Master Degree Project

UNIVERSITY OF SKÖVDE

A DEEP DIVE INTO THE CURRENT AND FUTURE CONDITIONS FOR VIRTUAL COMMISSIONING OF PRODUCTION LINES

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Abstract

The use of virtual commissioning has increased in the last years, but there are still challenges before the software code validation method is widespread in use. One of the additions to virtual commissioning is basing it on a digital twin to allow for improved accuracy. The aim of this thesis is to review existing standards and approaches to developing virtual commissioning, as well as to explore the definitions. The chosen approach to achieve the aim, is to perform a literature review of existing research papers and interviews with knowledgeable people in the industry. First, the definitions and classifications are reviewed, then the approaches for development of virtual commissioning and digital twins are explored in the literature. In three interviews with people of varying backgrounds and competences, the views of the virtual technologies are assessed to provide insight in the industry. The findings of the literature review and interviews are among others, the apparent need for standardisation in the field and that a sought-after standard in the form of ISO 23247-1 is under way. Furthermore, the digital twin is a concept with a promising future in combination with other technologies of Industry 4.0. In conclusion, this thesis provides a deep review of the challenges and possibilities of virtual commissioning and the digital twin and could be used as starting point for further research in standardisations and improvements sprung from the new standard.

Keywords: Virtual commissioning, digital twin, simulation, production system, classification, literature review, interview

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Skövde, May 2021

Anton Lidell

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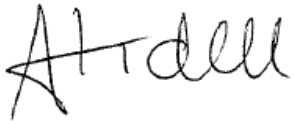
Certificate of Authenticity

Submitted by Anton Lidell to the University of Skövde as a Master Degree Thesis at the School of Engineering.

I certify that all material in this Master Thesis Project which is not my own work has been properly referenced.



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Nomenclature

3D	= Three dimensional
AI	= Artificial Intelligence
AR	= Augmented Reality
CAD	= Computer-Aided Design
CAx	= Computer-Aided technologies
DDT	= Deep Digital Twin
DM	= Digital Model
Discrete manufacturing	= manufacturing of distinct items
DS	= Digital Shadow
DT	= Digital Twin
FAT	= Factory Acceptance Test, process of evaluating production system equipment after assembly
FEM	= Finite Element Method
FMEA	= Failure Modes and Effects Analysis
FMI	= Functional Mock-up Interface
FMU	= Functional Mock-up Unit
FTA	= Fault Tree Analysis
HRC	= Human-Robot Collaboration
IOCO	= Input-Output Conformance
ISO	= International Organization for Standardization
IT	= Information Technology
KPI	= Key Performance Indicator
Mendeley Desktop	= a reference manager and citation generator application
OT	= Operational Technology, hardware and software of industrial control systems
PLM	= Product Lifecycle Management,
Process manufacturing	= manufacturing of products derived from formulas or recipes
SME	= Small and Medium-sized Enterprises
State-of-the-art	= cutting-edge, the highest level of general development
STEP	= Standard for The Exchange of Product, file-format for 3D objects
UML	= Unified Modelling Language
VC	= Virtual Commissioning
VFAT	= Virtual Factory Acceptance Test
VR	= Virtual Reality

1 Introduction

This chapter introduces the background of the problem and the importance of finding solutions to improve the current state of knowledge. The aim of the project and the objectives to achieve the aim are presented. Furthermore, the limitations to the scope of the projects are introduced as well as the general structure of the report and its chapters.

1.1 Background

For production system designers, the ability to create digital twins of the desired production line system and then evaluate the performance of the system has become increasingly interesting with time, as the tools have been developed. Evaluating a production line in a virtual environment before the physical production line is constructed is generally called virtual commissioning. Virtual commissioning consists of a digital twin, which parts are a model of the desired production line, the programming code to control the model and often algorithms for handling various behaviours, for example vision systems. A central part of virtual commissioning is evaluating the production systems performance through simulating different scenarios.

There are many reasons for using virtual commissioning. For example, to prevent errors and optimise the performance of the production line before any equipment is in place, thus allowing for changes to be made at a lower economical and timewise cost. This is due to changes in digital models mainly requiring cost in labour-time for the designer compared to material cost and labour-time for assembly and disassembly. As technology and digital tools have improved and evolved so has the possibilities for employing virtual commissioning as well, which has led to an increased use of digital twins and virtual commissioning in general.

While the virtual modelling, programming and control algorithms keep developing and improving, the knowledge and research regarding standardised and formal methods for virtual commissioning are less explored. Therefore, the focus of this report is to concretise and summarise the current knowledge of the conditions for virtual commissioning.

1.2 Aim and objectives

The research question of a research project should be feasible, interesting, novel, ethical and relevant to characterise good research according to the FINER framework (Elsevier Author Services, 2021). And preferably, the research question consists of a single question that will shape the whole research design (Thabane *et al.*, 2009). The research question of this project is: What are the current conditions and future for Virtual Commissioning of production systems?

The aim of the project is to study existing methods and standardised approaches for developing virtual commissioning simulations. This is to improve the utilisation of virtual commissioning models for production systems and the reliability, thus increasing cost and material effectiveness in the design process. The objectives are:

1. Perform a literature review of existing research papers on methods and standardised approaches for virtual commissioning of production systems.
    1. Identify important factors, such as challenges and prospects, for virtual commissioning of production systems.
    2. Compare the identified methods and approaches for virtual commissioning of production systems and present the conclusions.
2. Perform interviews to assess the current use of standardised and formal approaches for virtual commissioning of production systems in the industry.

1.3 Scope and limitations

As the nature of this thesis is to study the topic in depth, some limits to the scope of the project are necessary to maintain focus on the aim and objectives as well as keeping the work and timeframe reasonable. The primary limit of the research scope is to only study the closest related technologies to virtual commissioning and digital twins in order to maintain the depth of the study rather than width.

1.4 Scientific contributions

If the work of reviewing standardised and formal approaches for virtual commissioning is successfully conducted, the possible research contributions will be in two areas. Firstly, a scientific survey of the area, or literature review, of the current standardised and formal approaches have not yet been made. This means that the literature review in itself can contribute to the field through providing a summary of existing knowledge and approaches. Secondly, the interviews, which aims to assess the current

situation in the industry, can allow for conclusions of, for example, challenges and future directions of virtual commissioning to be drawn.

1.5 Report organisation

To give an overview of the report the different sections are presented as well as some short explanations of their purpose to give a first glance at the content to expect in each chapter. The chapters are as following:

1. ***Introduction*** - introduces the background of the reports problem as well as describing the objectives necessary to achieve the aim of the report.
2. ***Methodology*** - describes the chosen approach to the problem, how the methods are used and the reasoning behind choosing the methods.
3. ***Theory*** - provides a theoretical foundation of knowledge necessary for the reader to understand the terminology and technical aspects of the report.
4. ***Literature*** - presents the summaries of the selected research articles content as well as comparisons to conclude the findings.
5. ***Interviews*** - presents the approach and work of conducting the three interviews to assess the current situation.
6. ***Results*** - provides a summary of the results from the *Literature study* and *Interviews* as well as an analysis of the results.
7. ***Discussions*** - assesses the validity of the results and discusses possible improvements to be made to the methodology.
8. ***Conclusions*** - describes the work performed to this point as well as drawing conclusions on the results.
9. ***Future work*** - suggests areas of further studies in the research field and questions needed to be answered to make further advances.

2 Methodology

The methodology chapter's purpose is to present the proposed approach to solving the problem, achieving the aim and objectives of the project. To expand the knowledge in the area of methods for evaluating virtual commissioning a literature review is to be conducted. Interviewing so called experts in the industry can give some insights to how the methods of evaluating virtual commissioning are used currently by practitioners and ground the project to the real world.

2.1 Literature review

The purpose of a literature review is to gather information through exploring existing documents such as research articles or conference papers. A literature review is often used in an early phase of a project to identify possible research ideas, where it gives an overview of the subject area as well. After identifying and choosing a suitable research topic the literature review is then used to gather evidence to strengthen the claims of the project. (Oates, 2006)

Performing a literature review can be time consuming since there are more steps than simply reading research articles. The first step is finding the appropriate documents, and this can be achieved through searching databases such as *Google Scholar*, *IEEE Xplore*, *Academic Search Elite*, *Scopus* and *ScienceDirect*. At first preliminary search terms are needed to start the search and when articles on the subject are found a quick overview can be gained from skimming through the abstract and introduction. This overview should give further knowledge about the subject and the terminology of the area which can be used to improve or add new and more accurate words to the search terms. The search terms can be improved continuously until the desired and appropriate articles are found.

When the search terms give accurate search results, the identified and appropriate articles should be read thoroughly to deepen the knowledge in the area and of the subject. Next, the articles should be summarised and concluded to be able to analyse the content. For this project, the articles will be summarised in tables for comparison of current state of virtual commissioning to try to identify similarities and differences.

2.2 Interviews

An interview can be described as a controlled conversation between people, the interviewer, and the interviewee. The interviewer's objective is to gain information about a particular subject from another

person, who is the interviewee, and therefore the interview is planned and structured to varying extents. The interview can be structured, semi-structured or unstructured. In the former, the questions asked are pre-determined and standardised, this type is suitable for asking the same questions to a larger population to compare the answers. In a semi-structured interview, there are certain questions to be answered but the order of which they are asked are of less importance and determined by the conversation's flow. The interviewee has more control of how to answer the questions and may follow up with related answers. In an unstructured interview, the interviewer has less control of the conversation and the interviewee is given a topic which is to be answered in a freer manner. (Oates, 2006)

To gather information about the current state of development approaches for virtual commissioning in the industry and among practitioners, one or two people who can be considered experts in the area are to be interviewed. Since the interviewee in this case would possess great knowledge of the area the interview should be semi-structured to allow the interviewee to expand on the subject while still collecting answers to specific questions.

Regarding the ethics to consider when conducting qualitative interviews, Oates lists the rights of the participants; they have the right to not participate, to withdraw, to give informed consent, to anonymity, and to confidentiality. Since the nature of the interviews is technical, rather than personal, the most applicable rights are to not participate, to withdraw, and to give informed consent. Besides the rights of the participants, the researcher conducting interviews should also make sure to not make any unnecessary intrusions by asking questions by asking questions around the privacy of the interviewee if the question is not valid. Another ethical point is to maintain professional codes of conduct, such as being polite and respecting as well as portraying the interviewee's views in a fair manner. (Oates, 2006)

2.2.1 Interview questions

When designing and planning an interview there are a few important steps and since the conversation will be revolving around the questions asked, these are critical for receiving the most appropriate answers. Boyce and Neale suggest planning both how to start and conclude the interview as well as how to conduct the interview. The interview questions should be prepared thoroughly and that the order of the questions should be considered, for example, beginning with fact-related questions and asking more opinionated questions later. There should also be a maximum of 15 main questions. When setting up interviews the purpose should be explained as well as the expected length of the interview.

At the start of the interview the interviewee should be asked for informed consent to document and present the findings of the interview. After the documenting the interview the interviewee should be able to give feedback to prevent any wrong interpretations. (Boyce and Neale, 2006)

It is also suggested to start with an easy question for which the interviewee is likely well prepared for to allow the interviewee to get comfortable. To get deeper answers, the questions should be open-ended and complemented with probes, which are asking for further details or examples. After a question is answered, checks can be used to confirm that the interviewer interpreted the answer correctly. This can be done by reading out the documented answer for the interviewee to control before moving to the next. (Oates, 2006)

When conducting qualitative interview research, an interview guide should be developed and used in a test interview before the actual interviews. The interview guide should outline the interview and consist of an interview introduction, the questions, and a conclusion to the interview. The interview introduction should include thanking the participant, stating the purpose of the interview and how it will be presented and used, as well as asking the participant for consent to document the interview. The conclusion of the interview should include asking the participant if there is anything they would like to add, stating when they can expect to receive a draft of the interview, and finally, thanking them again for participating. The test interview can be conducted with a peer or a volunteer and the purpose is to get an opportunity for the interviewer to reflect on the chosen language, clarity of the questions, but also to practice listening skills. Conducting a test interview can also help assess the direction or style of the conversation to, for example, be an open dialogue with the interviewee. (McGrath, Palmgren and Liljedahl, 2019)

3 Theory

The theory chapter outlines the main topics of the thesis by explaining the basics of digital twins and virtual commissioning to provide the necessary information to inexperienced readers. The theory will also be used to improve the understanding of the topic and to be able to draw conclusions from the literature review as well as the interviews. The literature will also feed back to the theory as new knowledge is required to be able to interpret the literature.

3.1 Digital twins

Originally, the United States of America National Aeronautics Space Administration (NASA) coined the term Digital Twin (DT) around 2010 for a roadmap of simulation technology. DT can be used in multiple disciplines and domains, such as industrial production, supply chain management and logistics as well as design if smart cities. There is no common definition, likely due to the vast differences across the various domains, but for the industrial production domain DT can be defined as virtually replicating a physical system. (Mykoniatis and Harris, 2021)

Some common components of a DT of a production system are the mechanical, electrical, software and robot programming components, such as machines, tools, and conveyors. The mechanical components are modelled using Computer Aided Design (CAD) and provides most of the visualisation of the DT. The electrical components are less visual and regard the locating of power sources and defining the voltage, current and electrical flow. Software of a DT consists of, for example, Programmable Logic Controller (PLC) code and design of Human-Machine Interface (HMI). A PLC is a small processing unit with ports for input and output to be able to control automated systems and an HMI is the space of interactions between the human and the machines. Examples of an HMI are keyboard and mouse, physical button control panels and digital display control panels. The PLC's and HMIs are programmed using Computer Aided Programming software such as Codesys. The last common component of DT's is robot programming and consists of selecting robot, programming robot movements and safety protocols. (Bär, 2013)

3.2 Virtual commissioning

Virtual commissioning (VC), or emulation for logic validation as it is often referred for industrial production applications, is a testing process. VC is combining both a virtual plant model (visuals) as well as a virtual control model (PLC, HMI) with the purpose of discovering errors and problems before

the physical commissioning takes place. The line between DT and VC can be blurry but the difference is that VC can consist of a DT and is always performed before the physical commissioning. A DT can also be created after the physical commissioning with a purpose to improve the production system. The level of detail in VC can vary depending on which results are desired and accuracy necessary, while a DT is almost always an exact replica of the physical production system or object. (Mykoniatis and Harris, 2021)

There are a couple of types of virtual commissioning with different characteristics. The most prevalent are soft commissioning or Hardware-In-the-Loop (HIL) commissioning and complete virtual commissioning or Software-In-the-Loop (SIL) commissioning. Soft commissioning is linking a virtual PLC emulator to real hardware and complete VC is linking a virtual PLC emulator to virtual hardware. This is for verification and validation of the control logic of the production system in a virtual environment that displays the performance as accurately as possible. (Fernández, Eguía and Echeverría, 2019)

3.3 Simulation and emulation

Simulation and emulation in production systems is used to increase and optimise the performance of the system, both before and after the production system exists physically. To explain the relationship between simulation and emulation the main similarities and differences can be used. One similarity is the use of 3D representations of the physical production system, another is the use of accurate modelling, as well as using realistic components in the modelling. On the other hand, the difference lies in the aims, execution approaches, and different priorities of the two modelling approaches. (McGregor, 2002)

The different aims refer to the use cases of simulation and emulation. Simulation often is used to test solutions to aid decision-making regarding the physical layout, operation limitations, and experimentation in general. While emulation is often used to test the production system in a more precise manner through load conditions, and to verify the performance. In general, emulation is not used to experiment when compared to simulation. Simulation models are designed to be run quickly and many times, while emulation models are designed to run in real-time to reduce errors sources. For simulations, repeatability, the ability to run multiple times and still deliver the same results are important. But for emulations the robustness is more important since the reliability of the control systems is essential. In conclusion, simulations are more of an approximation designed to be run many times, while emulations are more precise and designed to be run in real-time.

3.3.1 Simulation types

Some examples of simulation types are Discrete Event Simulation (DES), Continuous Simulation (CS), Component Based Simulation (CBS), and Agent Base Modelling (ABM). In DES the variables of the simulation changes in discrete time and in discrete steps, while in CS the variables changes continuously (Özgün and Barlas, 2009). DES is, therefore, commonly used in simulations of discrete systems, such as an assembly line, and CS is commonly used for simulating tank content or temperature. In CBS, the components of the system is decomposed into general-purpose components, and then these are used to create the full simulation, and this is suitable for VC (Frątczak *et al.*, 2020). In ABM, the different stations of the production system are modelled as agents with different states, which allows for focusing on defining the behaviour of the individual stations, while still capturing the entire system (Mykoniatis and Harris, 2021).

3.3.2 Simulation tools

In terms of tools for modelling, defining, and realising simulations some examples are Codesys, Matlab, Simulink, ABB RobotStudio, Siemens SIMIT, and Simumatik3D. Codesys, or Controller Development System, is a digital environment for developing control software for industrial applications (Codesys Group, 2021). In other words, Codesys can be used to create software code for, for example PLCs. Matlab, or matrix laboratory, is both a digital environment for numeric computing and a programming language, and can be used to create user interfaces, implement algorithms, and to interface with other programs (Mathworks Inc., 2021a). An extension to Matlab is Simulink, which is a digital environment for programming dynamic systems, used to simulate automation control and signal processing (Mathworks Inc., 2021b). For robot programming, ABB Robotics RobotStudio can be used to program and simulate robot movement and behaviour offline (Connolly, 2009). RobotStudio uses graphical programming to create robot movements, debug the code, and optimise existing programs. Siemens SIMIT is a platform for simulation, which can be used for, for example VC of production systems (Fernández, Eguía and Echeverría, 2019). SIMIT only model behaviour and user interfaces of production systems, not geometry and physics. For emulating more parts of the system, such as behaviour, kinematics, physics, geometry, as well as robot programming, Simumatik3D can be used (Fernández, Eguía and Echeverría, 2019).

3.4 Industrial revolutions

The industrial revolutions mark distinct technological shifts in the context of industrial settings. Historically, products have been produced through crafting by specialised craftsmen, such as smiths, leatherworkers, and bakers. These crafts were characterised by being small-scale and requiring high skill of the craftsman. The first industrial revolution was started by the introduction of steam-powered machines, allowing for larger-scale industrialisation through mechanisation of the production at the end of the 18th century. (Bergman and Klefsjö, 2012)

At the end of the 19th century, the shift to mass production, and later, the introduction of the production line system marks the second industrial revolution. The third industrial revolution, in the second half of the 20th century, is connected to the utilisation of computers and electronics to control the industrial production, thus allowing for automation of production processes. Later during the third industrial revolution, some processes could move from the previous mass production to mass customisation, due to the increased flexibility of the automated production systems. Currently, the fourth industrial revolution is taking place and is often called "Industry 4.0".

3.4.1 Industry 4.0

The fourth industrial revolution, or Industry 4.0, is characterised by the utilisation of digital technologies to interconnect the physical and digital systems, called cyber-physical systems. The general concepts of Industry 4.0 are smart factories, human adaptation of production system, and automated information systems. Smart factories are sensor controlled and highly autonomous through increased computing capabilities and digitalisation, thus "smarter" than traditional factories. Adapting the production system to humans means designing the system after the need of the humans interacting with it, rather than adapting the humans to the conditions of the system. Automated information systems include data from distribution, organisation, and product intelligence to automatically control and predict the supporting manufacturing processes. (Lasi *et al.*, 2014)

Industry 4.0 and its components allow for shortening of development periods, individualisation of products, and increased flexibility in the production processes and product development. This is achieved through further mechanisation to support in physical operations, and digitalisation and networking to improve data gathering of products. The Internet of Things (IoT) is the individual connection of the components of the production systems, such as machines, sensors, and actuators, to allow for data exchange of the internet, either locally or globally. This interconnectivity over the

network allows for binding production data to individual products to let the factory adapt the production processes to the individual products.

3.5 Automation

According to Groover, automation can be defined as the technologies used to perform processes or procedures without human assistance. The author also notes the distinction between automation and mechanisation. Mechanisation is using machinery to assist human workers who still must perform the task themselves, while automation is mechanised equipment working independently and without monitoring from human workers. The automated system is divided into three elements, power for accomplishing the process, instructions to guide the process, and a control system to follow the instructions. (Groover, 2015)

The power to accomplish the process refers to the electrical power necessary to operate the process, the power type to carry out the process, such as mechanical, thermal, or electrical, and finally, the power requirements for automation such as controller units, sensors, actuators, data gathering, and information processing. Furthermore, the instructions to guide the process refer to the work cycle programs and decision-making for the work cycle. The work cycle program can, for example, be one or multiple steps performed in cycles to achieve a designated target. The decision-making is determining what actions are to be performed, varying depending on the products and can be manually controlled by operators. The control system executes according to the instructions and can be both closed-looped, where feedback continuously is returned to the controller, or open-looped, where the controller operates without the feedback loop.

For production systems, automation is divided into two categories, automation of the manufacturing system and computerisation of the support systems, the two are closely related in modern production systems. Automated manufacturing systems refer to the systems handling the physical product and includes processing, assembly, inspection, and logistics. The computerisation of supporting systems refers to integrating computing in the product design, manufacturing, and business controls in order reduce manual work. An example of computerisation is using CAD in product design.

Grover also lists some fundamental parts of the automated production line as transport of the product, inventory buffers, and the control of the production line. The transport of the product consists of fixtures, conveyors, and elevators, among others. The inventory buffers are placed between process stations to act as safety in case of errors in the station before and automatically controls the inlet and

outlet of products. The control of the production line consists of control functions such as sequence control, safety monitoring, and quality control.

3.5.1 Data standards

Some standards exist and are used in the field of automation, such as the Modelica Language, Functional Mock-up Interface (FMI), Automation Markup Language (AutomationML), and System Structure Parameterization (SSP). The Modelica Language is an open and equation-based language standard for modelling physical systems, including mechanics, electrical, electronics, hydraulics, and controls and is governed by the Modelica Association (Modelica Association, 2021b). The Modelica Association also controls the FMI standard, which is an interface for computer simulations, providing a platform for simplifying creating, storing, and exchanging simulation models (Modelica Association, 2021a). The FMI is implemented through creating a Functional Mock-up Unit (FMU), which is a software library. AutomationML is an open standard data format, stemming from the Extensible Markup Language (XML), and is used for storing and exchanging automation-related data (Bao *et al.*, 2019). AutomationML incorporates the different disciplines of automation such as mechanical designers, electrical designers, PLC-programmers, and robot-programmers. Another standard controlled by the Modelica Association is SSP, which is a standard for defining complete systems of FMUs, and is used for transferring information between simulation software (Modelica Association, 2021a).

3.5.2 Communication standards

There are also multiple standards for communication in the field of automation, such as the Open Platform Communication Unified Architecture (OPC UA), Ethernet, Process Field Net, or Profinet, Transmission Control Protocol (TCP), and Message Queuing Telemetry Transport (MQTT). OPC UA is a protocol for communication between machines in industrial automation settings, created by the OPC Foundation. Ethernet is a widely used network protocol for both local area networks and wide area networks, in both commercial and industrial settings, and is fundamental in many other network-related standards. Profinet is a technical standard for data communication using industrial Ethernet for data collection and controlling equipment and sets itself apart through fast response times. TCP is an internet main protocol, which enables data exchange between two hosts, and is basis for many other internet related communication protocols. MQTT is a network protocol running on the TCP network standard and is a standard protocol for publish-subscribe-pattern messaging to allow for scalable networks. (Lim, Zheng and Chen, 2020)

3.6 Sustainability

The term sustainability has become a common word with the increased focus on climate change since the United Nations document "*Our common future"* was published in 1987. Sustainability includes three main domains, which is environmental sustainability, social sustainability, and economic sustainability. Environmental sustainability refers to the understanding of how humans affect the earth and its nature. The Earth, with its limited resources, can only sustain a definite number of humans, and this number depends on the amount of resources used per human. This is also called the ecological footprint. The second domain, social sustainability, refers to how humans affect society and the quality of life of the current and future generations, which includes justice, equality, inclusion, and democracy. The third and final domain, economic sustainability, refers to how humans affect the market, and the local and global economy. (Gulliksson and Holmgren, 2015)

Historically, economic growth has come at the expense of the environmental sustainability, but the aim is to disconnect this through the green economy. The green economy means economic growth without impact on the environment through utilising new technologies for renewable energy and green construction, sustainable transportation, and sustainable water, and waste management. The three domains are connected through systems theory, this means that if failing in one domain, none of the other domains can be achieved either. For example, if the Earth's climate collapses, there are no room for neither societies nor economies. If there is no trust in the local and world political leaders, the change to sustainability is not possible. And, finally, if the economy halts, the entire society also stops.

3.7 Augmented and Virtual Reality

Everyday life and the digital world merges more and more through the digital evolution. One example of this is Augmented Reality (AR), which refer to the layering of the digital world over the physical world to give a virtual experience in the real world (Graham, Zook and Boulton, 2013). AR can be defined as the virtual world mediated by technology, information, and code to aid in the physical world. An example of an AR tool is Microsoft's Hololens, which is a wireless headband with a visor where information is overlayed depending on what objects are in the field of view of the user (Microsoft, 2021). The Hololens can present digital objects to the user, which allow for a user to interact with the holograms. This technology can be used for improving remote assistance and for providing visual instructions.

Related to AR, is the older technology Virtual Reality (VR), which is a technological medium for immersing the user in a system through computers, head-mounted screens, headsets, and motion-sensing clothing (Steuer, 1992). One definition of VR is the simulation of environments through head-mounted displays for interacting with realistic simulated scenarios. The first concepts of VR emerged in the 1980's and 1990's, but they never become widespread (Faisal, 2017). Through refinements by technological advancements and the general reduction in size of computers and other VR-related equipment, such as displays and batteries, VR gained renewed interest in the 2010's. Today, VR can be used for full immersion in realistic three-dimensional environments using so-called VR-headsets. The VR-headsets typically consists of a headband with a display enclosure isolating the view of the user from the real world, a local or network connected computer, and headphones for sound.

3.8 Artificial Intelligence

Artificial Intelligence (AI) is the ability of a computer program to mimic cognitive functions similar to those of the human brain. AI can be used for improving monitoring technologies efficiency and can be divided into knowledge-driven and data-driven methods. A subtype of data-driven methods is machine learning, where a program, for example, is dynamic and adapts to changes in the input-data without having to be manually edited by a human. Like machine learning being a subtype of AI, deep learning is a subtype of machine learning and can be used for computer vision systems, speech recognition, language processing, and bioinformatics. Deep learning is often implemented through artificial neural networks such as Convolutional Neural Networks (CNN). A CNN consists of multiple neural networks which are capable of extracting features during the training process to automate the step of feature extraction. (Khan and Yairi, 2018)

The term "deep", refers to the number of hidden layers for computing of neural networks and other systems. Other methods to neural networks are, for example, Variational Autoencoders (VAE) and Generative Adversarial Networks (GAN). VAE is a deep generative model using statistical models for reducing interference during the generation of variable models. GAN consists of two neural networks, the first generates variables, while the second evaluate the variables. This contest allows the GAN to automatically update without being monitored. (Booyse, Wilke and Heyns, 2020)

4 Literature review

The literature review is conducted to gain a deeper understanding in the research field of the thesis and to increase the knowledge of VC and DTs. The research topic of VC and DTs is still rather undefined, which makes it a complex topic to navigate in and many articles attempting to explain, define, and bring clarity were found. Thus, this literature review describes the current situation of VC and DTs, as well as possibilities and limitations. First, the terms VC and DT, and their definitions are explored. Next, some example frameworks and approaches to using VC and DT are described.

The approach of the literature review was searching for articles in research paper databases, mostly *Google Scholar*, *IEEE Xplore*, *ResearchGate*, and *ScienceDirect*, using search terms which changed and improved as more articles were read and the understanding of the topic increased. For further improving the search results, search logic was used, such as AND, and OR statements. For a view of the search word notes and an example search term with search logic, see Appendix A:. In certain articles with many citations, the citation list was also reviewed to find further articles in the same topic. In general, the most interesting articles were from 2018 or later. Articles of interest were saved and later overviewed to determine the possible usefulness. The most useful articles were then categorised and managed using Mendeley Desktop.

4.1 Definition and classification

When reviewing relevant literature for VC and DT, some limitations and difficulties were found due to a non-consistent terminology, definitions, and delimitations to the topic. Multiple articles were found during the literature review which seek to classify and define the topic of VC and DT and its terminology.

4.1.1 Virtual Commissioning and simulation

Already in 2010 Hoffman et al. reviewed approaches to, and presented concepts for VC of manufacturing systems (Hoffmann *et al.*, 2010). According to the authors, the goal of VC is to detect and correct errors early during the planning and design phase. Many studies on the benefits of VC had been done at the time and the feasibility of VC including geometrical, mechanical, and behaviour or logic validation was already established. In 1999, soft-commissioning was described as an early approach to VC, to detect logic errors which would otherwise be detected during the real commissioning.

Hoffman et al. lists four configurations for verification of control, or logic: real commissioning, simulated plant and real control hardware (hardware-in-the-loop), real plant and simulated control system (reality-in-the-loop), and full VC through simulating both plant and control. The authors also identify two research domains of VC at the time, which is the test and verification of control programs, and the scope of the digital factory. The test and verification are conducted through applying different techniques such as testing on the real plant to analysing the control logic. The scope of the digital factory means the integration of data management and digital tools, such as computer-aided planning, computer-aided engineering, and digital models.

Typically, the software tools used for VC is off the shelf from the vendor, requiring much training which can be very costly to conduct. Due to this, the more prominent users are larger companies, which can afford specialising, such as the automotive industry. Therefore, standardised model libraries are important to create the conditions for VC. Using a model library such as Festo COSIMIR could reduce the engineering effort by 50 percent and thus allowing for faster modelling. Hoffman et al. divides simulation modelling into two detail levels, high-level and low-level modelling. High-level modelling is advanced library components which includes mechanical components as well as functional interaction behaviour. This can for example be complete models of robots and sensors and make building models for VC relatively easy. Low-level modelling requires creating the simulation model from the ground, meaning that geometrical CAD data, mechatronic data and function behaviour needs to be combined manually.

Finally, Hoffman et al. present some necessities for VC to be widely adopted. One necessity is more and improved high-level modelling libraries to become available for the VC process to not require high expertise, to become feasible for more companies. Another necessity is more standardisation for data and structure formats for the models. AutomationML was mentioned as a possibly applicable and therefore promising standard for data formats at the time.

In 2020 Siemens AG, Dresden University of Technology, and Pforzheim University surveyed the current use, definitions and the future vison for simulation in a white paper (Bruckner *et al.*, 2020). The survey was extensive, and included 239 participants, where 22 was employed by research institutes or universities and the rest employed by companies.

According to the authors, simulation is used in all phases, product design, production planning, production engineering, and production execution, of both discrete and process manufacturing. The use-cases of the white paper of interest in this work are simulation-driven engineering and

development, and VC. Simulation-driven engineering and development is defined as supporting the engineering process through simulation. VC is defined as validating automation systems through modelling the logic signals. When the participants were asked for a suitable definition for DT, with multiple answers possible, the result was that 59 percent thought that "The Digital Twin is a virtual replica of a planned or existing physical entity" and 50 percent that "The Digital Twin is a simulation model of the plant or product" was a suitable definition.

When the participants were asked what drivers were the most important in their company, the top answer was quality at 92 percent critically important or very important. After quality came safety at 84 percent critically important or very important. The participants were also asked what use-cases were the most important for simulation. The top three responses were product design optimisation, VC, and early design of process, plant, or machine. Regarding the level of detail for simulation during engineering and commissioning, the participants answered that 49 percent simulates a subsystem of the plant or product, 39 percent simulates a unit or module, 33 percent simulates the complete plant, and 19 percent simulates a single component.

To survey the use of standards, the participants were asked if they use standards for model creation or exchange. The results were that 18 percent uses the Function Mock-up Interface (FMI) and Function Mock-up Unit (FMU) standards, 17 percent uses the Standard for The Exchange of Product (STEP) standard, and 7 percent uses other standards. Worth noting is that 29 percent did not know if they were using standards and that 38 percent of the participants knew they were not using standards. The share not using standards had increased from 30 percent in 2014, when the survey was last conducted. To see whether the participants were interested in creating and sharing solutions and content in an application store, the participants were asked if they were willing to buy content provided by other users. 45 percent of the participants answered yes, but with reservation that the functioning of the content must be guaranteed.

When the participants were asked how the decision-making was supported currently during the engineering and commissioning phase, the most important was the experience of individuals, at 67 percent. After that comes the use of industry norms and standards at 63 percent. Then the participants stated for what reasons simulation was not always used during the engineering and commissioning phase. The most common answer was that it is too expensive at 49 percent, secondly that it was too much effort at 47 percent, and finally, that they were missing skilled personal at 40 percent.

Lechler et al. defines the term and reviews use cases for VC in a research article (Lechler *et al.*, 2019). In the article, VC is defined as "the early development and validation of PLC code using a simulation model.". Furthermore, it is stated that VC can be used for logistic systems, process simulation, and automation system validation, but the focus of the paper is automation validation and optimisation. For validation and optimisation of automation systems the PLC code controls a virtual model, or behaviour model, that mimics the real machines behaviour.

When presenting the state of the art, Lechler et al. uses Figure 1 to show the difference between employing VC and not during the engineering process. This shows the modelling and use of VC integrated in the engineering and production phases, as well as the time for the real commissioning being reduced due to the integration. According to the authors, it can be difficult to introduce VC to an existing engineering process mainly due to high costs of implementation and the general complexity of VC. Therefore, much of the identified research at the time reviewed methods for automated VC model generation as well as evaluating different abstraction levels appropriateness for the simulation model. Another finding of the Lechler et al., was that standardisation of production system components would be beneficial for the reutilisation of VC models.

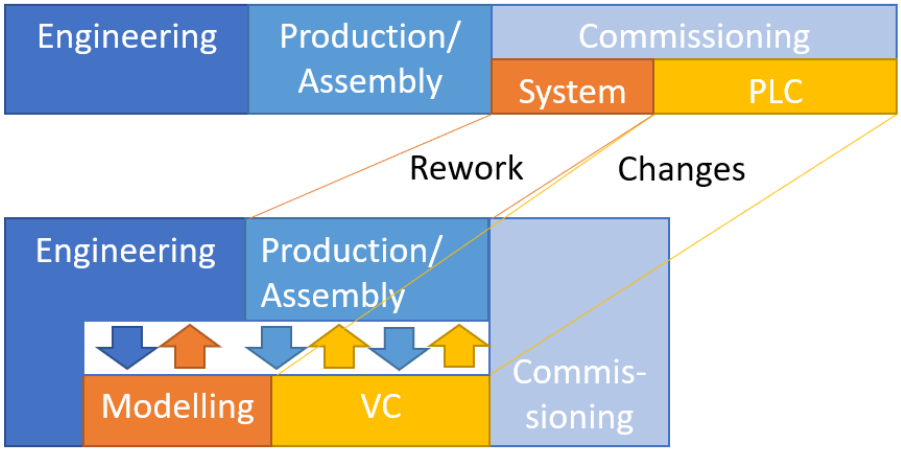

Figure 1 - Engineering with and without VC (Lechler et al.)

When sorting the articles of the literature review, the authors found that most would focus on the abstraction level of the automation level, in comparison to the robotics, process or energy levels, for the applications of VC. In the paper, some use-cases or applications of VC is also exemplified. The first is including humans in the VC process, for example for identifying risky designs and to gain worker acceptance for Human-Robot Collaboration by including workers in the engineering phase using VR. A second application is using VC to improve environmental sustainability, for example

through predetermining energy consumption of the production equipment and improving the electrical management control.

A final example of applications for VC is for special machine construction, where most projects are unique and often aims to get the implementation correct at the first try. This is due to a limited time for iterative processes, and it could be very beneficial to employ VC and DT in that scenario. Lechler et al. concludes the article by establishing VC as a fundament of the DT, where the use of DT can prolong the lifecycle of the VC.

Table 1 - Summary of articles exploring VC

	(Hoffmann et al., 2010)	**(Lechler et al., 2019)**	**(Bruckner et al., 2020)**
Focus	Review of approaches and concept of VC	Define term VC and review use cases	Survey of use, definitions, and future for simulation
Definition	To test manufacturing systems and the control programs using simulation before the real commissioning	Early development and validation of PLC code using a simulation model	Validation of automation systems through modelling logic signals
Description	Real commissioning	Use cases: logistics, process simulation, and automation systems	Use cases: product design optimisation, early design, and VC
	Hardware-in-the-loop		Level of detail: subsystems, unit, complete plant, and last single component
	Software-in-the-loop	Reduced real commissioning time	
	Full VC		Low use of standards and not knowing what standards exist
Challenges	Requires high expertise	High costs of implementation	Simulation too expensive
	Requires high effort		Too much effort
		Complexity of VC	Missing skilled personal
Tools	Off-shelf or developed	Software programming	FMI and FMU
	Standard model libraries	Communication platforms	STEP
Enabling technologies	AutomationML and CAD	DTs	Open-source tools
Conclusions	Improved detail in modelling libraries required	Need for component manufacturers to provide extended models	Simulation to become more important throughout lifecycle
	Standardisation for data and data structure formats required	Lifecycle of VC model to be expanded through DT	Simulation should be integrated with learning and training

4.1.2 Digital Twin

In 2018 Kritzinger et al. conducted a categorical literature review and classification of DT in manufacturing (Kritzinger *et al.*, 2018). The aim of the research paper was to define various forms of DT's. Three categories of DT were determined, Digital Model (DM), Digital Shadow (DS), and Digital Twin (DT). A DM is a representation of an existing or planned physical object, which does not use and automated data exchange between the digital and physical object. A DM is therefore not integrated with the physical object it is modelled after when it comes to data. The DS uses the same definition as the DM, except it is automatically updated with data from the physical object it is modelled after, but the dataflow is only one-way. Finally, the DT is also based on the same definition as the DM, except for the data automatically flowing both to and from the physical object it is modelled after. In a DT the dataflow is therefore circular.

The authors also identified some key enablers, in terms of technology, for the DT-terms. The enabling technologies were simulation methods, such as Discrete Event Simulation (DES) and Continuous Simulation, communication protocols, and other core technologies, such as Internet of Things (IoT), Cloud computing, and Big Data. When categorising the identified the reviewed literature, most were related to the concept development and description of DT, at 55 percent of the literature. Next, at 26 percent, were case studies, at 14 percent reviews, and the last 5 percent for definition of DT. The authors note that a large part of the research regarding DT is still immature. When analysing the integration levels used in the literature, all of them discussed "DT", but 35 percent instead described DS and 28 percent described DM. Only 18 percent of the literature described DT with fully automatic data integration between the physical object and digital object. In conclusion, most research regards the DS and focus on the planning and controlling of production. There is no common definition for DT, and the terms DM and DS is often used synonymously with DT.

Biesinger and Weyrich attempts to compare different facets or characteristics of DT, specifically in the automotive industry, since the amount of publications on the subject is increasing as well as the different types of DT described (Biesinger and Weyrich, 2019). The authors note that the DT described in the reference literature is very wide, keeps expanding, and covers fields such as, manufacturing, simulation (including VC and robot simulation), products, production planning, and cyber security.

For DTs in industrial production, some example descriptions and applications of various companies are provided. For example, ABB describes their DTs as PLM simulation and design models; and uses DT for design, behaviour simulation, predictive maintenance, and three-dimensional visualisation.

Airbus describes their DT as a digital model and use DT for cyber security. Daimler describes their DTs as integration twin, VC, and maintenance twin; and uses DT for integration planning, VC, maintenance, and virtual prototyping. General Electric describes their DTs as component twin, asset twin, process twin, and system or unit twin; and uses DT for future prediction, monitoring, simulation, and controlling and optimising lifecycles. Siemens describes their DTs as PLM simulation and digital model of products; and uses DT for forecast and optimisation of the product, production, and performance.

Biesinger and Weyrich also identified several types of twins in the automotive industry, some within the scope of this work within VC, are engineering twin (ET) and control twin (CT). The ET is supplied by the plant supplier and is used for robot simulation and virtual commissioning. It is a detailed simulation model, from which the production system can be constructed. The CT is a DT from the perspective of automation and control techniques. CT includes information from, for example, PLCs and IoT-devices, and can be used to integrate the physical plant into a cyber-physical context. Some enabling technologies for DT are also described, for example, digital models, such as CAD-models, position data, and three-dimensional scanning. Another enabler is the real-time coupling of controller to the physical plant for rapid fault detection.

Lim, Cheng and Chen performed a review of DT state-of-the-art in perspective of PLM through a literature review of 123 research articles along with 22 other references to concretise the survey (Lim, Zheng and Chen, 2020). The authors summarised the various definitions of DT across multiple researchers, see Table 2. The technical aspects are seen as fundamental and are described in detail. The authors describe how the techniques for DT creation are stacked on top of each other Error! Reference source not found., with communication at the bottom, representation one step above, computation another step above and microservices on the top. Communication includes data management and connectivity, such as architectures and data exchange protocols. Representation includes data representation, for example, data formats and ontologies. Computation includes data computation, such as modelling languages and analytics. Microservices includes virtualisation, simulation, and validation.

Table 2 - Definitions of the DT (Lim, Zheng, and Chen, 2020)

Author	Definition of Digital Twin
(Grieves 2014)	*"Virtual representation of what has been produced"*
(R. Stark et al. 2017)	*"Digital representation of a unique asset that compromises its properties, condition and behavior by means of models, information and data"*
(Söderberg et al. 2017)	*"Using a digital copy of the physical system to perform real-time optimization"*
(El Saddik 2018)	*"Digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds"*
(Zhuang et al. 2018)	*"Virtual, dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behavior, life and performance in a timely fashion"*
(Qi and Tao 2018)	*"Virtual models of physical objects are created in a digital way to simulate their behaviors in real-world environments"*
(Y. Xu et al. 2019)	*"Simulates, records and improves the production process from design to retirement, including the content of virtual space, physical space and the interaction between them"*
(Kannan and Arunachalam 2019)	*"Digital representation of the physical asset which can communicate, coordinate and cooperate the manufacturing process for an improved productivity and efficiency through knowledge sharing"*

The authors also compile future directions of the technical aspects of DT. First, modularised approaches to allow for flexibility and to save during DT creation. Secondly, modelling consistency and accuracy to increase reuse of knowledge and interoperability, and increased functionality of DTs to strengthen decision-making, respectively. Thirdly, improved real-time simulation of DT can improve the ability to predict and solve errors in production. Finally, a more efficient communication and processing can give greater confidence in the systems and its reliability.

In Liu et al.'s in-depth review, 176 research papers are surveyed to analyse DTs in terms of concept, technologies, and industrial applications (Liu *et al.*, 2021). The authors describe the increase of interest for the DT through the search results of the term "digital twin" in various databases, such as Google Scholar, Google Search, WebofScience, and Scopus. The total search results have increased by 17 times between 2003 and 2019. In the seven years between 2013 and 2019 alone, the search results increased by 14 times.

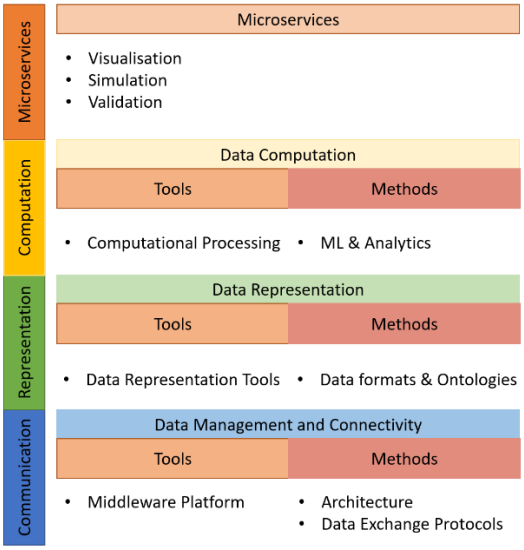

Figure 2 - Technology stack for DT creation (Lim, Zheng and Chen, 2020)

The authors divide the literature by their content into four categories based on the type of DT described: concept, technology, framework, and application. A large majority of the literature describes the applications of DT, while the second largest describes the framework of DT. The least found literature type is of DT concepts. The levels of integration of the DTs described in the literature is divided into DM, DS, and DT, where an almost equal amount of literature describes DS and DT, while DM is discussed the least. The literature is also divided into five groups based which phase of the lifecycle is in focus, design, manufacturing, service, retire, and the full lifecycle. Most articles focus on the manufacturing phase, in second comes the design phase, and the least articles focus on the service phase. After that comes the full lifecycle and last comes the retire phase.

Liu et al. also compiles the key points of definitions of DT found in the literature. Early definitions, from 2010, are "integrated simulation", while later literature, between 2015 and 2018, describe DT with "realistic model", "digital copy", "virtual replica", or "cyber copy". More recent definitions, from 2018 and 2019, describes "living model", "updated virtual model", "real-time data", or as "dynamic and bidirectional". Some key enabling technologies for DT found in the literature are described as well, divided into data technologies, high-fidelity modelling, and model-based simulation technologies. Data from DTs are often demanding as it comes at high volume, speed and in a great variety. Before starting the creation of a DT, crucial components to the systems functioning should be determined. Examples of High-fidelity modelling technologies are the standard Modelica for multi-physics modelling, while hidden Markov models and black-box modelling used simplified representations for the modelling.

The industrial applications of DT described that are relevant to the scope of this thesis work is in the design phase. The first example is “iterative optimisation”, which can reduce the cost of reworks since issues and incompatibilities are found earlier (Lutters, 2018; Liu *et al.*, 2019; Xiang *et al.*, 2019). Another example is “provide data integrity”, which means that data is better managed through the DT and thus improves the base of decision-making (Caputo *et al.*, 2019; Martin *et al.*, 2019). The last example “virtual evaluation and verification”, is that the discrepancies between the predicted and actual behaviour are reduced through using DTs (Guo *et al.*, 2019; Martin *et al.*, 2019).

The authors observe in the literature that the degree of digital design in most industries are low but that many of the application scenarios of the literature has been adopted in industries focused on digital design. Another note is that no literature studies regarding designing new objects were found and that most literature is about redesigning or optimising the performance of existing physical objects. Liu et al. also call out many of the reviewed papers in that they claim to provide complete data access, when that is not easy nor realistic. A recommendation from the authors is to integrate the manufacturing data with the DT of the product in order to create an accurate DT.

Concluding their review Liu et al. states that the concept of DT of today is wide and ambiguous, and that the concept needs to be clarified, specified, and based on practices from the industry. Even though the term of DT was coined around 20 years ago, most of the interest in the topic has been gained in the last five years, yet there is still no common definition or standardised creation process. The authors conclude with a concept for the connotations of DT is proposed as including being individualised, high-fidelity, real-time, and controllable.

In general, the authors found many different approaches and implementations of DT in the literature review. Some of them uses a technical engineering approach and a modelling-oriented view to achieve precise behaviours in the simulation of the physical world. While many frameworks and reference models for DT found in the literature review are proposed , none has yet become an industry standard. In conclusion, there is many difficulties in conducting systematic research in DT since work of others cannot be completely used by others and Liu et al. suggests collaboration in defining a systematic research architecture for research of DTs.

Table 3 - Summary of articles exploring DT

	(Kritzinger et al., 2018)	(Biesinger and Weyrich, 2019)	(Lim, Zheng and Chen, 2020)	(Liu et al., 2021)
Focus	Defining DTs	Compare characteristics of DTs	Review of DT in perspective of PLM	Review of DT concept, technologies, and applications
Definitions	DM: representation of object with no data exchange	ABB: for PLM, design, behaviour, maintenance, and 3D visualisation	Grieves: "Virtual representation of what has been produced"	DM: virtual model without self-driven data flow
		Airbus: digital model for cyber security	Söderberg et al.: "Using a digital copy of the physical system to perform real-time optimization"	
		Daimler: integration twin for VC, maintenance, and prototyping		
	DS: representation of object with data exchange to virtual representation	GE: component twin, asset twin, process twin, or system twin for prediction, simulation, and optimisation	El Saddik: "Digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds"	DS: virtual model with self-driven unidirectional data flow
		Siemens: PLM simulations and digital models for prediction and optimisation		
	DT: representation of object with data exchange to both virtual representation and physical object	Engineering twin: for robot simulation and VC	Xu et al.: "Simulates, records and improves the production process from design to retirement, including the content of virtual space, physical space and the interaction between them"	DT: virtual and dynamic model with bidirectional data flow
		Control twin: DT focused on automation and control		
Enabling technologies	DES, CS, communication protocols, and Industry 4.0 technologies	Digital models, position data, 3D-scanning, and real-time communication	Data exchange protocols, computational processing, and machine learning and analytics	Data technologies, hi-fi modelling, and model-based simulation
Conclusions	No common definition of DTs	DT will be important data source for AI	Continuous evolution of DTs requires understanding and definitions	Concept of DT need clarification
	Most research focus on DS	Currently data lacking quality for AI, interconnecting DT	Future directions: increase DT flexibility, increase interoperability, improve real-time simulation, and improve system communication	No standardised creation process
				DT to be individualised, hi-fi, real-time, and controllable

However, there is also a standard under way regarding DTs, "ISO/DIS 23247-1: Automation systems and integration - Digital Twin framework for manufacturing" (ISO/TC 184/SC 4 Industrial data Committee, 2021). ISO 23247-1 is a future standard being formalised by the Organization for Standardization (ISO). ISO is an independent, non-governmental, and international organisation consisting of 165 members, and only national standards institutes are allowed membership. ISO seek to form voluntary standards in consensus. (ISO, 2021)

The organisation behind the work in progress of ISO 23247-1, is the technical committee ISO/TC 184/SC 4 - Industrial data, and work for the interoperability of product data definitions, manufacturing, and visualisation. The secretariat responsible for the new standard is the American National Standards Institute (ANSI). ISO 23247-1 was approved and initiated as a project in January 2018. And is as of May 2021 in stage 50.0 - approval, which means a final text has been received or registered for formal approval on April 26th, 2021. The next stage is 60.0 - publication, after a voting ballot has been initiated and closed. All member institutes are allowed to vote in the ballot.

4.2 Frameworks

This section presents some high-level frameworks for VC and DT found through the literature search. Presented as well, are some further explored related topics to both VC and DT to give a wider view of the current situation in the research field of VC and DTs.

4.2.1 Virtual Commissioning frameworks

In the search for articles for the literature review, no articles addressing the more practical methods regarding the creation and performing of VC were found. Most articles were at a higher level in terms of VC approaches and methods, and some articles trying to define a common platform or framework for VC was found. The found articles are presented in this section and a summary of the articles can be seen in Table 1.

The first paper aims to create a platform for using in VC and focuses on scenario-based test specifications to simulate both expected and unexpected system behaviour (Schneider *et al.*, 2014). According to the authors, VC is comprised of modelling, realisation, and evaluation to simulate behaviour when setting up a production system, and the real commissioning of the production system can be reduced through VC test specifications, which can also act as quality control. The authors suggest a two-part test specification where the application scenarios are specified first, and the failure scenarios are specified next. The application scenario is the expected behaviour of the production

system during regular operation, as well as in manual and maintenance mode, while the failure scenarios are the unexpected behaviour and in what way the system should respond, such as entering a safe state. For the procedure of specifying the application scenario and the failure scenario see Figure 3 and **Error! Reference source not found.**, respectively.

Figure 3 - Procedure for application scenarios (Schneider et al., 2014)

The platform is evaluated and exemplified in a test on a real-world case of a monorail conveying system. An example of an application scenarios is the standard operation of moving a product from one station to the next. An example of a failure scenario is a shuttle derailing or colliding, due to lack of air-pressure, and switch or code related errors.

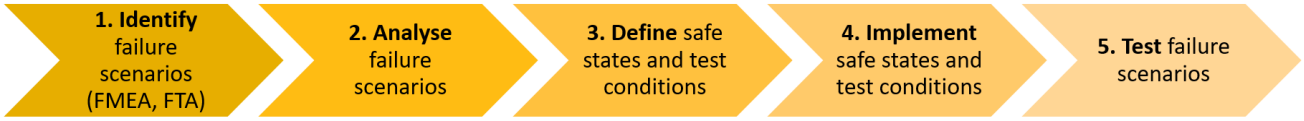

Figure 4 - Procedure for failure scenarios (Schneider et al., 2014)

The next paper presents a real-time co-simulation platform for VC of mechatronic systems (Scheifele, Verl and Riedel, 2019). The authors present the state-of-the-art regarding real-time co-simulation, off-line co-simulation, but also some challenges such as there only existing inadequate tool chains and model exchange standards in the field of VC. Furthermore, they claim that model-integration interfaces based on existing standards, such as FMI, are required.

The authors present the concept of real-time co-simulation, where the co-simulation is partitioning the full simulation model into smaller model blocks to parallelise the simulation calculations, and the real-time means maintaining the time determinism through lossless and clock-synchronised communication. The real-time co-simulation concept allows for a holistic description of the production system through multi-domain simulation. Through implementing the concept in a prototype environment, the concept was validated, and the authors conclude that the approach of the concept can provide an increased significance of the DT in the future, and thus also VC.

The final paper in this section aims to classify different levels of detail in VC in the perspective of production lifecycle specification strategies for new production systems and predicting future challenges for existing systems (Albo and Falkman, 2020). The authors note that VC requires proper cooperation between the different disciplines involved, such as mechanical engineers and PLC programmers. The authors also identify some challenges of VC, such as the need of a wide framework of standards within the different disciplines. The different conditions for VC implementation in a production system depending on if the system is new (greenfield), or an existing system (brownfield). The differences lie in requirements, what is wanted, and the current situation. Requirements can be to introduce a new product or perform a ramp-up or improve the system. What is wanted means to find the balance of necessary solutions, functionality, and cost. Finally, the current situation can vary since a greenfield scenario can allow for new rules to be set and less restriction, while a brownfield scenario might require backwards compatibility and access to existing data of the process. The formulated hierarchical framework of the different levels of VC is presented in **Error! Reference source not found.**.

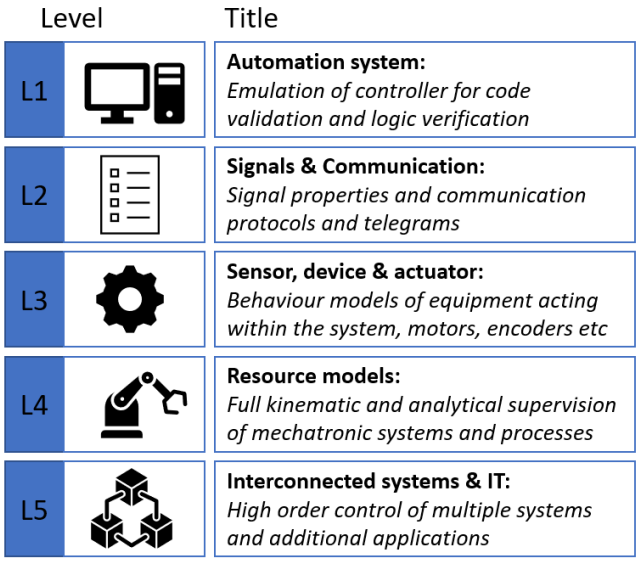

Figure 5 - Framework hierarchy of categorising different levels of detail for VC (Albo and Falkman, 2020)

The authors also suggest using Virtual Functional Acceptance Testing (VFAT) to verify the production system virtually using a VFAT checklist. They also conclude that standardisation is key for the implementation of Industry 4.0 in general, due to the requirements of interconnectivity and that communication between Operation Technology (OT) and Information Technology (IT) need to be improved for the same reason.

Table 4 - Summary of articles defining frameworks for VC

	(Schneider et al., 2014)	(Scheifele, Verl and Riedel, 2019)	(Albo and Falkman, 2020)
Core of framework	Platform for VC	Platform for VC	Hierarchical framework of 5 levels
Highlighted issues	Steady increase in system complexity	Lack of standardisation (tool chain and model exchange standards)	Need of wide framework of technological standards and disciplines
Focus area	Test specification: Application scenarios, failure scenarios	Real-time co-simulation Need of model-integration interfaces (ex. FMI)	Differences for green- and brownfield scenarios
Conclusions	Test specifications can support verification in VC	Platform increase significance of DT and therefore VC	Standardisation is key for Industry 4.0 and interconnectivity Improve communication of OT and IT Reduce cost/improve efficiency through standardised frameworks
Suggested further research	Procedure model for VC (detail design)	Investigating partitioning, parallelisation, synchronisation, and data exchange	Verify financial justification Impact of correlating factors

4.2.1.1 Behaviour models of Virtual Commissioning

In the found literature, presented in previous parts of the literature review, the need for improved Behavioural Models (BM) were pointed out by several authors. Some suggest that component manufacturers should provide BMs of their products, while others suggest the common model libraries should be expanded. Therefore, this section of the literature review seeks to explore the topic of BM and how to improve the creation of BM a little further. A summary of the reviewed articles can be seen in Table 5.**Error! Reference source not found.**

The first article presents a concept procedure for component manufacturers to provide behaviour models in a standardised way as well as how to use it in VC (Süß, Strahilov and Diedrich, 2015). When the user of VC must create their own BMs since they are not provided by the component manufacturer, the authors identify two main issues. First, how to model the behaviour and verify its consistency, and secondly, the user having to create the BM from the ground and up with only geometric models and product specifications, which requires much manual work. The authors suggest that the component manufacturers should provide BMs but that the reason that is not done currently is due to challenges in balancing sharing enough information and not sharing too much information and revealing sensitive information. Therefore, there is a need for a standardised model exchange.

The proposed solution is using an approached called FMI for co-simulation, where FMI is used to perform simulations of multiple FMUs and exchanges the results. The approach uses a co-simulation master connected to multiple FMUs as well as a PLC and visual part for behaviour simulation, see Figure 6. In conclusion the article establishes a framework of requirements for co-simulation using BMs: real-time communication, both synchronous and asynchronous communication, being scalable, and adequate usability. The proposed approach is only a concept and behaviour simulation needs further outlining.

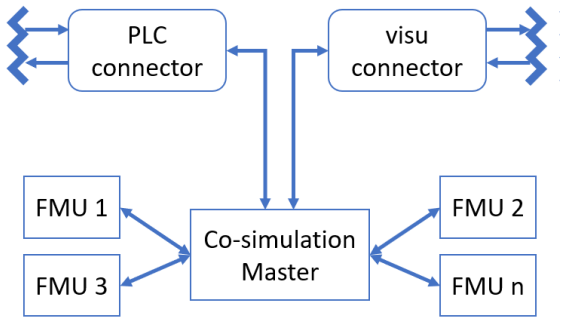

Figure 6 - Proposed behaviour simulation (Süß, Strahilov and Diedrich, 2015)

In the second and final article on BM and behaviour simulation a new approach to behaviour simulation is proposed, as well as automatised testing (Süß *et al.*, 2016). The authors report that standardising BMs in a model description format is required for the VC process. Another focus area is automatised testing in VC due to the current approach of performing tests demanding high effort. The suggested solution to the model description format is based on the approach proposed in the previous article, using FMUs in a master and slave configuration. For a visualisation of the further developed approach combining FMI and AutomationML, see Figure 7. The approach functions through inter process communication and integrating the BMs in the VC through establishing an information exchange between the BM and the control program. This enables association of control program variables to BM variables through AutomationML.

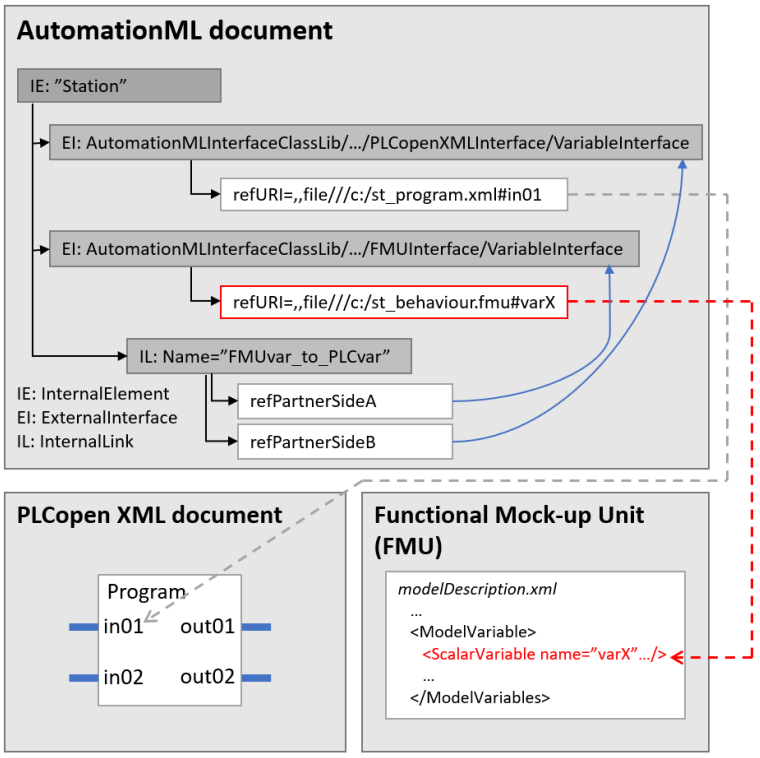

Figure 7 - Behaviour model integration with AutomationML (Süß et al., 2016)

In another chapter the authors also describe a proposed approach to automatise testing of VC. In short, the approach consists of the following activities: formalising the test requirements, which can be based on the request for tender, test-case generation, the execution of the tests, and evaluating the results. A test of the approach is performed to verify its functioning and an algorithm is used to synthesise a specification model.

Table 5 - Summary of articles assessing behaviour models

	(Süß, Strahilov and Diedrich, 2015)	(Süß, Magnus, et al., 2016)
Item	Concept procedure for standardising model sharing	Approach for behaviour simulation and automatised testing for VC
Highlighted issues	Component manufacturers do not provide BMs	VC for complex automation solutions is young
	When user create BM, they must start from the bottom	VC process requires standardisation for BMs description models
	User created BM do not have full specification of component	High effort to perform tests in VC means low test coverage
Focus area	Co-simulation	Integrating BM in VC process
	FMI	FMI
Approach	FMI for co-simulation	Improving exchangeability of BMs
		An automated VC test system
Description	Use FMI to simulate multiple FMUs	BM integration through AutomationML
	Exchange simulation results	Combining FMI and AutomationML
	Can be used in combination with proprietary tools	Formalising requirements, test-case generation, and performing and assessing results from tests
Conclusions	Component manufacturers to start providing BM	Presented approach allow for simulation in real-time
	Framework for co-simulation requires communication in real-time, consideration of both synchronous and asynchronous communication, scalability, and usability	Generation of test cases from requirements specification shown to work
Suggested future work	Need of further outlining of behaviour simulation	Elaborate on formal and standardised requirements
		Explore distribution of manufacturer BMs

4.2.1.2 Similar approaches for Virtual Commissioning

In the search for articles for the literature review, some articles presenting novel approaches similar to VC was found. The found articles are presented in this section and a summary of the articles can be seen in Table 6.

The first article presents an example of simulation for virtual design and optimisation of industrial production lines using the IMPROVE project's framework (Longo and Fantuzzi, 2017). The purpose of the IMPROVE project is to provide user support functions in self-diagnosis and self-optimisation possible for Small and Medium-sized Enterprises (SME) to use. The method of the IMPROVE project is defining requirements and characteristics of machines. Next is using simulation software, which supports physics, DES, industrial communications, and other plug-ins, to model a three-dimensional

model of the production system. Finally, the industrial production plant is developed using a mix of DES and System Dynamics (SD) to get the advantages of both methods, which is physics support and real-time PLC communication.

In the second article, the authors presents an approach to testing safety logic virtually through using the Input-Output Conformance (IOCO) as the validation criteria (Khan, Falkman and Fabian, 2019). According to the authors, safety PLC logic testing is, in general, performed manually, which hinders the full capability of VC. In most companies the engineering staff is disconnected from the PLC programming. In addition to the typical VC, the authors propose another approach to verify the PLC code called hybrid commissioning. A stepwise commissioning is performed in HC, using both the simulation model and the physical systems connected to a PLC. This can, for example, be testing sensors and actuator in simulation first and then replacing them with the physical hardware, and then moving on to the next subsystem.

The proposed approach also includes the use of IOCO as a validation criterion for the safety PLC code. Using IOCO means comparing the output and input actions of the PLC program to automatically identify errors. The proposed approach is tested through applying to the PLC code of a production cell and was deemed as a viable approach for testing safety logic.

Table 6 - Summary of articles suggesting new approaches to VC

	(Longo and Fantuzzi, 2017)	(Khan, Falkman and Fabian, 2019)
Approach	Simulating and optimising production lines through the IMPROVE framework	Testing safety logic virtually through using IOCO as validation criteria
Highlighted issues	Increased complexity of production lines	PLC code errors often corrected after delivery of production cell
	SMEs cannot afford latest production technologies	Engineering staff not involved in PLC programming
Focus area	Simulation and optimisation	Safety system validation
		Factory acceptance testing
Description	IMPROVE aim to develop self-diagnosis and self-optimisation for users	Model-based test
	Define characteristics of machines and requirements	Formal approach to assess a model by applying tests that tries to falsify the specification to find flaws in implementation
Differentiation	Simulate using 3D model of automation system, physics, DES modalities, communication solutions, and software code	Input-output conformance (IOCO)
	Mixing DES and SD for real-time PLCs and physics	Specification basis for implementation behaviour
Conclusions	Method was validated through real-world case	Approach is similar to VC
		Viable for testing safety logic system
Suggested future research	Developing optimisation algorithms	Improve concept through automatically adjusting flaws in implementation
		Improve test case generation

4.2.2 Digital Twin frameworks

In the search for articles for the literature review, the DT was found to be an important part of VC and the level of simulation detail in which the state-of-the-art of VC is focusing on. While no articles reviewing concrete methods in detail were found, some article trying to define a common approach or framework for creating DTs was found. The found articles are presented in this section and a summary of the articles can be seen in Table 7.

In the first article, an approach to the modelling and operations of DTs in the manufacturing industry is proposed (Bao *et al.*, 2019). The DT is presented as the convergence of the virtual and physical world and the authors present the DT framework in Figure 8. The connections of the DT to the rest of

the parts in the context of manufacturing can be seen in Figure 9, where the extension of the DT is visualised.

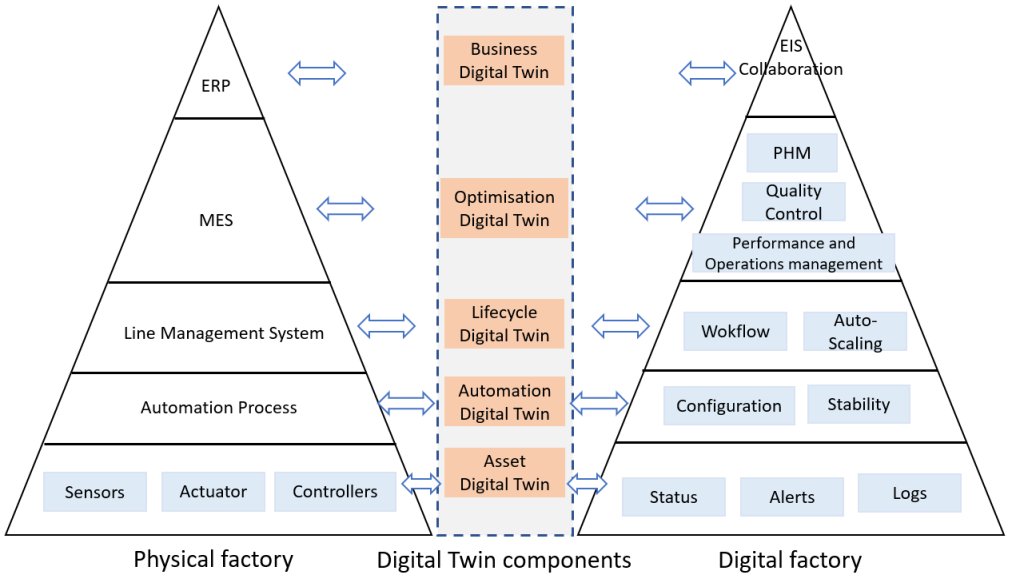

Figure 8 - The DT framework of factory automation (Bao et al., 2019)

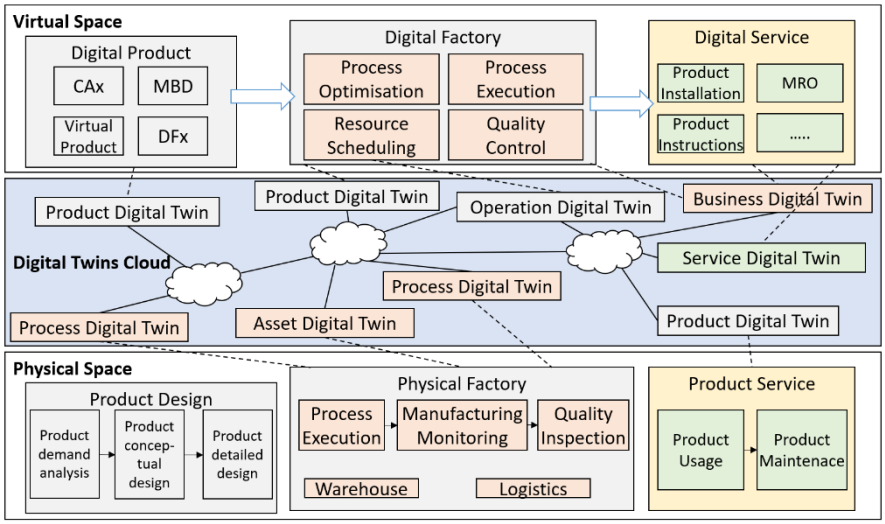

Figure 9 - Extension of DT in the manufacturing context (Bao et al., 2019)

The authors explain three types of DTs: the product DT, the operation DT and the process DT, in which the process DT is of interest in this literature review. The process DT consists of production process services, such as checking interferences, verifying programs, optimising processes, and predicting quality. This is performed through collecting data and sending to the process DT, examples

of data is cutting speed and force, and vibrations. When combining the collected data with intelligent algorithms such as a Convolutional Neural Network (CNN) or a Deep Neural Network (DNN) the production quality can be predicted. Real-time simulation and production data, as well as historical data from the production can be utilised too. The connection of the process DT, the product DT and operation DT as well at their connection to the industrial internet can be seen in Figure 10.

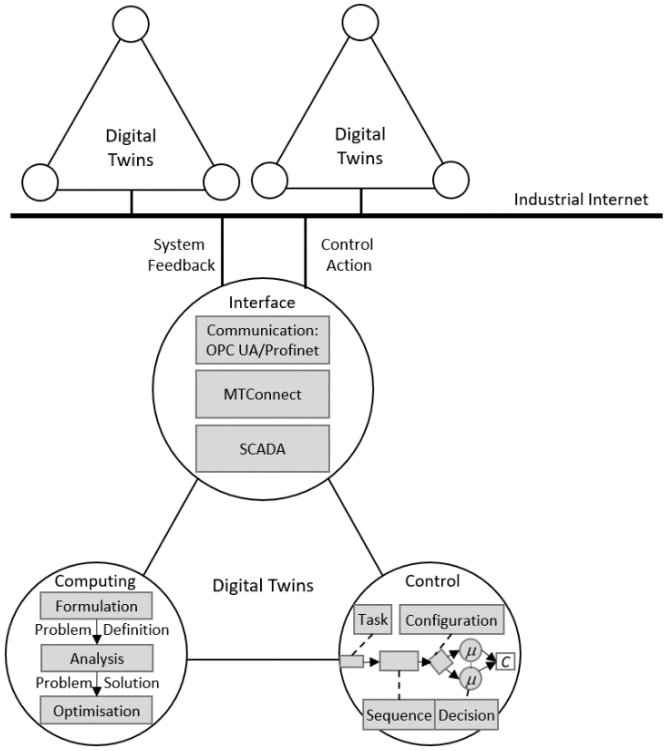

Figure 10 - Connection among DTs (Bao et al., 2019)

The authors of the second article finds it fundamental to define the necessary steps for developing DTs and proposes a method based on VC (Barbieri *et al.*, 2021). The shift to mass customisation and shorter product lifecycles increases the demand on the current production systems and DT is seen as the next technological trend of modelling, simulation, and optimisation. The authors describe their methodology for guiding the user in developing of the DT using **Error! Reference source not found.**, and aim to fully integrate the DT in manufacturing systems, meaning that, for example the Manufacturing Execution System (MES) and PLCs are interconnected and synchronised. The proposed methodology focuses on retrofitting existing production systems with DTs.

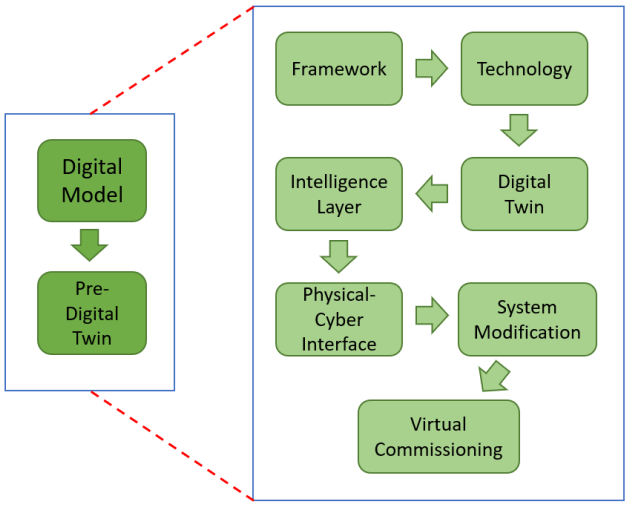

Figure 11 - Representation of the proposed DT methodology (Barbieri et al., 2021)

The DT of the proposed methodology is used to predict and optimise the behaviour of the physical object using an intelligence layer and physical-cyber interface. The physical object and intelligence layer exchanges data to survey the physical object and to implement changes. The physical object and the DT exchange data to synchronise to each other, and the intelligence layer and DT exchanges data to analyse alternatives and to make decisions. The authors conduct a case study to validate the proposed methodology, where a Genetic Algorithm (GA) was used as intelligence layer and for scheduling. A Unified Modeling Language (UML) sequence diagram was used as a physical-cyber interface.

Table 7 - Summary of articles defining frameworks for DT

	(Bao et al., 2019)	**(Barbieri et al., 2021)**
Core of framework	Approach to modelling and operations of DT	VC based approach for developing DT
Highlighted issues	Data communication between parts of the DT	Lack of methods for design, integration, and verifying DT
	Only static models	
Focus area	DT for convergence of virtual and physical space	Synchronise DT, MES, and PLCs
	Process DT	guiding user in DT Development
Conclusions	Provide method for constructing process DT	Fundamental to define architectures for stepwise development of DT
	Creating platform for integration and intercommunication	Fundamental to define architectures for integrating DT into manufacturing systems
Suggested further research	Integrating DT and Big Data for predictive manufacturing	Further validation of proposed concept in real case
	Construct DT method focused on workshops modelling and operations	Improve learning through VC
		Integrate failure detection in concept

4.2.2.1 Expansions of Digital Twins

In the search for articles for the literature review some articles presenting expansions to the DT as well as further applications was found. The found articles are presented in this section to highlight some examples of the current width of the term DT and a summary of the articles can be seen in Table 8.

The first paper addresses the shortcomings of Simulation-Based DT through combining existing implementation methods (Martínez *et al.*, 2018). Regular DTs only use measured data, which means that they can only predict what is given by that input data, and not foresee other occurrences. SBDTs, on the other hand, are based on First-Principle Models (FPM) which uses physics, engineering, and chemical descriptions to make high-fidelity predictions without historical data measurements. Though, the FPMs are tough and can be costly to develop, but the authors aim to simplify the development method of FPMs by introducing an Automatic Model Generation (AMG) method. The procedures of the AMG method can be seen in Figure 12.

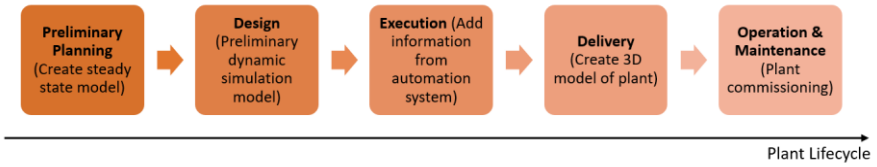

Figure 12 - Procedure AMG method (Martínez et al., 2018)

The second article also proposes a solution to the dependence of historical data and focuses on the use of a Deep Digital Twin (DDT) for system health and for predictive maintenance (Booyse, Wilke and Heyns, 2020). The authors present a framework for the DDT and asses its performance through testing it on a series of datasets. A definition of the DDT is that it is a DT developed using deep learning from operation data, physics models, digital models, data models, and probabilistic models. The deep generative models used by the authors for the deep learning are Variational Autoencoder (VAE) and Generative Adversarial Network (GAN) for explicit and implicit settings, respectively. The VAE and GAN methods are assessed and compared through an experiment to verify their capabilities. In conclusion, the GAN based method was evaluated as a well-suited approach, and the better option for developing DDTs compared to VAE.

In the third article a novel method for process automation design, implementation enhancement, and real-time surveying in creation of a DT in the manufacturing process is presented (Pérez *et al.*, 2020). Through creating a DT of a manufacturing system with a VR interface to simulate and analyse layout,

the approach can act as an aid in decision making. A visualisation of the proposed method can be seen in Figure 13. The method consists of a sequential workflow with feedback loops in creation of the DT. The main use case for the method is presented to be for Human-Robot Collaboration (HRC) and in multi-robot operation cells.

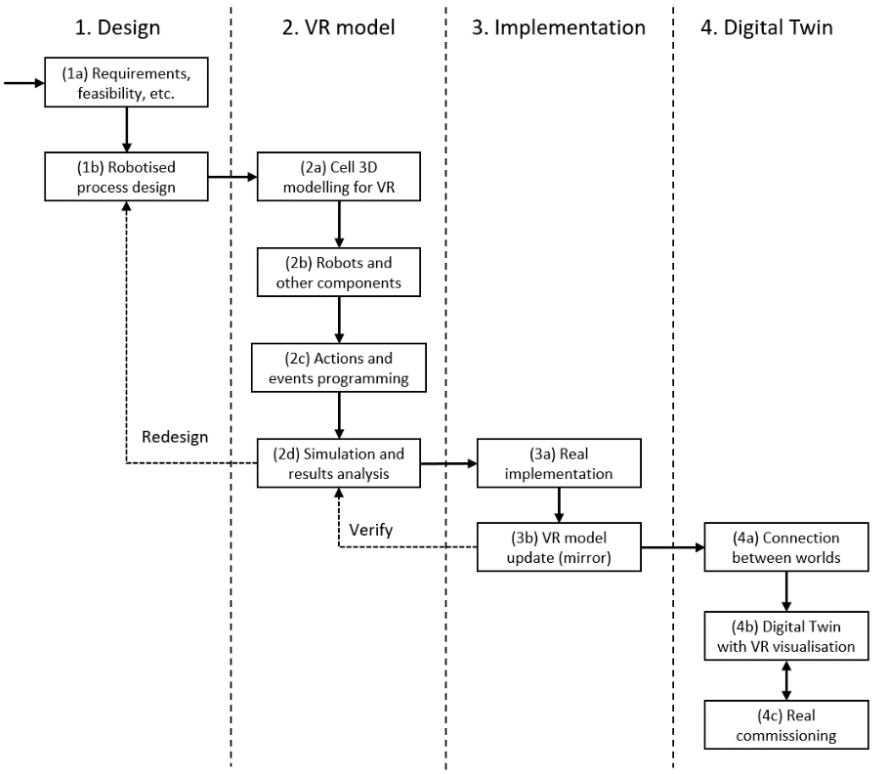

Figure 13 - Proposed sequential method (Pérez et al., 2020)

The fourth and final article, describes the Digital Twin Emulator (DTE) to be used in mechatronic automation systems to enable real-time data exchange (Mykoniatis and Harris, 2021). The DTE is another hybrid simulation approach and combines DES and Agent-Based Modelling (ABM). The DES capture product flow throughout the production process and is efficient resource-wise in detecting errors early. The ABM is used to model the production stations with different states with varying behaviour and rules.

Mykonatis and Harris state that the model must contain Key Performance Indicators (KPI) which represent the production process, its variability, and to capture the variability of the DT. The communication between the PLCs and the DTE is a mix of periodic execution to let events trigger the execution of the next program, while the DTE reads the PLC output when the PLC code is executed. In an experiment environment the KPIs, such as throughput, equipment usage, and capacities, were examined for validity. In the experiment simulation near real-time data collection was deemed critical

in order to match the real hardware. In conclusion, the DTE can be used for testing of the system behaviour off-line, and due the hybrid approach, the inputs can be parameterised.

Table 8 - Summary of articles highlighting expansions of DT

	(Martínez et al., 2018)	(Booyse, Wilke and Heyns, 2020)	(Pérez et al., 2020)	(Mykoniatis and Harris, 2021)
Approach	Automated generation of SBDT	Deep DT	Integrating DT and VR	DT Emulator
Highlighted issues	Shortcomings of SBDT	Losing use of deep learning when creating DT on historical data	Most research on product lifecycles is focused on physical products	Increasing productivity and cost-efficiency
	Typical DT only use measured data and cannot predict what is not in the data		Need of connecting physical and virtual product data	
Focus area	Creation of SBDT	Predictive maintenance	Method for process automation design	Hybrid simulation
	Process industry	Manufacturing industry	Human-robot collaboration	Mechatronic systems
Description	Automatic Model Generation	DT developed using deep learning data from operational data, physics models, digital representation, data-driven models, and probabilistic models	Based on creating DT with VR interface	Hybrid simulation of soft commissioning, Discrete Event Simulation, and Agent-Based Modelling
	Model integration with plant		Combines design, feasibility studies, VC, training, and monitoring	Simulation and data-driven approach
	Optimisation of model	Variational Autoencoder		Key Performance Indicators to represent production process
	Online parameter estimation	Generative Adversarial Network		Architecture: DT interacts with DES model
Differentiation from typical DT	Using AMG to simplify construction of FPMs	Combining DT and deep leaning (AI)	Virtual Reality for evaluating interactions, VC, and learning	Using a combination of simulation approaches
Conclusions	Presents method for AMG	GAN suitable for developing DDT	Proposed approach highlights Industry 4.0 technology synergies	Proposed approach is validated
	Possible to reduce effort for DT creation	DDT an alternative to DT with lower cost	Future requires human interactions with multiples machines	Can help overcome challenges and limitations of stand-alone simulation
Suggested further research	Further improvements to AMG	Evaluate other deep learning systems	Manufacturing processes should have DT	Include evaluation of fail scenarios identify limitations of approach
			Focus on manufacturing process with greater complexity	Test approach in other fields

5 Interviews

The proceeding preparations are essential to be able to get the most out of the interviews and a central part of the interview preparations are formulating the interview questions. The questions to be used during the interview were designed through defining what information is sought from the interviews. For example, how VC is used by the organisation today, what techniques or methods are used and how VC could be improved. After formulating eight questions, they were sent as a draft for the supervisor to review and suggest improvements. The questions were found to be generally good, but the supervisor suggested adding a complementary question to question four to get more exhaustive answers, and thus question five was added. The questions designed and decided to be used for the test interview are listed below.

1. How would you describe the VC your organisation uses today in general?
2. Are there any troubles regarding the terminology of VC and DT?
3. Do you use a systematic and standardised approach or framework for VC?
4. What kinds of errors are typically detected through VC today?
5. What kinds of errors are typically not detected through VC today?
6. How are the errors detected instead?
7. How could the errors be detected earlier with VC?
8. Can you describe some other shortcomings of VC as of today?
9. What do you see as most important advances of VC in the future?

In order to schedule the interviews, a list of possible interviewees was made and prioritised to contact the persons who were deemed the most interesting to interview. The main focus was to interview people located in Sweden, to get a deeper view of the knowledge of VC in Sweden, as well as simplifying the scheduling since different time zones could complicate the process. The source of persons to interview varied and some were found through the initial literature review, consisting of academics with multiple publications on the topic of VC and DT. Other sources for interviewees were webpages of companies working with VC and DT, and then company representatives working in management as well as end users were contacted. Unfortunately, no end users of VC and DT responded nor were able to schedule an interview. Staff at the University of Skövde was also asked to recommend interviewees in case they could think of someone suitable to answer questions in the topic of VC and DT.

Sending out the invitations to the interviews were done via electronic mail, where the general purpose, some outlining questions, and a time estimation were sent to the possible interviewees. To reduce the risk of being rejected if the receiver did not consider themselves as a good interviewee, asking to be referred to a better fit was included in the invitation. When a possible interviewee agreed to participate in an interview, an appointment was scheduled according to their schedule. To be able to conduct the interviews regardless of travel distance and not having to meet in person during the Covid-19 pandemic, the interviews were held via videotelephone.

To make sure being as ethical as possible, the interviewees were asked for consent at the beginning of the interview. Asking for consent also included being clear about the purpose of the interview as well as explaining how the data was going to be used. It was deemed that an oral consent would suffice since agreeing to participate could also be considered giving consent, because the interview was completely voluntary and that the questions were not of personal nature. Another way of safeguarding the ethics is to let the interviewee review a draft of the interview transcriptions to make sure their answers are interpreted correctly and portraying their views accurately. Furthermore, a test interview was conducted to assess the interview questions and approach; this is described in the following subchapter.

5.1 Test interview

The test interview was conducted with a fellow classmate in the one-year master programme. The classmate had also used interviews for her thesis and therefore had experience from both the theory and practice around interviews. In the test interview, the interview guide was walked through in full, including the introduction, all questions, and the concluding of the interview. While the test interviewee was not familiar with the topic of VC and therefore could not answer the questions, the questions themselves could still be assessed and reviewed. Conducting the test interview also allowed the interviewer to rehearse the questions and getting familiar with the questions in an actual interview scenario as well as increasing the confidence in the quality of the interview questions.

The test interviewee was very positive to the questions after the interview but suggested to add one introductory question regarding the interviewees' background and the current role within the organisation. The suggestion was to both make the interviewee more comfortable through starting with another easy-to-answer question, and to get the interviewees own description of their background and role for the presentation of the interview. The question was added to the interview guide is seen below. For the complete interview guide with all revised questions, see Appendix B:.

- What is your background within the organisation and your current role/work?

6 Results

In this chapter of the report, the results of the literature review and the interviews are presented. The literature review is a condensation of the tables from the whole literature review and the interviews subchapter includes the transcriptions from the interview as well as a summary of the interviews.

6.1 Literature review

The first part of the literature review was regarding definitions of VC and DTs, and a brief overview of the results can be seen in the tables in the literature review. Condensing the results of the first part of the literature review, the authors share a common, but not defined, view of VC as virtual validation of the software code, conducted before the real commissioning. Regarding the main challenges for VC, there are consensus regarding VC often being too complex and requiring high effort and expertise, thus being too expensive for many SMEs. The suggestions for simplifying the use of VC, is to improve standards regarding models and model libraries, as well as making the VC more viable financially through utilising the VC model better throughout the lifecycle of the production systems, mainly to prolong the life of the VC through the DT.

Regarding the definitions of DT, there are some discrepancies found in the literature. Where many discuss the DT, DMs or DSs are the actual subject of discussion. What a true DT should be defined as according to most of the literature, is a virtual model of a physical object, or object under development, where the data flows both ways between the virtual and physical space. The data from the virtual space should be used improve the physical object, while the data from the physical space should be used to improve the virtual model and simulation. Some enablers of DTs are data exchange and communication protocols, the improved interconnectivity that comes with Industry 4.0 as well as improved simulation methods. Although there is some consensus regarding the definition of DTs, there are no clear industry definitions and this is asked for in the literature, as well as standardised DT development process and further improvements to the capabilities of the DT through AI integration.

During the literature review and search for information the ISO standard 23247-1 was found, under development. What is included in the standard, except for general principles, is not fully presented by the organisation, but the general principles and framework would help in making the industry reach consensus regarding the definition of DT.

In the second part of the literature review frameworks and standards approaches to VC and DT are explored, as well as some further exploration of technologies related to VC and DTs. In the literature review of VC frameworks, the continuously increasing complexity of automation systems and the lack of standardisation regarding tools and model exchange are identified as challenges in the literature. The VC frameworks proposed currently in the literature, are at a high abstraction level and it is suggested that more concrete concepts and practical procedures for VC development is required.

In earlier parts of the literature review the need for improved standards regarding model detail, model libraries, and for component manufacturers to share their behaviour models, the related topic of behaviour models was explored as well. The literature used in this part of the literature review also sees the complexity of VC and component manufacturers not providing behaviour models as challenges. The immediate solution proposed to this is for the component manufacturers to start supplying behaviour models of their components. But it is also identified that the component manufacturers often struggle to share useful information without also sharing competition sensitive information. Therefore, simplifying the data sharing through standardised data exchange protocols is suggested as well.

In the final section of the literature review related to VC, some similar approaches (testing and verifying automation system and software code virtually), is explored. The literature, in which the complexity and cost of VC is also considered a challenge, suggest the approaches as a simpler and cheaper methods. The low collaboration between disciplines when not using VC is also noted in the literature. The proposed approaches based on IOCO and the IMPROVE framework are deemed as viable and cost-effective.

When exploring the literature for DT frameworks, the challenges found were the lack of standardised design methods and poor data communication and exchange protocols for DT. The conclusion of the literature for DT framework is that it is important to define architectures for the design and implementation of DTs. Furthermore, it is suggested to continue research on the integration of the DT and Big Data, as well as to use the DT further, for example, for learning and training of employees. In the final section of the literature review regarding DTs the literature is used to highlight the width of the field of DTs. In the literature, the DT is combined with deep learning to simplify the development of the DT, VR to improve the evaluations and training, and improve the DT with automated test generation.

6.2 Interviews

In this subchapter of the results, the full interview transcriptions are presented to show the discussions of the interviews in detail. The subchapter is concluded with a summary of each interview, both in text and with a summarising table.

6.2.1 Interview 1 – Bertil Thorvaldsson

Bertil Thorvaldsson has worked in robotics since the 1970's, first as a developer, system integrator, end user and in marketing of robot products. Today, Thorvaldsson is a product manager in Robotics at ABB and a senior adviser at the University of Skövde. ABB as a robot manufacturer do not use the VC techniques and methods themselves but supply system integrators with real robots and simulation and programming software tools such as ABB's RobotStudio.

According to Thorvaldsson the most common scenario is not using VC, and then there is often a clash of robot and PLC programming. Many times, the real commission is started before the preparation of the system, for example production line, is completed. This is very costly due to the prolonged commissioning time and increased the ramp up time. In some cases, the customer requires the system to be commissioned virtually in the specification of the contract or tender. In other cases, the system integrator can offer to use VC as an opportunity to differentiate from the competition.

Thorvaldsson also notes that sometimes the customer ordering the system, for example production line, can sometimes question the price of a quick set up of a system. This is due to the customer not seeing all the work behind the commissioning because it is made beforehand and virtually. The customer could then assume that a system integrator that takes a longer time for the real commission is doing more work when much of the work is in fact waste. In other words, the misconception is that working efficiently is not seen as working well since the work is performed in a non-visual manner. Just because the customer can see the work does not mean that it is value adding.

At ABB, VC is considered to have to be at a high level of detail for it to have a meaningful purpose and the company want to do as much as possible in the virtual world. Therefore, DT is the sought for and used level of detail for VC. Thorvaldsson adds that smaller things, such as a PLC, can be real hardware and be connected to virtual machines. But larger machines, such as robots, should be simulated virtually. In regards of VC and DTs, Thorvaldsson considers the leading company in Sweden to be AFRY.

When it comes to the terminology there are often confusions, but Thorvaldsson defined the DT as a very precise replica and model of an object and VC is one of the scenarios where the DT can be used. According to Thorvaldsson, almost every system integrator uses different approaches when performing VC, but in practice the approaches are still very similar. This is due to there not being too many tools to use or ways to do it.

When asked what errors are typically identified when performing VC, Thorvaldsson states that it is usually the unforeseen situations that reveal errors. In designing the system, for example a production line, the premiss is often the best-case scenario and that the different components will play along. This is in reality not the case. Another common problem source can be the lack of collaboration between PLC- and robot programmers during the design and programming phase. This causes the different components, such as machines and robots, to not properly communicate and work together when performing the VC.

Turning the question around and asking what types of errors and problems are not typically found through VC, the answer is a little different. According to Thorvaldsson the most common errors identified after VC are related to the production process itself. This can for example be quality issues when welding or spray painting and must typically be adjusted during the real commission. A solution for this can be to perform deeper process simulations but the accuracy of the process simulations is not adequate as of today. These simulations are according to Thorvaldsson complex and not available to perform in the industry today, but there exists mathematical simulation for spray paint particles.

Thorvaldsson describes the obstacles of VC to be small in technical regard and larger regarding culture and the lack of standards. The techniques, such as software, for VC exist but the compatibility between different software's and for example robots of different brands is still lacking. A part of this can be due to the industry leaders not being on standards since that could help the competition catch up. The solution to Thorvaldsson is for VC-developers to work together to set standards to make different softwares work together as well as with different hardwares and therefore increase compatibility. Thorvaldsson also notes a resistance to new techniques, which is quite common in other fields as well. People prefer doing what they know rather than trying new things, and even if a change will be positive in the long run there is often a reluctance since the situation often get worse before it gets better. In Thorvaldsson's experience it usually takes three to four changes of managers before a new technology firmly sets in an organisation.

The future of VC is bright, and the technology used today is cutting edge according to Thorvaldsson. When ABB released RobotStudio, the software helped car manufacturers greatly in improving their VC method, since the ability to review the robot programming increased. One new future step for ABB is supplying virtual robots alongside the regular physical robot. This is not available today but is a vision for ABB to offer their customers. The purpose of a virtual robot is to allow the customer or system integrator to test their systems more accurately before the real commissioning.

Thorvaldsson also expands on the topic, adding virtual and augmented reality as tools for visualisation of the production line. VR can be used to achieve a point-of-view experience during virtual commissioning and AR can be used to provide information from the VC to the workers performing the real commissioning. According to Thorvaldsson, adequate AR-tools exist and are relatively inexpensive, they simply need to be implemented in the real commissioning phase. AR-tools such as Microsoft HoloLens can provide data and information gathered from the VC, for example where safety zones are and machine specifications, to improve the real commissioning.

6.2.2 Interview 2 – Patrik Moberg

Patrik Moberg is a senior advisor and simulation and system safety specialist at Siemens Digital Industries Factory Automation. Moberg has over 20 years of experience within automation safety at Siemens. Siemens, as a company, is both a developer and designer as well as user of the VC and simulation tools. The software for VC of production lines developed by Siemens is called SIMIT and is a platform for real-time simulation. Siemens also offer services as system designers and integrators which use SIMIT for VC of production lines. Siemens SIMIT can be used for simulating both discrete and process manufacturing, including the characteristics of the hardware. For Siemens in Sweden, Skövde is the “simulation capital”, and the Skövde division uses simulation in almost every project. According to Moberg it is standard to perform virtual commissioning for at least two or three Swedish system integrators he knows directly, but it could be more as well.

When it comes to the terminology of VC and DT, Moberg is conflicted. He would define VC as a use case for simulation and would rather use the term simulation as uniting term since he typically associates VC with product design rather than production design. Moberg says that the term DT is hard to use since its meaning varies greatly depending on the desired delivery precision, which is always a balance between cost and accuracy, and that a standard would be helpful in unifying the use and definitions.

Moberg gives some examples of standards used at Siemens for creating VC-models, which are Modelica and FMI. He claims that Modelica is a very good and helpful standard which is being used often. Many times, the supplier of, for example pneumatic devices, provide CAD models to be used in virtual models. But these CAD models only include the geometrical properties of the device and not any behavioural properties, which are necessary for VC or simulation.

When asked for typical errors that are detected through VC, Moberg uses the process industry as an example. In his experience the process industry historically used to accept trial and error methods of constructing their production systems which often lead to many rebuilds. In one case, a wrong choice of pump was discovered through simulation where the requirements of the scenario were clearer than before the simulation. According to Moberg simulation and VC can provide a platform to reduce errors caused by a lack of communication or miscommunication between different disciplines, such as robot- and PLC-programmers or production and automation engineers. In this way VC improves the understanding of other disciplines.

When it comes to errors which are not detected through VC but during the real commissioning, Moberg says that it is mostly small details. He claims that the accuracy of the VC ranges from 80 to 95 percent depending on where the trade-off between cost for creating the simulation and the reduced cost due to simulation is determined by the customer. Going higher than 95 percent accuracy is generally not economically justifiable since some manual fine tuning of the commissioned production line will always have to be made.

Thus far, the total design and development time has not been reduced through VC, but rather the labour has been reallocated from the real commissioning phase to the virtual. This is of course positive since it reduces the downtime for production during the real commissioning which is often very costly. But now Moberg has noticed a change, where the use of VC and simulations has started to reduce the total project time. This means using VC can actually be cheaper option already at the contracting phase and this make it easier for the customer to choose a VC-employing company over a non-VC using company. For smaller consultant companies the reduced project times can allow taking on more projects per year, and therefore VC can help them grow.

Most projects that Siemens work on include advanced automation error control and systems monitoring the production line’s error status to automatically detect and reset errors to make the line more autonomous. Moberg says that including the real error behaviours and surveillance systems to the simulation to get an accurate result. This includes testing different fail scenarios, for example how

the production line system behaves when errors are introduced to the sensors or when overcurrent protectors and contactors are triggered. Therefore, adding the real-world behaviours of the components of the simulation and VC.

From Moberg's point of view the techniques for simulation and virtual commissioning exist today but are often hindered by more social and cultural reasons. The entire organisation, and especially the leadership must strive for and embrace the new technology for it to be fully adopted. Moberg links this to short-term thinking and often aske leaders in different organisations what their plan is for the next year, and what the plans for the coming three and five years are. In his experience few leaders can give a good answer to more than the coming two years, and therefore need to look further to realise the values of changes such as full simulation and VC.

Regarding important advances to the use of VC, Moberg highlights the need for having leadership and organisation that support the use of digital tools. His suggestions for adopters of changes in general and simulation and VC in particular is to keep it simple in the beginning. A company new to a technique or tool should start with low-level simulations and make sure to build the simulations and VC with real and practical production experience as a foundation. Moberg also think the current certifications for automation safety help maintaining the competence and suggests that a similar certification for VC or simulation in general could perhaps be an approach of the future.

In addition to the questions, Moberg would also like to point out that money is always the decider when it comes to investments. He thinks that it is important that contractors, such as designers of production lines and system integrators, who delivers their product in steps should also be paid accordingly. In other words, 60 percent pay should be granted when 60 percent of the work is completed to give incentives to do VC. Therefore, the customer who orders a new production line also has a responsibility for the sustainability of the business. While the large companies in the world can develop their own software tools or license entire software suites, many smaller companies do not. To help SME's; Siemens split their services to let smaller companies pay for what they need and use to be able to afford software systems.

To Moberg the VC phase of the production line's lifecycle has reached such a high maturity in practice that he does not find the topic to be too interesting anymore. Instead, his interest and focus lie within keeping the DT alive and utilise the data from the simulations throughout the production line's entire lifecycle. One part of this is using AI to analyse data and learn from the real production line to then feedback this information to improve the simulations or DT. Another part is to keep using the

simulations for improving training solutions, for example training in VR. One of the main goals of Siemens work with digitalisation within production line design is to erase the border, or wall, between the designer and the end user of the production line.

Siemens' other focuses in the lifecycle of the production line is to also include continuous safety, comfort, and fire safety to list a few, according to Moberg. The continuous safety regards keeping the human safety up to date with new standards and changes to the production environment. Digitalisation of comfort is for example controlling the production environment through advanced automated ventilation. And fire safety, which is often overlooked in the production environment and yet can be very costly, need to be improved with advanced digitalisation, Moberg says and points to some recent plant fires which can affect the entire supply chain. Another aspect described by Moberg was improving the DT through creating robust and integrated OT and IT solutions, for example expansion of IoT equipment.

Moberg also mentions an interesting social aspect of VC and doing more of the work virtually and in the office. While young automation engineers might enjoy travelling far and often to perform the real commissioning, they might not enjoy travelling as much when they grow older and perhaps have a family. This has caused automation engineers to sometimes quit and move to other disciplines or fields. VC can to some extent help solve this since junior and senior workers do more together in the office, while the juniors can help with the real commissioning with support from the seniors still in the office according to Moberg. In this way VC helps the company maintain the experience and competence of the senior automation engineers.

6.2.3 Interview 3 – Magnus Holm

Magnus Holm is a senior lecturer and since 2014 head of division at the School of Engineering Science at the University of Skövde. Holm has also published a couple of articles in the field of virtual production technology, especially regarding artificial reality, simulated twin, and human-robot collaboration. At the University of Skövde, the School of Engineering Science's research focusses on the field of virtual engineering and utilise applied science to improve the understanding of development and virtual models for developing products, processes, and systems.

Holm would describe the evolution of VC as a timeline, where the first step was the ability to work offline, meaning the possibility to program and test PLC and robot software, independently from the physical hardware. The next general step in the evolution of VC was the possibility of creating and using DTs. These two steps are the general timeline of the evolution of VC and are interconnected and

dependent of the increased processing capacity from the advancement of computing power. VC is performed to compress the design process of the, for example, production line by allowing programming of robots earlier in the design process, thus allowing for more sub-processes to be performed in parallel.

When asked if any problems regarding the terminology of VC and DT have been encountered, Holm cannot name any specific cases, but that the terminology is generally not too well defined. Regarding systematic and standardised approaches to VC, Holm says that the development of VC is not always driven by the engineers. Instead, it can be, for example, PLC or robot programmers with a technical interest who initiate the use of VC in some companies. Therefore, the use of VC can sometimes be rather ad hoc. Sometimes, local standards can occur in the geographical surroundings of large or dominant users, Holm lists Södertälje and Göteborg as some examples of this, where Scania and Volvo respectively are dominant companies. The local standards are not necessarily standards per se but occur when supporting companies try to adapt their tools and methods to the local leader to offer compatible solutions.

According to Holm, the types of errors detected through VC depend on the application scenario. Examples of application scenarios of VC can be the typical to run the PLC program to see if the software works as intended, or other scenarios such as reach analysis of robots and evaluation of ergonomics and visibility of HMIs using VR. The purpose of the robot reach analysis is to control that the robot can sufficiently reach the positions required to perform the desired operations. Errors not detected through VC are typically identified during the real commissioning phase.

When it comes to future improvements for VC, Holm lists several areas to make the implementation of VC easier. He lists knowledge and experience of the VC process as important factors for successful implementation of VC. Another is the digital maturity or infrastructure of the company, which need to be up to date for the VC to be profitable. Though, Holm also says that it is possible to skip steps in the digital technological advancement, but this requires knowledge as well as new technology working independently from the old technology. In all of the new technology and tools it is also important to maintain the knowledge and competence around the actual process which is to be modelled and simulated.

Another important aspect of implementing VC, which Holm points at, is for the entire organisation to understand the reasoning, goal, and purpose of the VC process. A common goal and support for VC is necessary. This applies to all changes introduced to an organisation. A common issue or shortcoming

related to VC is keeping the virtual model or DT up to date. The virtual model is often forgotten after the real commissioning, but to maintain the value of the virtual model online changes made to the physical object need to be added to virtual model. Holm likens this with having a backup of the production line's PLC and robot software, but the backup is not very useful if it is not up to date with the latest revisions.

When asked about the shortcomings of VC today, Holm says there is not much to do with the technology, it is what it is, and one cannot say whether the tools are right or wrong. The evolution of technology and tools happen fast, Holm uses the evolution of smartphones as an example which did not exist 13 years ago but are an essential everyday tool for most people today. The challenge is translating the technology and tools into fruitful use, and good practice. Furthermore, the internal processes of companies need to allow changes such as VC. Often, implementing changes in a company can take time, partly due to many steps of realisation of the change. It is common for the change to start as an idea, then entering an acceptance phase where support from different parts of the organisation must be gathered. Next, is specifying the change, and then to standardise it to be used in the same way by everyone in the organisation, finally is the implementation.

Regarding important advances for VC, Holm views the standardisation of the VC process as a key factor further success for VC. This is to allow for a broader use, and Holm uses the AC power plug and sockets as an example of both unification and differentiation. Global companies operating in multiple countries might need a standardised VC process to be able to use the same virtual models in multiple countries. Another important factor is the general acceptance of digitalisation and Industry 4.0, in which VC is a part. Holm adds that for societies to grow and become more accepting of changes need a capability to foster ideas and knowledge. The capability is improved by education and other enablers such as adequate internet access for the mass, allowing for information gathering and further education.

Holm puts VC in a larger and general context by discussing a possible competence gap that can be created when younger generations with a more natural relationship to digital tools than the previous generations enter the working life. The gap in competence is the new generation having competences in newer areas, such as digital tools, compared to the older generation which often have more competence in related to the process. In a historical perspective, the manufacturing industry has been the foundation for society as a large employer and motor of wealth, but a change in demand for the type of competences can put new requirements on the knowledge of the employees. For example, a

shift in work types from more simple and manual tasks to more digital, automatised, and officed based work types.

Expanding on this, Holm also reflects on the following consequences for higher education, when the students of today are expected to be equipped to handle not only existing technologies, but also technologies coming in the 15 years. Previously, getting an education is done before starting the working life and then working until retirement. The solution of tomorrow seems to require more flexibility from the employee to update their competence and getting either a specialised or a completely new education once or more during the span of their working life.

6.2.4 Summary of interviews

The interviewee of the first interview was mainly connected to the business world, while still influenced by the academics through working with the University of Skövde. Here it was stated that the most common practice is not using VC, that the DT is a precise replica of a physical object, and that VC is a use case for the DT. Highlighted obstacles for the development and use of VC were related to the lack of standardisation, and to cultural and social aspects of implementing new technologies and work methods. Some other interesting thoughts raised by the interviewee was the paradox of using VC efficiently and reducing the real commissioning time, and thus working more in the office can fool the customer to think that the assignment was easier than they are paying for. In general, the interviewee proposed using AR and VR to prolong the lifecycle of the DT outside the use in VC, while also using AR as support during the real commissioning.

In the second interview, where the interviewee was completely in the business world as well as being oriented to marketing, it was stated that VC is a standard procedure for at least two or three companies working with system integration. Here, VC was also seen as a use case for the DT, and the main obstacles for using VC are also related to organisational and cultural limitations. The interviewee was very clear with not being too interested in VC anymore since he thought the process was adequate and wanted to focus on the rest of the lifecycle of the DT. Parts of this are using AI and VR tools to make more use of the DT. As in other fields, the interviewee suggested that there could be organisations to certify the VC process of companies in order to harmonise approaches and verifying to potential customer that the company is using a proper VC process. Finally, a major possibility due to the use of VC is improving the social sustainability of the workplace. Through increasing the time spent in the office and for normal work hours, while reducing the time needed for the real commissioning, the work conditions of the employees of system integrators. Some are forced to quit due to the private life

clashing with the work of real commissioning on site, which can often require much travelling and overtime.

The third and final interview, in which the interviewee was purely academic and therefore could not give very detailed or specific answers regarding VC technology and methods. The interviewee notes that in some companies it is not engineers who drive the use of VC, and therefore the approaches and methods in those cases can often be ad hoc or improvised. The main obstacle for a wider use of VC is viewed as cultural limitations. Also in this interview, the interviewee noted the need to prolong the lifecycle of the VC and utilising the DT more. With the academic background, an interesting point was also added regarding the role of higher education as the rate of the technological and digital evolution increases. Finally, one addition made is the effects on society introduced by the shift in competence demand from process knowledge to competences in technological and digital tools, which can create a competence gap in the labour market. A short summary of the interviews can be seen in Table 9.

Table 9 - Summary of interviews

	Interview 1	**Interview 2**	**Interview 3**
Description of VC	Use case for DT	Use case for DT	Use case for DT
Use of standards	In practice similar approaches	Modelica, FMI	Local "standards"
Standardisation of DT and VC	In need of standardisation	In need of standardisation	In need of standardisation
Other improvements from VC	Collaboration between disciplines	Collaboration between disciplines	Collaboration between disciplines
Errors not detected through VC	Process related (spray paint, weld)	Small details (last 5 percent)	Not specified
Obstacles	Culture/Social	Culture/Social	Culture/Social
Future of VC	Prolonging lifecycle (AR, VR)	Prolonging lifecycle (AI, VR)	Prolonging lifecycle (VR)

7 Discussions

The discussion chapter reflects on the results of the literature review and interviews, as well as on the literature and interviews in the context of each other. Included the reflections are some own thoughts, possible outcomes, and a review of the chosen research method, based on contents of the report.

7.1 Literature review

One of the most agreed upon, and written about in the reviewed literature, aspects and challenges related to VC is the complexity. The complexity, and the cost that come with it, might be why many smaller companies choose to not employ VC. When discussing a technology, such as VC, it is often the state-of-the-art, and most advanced use cases for the largest users which are in focus, and maybe that is not for everyone. For smaller companies, it could possibly better to use simpler and similar approaches instead, such as the presented methods of IOCO and IMPROVE framework. The simpler approaches could make the concept of verifying the software code before the real commissioning viable for smaller businesses as well.

Although the differences between DM, DS, and DT may seem small, and a common definition may seem trivial it is important to know which type the object of interest is to avoid confusions. Which is why the standardisation, common definition, and common vocabulary is important. Also made clear in the literature review is the importance of Industry 4.0 and its related technologies. The type of interconnectivity between machines, networks, and operators included in Industry 4.0, could allow for the automatic and bidirectional data exchange which is the core of the DT. Even if DMs and DSs, which are the standard today, are useful, it is the full automation of the dataflow which makes the DT an interesting. Systems that do not automatically update require more work to keep alive and are often forgotten and outdated.

During the literature review, some challenges were encountered. The lack of a common and defined terminology made for a steep learning curve when starting to search and review literature. Since there is not much standardisation in neither VC nor DT, the literature review process was time consuming. Even papers with abstracts that seemed to fit the topic of the thesis, they could much later, during the deeper review, be discarded due to not being useful as they were discussing an entirely other topic. This could also lead to be a flaw of the of the literature review, since the topic is difficult to navigate, it could be hard to know for certain that all appropriate articles were found to then be reviewed. If,

perhaps, some more preparations were done before starting to conduct the literature search, the end result would have been even more satisfactory.

7.2 Interviews

While the background of the interviewees differed, they also highlighted some common key points, as well as giving different and some inconsistent answers. In one way, the interviewees were quite consistent is the way they describe VC, as a use case for the DT, as well as describing the DT as a very detailed model of a physical object. Although they use similar descriptions of the terms, they all agree that standardisation is necessary for making further advancements in the field due to the vague definitions and varying descriptions of today in general. Another common ground regarding the advancement of VC and DT is pointing out the importance of organisations having a culture where the acceptance for new technologies and work methods are high in general. All three interviewees notes that VC, apart from reducing the time of the real commissioning, also improve the collaboration and communication between the different disciplines, such as mechanical designers, PLC-, and robot programmers. Another point where the interviews seem to agree is the importance of prolonging the lifecycle of the DT created for VC, through keeping the DT up to date as well as utilising it for other purposes, using for example AR and VR.

Though there were some differences in the interview answers as well, for example, in the first interview it was stated that VC is not common, while in the second interview it was stated to be standard practice in at least two or three companies in Sweden. Although, the statements could be consistent, just expressed in different ways and from different perspectives. For example, the first statement probably refers to the entire industry ranging from small to large companies where the scale of projects does not allow for VC to be of value. The second statement could refer to VC being a standard practice among large companies and the industry leaders.

Some other differences are, for example, in the second interview where the interviewee would rather use the word simulation as an umbrella term, instead of DT, to be more easily understood by people of varying background. It was also said that Siemens use standards, such as Modelica and FMI in the creation of the VC and DT. For the third interviewee, the understanding was that the standards were mostly local and determined by the dominant company in a geographical area. In the third interview some other use scenarios for VC was exemplified in analysing the reach of robots, as well as the visual ergonomics and visibility of HMIs. One important aspect for increasing the use of VC is the

requirements on the company's digital infrastructure, which was not highlighted by the other interviewees.

Finally, some differences regarding the examples errors typically not detected through VC were found. In the first interview, the answer was that most non detected errors were related to the production process, such as welding and spray painting. These errors require separate mathematical simulations which are often not viable economically compared to manual adjustment of the process. Perhaps this is the break-even point of today, and more economic to adjust afterward than to do the intricate simulations of particles before the real commissioning. In the second interview, the non-detected errors were seen as small details, which are not deemed to be expensive enough to warrant more time during the VC but are cheaper to discover and correct in the real commissioning.

Although it is not possible to draw any solid conclusions representing the whole situation for VC from only three interviews, since the few answers are more anecdotal, the interviews still provide some interesting insights to how VC is viewed by practitioner and academics. Another thing to keep in mind when analysing the interviews is that representatives of companies should always be viewed as trying to market their company and put it in the best light. This applies to the first two interviews and likely the second one the most since that interviewee is not connected to the academic world at all. But keeping this in mind can allow for discovering new perspectives and views regarding VC and DTs.

Furthermore, as of writing this report, only one of the interviewees has responded with feedback to the draft of the interview transcriptions. If this is because they have not reviewed the transcriptions at all, or if they found the draft truthfully representing their views and therefore did not deem it necessary to respond, is unknown. This could possibly affect the quality if the two transcriptions not are not accurate. In an ethical standpoint all interviewees have had the opportunity to review their statements, even if some of them chose to not respond.

Finally, conducting the interviews was very interesting, the feeling at least seemed mutual, and many interesting discussions were had. Another interesting fact is how long the different interviews required. Two of the interviews were completed in 45 minutes, while one interview required two sessions and 110 minutes in total. In this case, the interviewee was well prepared for the interview, sharing his own presentation, and presented what he wanted to share before answering the interview questions. The interview had to be continued later due to other appointments after 60 minutes and in the second session when the interviewee had said what he wanted, he was more inclined to answer the interview questions freely. What can be learned from this is that talkative interviewees might need to be emptied

of what they want to express before answering the questions, which can be useful advice for other interviews.

7.3 Summary

Overall, in both the literature and interviews, the need for standardisation was made clear, not only in defining the terminology, but also for standard approaches to design VC and DTs, as well as for data exchange and communication protocols. In this regard the ISO 23247-1 standard could bring some much-needed clarity and definition to at least the DT. Before the standard and its content is published, it is hard to completely predict the entirety of the outcomes. But to speculate, the standard should allow for a widely accepted definition of DT as well as data exchange protocols for interconnectivity and automated dataflow.

On another note, Schneider et al. present the procedure for designing failure scenarios, which is presented in chapter 4.2.1. Besides aiding in determining the automation systems behaviour in case of errors, the process of identifying and reflecting on failure scenarios could also be used to prevent or even eliminate the failures entirely.

All these aspects and technologies for simplifying and improving the use of VC and DT are important for increasing the use of virtual tools and methods, such as VC and DT. The increased use of VC and DT is important for many reasons, such as increasing safety for operators through minimising harmful situations and correctly validating safety systems, as well as allowing improved working conditions, as described in the second interview. Furthermore, increased use of VC and DTs should also make the process of designing and developing production systems more cost-effective. This is due to not only reducing the time needed for the real commissioning, which is expensive time, but possibly even reduce the time for the design and development as well, as discussed in the second interview. More use of VC and DT could also minimise wastes, such as ordering wrong components and machines, and to optimise the resource and energy usage through simulations and using the DT.

As for the generalisation of the results of this thesis, it is not obvious due to the work being very specific to the technologies of VC and DTs. A theme of this thesis has been the need for standardisation, which could be applicable to most new technologies and techniques. When narrowing down the width of the generalisations to related fields, some other can be made. The focus of this thesis has been VC of production systems, but some of the results, such as the ISO standard could also result with simplifications and improvements to VC and the DT of, for example, products and operations.

This kind of close generalisation can also be made regarding extending the lifecycle of the DT for products and operations. Furthermore, the use of qualitative interviews is not very widespread in the field of engineering, but in the case of this thesis, the interviews gave many interesting new perspectives and insights. Thus, interviews as a data collection technique should be used more to allow for more interesting discussions in other works.

8 Conclusions

The current situation for the use of VC and DT has been examined through a qualitative literature review as well as interviews with knowledgeable people in the industry. The literature review consists of two main parts, where the first part is trying to improve the understanding of terminology and definitions regarding VC and DT. The second main part of the literature review explores the use of VC and DT, and the related technologies. The three interviews were conducted to explore the current views of VC and DT in the industry of Sweden, as well as to gain a glimpse of reality to ground the thesis in the practice.

One benefit of VC is that the process tends to make the different disciplines involved, such as mechanical engineers, software programmers, and robot programmers, collaborate and communicate more, which reduces errors even more. In the literature, it was stated that the engineering staff often is disconnected from the software programming, and in all three interviews, VC was regarded as good way to make the different disciplines communicate and solve issues together.

Related to data exchange is model and behaviour model exchange, which also was a widely expressed challenge for VC and DT. One given reason for this, both in literature and interviews, was that component manufacturers struggle to share the necessary information about their product without revealing company secrets, and therefore do not provide behaviour models at all. Though, in the first interviewee also stated that ABB is approaching a solution where a complete and virtual robot is provided along with the physical robot. If that means including behaviour models, the demand highlighted in both literature review and the second interview could possibly be close to being met by at least one component manufacturer.

Furthermore, the need to make better use of the VC and to utilise it throughout the entire lifecycle of the production system was expressed by literature as well as the interviews. The natural solution is utilising the DT created for the VC to use in, for example, optimisation, training, and predictive maintenance. For this to be possible, it was said in both literature and interviews that improvement of OT and IT was needed, and this should be attainable within the Industry 4.0. Other improvements to the DT deemed necessary by both literature and interviewees was the use of AI and deep learning technologies to improve optimisation and prediction of future events even further. Another technology crossover is AR, VR, and the DT, which was described in both literature and interviews, but especially in the first interview as the future of learning at the workplace as well as aiding the construction staff during the real commissioning.

As to answering the research question of, "*What are the current conditions and future for Virtual Commissioning of production systems?",* this study, through both the literature survey and interviews, reveals the following results:

- Need of definition and standardisation for VC and DT.
- ISO 23247-1, promising work-in-progress standard for DT.
- Prolonging the lifespan of VC through the DT.
- Improving the DT through combinations with other technologies.
- There exist cost-effective VC solutions for SMEs.
- VC provides a platform for collaboration.
- VC and DT are often hindered by resistance to change.

All of the results are essential for the continued and expanded use of VC and DTs, which is important for improved sustainability of social, economic, and environmental dimensions.

9 Future work

The conclusions of this thesis can be used to aid in the work of defining and standardising the use of VC and DTs, such as differentiating the different types of DTs. The ISO 23247-1 standard is promising, and when completed and published should provide a common foundation when discussing and developing DTs. Thus, the standard should allow for further improvements and standardisations at more concrete levels of detail, as well as simplifying future research in the field through common vocabulary and definitions.

Furthermore, the improved conditions created by the ISO standard, should be leveraged in the research field and practice in order to develop standardised techniques and concrete approaches for VC and DT creation. One of the interviewees highlighted cause of errors not detected during VC as process related, such as welding and spray painting. Currently, the detailed particle simulations are too complex, and therefore not used, causing the errors of the process to be corrected manually during the real commissioning. If research into improving and simplifying those types of process simulations, the processes could instead be validated before the real commissioning. The interviews gave valuable insights to the current conditions of VC and the DT, but the topic could be further explored through even more interviews. The interviews could include the users and customers of VC and DTs to add new and other perspectives to the research.

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Appendix A: Search term notes

Search terms:
stress testing methods
worst-case
ultimate strength
automation
production lines
virtual simulations
virtual commissioning (Emulation for logic validation (ELV))
Digital twins
accuracy
modes of failure
error handling
validation
& verification
scenarios
error detection
weaknesses
challenges
KPI
best practices
techniques
state of the art
case study (to gather approaches of different case studies)
heuristics (finding solutions that work but may not be optimally)
standards
guidelines
virtual pilot plant
improve
enhance
anomaly
framework
key factors in
predictive analytics
approach
test case design
generate test case /environment
behavior/behaviour model
design principles

Last search phrase: behaviour OR behavior models "virtual commissioning" OR "digital twin" industrial production

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Appendix B: Interview guide

Introduction

Thank for choosing to participate!

The purpose of this interview is to gain knowledge on how VC is used currently in the industry.

The interview will be used as a complement to my literature review in my master's thesis.

The interview will take approximately one hour, depending on how thorough answers you give.

I will ask ten open ended questions around the use of VC.

For the record, do I have your consent to document this interview and publish the conclusions in my thesis report?

Interview

1. What is your background within the organisation and your current role/work?
2. How would you describe the VC your organisation uses today in general?
3. Are there any troubles regarding the terminology of VC and DT?
4. Do you use a systematic and standardised approach or framework for VC?
5. What kinds of errors are typically detected through VC today?
6. What kinds of errors are typically not detected through VC today?
7. How are the errors detected instead?
8. How could the errors be detected earlier with VC?
9. Can you describe some other shortcomings of VC as of today?
10. What do you see as most important advances of VC in the future?

Concluding

Is there anything you would like to add?

I will summarise the interview and draft the results for you to feedback this week if you are interested.

Thank you for taking your time to help me with my thesis!