X, Y and Z coordinate in the Plant Simulation environment. The crane positions and coordinates with the position description are collected in Table 5.

Table 5: Defined crane positions with coordinates

Crane Position no.	HookX	HookY	HookZ	Position description
0	0	0	500	Zero position
1	1000	2800	500	Over the roll to be processed
2	1000	2800	2500	Hook down to lift roll
3	1000	2800	500	Roll lifted up
4	3120	5100	500	Position over the grinding machine
5	3210	5100	2750	Lowering the roll to the grinding machine, faulty X?
6	3120	5100	2750	Lowering the roll to the grinding machine
7	3120	5100	2750	Same as the number 6
8	3120	5100	500	Lifting the hook up from the grinding machine
9	1000	2800	500	Moving finished roll above the buffer transportation
10	1000	2800	2500	Lowering the roll for the buffer transportation
11	1000	2800	500	Lifting the hook up

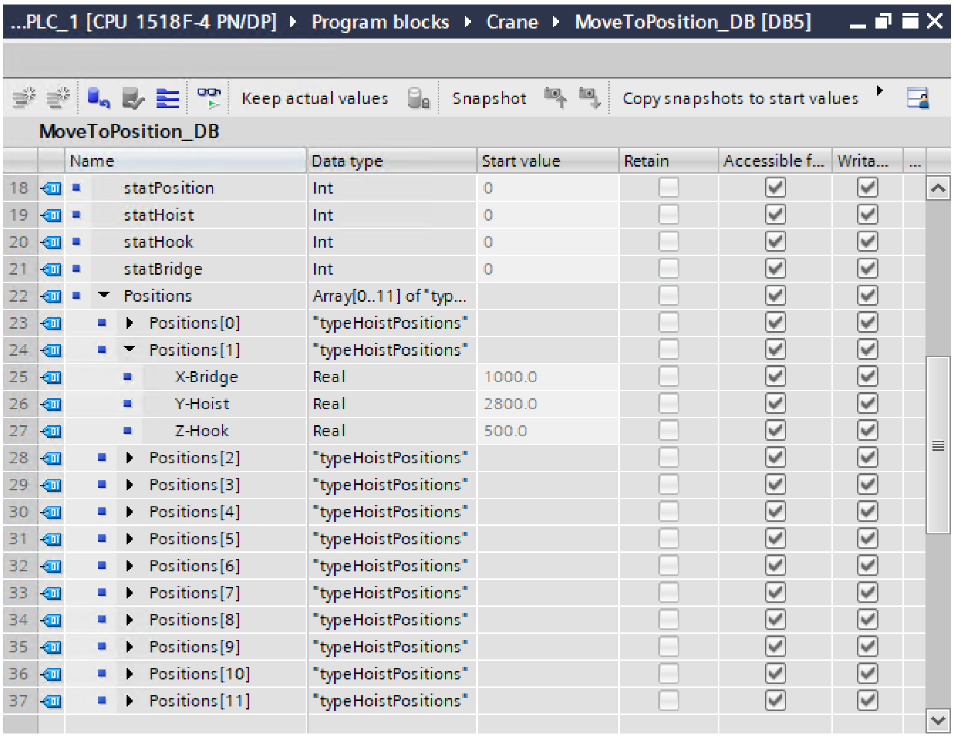

Figure 20: Crane positions in the TIA Portal

These crane position numbers shown in the table above are the same ones used as the crane control Setpoint values in the Opcenter. For the each Setpoint it is possible to define multiple default values. Although this is possible, it is not possible to set different default values from the list for the different Work Order Operations that use the same Setpoint. Thus, even if one Setpoint can have several default values, only the first of these can be automatically selected when set to the WOOs. This feature was confirmed from the Siemens training materials. This Setpoint feature lead to the situation where instead of defining one Setpoint with the default values 0–11, twelve different Setpoints were defined, each with a one crane position number as its default value. These Setpoints are shown in Figure 21.

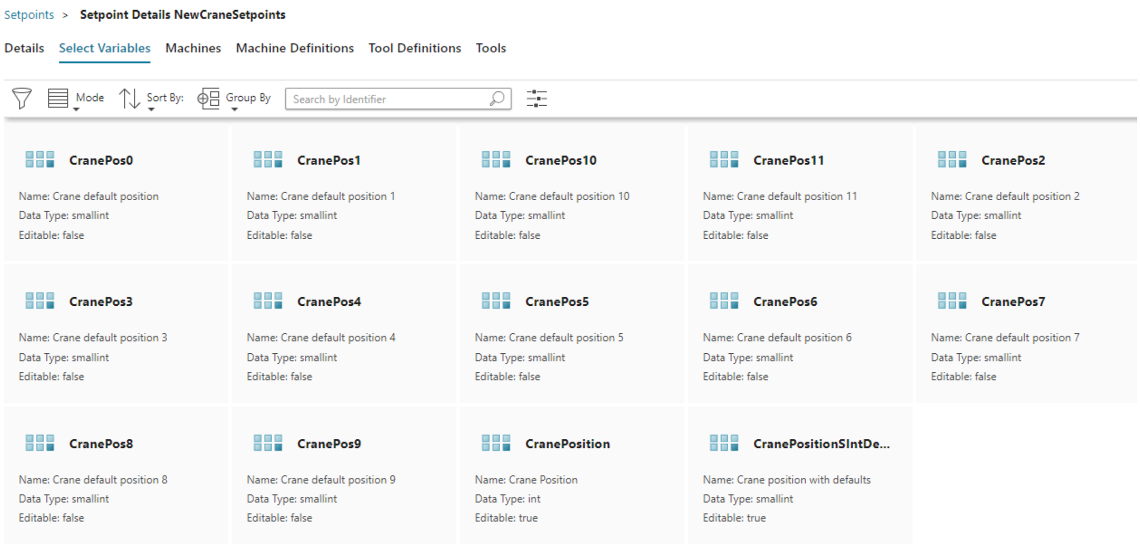

Figure 21: Defined Setpoints

The realisation that only a one Setpoint can be set for one Work Order Operation required changes to the crane process diagram previously shown in the Figure 10. The process should be divided into different operations which each containing only one predefined crane position. This new modified crane process diagram is shown in Figure 22. It also includes the crane position numbers for each step based on the values in the Table 5.

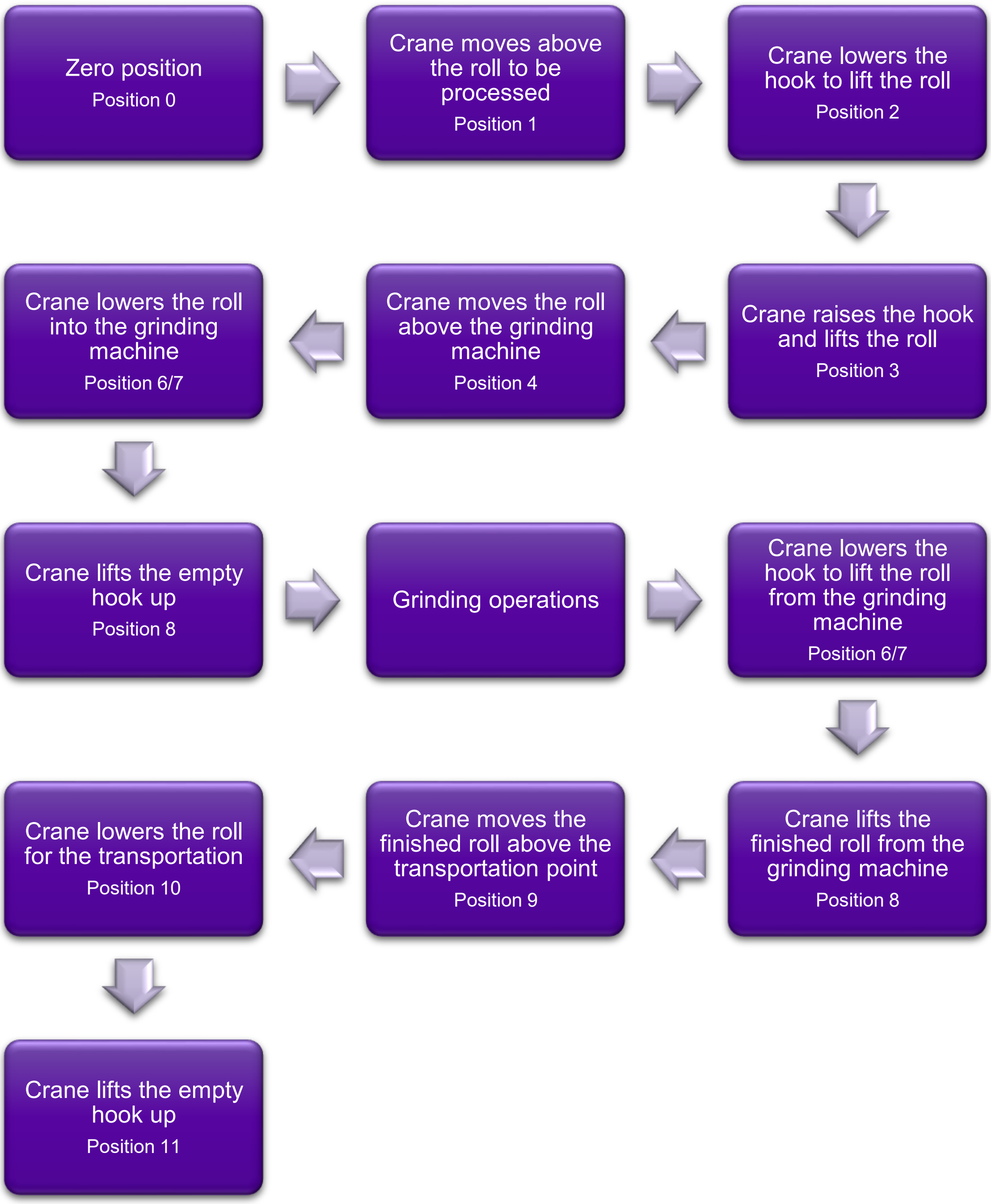

Figure 22: Crane process diagram with the crane position numbers

As can be seen in the Figure 22, not all the positions of the crane are used. Some of the positions are used multiple times. As it can be noticed from the Table 5, some of the positions have exactly same coordinates such as positions 2 and 10. Thus, it could be possible to use the same positions several times and by this way to reduce the total number of the positions. Since the PLC code and positions were given, they were not changed during this thesis.

In the Opcenter, it is possible to define different types of the Work Operations associated to the Work Order Operations. The Work Operations are used to define the runtime behaviour of the WOOs. Multiple pre-defined Work Operations are available in the system, but it is also possible to create your own ones. In this integration task, the interesting parameters for the creation of the Work Operations were the Auto-Complete and the Auto-Start. These parameter names are self-explaining, the Auto-Complete automatically completes the WOO after it has been started. The Auto-Start automatically starts the WOO when preceding Work Order Operation has been started or completed depending on the defined dependency schema. (Siemens AG, 2020b)

Four different types of the Work Operations were defined and tested. One had the Auto-Start parameter selected, another had the Auto-Complete, the third one had both Auto-Start and Auto-Complete parameter selected and the fourth neither of these, being completely manual. When both the Auto-Start and the Auto-Complete are used, the Opcenter cannot transfer the setpoint data to the PLC. The Opcenter successfully Auto-Starts and -Completes the Work Order Operations but the crane position in the PLC gets stuck at the first transferred value. Looking at the Genealogy's ATN Transmission History in the Opcenter confirms that the only transferred value is in the first Operation. This is shown in Figure 23.

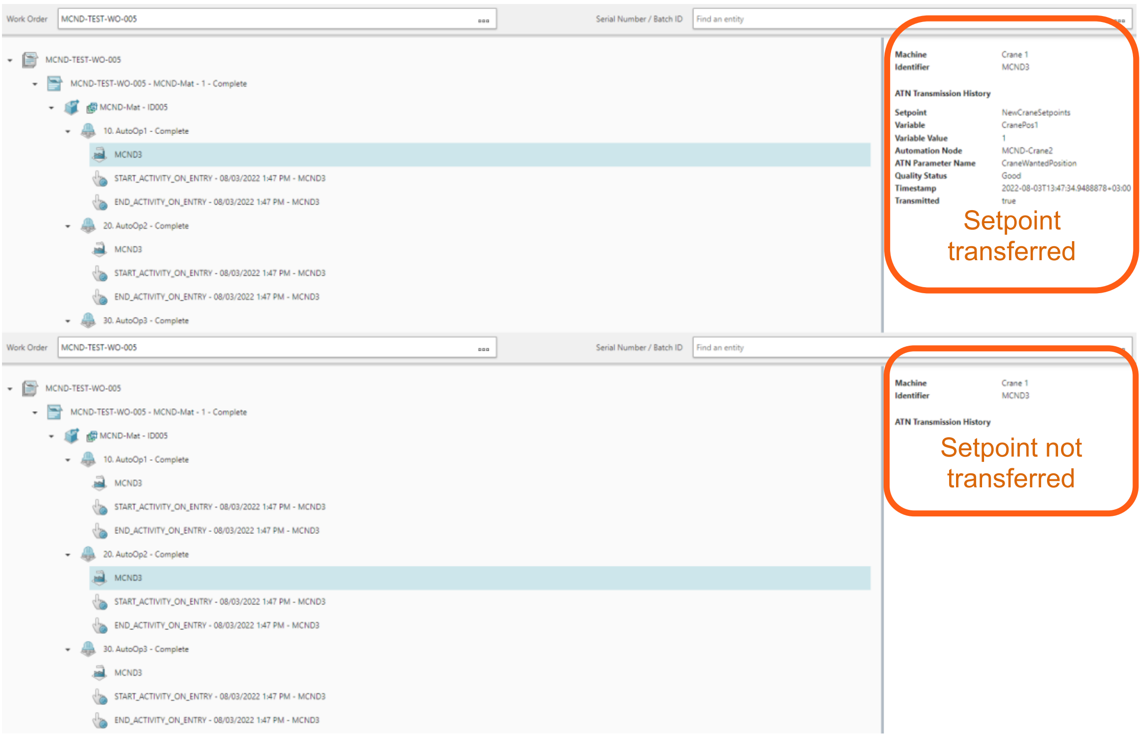

Figure 23: Opcenter Genealogy ATN Transmission History

Completely similar issue was identified when using only the Auto-Start parameter. Therefore, the Setpoint value transfer issue was identified to the Auto-Start parameter. When using only the Auto-Complete parameter there is no issues with the data transfer. The only drawback noticed was that the Opcenter page needs to be always refreshed after the Work Order Operation starting to get this WOO to be marked as a complete and be able to start the next WOO. In the comparison tests between the fully manual starting and completing and manual starting and Auto-Complete, it felt easier to control the PLC in the full manual mode. In this way the flow of the process was smoother. Therefore, the final implementation was done using this fully manual starting and completing of the Work Order Operations.

The new Process was determined in the Opcenter based on the process shown in the Figure 22. The only difference between the determined process and the process in the Figure 22 is that the process in the Opcenter does not have the zero position at the beginning. This is because the simulation model in the Plant Simulation automatically moves to this position when the simulation is started. The defined Process Operations are shown in Figure 24.

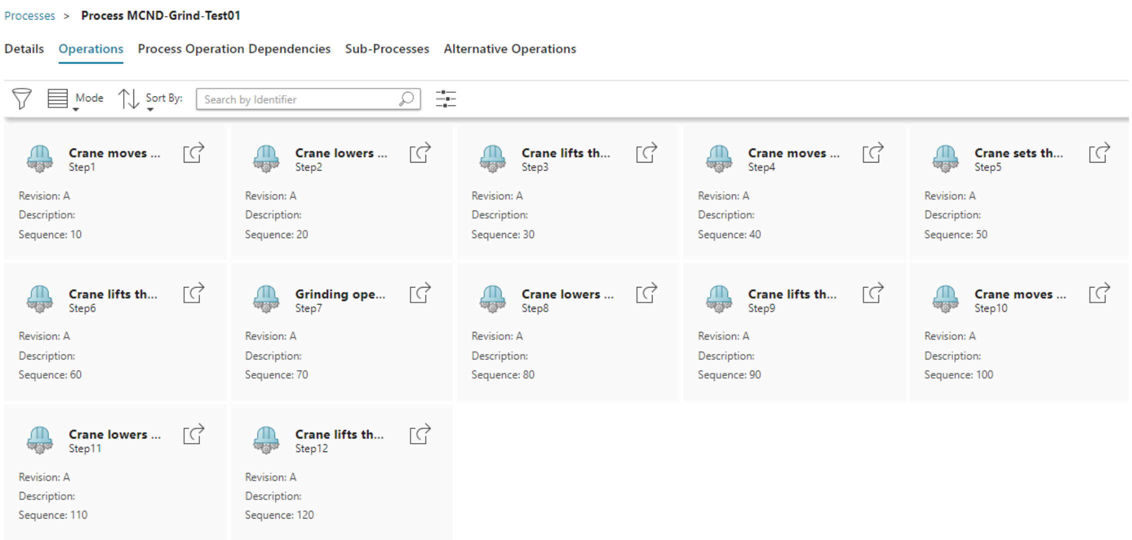

Figure 24: Process Operations

For all the Process Operations, the Dependencies between different Operations were set to the After End. It is logical because the previous Operation must be completed before the next one can be started. Part of the Dependencies between the Process Operations are shown in Figure 25.

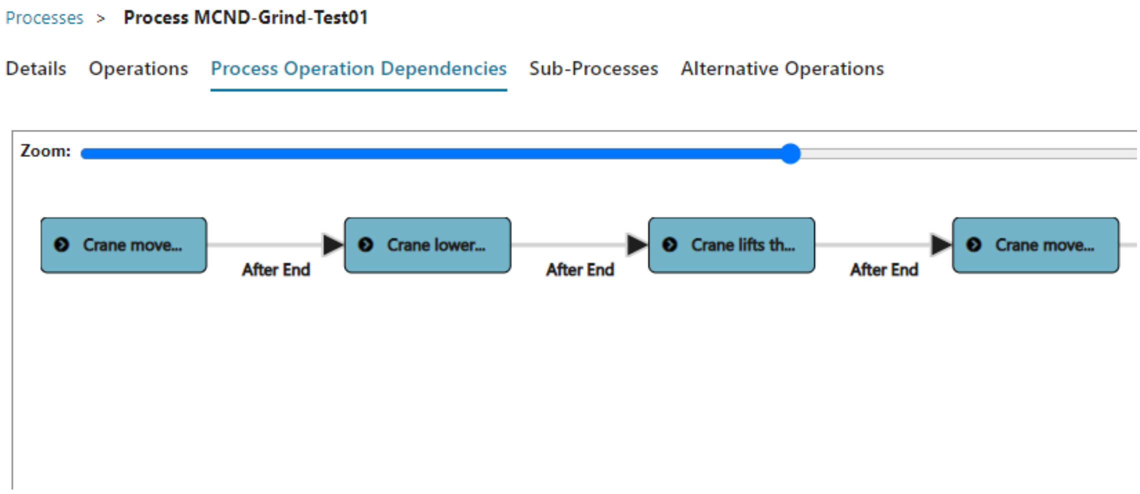

Figure 25: Process Operation Dependencies

The first idea for implementing the Process in the Opcenter was to combine multiple required Process Operations into the Sub-Processes. This type of implementation would have made the Process cleaner by running the different Sub-Processes one after the other instead of the multiple WOOs. This type of implementation was not successful. It seems that the Opcenter Sub-Processes are meant to be used in a different way. A suitable way to divide the previously described Process into the Sub-Processes or other smaller sub-components was not found.

The final step in the Opcenter configuration was to create the Work Order based on the defined Process. When the defined Work Order is released the Work Order Operations must be started and marked as completed manually. When starting, each WOO transfers one Setpoint value to the PLC as described above. The correct crane position changes using the Setpoints were confirmed using the PLCSIM Advanced and Matrikon OPC UA Explorer. Therefore, the last main step in the crane integration process was to implement the PLC value transfer to the Plant Simulation model.

3.4.4 Automation and Digital Twin Integration

The integration between the PLCSIM Advanced and the Plant Simulation model was straightforward to implement. The Plant Simulation has many different Inter-Process Communication Interfaces defined inside the software. There is two suitable ways to link the Plant Simulation to the PLCSIM Advanced. The first one is the PLCSIM_Advanced-object which can be used to transfer PLC Out and PLC In signals between the software (Siemens PLM Software Inc., 2019).

The second option is to use the OPC UA Interface in the Plant Simulation. In the Plant Simulation, the OPC UA Interface works as an OPC UA client and can read and write the data (Siemens PLM Software Inc., 2019). In this implementation, the OPC UA Interface is used because the OPC UA connection is also used between the MES and the PLC. It is also better in terms of the generalisability of the implementation. The PLCSIM Advanced interface would only work with the simulated PLC whereas the OPC UA interface would also work with the real PLCs. This is an important detail if the goal is to replace the simulated PLC with a real one in the future.

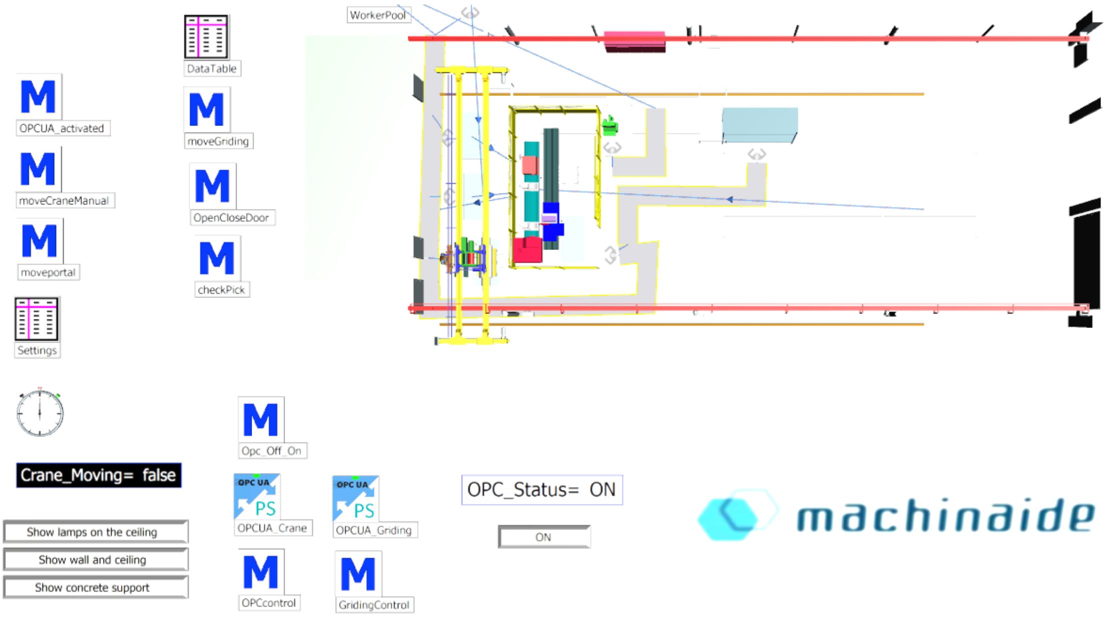

Figure 26: Plant Simulation model interfaces and methods

The use of the OPC UA Interface is very simple. The OPC UA Interface object is added to the simulation model and the correct parameters are set to connect the simulation model to the virtual PLC in the PLCSIM Advanced. Two used OPC UA Interfaces and the main used methods are shown in Figure 26. The Plant Simulation methods are then used to transfer the data from the OPC UA Interface to the simulation objects. This allows the PLC to control the simulation. These methods with the OPC UA Interface were already implemented as a part of the crane and the virtual grinding machine simulation model. Therefore, the details of the methods are not discussed in this thesis because there was no need to make significant changes to these.

3.4.5 Implemented Integration Architecture

The proposed integration architecture to interconnect the MES, the PLC and the DT is shown in Figure 27. It also includes the main software used in this thesis demo implementation. It follows the similar integration architecture as Azarmipour et al. (2020), Negri et al. (2020), Barbieri et al. (2021), Guo et al. (2021) and Onaji et al. (2022) have proposed.

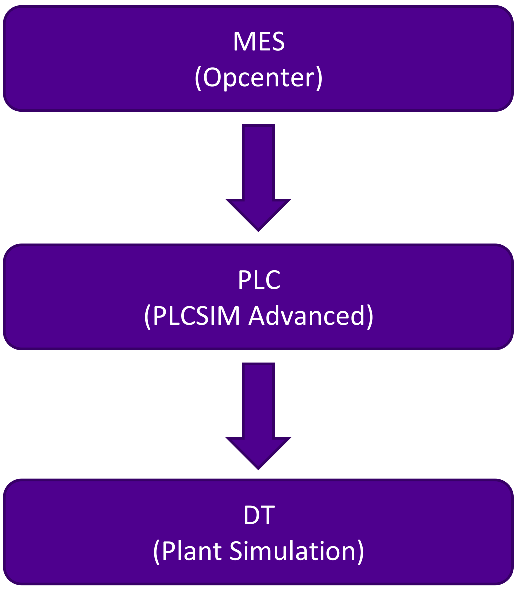

Figure 27: The Digital Twin integration architecture

As can be seen from the Figure 27, the MES is connected to the PLC and the PLC is connected to the DT. The MES sends the data to the PLC which transfers this data to the DT. In this case, there is no real production system to be controlled by the PLC. As mentioned earlier, adding the physical system would not change the integration architecture much. It would add a one additional part to it as can be seen from Figure 28.

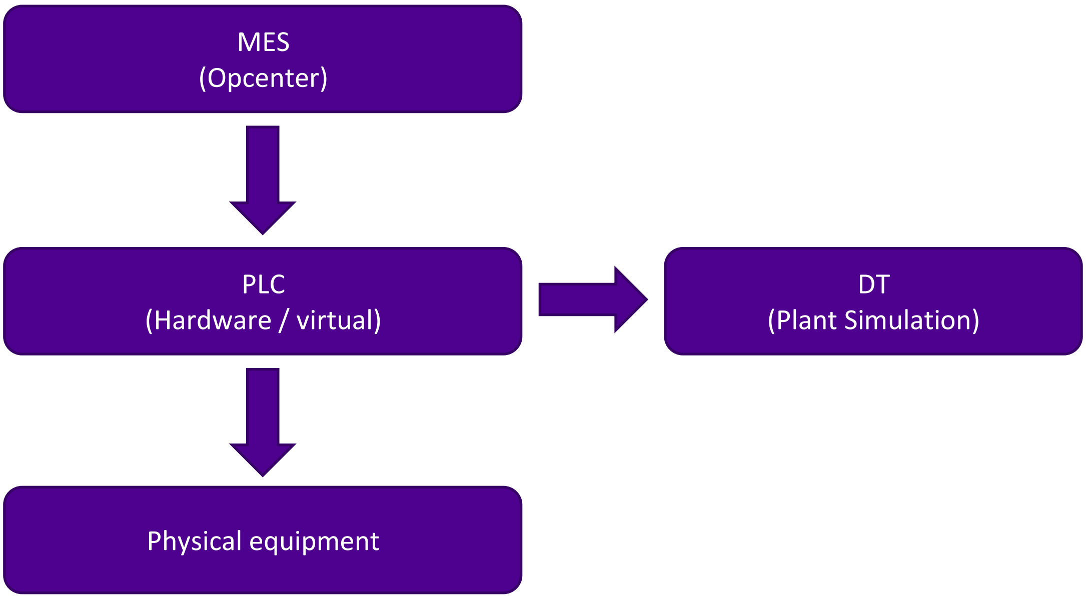

Figure 28: The Digital Twin integration architecture with the physical system

Comparing Figure 27 and Figure 28, it becomes clear why adding a physical system to the proposed integration architecture does not really change it. The data transfer between different systems remains unchanged. The only difference is that now the PLC sends the data to the DT and to the physical system, whereas before it only sent it to the DT. This type of integration architecture is also modular because it allows system components to be easily added and removed without disrupting the system's operation.

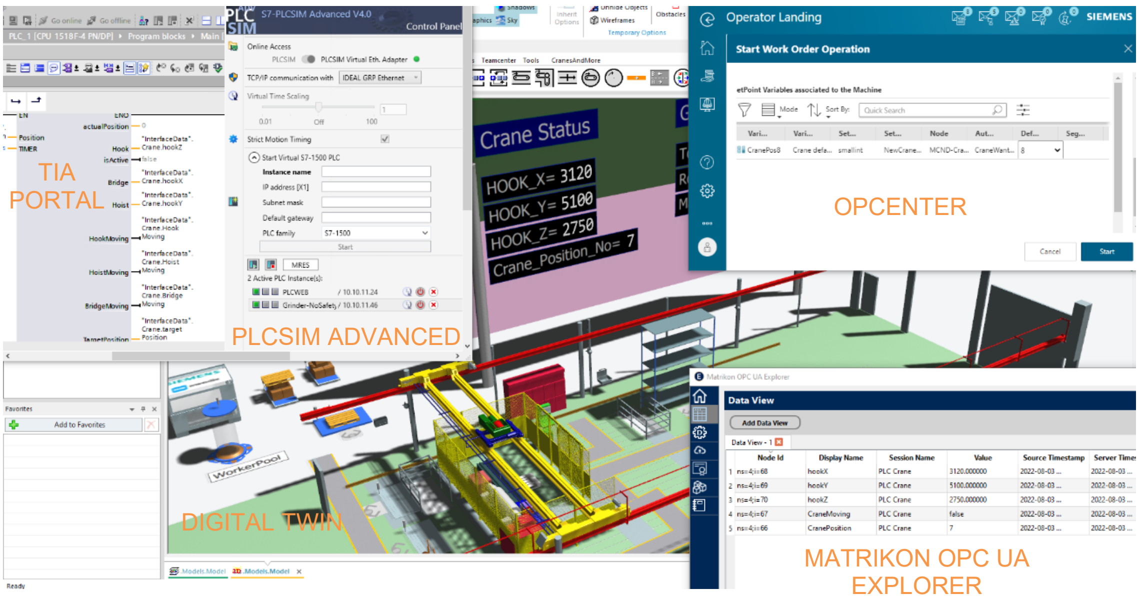

Figure 29: The complete MES connected Digital Twin

During this implementation, all the software for the DT were from the same developer Siemens. Overall view of the used software setup is shown in Figure 29. As was mentioned, the software contains specific communication ways to connect different Siemens software together. However, those were not utilised during this architecture demo implementation. The use of the OPC UA makes this architecture more generalised for the different developer's software, and all the software does not even have to be from the same developer. For example, it would be easy to change the PLCSIM Advanced for the different PLC simulator. The only necessary changes would be in the configuration of the PLC simulation software and possibly in the changes of the IP address of the PLC for other used software. The PLC could even be the hardware one and it would not require significant changes.

4. RESULTS

The literature review was the main research method to find the answers for the research questions 1 and 2 which were the following:

RQ1. What are the potential applications of the Digital Twin and what value can these bring?

RQ2. What are the current major challenges for companies in the Digital Twin implementations?

A one interview was also done to support the findings from the literature and give the results the real industrial perspective. The potential DT applications found from the literature and the interview were introduced in the chapter 2.5. These identified potential applications for the Digital Twin were the following:

- Monitoring
- Optimisation
- Maintenance
- Simulation
- Virtual commissioning
- Training

Multiple main advantages and challenges were identified from the literature and the interview. These were introduced in the chapters 2.6 and 2.7. The findings from the literature review and the interview are collected in Table 6. It is not mean to be a complete list of all the advantages and challenges of the DT. It only contains the most frequently mentioned advantages and challenges identified during the literature review and the interview. Therefore, these can be considered the most important ones which is why they are presented in this thesis.

Table 6: The Digital Twin challenges and advantages

Challenges	Advantages
Standardisation	Flexibility
IT infrastructure	Reliability
Modelling	Predictability
Data	Transparency
Connectivity and communication	Data management
Privacy and security	System understanding
Organisation and people	Production cost reduction
Cost	
Technology immaturity	

Based on the literature review and the interview, the following findings and conclusions can be defined for the research questions 1 and 2:

- The DT has many potential applications, some of which are completely new and some of which the DT brings new advantages over the current methods.
- The Digital Twin widespread implementation in the industry seems quite unrealistic at this moment. It has many challenges that slow down its wider adoption.
- The most significant challenge of the DT is the lack of standardisation, and many other challenges are related to this standardisation challenge.
- The overall purpose of the DT should affect for all the choices made during its implementation.

Summarising the findings for the RQ1 and the RQ2, it can be said that the DT has a lot of potential, but still many challenges need to be overcome before it can be achieved. These findings were done from the literature review and interview. Therefore, commercial implementations of the DT can be difficult. When its maturity level increases, and major challenges have been solved the situation should be re-evaluated.

For the research questions 3 and 4, the integration demo case study was implemented during this thesis. Some DT integration architectures were identified from the literature. Observations were made from these and these were used in this thesis. The research questions 3 and 4 were the following:

RQ3. How to add the Digital Twin as a part of the MES and automation integration?

RQ4. How does the Digital Twin affect the MES and automation integration?

Several interesting findings were done based on the DT integrations in the literature and thesis case study implementation. These findings and conclusions were as follows:

- Five of the six integration architectures identified from the literature had a similar structure where the MES sends signals to the PLC which then updates the virtual model.
- PLC Tag value transfer from the MES to the PLCSIM Advanced was successfully achieved in the case study.
- Connection between the PLCSIM Advanced and the Plant Simulation was successfully achieved.
- The Digital Shadow level of the integration was achieved successfully.
- Feedback loop from the virtual model to the physical world is not straightforward to implement.
- Adding the DT as part of the integration of the MES and automation has no significant effect with the integration architecture used in this thesis.

For the RQ3, the findings showed that the best suitable integration architecture for the integration between the DT, the MES and automation is that where the MES sends signals to the PLC, and it then updates the virtual model. No issues were identified from the literature or the case study in this integration architecture usage. Therefore, this type of architecture usage can be recommended when integrating the DT, the MES and automation together.

For the RQ4 point of view the DT does not seem to affect for the integration. Adding the DT as a part of the system had no effect in the case study, and there were no mentions of issues related to this in the literature. Adding DT to the system had no effect in the case study, and there was no mention of problems related to this in the literature. Therefore, adding the DT as a part of the MES and automation integration should not cause any issues in the integration point of view.

5. DISCUSSION

This chapter analyses the results gathered during this thesis and shown in chapter 4. In the following subchapters the results reliability, relevance and scalability are discussed. The gathered results are compared to the goals set by the research questions and their fulfilment is analysed. The DT applications, advantages and challenges collected from the literature are analysed. Similarly, the findings from the implemented integration architecture are analysed and discussed. Finally, the potential future research areas are discussed.

5.1 Results Analysis

The Digital Twin is relatively new technology, especially in the manufacturing field where it was introduced in 2013. The research in this area is very active which can lead to the rapid obsolescence of the previous results. Therefore, from the beginning of the thesis it was seen important to choose as new material as possible. The used DT related material was tried to choose carefully by favouring as new articles as possible. This can be seen to have been quite successful as most of the articles related to DT are newer than 2019 and the majority newer than 2020. This increases the gathered results relevance and reliability.

There were multiple potential applications identified for the DT from the literature. All these applications are currently implemented using other technologies. Monitoring, data management and training area good examples of that. To many of these, the Digital Twin will be able to add new features and bring new possibilities. The DT can also increase the benefits gathered from these applications. In the future, completely new applications for the use of the DT may be found when its use becomes more common.

Most of the potential benefits of the DT usage found in the literature were mostly from laboratory implementations and estimates of its theoretical potential. There was not much literature available of the DT implementations in the real industrial manufacturing systems. If material from real industrial use cases was available, the results were not long-term or not very accurate. This sets the clear limitation for the relevance of the identified DT benefits. On the other hand, the use of the DT may have other significant advantages, or the already identified advantages may become even more obvious when more real industrial DT implementations become available.

There is some limitations and uncertainty for the DT benefits identification as was mentioned above. These may be the reasons why there is not very many identified benefits. When considering the DT related challenges, the situation is different. There are many challenges mentioned in the literature and the same challenges are identified in multiple different sources. The most common being the standardisation. Like the benefits, most challenges were identified from the laboratory implementations. The difference is that many challenges are already faced in the design phase of the DT, while the benefits can only be gathered after some time. This may be one of the reasons why more information about the challenges is available in the literature.

The material collected and analysed to identify the DT applications, advantages and challenges can be seen relevant and high in quality. It mostly consists of peer-reviewed articles that were newer than 2020. All listed applications, benefits and challenges were mentioned at least in two different sources. Therefore, the results presented in this thesis can be seen to fulfil the goals of the research questions RQ1 and RQ2.

To find the suitable answers for the research questions RQ3 and RQ4 the one integration example was implemented. It was done using Siemens software, which limits the integration process and results to that software. With the different software the implementation procedure may be completely different. The used connection was the OPC UA which makes the connection between different systems more universal. Overall, the done integration example gives a good example and overview of the integration process with the certain limitations.

The suitable integration architectures were identified from the same literature as the applications, advantages, and challenges. Six architectures were found, which can be seen as an appropriate number to draw conclusions from these. Five of them have a similar structure and the implemented integration architecture was based on these. In this the MES sends signals to the PLC and the digital model is updated based on the PLC values. Based only on the literature this integration type seemed to be most straightforward to implement and its structure seemed logical without major issues. The integration case study confirmed this type of integration architecture being suitable for the DT usage with the MES and automation. No major issues were identified regarding the integration and interfaces between different systems.

The integration case study was overall quite successful. The OPC UA connections between different systems were successfully achieved which was one of the main goals of this thesis. Another goal was to achieve suitable controlling of the Plant Simulation model with the Opcenter MES. This was achieved at a good level. When configuring the

Opcenter to control the defined Plant Simulation model, it was noticed that the Opcenter EX DS version 3.3 was not the most suitable software for that purpose. In many tasks, the program felt very strict in terms of configuration, and it was easy to notice that it was not intended for such a use. These were important findings for the potential future DT implementations, even though they were not actually part of the goals set for the thesis.

Depending on the integration type, the DM, the DS, or the real DT it sets the different requirements for the integration. The literature review analysis indicated that the Digital Model and the Digital Shadow levels are easier to achieve than the real Digital Twin. This was confirmed during the integration task case study when it was noticed that there is not ready and easy solution available to implement the virtual-to-physical world connection which is the requirement for the real DT.

5.2 Future of the Digital Twin Standardisation

The most significant challenge of the DT seems to be the lack of standardisation and it is also the most frequently mentioned challenge in the literature. Many of the other challenges presented in this thesis are somehow related to the lack of the standardisation, such as connectivity and communication. There does not exist one single definition for the Digital Twin which would be the first step towards the more standardised and unambiguous DT. Now there exist the DM, the DS, and the real DT which all are called as the DT in the different contexts. This can cause issues because different people can discuss about the DT but still mean different things. Especially difficult this is if some company is trying to sell or buy the DT implementation from another company. Without a clear definition the DT can mean different things to them.

This standardisation issue is identified and solutions for it has been started to seek. Guo et al. (2021) mention about one potential standard for the DT implementations. It is ISO 23247 – Digital Twin Framework for Manufacturing. Researching this ISO 23247 standard confirmed that it has been published in October 2021. It is meant to give a generic manufacturing DT framework which can be then applied for the case-specific DT implementations. This can be an important step towards the more standardised DT implementations. It can help the companies to make the investment decisions about the DT when a standard is available that defines the structure of the DT and its connections to the other systems. These are important things to ensure that the DT structure will be more general which helps its understanding. Another important thing is the connectivity, because the existing standard should allow the easy connection of the different DTs from the different sources to each other.

It must be mentioned that the standardisation itself will not solve all the DT challenges. There are still many challenges which are not connected to the standardisation issues. For example, the modelling has many challenges related to the model fidelity. The cost issue is important and closely related to the modelling. Overall, it can be said that all the challenges are related to each other, and these challenges are related to the requirements that the defined applications set for the DT structure.

5.3 Future Work

During the literature review, only two different main integration architectures were found. The used integration framework in the case study does not show any major issues related to its architecture. Despite this, it would be beneficial to do research about other potential integration frameworks. Thinking about the future and potential wider adoption of the DT, it would be very beneficial to do a wider comparison and analysis between potential different integration architectures. Of course, it may be that there are not many different architectures available but wider research about that would still be beneficial.

One integration case example was done in this thesis and the Digital Shadow level in integration was achieved. The main goal of the integration case study was to achieve at least the DS level in the integration. Therefore, this goal was fulfilled. The next step would be to try to implement the real DT level of the integration which would require the feedback control from the DT to the physical world. It was not possible during this thesis because of the time limitations. It was identified that it would probably require much more work and time than the DS level of the integration and it was decided to be left as a future task.

To transfer the Digital Shadow to the real Digital Twin the connection from the Plant Simulation model to the real world is required. It would be possible by adding a connection from the DT to the MES. The integration architecture with this addition is shown in Figure 30, where the needed additions to achieve the real DT are shown in dashed lines.

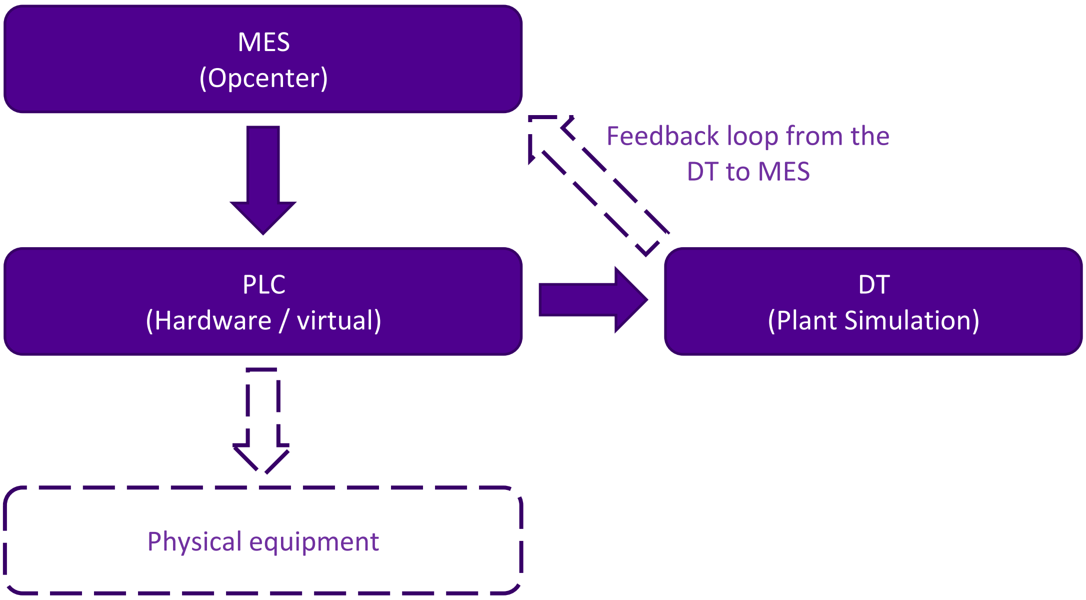

Figure 30: The real Digital Twin integration architecture

Because the PLC and the production would be controlled by the Opcenter MES, the most suitable way to realise this DT virtual-to-physical connection would be to connect the Plan Simulation model to the Opcenter. In this way there would be the feedback loop from the virtual world to the physical world. It would also ensure that the MES stays up to date, which is important in terms of the production control. This way of realising the virtual-physical connection was also the most frequently mentioned way in the literature.

The used Opcenter EX DS version during this thesis was 3.3 which is a couple of years old version. Some of its features increase the amount of work required if it is used with the DTs. These make it a little unsuitable for the DT usage. With the newer Opcenter versions, the integration process may be more straightforward and simpler. These could also have a completely new capabilities compared to the used version. Therefore, investigating the features of a newer version of the Opcenter EX DS would be a one interesting tasks in the future. At the same time, it could have a better readiness for the real DT integration level.

The PLC code and coding were left outside of this thesis scope. It would be beneficial to explore the used test code more in detail and think how it should be improved to work better in the DT usage. In general, it would be beneficial to do research on PLC code with the DT. It may be that the use of the DT sets new requirements for the PLC code and researching these would be an important future task.

6. SUMMARY

The Digital Twin is an interesting new technology which is under wide research. It has been identified to have multiple potential uses in the manufacturing field and those were discussed in this thesis. The most important application areas are monitoring, optimisation and maintenance. The DT use in these areas can lead to achieving higher flexibility and reliability which can lead to cost savings in the production.

Before these benefits can be achieved, several DT related challenges must be overcome. The most recognised challenge in the literature is the lack of the Digital Twin standardisation. It has been mentioned in most of the articles that listed the DT challenges. Many of the other DT challenges, such as connectivity and communication, are related to this standardisation challenge. Other important challenges for the DT are for example modelling, privacy and security, and cost.

Six integration architectures between the DT, MES and automation were found from the literature. Five of them had a similar structure and it was used in this thesis integration case study. In this case study, the Digital Shadow level was achieved. The case study supported this type of architecture suitability for the DT integration with the MES and automation. Another main finding was that the feedback loop from the DT to the physical world is not straightforward to implement. Each integration architecture with the real DT required some additional layer to achieve this feedback loop.

The real Digital Twin has the highest potential, but at the same time the most significant challenges. There has been a lot of research on the Digital Twin, but in many cases, it has remained at the Digital Model or the Digital Shadow level. This is why it is important to do more exploration and research about the real Digital Twin in the future. It would be needed to release its full potential and help this technology spread more widely across the manufacturing industry.

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