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Implementing the virtual factory in manufacturing industry

A step-by-step strategy to enable smarter decisions based on observable facts

Master's thesis in Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

A substantial challenge for manufacturers today is to create a flexible and efficient production system. One way of managing this challenge is to establish a virtual factory, a digital model of the production unit. Working smarter by using the advantages that digitalization implies enables production in smaller batch sizes at increasing speed. This thesis explores how to implement a virtual factory by stepwise increasing its maturity. Evaluated at a large scale Swedish manufacturer, local needs and enabling technologies benchmarked at industry leaders have been identified and strategically mapped to their corresponding maturity step. This thesis proposes a step-by-step implementation plan for a virtual factory relying on standardized work procedures, ensuring its use as a decision aid throughout the company. Implementing a virtual factory in this manner will facilitate user-driven development and more accurate decision making, generating support for more efficient production systems.

Keywords: virtual factory, implementation, strategy, smart manufacturing, digitalization, maturity, digital twin, production.

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Amanda Dalstam & Marcus Engberg, Gothenburg, May 2018

Contents

Glossary

This glossary presents key terminology used throughout this thesis and the definitions are specific to its field of research.

Advanced analytics
A collection of different techniques for generating descriptive and predictive analyses through autonomous or semi-autonomous examination of data.

Artificial intelligence (AI)
The science of making machines perform actions that otherwise would require human intelligence.

Back-end
The part of a system which solely the developers interacts with, it is the server-side containing the raw data from the production unit.

Benchmarking
A continuous systematic process of evaluating companies recognized as industry leaders, to determine business and work processes that represent best practices and establish rational performance goals.

Data
Quantitative facts about events or qualitative facts describing a subject.

Digital factory
An umbrella term, describing the model environment, as well as the use of digital tools, methods and data management systems in an enterprise.

Digital tools
A collection of software and digital interfaces providing support in development and operations.

Digital twin
A digital copy of the production unit, denoting the virtual factory when it depends on real-time data. It represents the production unit's current state and accurately reflects its inner workings.

Digitization
The conversion of information, such as text and pictures, into a digital format that can be processed by a computer.

Digitalization
The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business.

Discrete event simulation (DES)
A type of simulation founded on time-based leaps between different system events.

Effectiveness
Relates to the output of a system and means doing the right thing.

Efficiency
Relates to the input to a system and means doing things right.

Front-end
The part of a system which the user interacts with, it is client-side represented by the modules in the virtual factory.

Information
Data that has been further processed for use in simulation models and other means for visualization.

Input data management (IDM)
A method to identify and collect as well as to extract process data.

Kaizen
A philosophy stemming from lean production and denotes the process of incremental improvements to reduce waste – continuous improvement.

Machine learning (ML)
The process of finding and describing structural patterns in data and thereby giving a computer the ability to learn.

Modularization
Deconstruction of a system into independent units.

Module
A software or a mathematical model used for analyzing the virtual factory's output data.

Validation
The process of comparing if the simulation model's output satisfies the accuracy of the real-world scenario.

Verification
The process of ensuring that the simulation model is mathematically correct.

Virtual factory
The model environment which contains geometrical and mathematical representations of resources. It consists of virtual work cells, virtual machines and virtual processes.

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1
Introduction

This chapter introduces the master's thesis, providing the background to the topic and a brief description of the company. Finally the chapter ends with declaring the aim and delimitations.

1.1 Background

As industries grow on a global scale, companies must meet the demands of an increasingly competitive market. To satisfy customers, challenges including manufacturing of high quality products to low cost become apparent. Stimulating such innovation while maintaining cost efficiency require companies to utilize available resources and competences as efficiently and effectively as possible. To increase competitiveness in such a market climate, recent development trends in industry located in high-wage countries focus on an increased level of digitization (Schönsleben and Duchi, 2017). This development is fueled by the potential to reduce lead time and cost as well as support decision making processes (Becker et al., 2005; Terkaj et al., 2015).

SKF Group is a company specializing in bearings technology, seals, mechatronics, lubrication systems and related services (SKF Group, 2018). Worldwide in 2017 they had 43 814 employees present in 130 countries. During the same year the company presented a total net sales of 77 938 billion SEK and further a net profit of 5 760 billion SEK (SKF Group, 2017d). The company is mainly acknowledged for their outstanding product quality as well as innovative product solutions; the aim being to increase the product life cycle and thus reduce running costs for the end customer (SKF Group, 2014a,b, 2017a,b). The Swedish subsidiary of SKF Group is SKF Sverige AB and constitutes the case company for this thesis, henceforth known as the company.

One of the factories in Gothenburg, Sweden, was recently transformed into the first highly automated production unit within SKF Group (SKF Group, 2017c). An investment of 190 million SEK was made to develop and implement the new automated and initially digitalized factory (SKF Group, 2015). However, the company's journey towards smartifying the Gothenburg factories is not final but a continuous project driven by the department of process development. The department manages all machine and process related investments in the Gothenburg factories. As a consequence of the many dimensions of a production system a project team constitutes of many different stakeholders, each representing a vital part of the production system

(Bellgran and Säfsten, 2009). Similarly at the company their production development projects have started to involve more stakeholders with the increased amount of digital technology. As the production system becomes more complex the probability of making well-informed decisions decreases due to the large amount of data available and thus more aspects to consider (McAfee et al., 2012). If consolidating all the available production data to one common platform, enabling data-driven decision making, both productivity and profitability can increase (McAfee et al., 2012). Creating such a platform is what SKF call smartifying the industry (Gerdin, 2016).

One way to provide decision makers with relevant information is the implementation of a virtual factory. A virtual factory is a digital platform where production data is consolidated and presented visually as relevant and precise information for the individual user or user group and can act as a foundation for data-driven decision making in process development (Terkaj et al., 2015). Furthermore the virtual factory can help the user observe events and effects of changes in the production system, thereby providing a holistic understanding of the system (Becker et al., 2005). In summary, the virtual factory provides a way for basing decisions on observable facts rather than on perceptions enabling more efficient management of resources and thus working smarter not harder.

1.2 Aim

This thesis aims at evaluating different dimensions of the implementation of a virtual factory at the company. First, the needs and motivation for using and implementing such technology are to be investigated. Second, different aspects of technology will be explored as well as organizational requirements for developing, using and maintaining the virtual factory. The aim is to evaluate how the virtual factory can be implemented and present a plan anchored in the needs at the company. An important objective is to facilitate continuous and accurate use of the virtual factory.

The purpose of evaluating the implementation of a virtual factory relates to the increasing competitiveness on the global market affecting the company. By investigating the concept of a virtual factory an important objective is to shape and concretize the journey towards a fully smartified factory and digitalized enterprise.

Taking the background and the aim into account the following two research questions are proposed:

1. How can a virtual factory be implemented?
2. How can a virtual factory become value-adding in current practice?

1.3 Delimitations

The scope of this study includes the department of process development, no other departments will be considered in detail. The analysis does not include suppliers, distributors or customers but will solely focus on the in-house processes, from incoming material to finished product. Furthermore, no aspects of cybersecurity are considered. Lastly, no economic analyses or sourcing strategies for the equipment and systems considered in the thesis will be performed.

2

Frame of reference

This chapter describes the theoretical framework. Key topics derived from literature concerning emerging research related to virtual factories and the methodology of this project are reviewed.

2.1 Overview

This chapter has been divided into five main themes, as depicted in Figure 2.1, the first four relates to the theory of the virtual factory while the fifth one concerns the research methodology. The first theme, Concepts, found in Section 2.2 includes emerging digital concepts and their applications in industry, creating a framework for the appearance of a virtual environment. The second theme, Virtual tools, found in Section 2.3 describes physical attributes as well as methods for creating a virtual environment and provides a deepened understanding of the models. The third theme, Data, found in Section 2.4 concerns the input to the models and generates information when extracted from the virtual environment. The fourth theme, Efficiency, found in Section 2.5 enfolds different perspectives on how value is added within a production system. The last theme, Study, found in Section 2.6 describes different topics related to the design of this study.

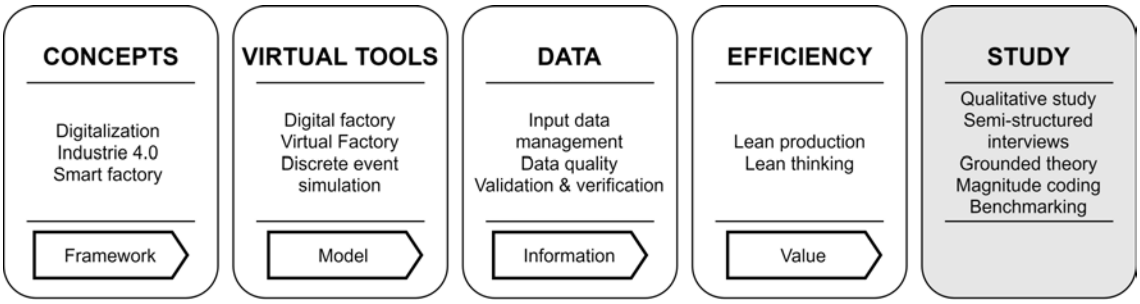

Figure 2.1: The five themes which the frame of reference is divided into.

2.2 Concepts

The manufacturing industry was born two centuries ago and has gone through several manufacturing paradigms (Hu et al., 2011). The first paradigm was craft production which was followed by mass production and then mass customization (Koren, 2010). Today's society demands not only customized products, implying large variation, but also that the personalized products are sold at mass production price which naturally brings requirements of speed and flexibility to the manufacturing industry (Koren, 2010). From this stems the fourth and current paradigm - personalized production (Hu, 2013). The key enabler to the current manufacturing paradigm is Information Technology (IT) and the internet whereas the prior paradigm, mass customization, was enabled by computers (Koren, 2010).

2.2.1 Digitalization

The introduction of computers facilitated the conversion of information, such as text and pictures, into bits which could be stored and sent over a network – things became digitized (Brynjolfsson and McAfee, 2014). However, the personalized production paradigm, in practice, could be seen as an extension of digitization; digitalization (Lasi et al., 2014). Digitalization is herein defined as: "*The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business*" (Gartner, 2018b). Combined with a modular and efficient production system digitalization can facilitate manufacturing of personalized products in batch sizes of one while maintaining the cost of mass production (Lasi et al., 2014).

2.2.2 Internet of things

One crucial enabler for realizing the value that digitalization offers is the network between resources, information, objects and people, namely the Internet of Things (IoT). This technology makes it possible to connect the entire manufacturing process which converts factories, and enterprises, into smart environments (Kagermann et al., 2013). However, IoT is not limited to manufacturing but was coined in 1999 in the context of supply chain management (Ashton, 2009). IoT can be applied in a large range of areas, which can be realized in the following definition: "*Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications*" (Gubbi et al., 2013). For example, IoT can lead to the emergence of smart grids in energy supply, sustainable mobility services and smart health, as well as smart products and systems in manufacturing (Kagermann et al., 2013).

2.2.3 Industrie 4.0

The German federal government coined the expression Industrie 4.0 in 2011 when it officially was adopted in the action plan for *High-tech Strategy 2020* (Wang et al., 2016). The 4.0 illuminates the potential fourth industrial revolution that this trend implies, enabled by integration of information and communication technology in industrial production (Schuh et al., 2017). The concept of Industrie 4.0 stems from the idea of cyber-physical systems (CPS); "*physical and engineered systems that whose operations are monitored, coordinated, controlled and integrated by a computing and communication core*" (Rajkumar et al., 2010). Nevertheless, besides the cyber-physical production system does Industrie 4.0 integrate production facilities, logistics, warehouse systems and social requirements which results in a global value creating chain (Wang et al., 2016).

There are several technologies that different research groups and industries are including in their scope of Industrie 4.0, it therefore does not exist a shared exact definition of the concept. Lasi et al. (2014) includes smart factories, CPS, self-organization and corporate social responsibility in their definition of Industrie 4.0. While a German researcher forum describes the technology as intelligent, digitally networked systems with the ability to self-manage production processes (Platform Industrie 4.0, 2018). The core idea of Industrie 4.0 is thus using emerging information technologies to facilitate the implementation of IoT and related services in order to create a flexible and efficient production system which can produce high quality products and services in small batch sizes, allowing for mass customization (Lasi et al., 2014). In summary, Industrie 4.0 can serve to create horizontal value networks, provide end-to-end engineering and enable vertically integrated and networked design of production systems (Kagermann et al., 2013).

2.2.3.1 Industrie 4.0 maturity index

The main economical incentive for transforming a business towards Industrie 4.0 lies in it's ability to accelerate corporate decision-making and adaptation processes (Schuh et al., 2017). The transformation will be different for every company due to different prerequisites and it is therefore necessary to map each company's current state. To enable this analysis a *Industrie 4.0 Maturity Index* has been developed by Schuh et al. (2017). This maturity index constitutes of a six-step grading where each stage builds on the previous one, see Table 2.1. The first two stages however are not formally parts of Industrie 4.0 but are rather necessary to transform into an agile and flexible production system, allowing production to quickly adapt to changes in customer demands.

Table 2.1: The six levels of maturity for Industrie 4.0 according to Schuh et al. (2017).

Maturity stage	Theme	Description
Computerization (1)	Digitalization	The use of IT in isolation to each other.
Connectivity (2)	Digitalization	The isolated deployment of IT is replaced by connected components.
Visibility (3)	Industrie 4.0	To have up-to-date digital models of the factories at all times.
Transparency (4)	Industrie 4.0	To understand why something is happening based on the retrieved data
Predictive capacity (5)	Industrie 4.0	To be able to simulate different future scenarios.
Adaptability (6)	Industrie 4.0	To be able to use the data from the simulations to make decisions that have the best possible results.

2.2.4 Smart factory

Smart factories or smart manufacturing is a concept closely related to Industrie 4.0. Naturally, the challenge of global manufacturing concerns the whole globe, not just the German industries. The United States of America launched their research platform *Industrial Internet Consortium* in 2014 where one of the emerging topics was the integration of the IoT in manufacturing, creating a smart factory (Industrial Internet Consortium, 2018). Many countries have launched their own research agendas where smart factories or smart manufacturing are key concepts, all enabled by the integration of IoT. Two examples are the Chinese government's *Internet+* (Premier of the State Council of China and Li, 2015) and the Swedish initiative *Produktion 2030* (Produktion 2030, 2017).

A smart factory is described as an integration of systems that facilitates real-time interactions of people, machines, assets, systems, and things (Smart Factory Task Group, 2017). This can be translated into a cyber-physical-system equipped with the ability to communicate, making it a smart environment. Nevertheless, the smart factory is described as having a new approach to production if compared to the traditional factories. In a smart factory products are uniquely identifiable, smart, and can be located at all times and carrying their own history, current status and alternative routes through the complete process (Veza et al., 2015). Furthermore, can the key characteristics of the smart factory be summarized as the following (Veza et al., 2015):

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

2.3 Virtual tools

Making changes to established manufacturing systems is getting more important than developing completely new ones due to changing requirements, this is a trend seen in both developed and developing countries (Kühn, 2006). To make these changes in an efficient way their impact must be analyzed in a holistic manner. Furthermore, the planning and analysis of the system must be performed more efficiently in order to meet the changing requirements. For this, the virtual factory and the tools it provides show great potential (Yang et al., 2015).

2.3.1 Digital factory

The digital factory is in this thesis considered as an umbrella term, describing the model environment as well as the use of digital tools, methods and data management systems in an enterprise (Yang et al., 2015). Compared to the smart factory, a system in the physical world, the digital factory is a synthesis of the physical and the virtual world. This relation is depicted in Figure 2.2 where the virtual factory described in Section 2.3.2 is included as well. The technology found in the digital factory serves to integrate various levels in the organization. As such it facilitates control of production, planning phases, system and process design as well as product development, further supporting collaboration and information management within an organization (Kühn, 2006). It can therefore be interpreted as an overlapping function between the physical system and the virtual system.

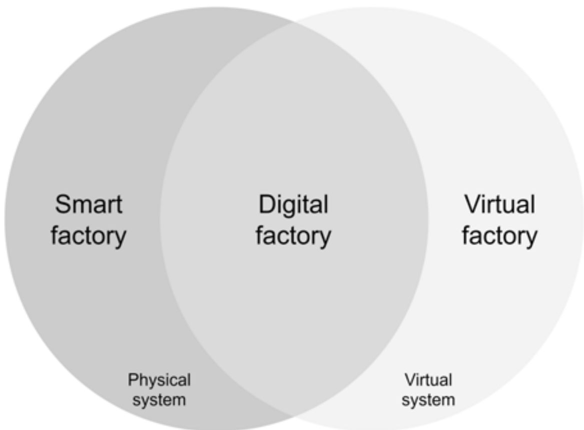

Figure 2.2: The relation between the smart factory, digital factory and virtual factory.

2.3.2 Virtual factory

Deriving from the terminology of the digital factory, the virtual factory is considered as the model environment containing geometrical and mathematical representations of resources (Yang et al., 2015). The virtual factory considers back-end systems which are not directly seen or interacted with by the user. In this thesis, it consists of two or more linked virtual workcells, which in turn consists of one or more virtual machines, finally being built from virtual processes interpreting the products moving through the virtual production system. This hierarchical structure is illustrated in Figure 2.3. Moreover, a distinction between virtual factories and digital twins is made. The digital twin is herein being considered as a virtual factory also relying on real-time production data exhibiting an near identical behavior to the real production unit (Schleich and Wartzack, 2017). The fundamental subsystems of the virtual factory, as defined by this thesis, are described in Section 2.3.2.1 to 2.3.2.4.

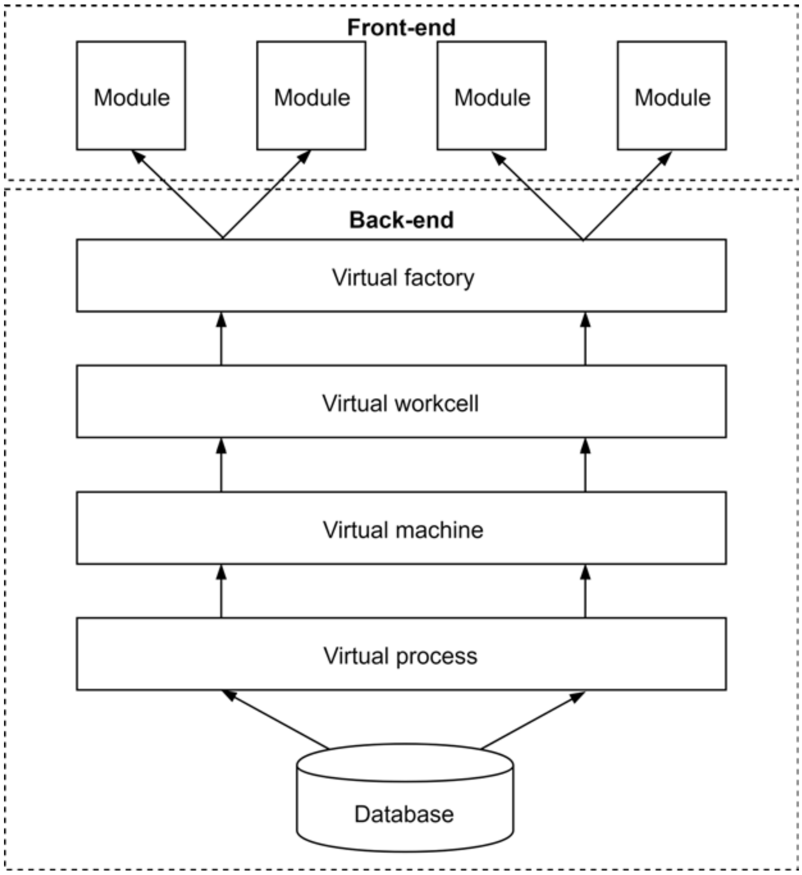

Figure 2.3: The defined structure for the virtual factory and its subsystems.

2.3.2.1 Virtual process

The core of the virtual factory is the virtual process. This concept consists of the logic describing the behavior of a single process. The virtual process is most directly affected by the products moving through the production system enabled by, for instance, calculation of different processing times. It consists of physical-science-based equations describing different properties of certain machine behavior.

2.3.2.2 Virtual machine

Depending on the output data from the virtual process, the virtual machine is comprised of one or more processes describing the range of its operations. As such, a virtual machine can describe a multi- or singlepurpose machine depending on the hardware being simulated. For instance, a machine with both grinding and polishing capabilities is considered as multipurposed. However, the virtual machine does not consider any aspects outside of the machine's functions and operations, such as kitting. The output of the virtual machine can be considered as single-resolution performance data meaning that no interactions are accounted for, comparable to that of the real-life machine.

2.3.2.3 Virtual workcell

The next level is the virtual workcell and is comprised of one or more virtual machines and considers the internal dependencies and interrelations of a certain part of production. It relies on external factors, such as operators, setup times and breakdowns. Its output is seen as sets of multi-resolutional performance data depending on interactions between multiple independent operations and subsystems.

2.3.2.4 Module

Different analyses are enabled through different modules, front-end systems and user experience interfaces (Colledani et al., 2013). These modules interpret the virtual factory through different perspectives depending on the objective of the analysis, providing relevant information for the end user. In this thesis a module is considered as a tool for analyzing the output data where stakeholders are able to experiment with the model.

2.3.2.5 Virtual factory maturity index

As digitalization projects in industry are at different levels of development, so can their respective level of maturity be described (Schuh et al., 2017). Likewise can the maturity of the virtual factory's capabilities be measured. Different levels of functionality is utilized to define six steps of maturity based on the framework proposed by Bjarnehed and Dotevall (2018), similar to the model in Section 2.2.3.1. As depicted in Figure 2.4 the levels consider six consecutively dependent stages and are further described in detail in Table 2.2. In this thesis, not having established a Digital Model, will be referred to as step 0.

The input data used in the simulation model must be correct and of sufficient quality to produce useful results (Bengtsson et al., 2009). The virtual factory will therefore never be more capable than the weakest part of its backbone due to the dependency on the preceding steps as well as the data used to design and run the model.

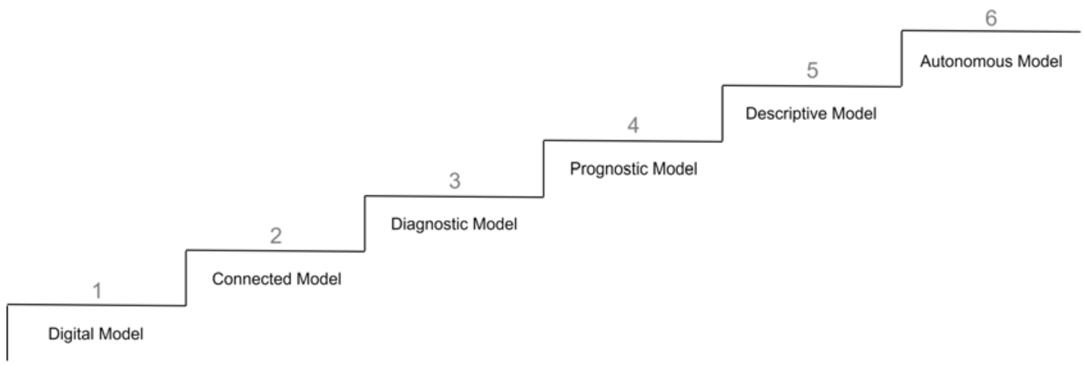

Figure 2.4: The six steps used to describe the maturity of a virtual factory.

Table 2.2: A description of the six steps of maturity for the virtual factory as defined by Bjarnehed and Dotevall (2018).

Maturity stage	**Description**
Digital Model (1)	Considers the establishment of a digital simulation model. The model represents the current state of operations and thus serves as a virtual representation of the physical production unit and does not rely on real-time data.
Connected Model (2)	Considers the digital model supplied with real-time production data. At this step the virtual factory represents the production unit's current state and accurately reflects its inner workings — a digital twin is created.
Diagnostic Model (3)	Considers the ability to diagnose the different operations and processes in the factory; utilizing the collected real-time data to produce up-to-date analyses.
Prognostic Model (4)	Considers the ability to produce information as prognoses, predicting certain events and outcomes, of the production unit it is representing.
Descriptive Model (5)	Considers the ability to continuously learn from experience and suggest actions depending on different current and future states.
Autonomous Model (6)	Considers a self-governing virtual factory. The model now have the ability to make decisions without human interaction, it is able to control production.

2.3.3 Discrete event simulation

Simulation denotes the representation of a system with that of another, the purpose being to study it in a laboratory environment (Ingalls, 2011). There are several different forms of simulation depending on the circumstantial needs of a product or system. In this thesis discrete event simulation (DES) is considered as the established simulation environment to model the real-world production system. DES refers to time-based leaps between different system events, as opposed to being calculated based on fixed time intervals, saving processing power (Ingalls, 2011). Events consider separate actions performed by the system and states, as such being calculated when a new event occurs. DES models are herein considered as dynamic, meaning that variables within the simulation changes without external influence from its users. Consequently the system is affected by the passing of time in the model (Ingalls, 2011). Finally, the simulation that the virtual factory requires often assumes a stochastic approach, meaning that occurrence of different events never become fully certain but rather more or less likely than others (Hartig et al., 2011).

2.4 Data

Data can be defined as: "*quantitative facts about events*" (Skoogh et al., 2012). Information is defined as data that has been further processed for use in simulation models or in other models for visualization. As described in Section 2.3.2.5 the virtual factory is dependent on the data used to design and run the model, and requires that the data meets certain quality requirements for generating any useful results.

2.4.1 Input data management

The simulation model receives information which can be categorized in different ways. Consequently, the data must be accurately acquired and meet certain quality standards to produce useful, i.e. truthful, output. The methodology enabling this is referred to as input data management – a method to identify and collect, as well as to extract process data (Bengtsson et al., 2009). Input data can be collected from several sources such as corporate business systems, e.g. operational data from Enterprise Resource Systems (ERP) and Manufacturing Execution Systems (MES), and project specific data from the project teams (Skoogh et al., 2012). Four different methodologies for gathering input data and feeding it to the simulation model is presented below. The choice between the different methods depends on the virtual factory's maturity, the knowledge of input data management at the company as well as available resources and the company's needs.

Method A
The first methodology for collecting data (A) considers manual data collection and direct input into the simulation model, mainly performed by the team responsible. As such, depending on the systems to be simulated, data is collected in numerous

ways ranging from interviews with domain experts to extraction from established computer systems. Benefits of the methodology considers its simplicity and the data being continuously verified. Disadvantages of the method can be seen in it being time consuming, larger systems being increasingly hard to keep up-to-date as well as having difficulty for finding human errors in the input data. (Skoogh et al., 2012)

Method B
The second methodology (B) is also based on the project team manually collecting data herein updating spreadsheets outside the model environment which then communicates the changes to the simulation model. Benefits includes added flexibility for updating input data and individuals without model building experience being able to update its contents. However, the manual methodology of data collection still being relatively time consuming. (Skoogh et al., 2012)

Method C
The third methodology (C) enables automatic updates. Herein the real system automatically collects input data to a separate database for external data storage which is then later transferred to the simulation model. Benefits can be seen in the added functionality and ease of what-if simulation, increased simplicity of input data management as well as the more frequently updated simulation environment. Disadvantages of the method may consider the inability to confirm data quality and thus the validity of the simulation. (Skoogh et al., 2012)

Method D
The final methodology (D) has the real system directly linked to the simulation model, transferring data without an intermediate database. As such, transfer speeds are increased and data errors are reduced. Due to the many connections required to establish such a system, its complexity as well as time for implementation becomes considerable. The method further elevates the risk for data duplication due to many connections between data sources. (Skoogh et al., 2012)

2.4.2 Data quality

To develop an accurate simulation model the results must be accepted on the grounds of reliability and credibility. One method to achieve acceptability is to perform input data validation in a structured manner (Bokrantz et al., 2017). Table 2.3 presents 11 dimensions of data quality that should be assessed in order to yield high-quality simulation data (Balci et al., 2000).

Table 2.3: The 11 dimensions of data quality according to Balci et al. (2000).

Dimension	**Description**
Accessibility	The degree to which data are available or easily and quickly retrievable.
Accuracy	The degree to which data possess sufficient transformational and representational correctness.
Clarity	The degree to which data are unambiguous and understandable.
Completeness	The degree to which all parts of the data are specified with no missing information.
Consistency	The degree to which data are specified using consistent measurement units, uniform notations and terminology, and any one data value does not conflict with any other.
Currency	The degree to which the age of the data is appropriate for the use of the data in the model.
Precision	The degree to which data possess sufficient number of significant digits in their numerical values.
Relevance	The degree to which data are applicable for use in the model.
Resolution	The degree to which data possess sufficient level of detail.
Reputation	The degree to which data are trusted or highly regarded in terms of their source or origin.
Traceability	The degree to which data are easily attributed to a source.

2.4.3 Verification and validation

Verification is the process of ensuring that the simulation model and its implementation are mathematically correct (Sargent, 2013). Validation is the process of substantiating that the model, within its specified domain of applicability, produces output that satisfies the accuracy of the real-world scenario (Sargent, 2013). As a consequence, a simulation model can be valid in one scenario but invalid in a different one depending on the experimental setup. Moreover, verification is performed before the validation of a simulation model.

2.5 Efficiency

Efficiency relates to the input to a system, i.e. resources, and denotes doing things right. It is not to be confused with effectiveness which means doing the right things and is affecting the output from the system (Bellgran and Säfsten, 2009). One well-known methodology for creating efficiency in production systems is lean production which provides guiding principles to improve not only efficiency but also quality and speed (Liker, 2004).

2.5.1 Lean production

Lean production is a philosophy derived from the Toyota Production System (TPS), focusing on the elimination of waste and improvement of customer value (Gao and Low, 2014). TPS, moreover considers a continuous improvement process rooted in principles of company culture. The continuous improvement, also commonly known as the Japanese term Kaizen, is another characteristic for lean production and enfolds the process of making incremental improvements with the goal to eliminate waste. Kaizen should furthermore be regarded as a philosophy that strives for perfection and sustains the TPS on a daily basis (Liker, 2004). The concept of lean production can be seen to relate to 11 different subjects, presented below (Gao and Low, 2014).

- Reduce the share of non-value-adding activities
- Increase output value through systematic consideration of customer requirements
- Reduce variability
- Reduce cycle time
- Simplify by minimizing the number of steps, parts and linkages
- Increase output flexibility
- Increase process transparency
- Focus control on the complete process
- Building continuous improvement into the process
- Balance flow improvement with conversion improvement
- Benchmark

In general, the principles of lean production are focusing on achieving the right processes for the company's operations, rather than primarily analyzing its business results which creates a long-term thinking and acting (Liker and Hoseus, 2008).

2.5.1.1 Waste

Waste is defined as: "*anything that absorbs resources but creates no value*" (Gao and Low, 2014). The different types of waste to consider in a production environment can be described by eight different dimensions; inventory, movement, overproduction, waiting, transportation, extra processing, defect products and non-utilization of talent, i.e. employee creativity, as seen in Figure 2.5.

Figure 2.5: Eight elements of waste according to lean production.

2.5.2 Lean thinking

Lean thinking consists of a framework, relating to lean production and is based on five principles as described in Table 2.4. Applying lean thinking in an organization implies to focus on quality and value as defined by the customer, thus rationalizing the identification of waste in the organization. By eliminating activities that do not contribute to the creation of a perfect product the purpose of the philosophy is to save cost. (Gao and Low, 2014)

Table 2.4: Five principles constituting the framework for lean thinking.

Principle	**Description**
Value	The end customer value. Said entity can further be regarded as any downstream process depending on different needs.
Value stream	Analyzing the activities of the value stream to determine which can be avoided or improved to create additional value.
Flow	Creating a production system were products move to the customer continuously without experiencing interruption.
Pull	The production system only produces products according to customer orders and demands.
Pursue perfection	Applying continuous improvement to pursue perfection and complete elimination of waste.

2.6 Study

It is necessary to characterize the link between the theory of scientific research methodologies and the conducted research project and there are several issues that must be considered (Bryman and Bell, 2011). The first consideration relates to which theory to use while the second concerns what data is to be collected to test or build theories on. A research project can be interpreted through a set of different characteristics, each relating to different aims (Wallén, 1996), as presented in Table 2.5.

Table 2.5: Four characteristics of a research project.

Type	Description
Explorative	Researches the scope of the subject and context. The aim is to gain fundamental knowledge of the subject and a more general understanding.
Descriptive	Collects and organizes data to determine specific properties of the object central to the study and locating patterns.
Explanatory	Attempts to explain aspects central to the study, for instance why certain patterns evolve.
Normative	Relates the findings to existing frameworks and standards in order to compare different aspects central to the study.

2.6.1 Qualitative study

There are no universal standards considering interview studies, a qualitative study, and they must therefore be adapted to their respective context and desired outcome (Kvale and Brinkmann, 2014). As such, the topic of the study should dictate the chosen methodology. General traits of its methodology can however be described by seven consecutive phases, listed in Table 2.6.

Table 2.6: The seven phases characterizing a qualitative study.

Phase	Description
Thematize	Describe the purpose of the study and its topic of interest. Formulate a research question.
Plan	Consider how and what information is to be gathered from the interviews based on the research question and the context of the research project.
Interview	Carry out interviews.
Document	Document the interviews through transcription or notes.
Analyze	Choose appropriate methods of analysis depending on the scope of the study.
Verify	Challenge the methodology considering validity and reliability.
Report	Present results.

2.6.2 Semi-structured interview

Semi-structured interview methodology implies a format wherein the interviewer has a set of defining topics. During the interview additional topics might be included depending on the answers from the interviewee. The questions asked by the interviewer does furthermore not conform to a specific order, but follows the pace of the session. During the interview all predefined topics are covered, but considers the interviewees previous knowledge and as such partly allows for tangents during each session, striving to capture the varying perspectives of each interviewee (Bryman and Bell, 2011).

2.6.3 Grounded theory

Grounded theory can be defined as: "*theory that was derived from data, systematically gathered and analyzed throughout the research process*" (Bryman and Bell, 2011), although there are some discrepancies regarding its definition. A prominent part of grounded theory is coding of collected data. By breaking down data into components as the data collection is performed, the researchers shape the code as their perspectives on the subject of interest grows throughout the study. Open coding is a methodology referring to the coding practice of the data retrieved through interviews and breaking down, examining, comparing, conceptualizing and categorizing said data in order for it to be contextualized and categorized (Bryman and Bell, 2011). Grounded theory overall constitutes the most widely used methodology for interpreting qualitative data (Bryman and Bell, 2011).

2.6.4 Magnitude coding

Magnitude coding is defined as the practice of grading collected data through scales, interpreting the meaning of, for instance, qualitative data as an index of different weights (Saldaña, 2009). This method is well-suited for evaluating qualitative data such as text gained from interviews (Quinn Patton, 2002).

2.6.5 Benchmarking

Benchmarking is defined as: "*a continuous systematic process of evaluating companies recognized as industry leaders, to determine business and work processes that represent best practices and establish rational performance goals*" (Rolstadås, 1995). Through the process of benchmarking different practices at a company are compared and possible improvements, based on the performance reported by the study, are determined. Benchmarking can generally be considered through either internal or external perspectives, referring to either the internal processes at the company or external environment. Among external benchmarking analysis the technique of best practice benchmarking considers seeking out innovative and value-adding practices, having the aim of altering one's activities to increase the competitiveness of the organization (Rolstadås, 1995).

3

Methodology

This chapter presents the methodology and the work procedure used in this thesis. It follows the sequence of the conducted steps and discusses important aspects of validity and reliability of the methods used.

3.1 Procedure

This study consisted of three data collection phases; a literature study, an interview study and a benchmarking study. The information gathered in these steps was further analyzed in a fourth step where an implementation plan was developed. This sequence is depicted in Figure 3.1. This approach is aligned with the seven stages of an interview study discussed in Section 2.6.1. The first phase, the literature study, corresponds to the first stage according to Kvale and Brinkmann (2014) and is of an explorative nature, which is suitable when searching for relevant variables as well as for establishing the scope of a study (Wallén, 1996). Next, the interview study and benchmarking study, both of a descriptive nature were used to decide the characteristics of the studied objects (Wallén, 1996). Finally, the last phase, labeled as normative, provided guidelines and descriptions of consequences based on the collected data Wallén (1996).

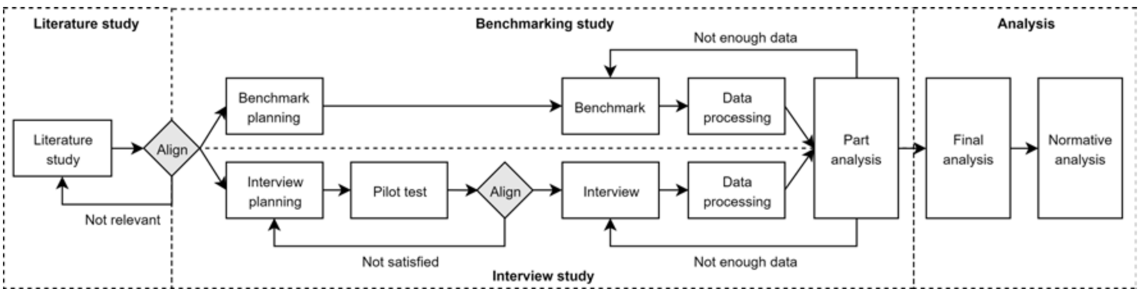

Figure 3.1: The established procedure for gathering data from literature, interviews, and benchmarking for analysis.

Considering the aim of this thesis, an exploratory approach was required due to the unconventional nature of its field of research. As such, a qualitative research methodology and inductive approach was chosen as the basis for the study, facilitating the emergence of information (Bryman and Bell, 2011).

3.2 Literature study

The explorative approach, as described in Table 2.5, allowed the establishment of broad knowledge about the main topic as well as adjacent research. The objective of this literature study was to develop both contextual and technical knowledge in order to establish a mutual understanding between the team, stakeholders and interviewees during the proceeding stages. The main literature in this study was research papers from well-known scientific journals. The key topics included; virtual factories, digital twins, digital tools, simulation, verification and validation of simulation models, input data management and lean production. This provided a rich and company relevant terminology which was necessary in order to develop an adequate interview framework later on.

3.2.1 Alignment

The findings from the literature study was validated through an expert panel with members from both academia and the company. Relevant findings, meaning and significance of terminology, were discussed with the aim to unite the perception of the topic. When all stakeholders agreed on the proposed terminology the alignment was considered successful.

3.3 Interview study

The interviews were realized in a semi-structured manner, see Section 2.6.2. The semi-structured interview was chosen since accounting for the different perspectives of the interviewees were essential to provide a relevant foundation regarding the needs associated with virtual factory technology at the company. The content is presented in five sections relating to planning, pilot interview, interviewing as well as data processing, analysis and alignment.

3.3.1 Interview planning

The interview methodology considered the seven traits of a research interview as described in Section 2.6.1, in order to facilitate the quality of its results. Furthermore, data processing and interview analysis methodology was established in the planning stages of the project as described by Kvale and Brinkmann (2014). The basic framework for the interviews was based on five main sections: introduction, information, readiness, acceptance and summary. These sections are described in detail in Table 3.1. This structure of distinct sections was created in order to facilitate review and analysis of its qualitative content. Lastly, to account for research ethics the interview was formed to not relay on the interviewee's name or work title, giving the interviewee an option to choose anonymity without feeling compromised. Also, a well-informed consent for recording the interview was established through an oral agreement. These two aspects combined can be seen to align with current guidelines for research ethics (Bryman and Bell, 2011).

Table 3.1: A description of the sections the interview was divided into.

Section	Description
General introduction & introduction	Served to introduce the project to the interviewee as well as to inform about how the gathered material would be used and how the interviewee could access it at the project's completion. The purpose of this step was to orientate participants regarding the scope of the study and generate a more holistic understanding of their role in the project.
Technical readiness	Considered aspects regarding knowledge of the interviewee and to assess how technologically prepared the organization was considering the implementation of virtual factory technology.
Acceptance	Strived to assess the interviewees acceptance of the virtual factory technology and how it should be customized in order for the interviewee to be able and willing to use it on a daily basis.
Needs	Strived to map the requirements of virtual factories considering different perspectives of interviewees. This step served to map fields of application relevant for the company.
Summary	The final section was a feedback session, serving to review and confirm important aspects, such as interviewee anonymity.

3.3.2 Pilot test

To validate the interview methodology and minimize prominent errors in the collection of qualitative data throughout the interviewing a feedback session and a pilot interview was performed with experts within the field of production engineering, having extensive knowledge and experience of interviewing, as proposed by Bryman and Bell (2011). Through feedback sessions, the contents were reviewed and altered to create a framework less receptive to misunderstandings and thereby improving its quality. The final interview template can be found in Appendix A.

3.3.3 Interviews

Interview sessions were carried out in accordance to the proposed framework considering in-depth interviews as discussed by Kvale and Brinkmann (2014), to maximize the accuracy and amount of available data for processing. As such, interviews were carried out in a semi-structured manner, supported by both audio recordings and notes. The behavior of the interviewer was furthermore aligned with the principles as defined by Guion et al. (2011).

The interviews were carried out during eight weeks, each conducted individually and with a maximum duration of 45 minutes. In total were 25 employees interviewed, mainly from the department of process development since it constituted the primary scope for the study as well as the primary users of the virtual factory. Additionally, interviews were conducted with employees from the departments of production technology, manufacturing development, product engineering and factory management. This distribution of interviewees is reviewed in Table 3.2. The inclusion of the adjacent departments was made to define requirements of usability and organizational collaboration.

Table 3.2: The distribution of interviewees from each department at the company.

Department	**No. of interviewees**
Process development	17
Factory management	3
Product engineering	2
Production technology	2
Manufacturing development	1

3.3.4 Data processing

Additional processing was required to generate information from the qualitative data gained from interviews. The data processing was performed through open coding and grounded theory, as presented in Section 2.6.3, as well as additional processing through magnitude coding, per Section 2.6.4, preparing the foundation for analysis. The open coding consisted of organizing the gathered data from the interviews according to expressed needs and considerations for implementation. It primarily built the foundation for the needs of the virtual factory and its modules.

Magnitude coding was utilized to construct scales of technical readiness, knowledge about the subject, and acceptance within the organization. Technical readiness constituted of three subcategories; digitalization, simulation and virtual factory. Each subcategory designed to provide insight into the topics adjacent to the concept of the virtual factory. The range for the magnitude coding was determined to three discrete levels (-1, 0, 1), described in Table 3.3, for both categories and its subcategories. The subcategories for technical readiness was merged through a weighted average. The weights were distributed to reflect the adjacency to the main topic and were chosen to 0.25 for digitalization and simulation, and 0.50 for virtual factory. Since the scale only constituted of discrete levels a floor function was used to round down to the weighted average to an integer, this to remain conservative. The complete framework for the interview coding can be found in Appendix B.

Due to virtual factories and digitalization efforts overall consisting of a considerably large range of definitions and interpretations, further addition of levels was not deemed to reliably be able to improve the accuracy of the outcomes. The approach of magnitude coding was well fitted as to interpret the qualitative data (Quinn Patton, 2002). The coding was carried out as soon as possible during sprints every three interviews as proven beneficial (Bryman and Bell, 2011).

Table 3.3: A description of the coding scheme used for interpreting the interview data.

Level	Technical Readiness	Acceptance
-1	No knowledge	No acceptance
0	Some knowledge	Neutral acceptance
1	Full knowledge	Full acceptance

3.3.5 Interview analysis

Analysis iterations were conducted every three interviews. This methodology was chosen as it enabled the project to develop its knowledge over the course of data collection, thus developing its accuracy along the way (Kvale and Brinkmann, 2014). The agile analysis was central to the methodology of grounded theory since it reflects on the recursive nature between data gathering and analysis (Bryman and Bell, 2011).

3.4 Benchmarking study

To understand which strategies and tools that are available and used in practice by other companies, a benchmarking study was performed. A benchmarking study can be performed with a vast range of objectives, in this thesis the main objectives are (1) to find the current state of the virtual factory and (2) to find the future state of the virtual factory. From these objectives facts about the motivation for developing and using a virtual factory, how data is collected and organized, which tools are used for analyzing the output of the virtual factory, and the implementation strategy could be collected. In Section 3.4.1 to 3.4.3 the planning, conduction and analysis will be presented in detail.

3.4.1 Benchmarking planning

Per the qualitative research methodology described by Kvale and Brinkmann (2014) benchmarking was initiated by a planning phase, which considered conduction and analysis of benchmarking. The sessions were independently planned to increase their relevancy to their respective benchmarking company. The established template can be seen in Appendix C. This planning phase facilitated the quality of the gathered data and ensured its validity and scope for analysis.

3.4.2 Benchmarking

Benchmarking was performed with companies that were considered industry leaders and characterized as large scale manufacturers of high quality products or services with well established organizations located in Sweden. The benchmarking companies were chosen based on recommendations from academia and the company. A benchmarking session constituted of a study visit where a meeting with a subject matter expert took place. The primary deliverable from a benchmarking session was a semi-structured interview with the subject matter expert to gain knowledge about their virtual factory and its implementation. This, combined with a preview of the facilities, generated a holistic foundation which enabled comparison to the company's needs.

3.4.3 Benchmarking analysis

The benchmarking analysis served to assess the current maturity of the virtual factory at the benchmarking company, how the current state was reached as well as what was considered for future development. As such, the current maturity of the virtual factory solution was assessed through the content presented in Section 2.3.2.5. The contribution to this thesis being to provide technical and organizational insights and foundation for the establishment of an implementation plan.

3.5 Analysis

The framework for creating the implementation plan can be seen in Figure 3.2. Its structure assesses all of the gathered information throughout the project and ensures the validity of the provided solution. The strategy was founded on two perspectives; the needs expressed by stakeholders of the virtual factory at the company and the available technology found at industry leaders and through examination of current research. Furthermore, to ensure the ability to combine these perspectives, prerequisites of technical readiness and acceptance was considered to facilitate a user-driven and continuous development. These prerequisites and further the enabling technologies funneled the information into a feasible solution, the implementation plan. Local organizational requirements were explored as well and the findings were further consolidated to empower the implementation plan. This strategy for implementation was structured in accordance with the model of virtual factory maturity, as depicted in Figure 2.4, creating a step-by-step solution.

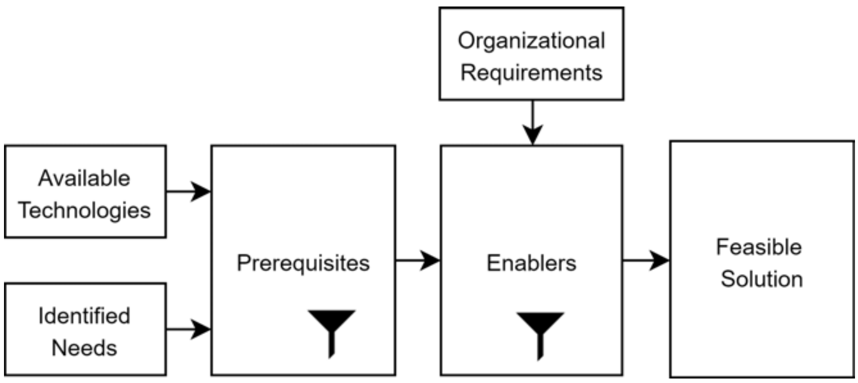

Figure 3.2: The structure for analysis where the output is an implementation plan for the virtual factory.

3.6 Validity and reliability

By gathering data in accordance to empirically tested methods the validity of the used method was ensured. Reliability was further facilitated through data collection close to its source of creation; designated user groups at the company and field experts at industry leaders. To further prevent loss of data during coding, each session began close to the instance of the interview, the contextual aspects of said interaction being considered, improving the reliability.

4

Identified needs and prerequisites

This chapter presents the identified needs at the company which have been divided into two categories; technical and organizational needs. Additionally organizational prerequisites, technical readiness and acceptance will be presented.

4.1 Technical needs

Technical needs concerns the functionality of the virtual factory, and should be interpreted as a desired toolbox. In Table 4.1 all identified technical needs are presented in descending order of the frequency they occurred during interviews. Altogether 29 unique needs were distinguished among stakeholders of the virtual factory. Even though some needs were expressed more frequently than others it does not necessarily imply that they are more important. Furthermore, each identified technical need has been labeled with a capital letter which will be used later in Section 6.2.

Table 4.1: The identified technical needs at the case company and their respective frequency.

Label	Expressed need	Freq.
A	Simulation of production flows	16
B	Visualization for educational purposes	10
C	Make what-if analysis	10
D	Common information platform	8
E	Factory layout support	8
F	Economical investment decision aid	8
G	Allocation and/or optimization of resources	7
H	Evaluation of available capacity	7
I	Representation of factory layout	7
J	Cost calculations for products	7
K	Simulation of process parameters	6
L	Test product-production feasibility	4
M	Planning of production logistics	4
N	Planning of maintenance	3
O	Commissioning for machine installation	3
P	Reuseability of base model	3
Q	Path planning and collision tests	3
R	Online based model	3
S	Traceability of sources of errors	3
T	Simulation of staffing in production	3
U	Simulation of work environment and ergonomics	2
V	Integration of CAD-models	1
W	Evaluation of product quality	1
X	Make accurate virtual measurements	1
Y	Perform virtual first and second acceptance test	1
Z	Traceability of machine changes	1
AA	Simulation of assembly of products	1
AB	Optimization of operator movements	1
AC	NC-programming support	1

4.2 Implementation needs

In Table 4.2 the expressed needs for implementation are presented. These needs account for the experience and expectations at the company considering the plan for implementation. The needs were categorized into four different blocks; organizational change, work methods, education and system requirements. Expressed needs regarding organizational change considered the development of pilot projects with key individuals supported by active leadership. Moreover, ensuring a wide range of users as well as preventing single key users was deemed important. Also, developing a stepwise implementation plan of modules and functionality was expressed important for enabling value-adding activities throughout the implementation.

The second block, work methods, expressed needs regarding prioritizing simplicity through standardized work procedures and striving for minimizing the amount of imposed administration to enable a successful implementation and widespread use. In this regard local full-time personnel responsible for the virtual environment were deemed required to ease simulation and development efforts. Relating to the ease of development educational aspects considers practical training and relevant competences for personnel as well as the need for accessible local, in-house competences.

The final block considers the specific needs of the system architecture and its functionality. Regarding the software infrastructure, needs to enable communication between different software, sharing information between personnel and throughout various departments were expressed. In this regard, modularization of the simulation environment (Johansson, 2006) was also deemed important, creating different sets of tools for different users. Moreover, an online-based environment, creating ease of access and the possibility to view production environments from different locations was also desired. Lastly, the need for proper routines to assess aspects of input data management and data quality were expressed, as well as the need for general maintainability of the system. The collected production data further requires sufficient level of detail to represent the real production environment.

Table 4.2: The identified implementation needs divided into four blocks at the company and their respective frequency.

Organizational change	**Freq.**
Active leadership	2
Pilot projects	2
Driven key individuals	1
Prevent single key user	1
Stepwise implementation	1
Consider integrity of operator movements	1
Work Methods	**Freq.**
Allocate full time personnel for simulation/model development	7
Support standardized way of working	6
Minimize the amount of administration	1
Local personnel responsible for virtual factory infrastructure	1
Education	**Freq.**
Practical training	8
Education of relevant competencies	6
In-house competences	2
System requirements	**Freq.**
Input data management and data quality	8
Focus on usability	8
Level of detail sufficient to represent real factory	5
Maintainability	4
Visually striking for sales purposes	4
Shared infrastructure between plants	3
Match tool functionality to employee's needs	3
Ability to handle different file formats	2
Compatibility of software and available technology	2
Modularization of the system	2
Easy access to the platform	2
Interface for key parameters	1
Standardized simulation functionality	1

4.3 Organizational prerequisites

The distribution of interviewees' acceptance and technical readiness is depicted in Figure 4.1 where the bubbles' area corresponds to the number of interviewees. The acceptance is very high at the company, with the exception of one interviewee who was neutral. The technical readiness shows a wider spread among interviewees, ranging from no knowledge to full knowledge about the topic. To conclude, acceptance for implementing and using a virtual factory is close to full and the technical readiness upholds a wide spread. Due to this, the plan for implementation will focus on decreasing the spread while increasing the average technical readiness.

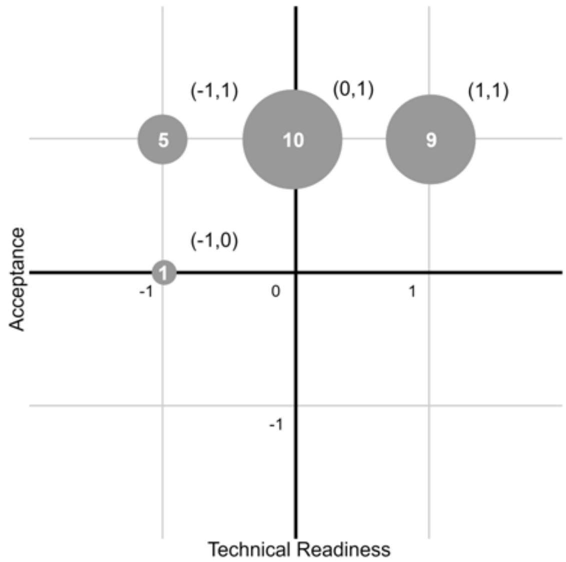

Figure 4.1: The distribution of acceptance and technical readiness among the interviewees.

5
Available technologies

This chapter describes the different technologies found at the benchmarking companies, starting with mapping their respective virtual factory maturity. Also, benchmarked ways of working with the virtual factory are presented.

5.1 Industry leaders' maturity

The three Swedish companies identified as national industry leaders and chosen as benchmarks are herein called; α, β and γ. α and β are automotive manufacturers and γ considers a digitalization project in the energy sector co-developed with a Swedish engineering consulting firm.

In Figure 5.1 the benchmarking companies' current virtual factory maturity is mapped. Company α exhibited no digital simulation model of any factory, placing α at step 0 in the maturity model. Company β exhibited a Digital Model of the factory, placing β at step 1 in the maturity model. Company γ has developed, in collaboration with the engineering consulting firm, a Prognostic Model placing them at step 4 in the maturity model.

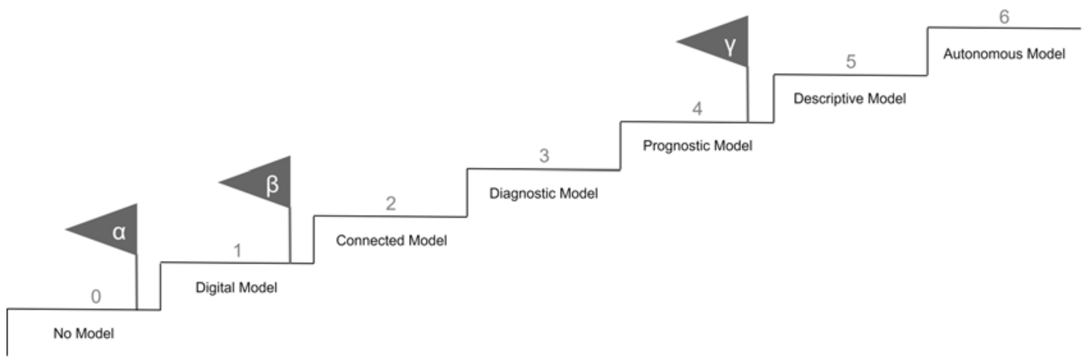

Figure 5.1: The benchmarking companies' current virtual factory maturity.

5.2 Company α

Technologies

Company α showed a well-established digital toolbox for product development, assembly work, workcell design and similar. Some simulation of processes and flows existed but was not connected to real-time data. In addition, the majority of factories owned by α had been 3D laser scanned, a technique used for rapid and accurate digitalization of spatial properties of objects or surroundings (Lindskog et al., 2012). An example of a 3D laser scanned environment is given in Figure 5.2. α currently focuses on developing a common platform where the existing digital tools will be merged, efficiently communicating with each other, building the foundation for the virtual factory and reaching step 1. Furthermore, company α aims at developing a Prognostic Model (step 4).

Figure 5.2: An example of a 3D laser scanned production environment from Chalmers Production System Laboratory.

Organization

One main driver for developing a virtual factory is the opportunity to plan and realize projects at an earlier stage than today, according to α. This is enabled by the common platform for sharing information that the virtual factory invokes which can serve to reduce misinterpretations and include different stakeholders early in the development process. Furthermore could the amount of rework in production development projects be limited due to the use of up-to-date and representative data which more accurately depicts the effects of changes. To realize these advantages α argues that an understanding for the responsibilities for the virtual factory and its interfaces must be established alongside with the allocation of resources for maintenance of the model. This, according to α, implies a new organizational structure to be able to develop, use and maintain a virtual factory.

Company α argues that the organization must view the virtual factory to be the primary representation of the production unit, being the superior to the physical production unit. Therefore should all changes to the physical environment be evaluated in the virtual model first which not only contributes to visualizing the effects but also serves as a vehicle for a more holistic perspective.

Success stories
Company α are using 3D laser scanning and the success story related to this effort was identified to rely on standardized and integrated work methods. In the scanned factories physical datum points are marked out to ensure accurate merging of 3D point clouds when re-scanning. Re-scans are mandatory for all changes made to the production environment, for suppliers as well. By continuously and frequently scanning the environment the virtual model is ensured to be up-to-date, creating an accurate representation of the real production system. The scanned models, later combined with CAD-models, have provided a way for α to easily visualize factory layouts and support installation of e.g. new machines due to the ability of making accurate measurements in the virtual environment.

5.3 Company β

Technologies
The current model at β was not connected and primarily used for what-if simulation in production development at process, line, factory and supply chain level. Company β utilized two different simulation software, one commercially available and the other in-house developed in collaboration with academia. The latter provides Artificial Intelligence (AI) and Machine Learning (ML) algorithms for multi-objective optimization. The two software are used simultaneously, enabled by a connector, and is stored online making it accessible to a certain group of engineers. Furthermore, β utilizes simulated value stream mapping, a method for mapping all actions currently required to bring a certain product through the main flow, to visualize certain simulation data in a recognizable manner. In the future model development is connectivity the focus, as well as further developing AI, which would place β on step 2. Furthermore, an online based platform is to be established to facilitate the ease of access to the virtual factory.

Organization
To facilitate the simulation model's development a team of four full time simulation engineers has been established, motivated by an increasing need to analyze the complex production environment and support decision making. Currently this team support plants both in Asia and in Europe but intentions of establishing local on-site competencies to retain knowledge within the organization are expressed. Further development also considers expanding the user group to include different departments, making maximum use of the simulation model. Economical potential is further seen in collaboration with business development and to evaluate lean strategies. The present model is however mostly used by the simulation team for

buffer and flow optimization, routing and continuous improvement of machine data input parameters.

Currently, β has established standardized work methods for continuous development of the model. As such, simulation projects are considered as a mandatory part of development projects in production, improving their quality and outcome. The increased influence from simulation is further expressed as a vision of virtual confidence by the year 2020. By herein interpreting the virtual factory as the original development environment and the real production unit as a copy, increased activity in early planning stages are to be facilitated, much akin to the concepts presented by α. Standardized work methods within the simulation group itself is also considered and presented through a 13 step simulation methodology, as seen below. Moreover, the simulation coding is to be partly standardized through the establishment of standardized function blocks to reduce the knowledge and overall resources required for development of the simulation model.

1. Problem formulation
2. Evaluation of simulation needs
3. Evaluation of software requirements
4. Evaluation of required resources
5. Adding job to cloud service
6. Model conceptualization
7. Gathering of data
8. Model translation
9. Planning of experiment
10. Conductance of experiments and analysis
11. Compare results to problem formulation
12. Documentation
13. Final approval of results

Models are furthermore established in both 3D and 2D depending on the events to be evaluated and the experience of the team members. 2D models are used when team members are more familiar with the physical production unit that are to be model, otherwise 3D models are used to increase understanding. These 3D models are to some extent based on 3D laser scanned environments complemented with developed 3D models presenting the inner workings of the production system.

Practices regarding input data management at the company considers manual collection methods utilized to keep aggregated data bases fairly up-to-date representing a snapshot of the production unit, the data therefore suffers from a general lack of continuity. The validation process of said data utilizing technical experts in production to interpret the model output, comparing it to the behavior of the real production unit. In the future, β intends to automate and standardize aggregation of said input data to improve the quality of simulation results.

Success stories

By establishing 3D simulation models of its production unit and work methods, production lines have successfully been replicated over national boarders at different production plants, generating greater returns from development projects.

5.4 Company γ

Technologies

Company γ displayed the highest maturity, its model being a fully connected 2D representation of a production unit within the company and is stored on local servers. Having greatly automated input data management γ enabled a continuous communication between the real and the virtual factory creating a digital twin. The data is transferred via wired internet due to cyber security requirements. The digital twin depicts the theoretical output, the ideal state, of a turbine plant. The virtual model also predicts maintenance actions, enabled by advanced analytics, which helps optimizing the performance of the plant. Noteworthy in this case is the relatively small amount of data that is being collected, only a few key parameters are measured and included in the model. Additionally, the turbine plants inner workings are well-known and can with well-established mathematical relations be calculated. Company γ is currently focusing on replicating the model to other units in the company, and not directly developing the model's functionality.

Organization

Company γ decided to connect the virtual factory to real-time data to support employees in monitoring operations and decision-making in a high risk environment. The interface is designed for the end users, operators in the control room, and in addition to the 2D model provides easily interpretable graphs. An important perspective is to see the virtual factory as a supporting system not only as an isolated tool for monitoring processes or development projects.

Success stories

By using the virtual factory can maintenance actions be accurately planned and performed. The developed algorithm for the particular maintenance action at γ has optimized the performance and at least 3 000 MWh per year have been saved (Nohrstedt, 2018).

6
Implementation

This chapter presents the efficiency improvements that the virtual factory can generate and proposes a stepwise implementation plan, tailored to match the needs at the company.

6.1 Improving efficiency

As seen at industry leaders the current development within manufacturing industry strives to increase efficiency, reduce lead times and improve routing and process parameters, per se reducing the overall manufacturing cost. By utilizing simulation models of a production unit such results have been proven attainable (Freiberg and Scholz, 2015). An increased product quality, reduced resource consumption and increased productivity are herein shown to generate significant cost savings in manufacturing. The organizational change simulation entails further improves the problem solving capabilities in the organization, proving especially beneficial for companies where innovative design is considered a strategic priority (Becker et al., 2005). To successfully attain these associated benefits and organizational change a user-driven development is required to prevent the so called productivity paradox, not gaining any economical advantages even tough the IT technology implies great benefits (Leclercq-Vandelannoitte, 2015). Thereby, founded on the needs of the company, prerequisites and organizational support as well as benchmarks performed at industry leaders, an implementation plan has been established accordingly.

6.2 Implementation plan

The remainder of this chapter present a plan for implementation of the virtual factory considering its different levels of maturity. In Figure 6.1 the identified needs, as listed in Table 4.1, are presented in accordance to their corresponding level of required maturity. Since no present needs require the technology associated with a maturity higher than step 4, this study concludes its plan for implementation at said step to preserve user-driven development. However, important considerations for preparing the development of the remaining steps will be described. To create a competitive strategy, the long-term vision for the virtual factory should be to reach step 6 in the maturity model. Nevertheless, an important objective in the proposed implementation plan was to create milestones, short-term value-adding functionality, along the journey to reach the final step.

The implementation plan is presented in a step-by-step manner, following the same structure for step 1 to 4. Each step prescribes a set of enabling technologies which fulfills the needs at the particular step. Further requirements have been added, not covered by the identified needs. These are necessary to consider in order to be able to move to the succeeding maturity steps as found at industry leaders and in current research. These extra requirements will be labeled as mandatory in the summarizing tables.

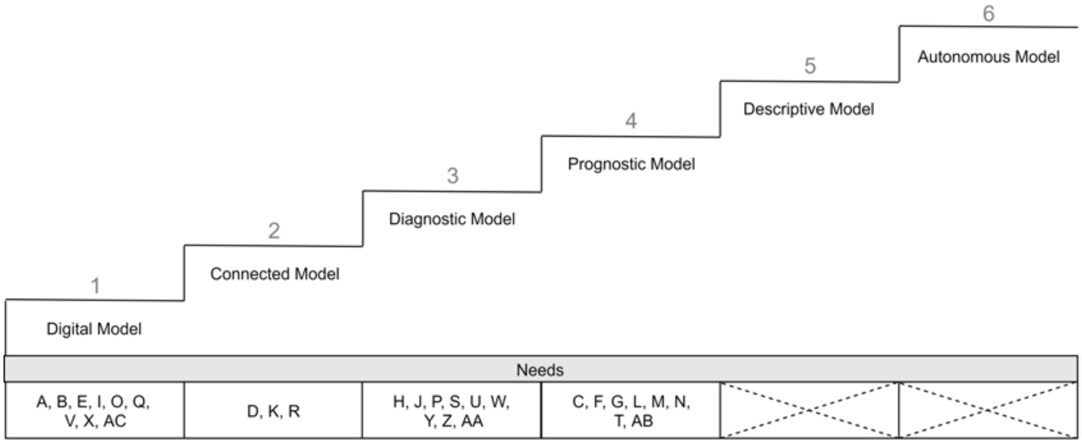

Figure 6.1: The identified needs mapped onto the six maturity steps of the virtual factory.

6.2.1 Reaching step 1

Technology

The first step serves to create a Digital Model, a fully functional simulation model representing the production unit. The model is fed with data from historical records which can for instance be a statistical distribution for downtime or processing times for different resources. Consequently, the needs associated with the first step considers utilization of the virtual factory offline. At this point the virtual factory constitutes of a DES model and thus enables fulfillment of analysis of parameters not related to real time production data. At this step the virtual processes, virtual machines, virtual work-cells are defined which creates the foundation for the virtual factory. Beyond satisfying the identified needs, it is necessary to facilitate collection of production and product related data in order to describe the behavior and constraints of the production unit. Also, depending on the desired level of detail and visualization requirements, accurate measurements of the production facility are needed. Finally, the correspondence between the virtual model and the real-world production facility it represents needs to be confirmed.

The enabling technologies identified in order to satisfy transition to the first maturity step is summarized in Table 6.1. With the main technology, DES software, a model of the production flows can be realized. Also implementing software for layout design and creating designated APIs to enable transfer of data between the different software and databases are crucial to enable an efficient solution. Moreover, 3D laser scanning equipment to quickly and accurately model the production environment in 3D should be acquired. To model the inner workings of the system process, product, and machine parameters also needs to be acquired and a verification and validation study needs to be performed to ensure accurate behavior of the Digital Model. Additionally must the model be equipped with the ability to manage versions of the model in order to run and save different scenarios issued by different users. These technologies are summarized in Table 6.1.

Table 6.1: The proposed enabling technologies and the needs they fulfill for reaching step 1.

Enabling technology	**Needs fulfilled**
DES software	A, B
Layout software	E
Designated APIs	Q, V, AC
3D laser scanning	O, I, X
Process, product and machine data	Mandatory
Verification and validation study	Mandatory
Model version management	Mandatory

Organization

To build the simulation model special competence and skills are required, for instance the skill set that a simulation engineer posses. In accordance with β dedicated full-time personnel should be assigned for the development of the model and act as a local competence cluster with the aim to evolve into a global support. This group is responsible for the establishment and the development of the DES model and its functionality. To simplify the building of the simulation model the creation of a library of standardized function blocks should be an objective, as demonstrated by β. Alongside the development of the model a comprehensive work method should furthermore be established together with the end users. This work method could preferably resemble the one found at β but must be aligned with the company's current project management office guidelines.

Concerning the 3D laser scanning of the production environment, besides relevant competencies, standardized routines should be established. Preferably in a similar manner to what company α demonstrated to ensure that the virtual model is up-to-date when changes are made to the physical system. It is important to share this way of working to suppliers and contractors in order to create an accurate virtual model.

In order to create a long-term solution for the Digital Model the technical readiness at the company needs to be increased. Training packages should be launched together with the launch of the Digital Model at an early stage to create understanding. The training should not only focus on theory about the Digital Model's inner workings but should also include practical training i.e. using the model, as described in Section 4.2. Furthermore the technical readiness could be augmented by initiating pilot studies where different user groups are included in the development to raise awareness and simultaneously create opportunities for user-centered design. Pilot studies could be a good method to build in domain knowledge in the system, making it more adapted to the end users.

6.2.2 Reaching step 2

Technology
The second step, a Connected Model, focuses on connecting the previous developed Digital Model to real-time data from the production unit. The needs met at this step relates to sharing of information, utilizing the connected platform and the ability to collect data in real time from production processes. Further requirements includes collection, cleaning and mining of data, connectivity, online accessible storage, as well as automatic and continuous updates of the simulation model. An important consideration for data cleaning and mining encompass storing raw data, not cleaned nor mined, or storing solely manipulated useful data.

Enabling the prescribed needs and requirements, production resources need to be equipped with sensors to transfer their behavior into a computer readable format. Additionally, 5G networks or equivalent connectivity technology is required to communicate the data to online storage, for either raw data or manipulated data. The virtual factory is now converted into a Connected Model, a digital twin is created, and should be uploaded to a server to enable organization-wide accessibility. The stored data, serving as input to the Connected Model, must be sorted, labeled and copied to the virtual factory by an API per its request. The prescribed technologies are summarized in Table 6.2.

Table 6.2: The proposed enabling technologies and the needs they fulfill for reaching step 2.

Enabling technology	**Needs fulfilled**
Sensor equipped production resources	D, K
5G or similar	D
Online data storage	D
Server storage for the model	D, R
Designated APIs	Mandatory

Organization
The competences required to enable a Connected Model stems from management of data, both considering hardware and software infrastructure. As demonstrated by γ consultant companies can herein be utilized to fill gaps in current company knowledge and facilitate the establishment of a Connected Model.

This connected infrastructure of the virtual factory further requires establishment of input data management routines. As such, different sets of work methods depending on the type of data need to be established, see Section 2.4.1. Due to the varying levels of automation in production at the company can methodologies ranging from automated collection of sensor data to manual collection be used, as seen applied by β. Furthermore, routines considering evaluation of data quality to ensure the validity of the virtual factory simulation results need to be established in accordance to the 11 steps of data quality, described in Section 2.4.2.

As input data management routines are essential to the value-adding capabilities of the virtual factory, educational packages regarding the online model and the importance of proper data management needs be performed. Such education should include a theoretical background as well as practical training in data collection to support and create understanding among domain experts of the different methodologies.

6.2.3 Reaching step 3

Technology

When the virtual factory reaches step 3, a Diagnostic Model, the main functionality constitutes of a current state analysis. Thus all identified needs which require the ability to evaluate the present operations could be mapped onto this step. Provided that the Connected Model is accurate and mirrors the real production unit no further requirements beyond the expressed needs are found. The Diagnostic Model could be viewed as to provide different modules where data is presented as relevant information about operations and events for the user, and it is therefore only the user needs that should dictate the introduced modules. This is summarized in Table 6.3.

The identified needs at this step could be fulfilled by firstly developing the ability to copy the base model which enables several users using different modules, diagnosing different aspects, at the same instant of time. Furthermore the following simulation or mathematical models should be developed and added onto the base model; a product cost model, a product quality model, an ergonomic simulation of operators at work stations, and a simulation of assembly of products. These models and simulations should represent different interfaces of the virtual factory and data is further visualized to fit the needs of a specific task. This puts further requirements on proper communication between different software, designated APIs, and data storage for results from diagnoses. Lastly, from the diagnoses provided by the virtual factory could changes to the physical system be proposed and thereby must changes to the virtual system, the base model, be made. This calls not only for an adaptable base model, accessible for a constrained group of users, but also for a change log functionality where changes made to machines and other resources can be tracked when unexpected events occur.

Table 6.3: The proposed enabling technologies and the needs they fulfill for reaching step 3.

Enabling technology	Needs fulfilled
Copy base model	H, P, Y
Product cost model	J
Product quality model	W
Ergonomic simulation software	U
Product assembly simulation software	AA
Automated change log	Z, S
Extended data storage	Mandatory

Organization
Introducing the diagnostic tools in the virtual factory enables analysis of the production unit which requires conscious selection and evaluation. When implementing new modules, the needs of different user groups, resource requirements and estimated effects from use should be considered. To ensure its continued use project management as seen at β can be utilized, requiring use of the modules to approve different kinds of investments and changes in the production unit. Practical training, continuous follow-up and feedback sessions are essential to ensure the module is used correctly by the users, its full potential being realized. Furthermore, as the inner workings of modules are defined so need the general methodologies of simulation projects be established. Structured work methods as seen at β, explained in Section 5.3, could prevent the loss of information, facilitating proper documentation and fact based analysis of the production unit.

6.2.4 Reaching step 4

Technology
If the prior step depicted the current state of operations the fourth step depicts the future state of operations, being a Prognostic Model. The main functionality at this step is based on the virtual factory's ability to forecast and calculate when different properties change, hence supporting an optimal use of resources. The identified needs which require the ability to run what-if simulations, testing different scenarios, was therefore assigned to this step. Further requirements are issued together with the ability to perform a vast number of different scenarios and discard them if necessary. These technologies are summarized in Table 6.4.

The ability to forecast relies on proper examination of data and the enabling technology are therefore advanced analytics. This is a collection of different techniques for generating descriptive and predictive analyses through autonomous or semi-autonomous examination of data and content (Gartner, 2018a). Examples of advanced analytics techniques include pattern matching, semantic analysis, multivariate statistics, machine learning and neural networks. New modules, for visualizing the predictions, should be developed and includes an investment calculation model, production logistics simulation, a maintenance model, advanced scheduling algorithms for allocation and optimization, as well as support for operator movement tracking. Also, the modules in the previous step should be equipped with advanced analytics to extend their functionality.

Table 6.4: The proposed enabling technologies and the needs they fulfill for reaching step 4.

Enabling technology	**Needs fulfilled**
Advanced analytics	C, F, G, L, M, N, T, AB
Investment calculation model	F
Production logistics simulation	M
Maintenance model	N
Advanced scheduling algortihms	G, T
Operator movement tracking	AB

Organization
Using advanced analytics requires that the organization acquires new skills in data analysis techniques and uses domain experts to develop accurate models as well as to validate them. This competence could either be developed in-house or acquired, however the inclusion of domain experts will be crucial. Furthermore the previously established work methodology should be re-evaluated to fit the requirements of making predictions and basing decisions on the generated data. It is important to establish routines for what data and model constrains to save, as well as how to save and when to save in order to support traceability.

Crucial to this methodology is the perspective on the virtual factory being the superior, identified as important at α. Changes to the virtual factory should therefore be issued when an investment decision is concluded by the department of process development. This means that the group responsible for the development of the virtual factory makes changes to the virtual environment before the physical environment is changed. This puts further requirements on properly developed and established work methods and conscious use throughout the organization.

6.2.5 Preparing step 5 and 6

As can be seen in Figure 6.1 no identified needs could be mapped onto step 5 or 6. Therefore no implementation plan will be prescribed for these steps since this thesis strives for developing a user-driven process for realizing the virtual factory at the company. Nevertheless, if realizing step 5 and 6 the virtual factory will gain significant intelligence by including more advanced ML algorithms as well as powerful AI.

7
Discussion

This chapter presents a discussion on the value that the virtual factory can provide, important technical aspects and how a new mindset must be developed. Lastly is the replicability of the used methodology discussed.

Value beyond cost
The large costs associated with the development and maintenance of a virtual factory requires the capabilities of the technology to be thoroughly investigated to motivate its investment. Company α utilizes the broad perspectives and planning features of the model environment to facilitate faster product realization. This, furthermore, creates less rework as a result of individuals having an increased holistic understanding of adjacent activities in the organization. At β the virtual factor is mostly used to enhance the proficiency of flow analysis and resource optimization. Finally γ then utilizes the simulated representation of the real world production unit for predictive maintenance, increasing safety and stability of the system while achieving significant cost savings.

The common denominator among industry leaders can be seen in the efforts for reducing waste through the use of the virtual factory. Reducing waste is herein achieved through the additional means for analysis that the technology implies, more easily being able to locate and visualize it in the current production unit. As such, the virtual factory can be seen to align with the principles of lean production. For instance, through its ability to augment process transparency, provide holistic perspectives and increase complete system control can the overall efficiency of the production unit be improved. Concurrently, the principles of lean thinking is supported since the increased transparency allows for an interlinked understanding of the end customer value. Through these means it becomes easier to choose the most effective development projects from start. By further facilitating waste not being built into the system through future and ongoing implementation projects, waste can significantly be reduced in production over the continued long-term use of the virtual factory.

The value-adding capabilities of the virtual factory is as such seen through the cost savings directly associated with the production unit and resource utilization, but also further through the effects gained from the organizational change it requires. By further increasing the amount of information available for decision making the ability within the organization to implement changes without requiring various levels of rework is facilitated. This generates the prerequisites for the department of process development to practice a more agile and faster production development.

Supporting sustainability

The implementation plan for the virtual factory has been aligned with the aspects of sustainability, both societal, economic and environmental. This was deemed important since many organizations, the company in particular, considers this to be a crucial part new investments. The societal dimension is expected to be increased due to the enlarged possibilities to share information, creating a shared belief among employees. This strives to reduce rework, the efforts required for finding the right information and consequently create a more agile work environment where the employee can devote more time to creative work. The economical benefits are most prevalent since the virtual factory can serve to reduce the waste as well as speed up development processes, making the production system more cost efficient. Lastly, the environmental positive effects from using the virtual factory stems from the ability to evaluate scenarios and with relevant modules can for instance energy consumption and emission of greenhouse gases be simulated and act as a decision-aid. In summary, by providing the means for visualizing, diagnosing and predicting effects of the production systems can long-term and more conscious choices be made with respect to all three dimensions of sustainability.

Even though the positive effects of the virtual factory are prominent there are still important aspect worth considering. The virtual factory will require new competencies and its development might induce uncertainty in the organization. Large scale change requires safeness to create acceptance and enthusiasm about development projects, this could as such threaten the establishment of the virtual factory. Active leadership is therefore of considerable importance to establish a sustainable social climate of change. Another prominent risk can be seen in leadership becoming more distant from the shop floor, since the virtual factory offers the opportunity to monitor and assess the operations and performance of production without being physically present. Active leadership being essential to the development of the virtual factory, as well as the human in production being difficult to model accurately, the presence of management can not be disregarded. Finally, the significant overall investment that the virtual factory requires entails that the value-adding abilities for the end user is central to optimize cost. To create a long-term sustainable economical development it is necessary to evaluate what the technology should do for the end user and not what technology could do.

Collaborating with technology

The implementation plan for realizing step 1 to 4 showed a vast mix of technologies and to successfully merge them into an efficient common platform a comprehensive system perspective is required. Despite no needs where expressed for developing the virtual factory to reach step 5 and 6 it is still important to take future development and system architectural demands into account. This to ensure the ability to realize additional cost savings at higher maturity steps e.g. predictive maintenance as seen at γ.

From benchmarking sessions it was deemed that involving users early in the development process is key for the virtual factory's success and the incorporation of domain knowledge into the system, making it truly tailored for the company. By applying a similar methodology per this thesis at later maturity stages, a user-driven design can be facilitated. The frequency of the identified technical needs should therefore dictate the priority of which technology that should be implemented first at each step. However, it is necessary to apply a holistic perspective by accounting for limitations in contingency to reach the next maturity step, which must be prioritized over the frequency. By first evaluating the needs for the later steps, more effective investments in required competences for establishment of advanced analytics algorithms can be facilitated. Furthermore, the development of a virtual factory requires to continuously update the scope and to find new suitable technologies since few complete solutions exist on the market today. This is valid for the preceding steps as well; an agile mindset and development being required to implement a best practice solution.

The establishment of a dedicated organization and standardized work methods for the virtual factory was benchmarked as success stories. As demonstrated in the case for company β, when a complete production line was replicated from one factory to another, the co-development of ways of working with the virtual factory was crucial to ensure that value was added to the organization. For the case company this is of particular importance since the technical readiness was identified as a prioritized objective in the implementation plan. Otherwise the organization risks that the virtual factory becomes an isolated tool instead of being integrated in the current practice. The virtual factory needs to be regarded as a supporting function, not only a tool for process development, and therefore requires that employees interact with it on a frequent basis to create preconditions for a value-adding system. As such, sufficient educational aspects need to be considered in order to facilitate the perceived effort associated with its initial use.

A digital mindset

The concept of digitalization compromises not only of the use of digital technologies but also implies the process of transforming into a digital business. Transforming a business into a digital one can in many ways be a radical change that requires a new mindset – a digital mindset. This new mindset enfolds increased agility and adaption of new technologies and ways of working. To facilitate this transformation to a digital mindset must the organization put strategies in place for encouraging participation. Organizational change is in most cases a long-term process due to the necessity to change the culture and the transformation process goes hand in hand with the implementation of the virtual factory. In the same manner as the implementation plan for the virtual factory the transformation should yield short-term functionality, forming milestones along the journey towards becoming a digital business.

Despite that digitalization uses emerging technologies the technology itself should not be the single focus. It is important to recognize that the people for whom the technology should be designed for are equally important. If people are not included as an objective in the virtual factory the project risks not being able to realize the value that the virtual factory beholds. To create a vision, developing the virtual factory to reach step 6, is important in all types a project not at least in large transformation projects. Further, the vision needs to be communicated to all stakeholders to anchor understanding and trust. The organization must empower others to act upon the vision, to stepwise create the virtual factory and the related ways of working. The implementation is a continuous process and should be treated as a Kaizen activity, to always look for improvement opportunities. The concept of a virtual factory is not for pioneers, other companies have already started their journeys. It is therefore necessary to include emerging, not only well-established, technologies in the vision to be able to create a competitive strategy for being a successful early adopter of a virtual factory.

Since the virtual factory will never be more capable than the least developed part of its backbone. It is therefore necessary to identify the gaps between the current state and the vision that needs to be filled. This perspective holds true for each individual maturity step's objectives as well. To reduce the risk of overdeveloping parts that the company posses great knowledge and experience in an important aim of each project should be to find the weakest link and eliminate it to the greatest extent. If the organization can manage data collection and further analysis of data will it most probably be a successful early adopter of the virtual factory technology. Nevertheless, it is when the digital mindset and the long-term vision is spread throughout the organization the implementation of the virtual factory can generate the great advantages it implies. By creating a virtual factory it simultaneously facilitates the transformation into digital business and can thus support the establishment of a digital factory. A factory were individuals and teams work smarter, with the help of technology, not harder.

Methodology

Few companies have identical prerequisites, e.g. technical readiness and acceptance, nor identical needs which makes this particular solution inappropriate to copy and paste. However, the methodology as such could be applied at other companies striving for developing a virtual factory. The company is a well-established organization with mature production units and mixed age of equipment which makes this implementation a brownfield project, modification of existing resources. The methodology developed in this paper are not necessarily directly applicable on greenfield projects or in a start-up setting since the prerequisites may appear redundant.

Furthermore, the results retrieved from interviews must be considered through a critical perspective. It is important to acknowledge the biases that might have appeared among interviewees before or during the interviewing process. For instance, the risk of misinterpretations between the interviewer and the interviewee needs to be taken into account. This was treated by combining oral and visual representations of discussed topics during the interview, as well as aligning the interview questions with experienced interviewers in academia to minimize the risk of ambiguities. Coding is an efficient method for organizing large sets of qualitative data, but also implies a risk of overlooking and loosing important perspectives. Efforts for minimizing the loss of data included coding close to the interview session, supported by both notes and audio recordings. The magnitude coding was further supported by the developed framework, which was used as a reference when equivocalities occurred.

Future research

Future research should consider the domain specific areas associated with the establishment of the first maturity step. Investigating the particular requirements for the implementation of each enabling technology to provide a further detailed action plan and architecture regarding its realization. Finally, pilot studies with key user groups could be initiated to establish a Digital Model and advance its functionality. Simultaneously, greater knowledge about the topic should be established, standardized work methods be developed and evaluated throughout the company in accordance with the proposed implementation plan.

8
Conclusion

This thesis has evaluated how a virtual factory can be implemented and become value adding in current practice, using a step-by-step strategy. The strategy is organized into four consecutive steps regarding the level of maturity and enabling technologies of the virtual factory. Its value-adding capabilities in current practice was targeted through user-driven development, standardized ways of working as well as by mapping technical readiness and acceptance. The step-by-step strategy was founded on a literature study, interviews with stakeholders and by benchmarking industry leaders. It found two categories of needs at the company, these considered aspects of technology and implementation. The interview study identified 29 technical needs and 26 implementation needs. It was further concluded that acceptance was nearly full, while the technical readiness showed a wider spread within the organization. Three benchmarking companies were chosen, providing perspectives on emerging technologies and work methods related to the virtual factory.

By providing a holistic perspective on the implementation of a virtual factory, including technology and organizational aspects, a framework for further in-depth and domain specific research has been facilitated. Advancing the virtual factory's maturity stepwise and ensuring a continuous use within production and process development, this thesis has provided a structured way to enable decision-making based on facts; working smarter not harder.

Bibliography

Ashton, K. (2009). That 'internet of things' thing, *RFID journal* **22**(7): 97–114.

Balci, O., Ormby, W., Carr, J. T. and Saadi, S. D. (2000). Planning for verification, validation, and accreditation of modeling and simulation applications, *Proceedings of the 2000 Winter Simulation Conference*, 10-13 December, 2000, Orlando, FL, USA, pp. 829–839.

Becker, M. C., Salvatore, P. and Zirpoli, F. (2005). The impact of virtual simulation tools on problem-solving and new product development organization, *Research Policy* **34**(9): 1305–1321.

Bellgran, M. and Säfsten, E. K. (2009). *Production development: design and operation of production systems*, London: Springer.

Bengtsson, N., Shao, G., Johansson, B., Lee, Y. T., Leong, S., Skoogh, A. and Mclean, C. (2009). Input data management methodology for discrete event simulation, *Proceedings of the Winter Simulation Conference 2009*, 13-16 December, Austin, TX, USA, pp. 1335–1344.

Bjarnehed, H. and Dotevall, J. (2018). *The Energiforsk Annual Nuclear Conference 2018: Increased Business Value with Digital Twins*, 23-24 January, Stockholm.

Bokrantz, J., Skoogh, A., Lämkull, D., Hanna, A. and Perera, T. (2017). Data quality problems in discrete event simulation of manufacturing operations, *Simulation: Transactions of the Society for Modeling and Simulation International* pp. 1–17.

Bryman, A. and Bell, E. (2011). *Business Research Methods*, 3 edn, Oxford: Oxford University Press.

Brynjolfsson, E. and McAfee, A. (2014). *The second machine age: Work, progress, and prosperity in a time of brilliant technologies*, New York: WW Norton & Company.

Colledani, M., Pedrielli, G., Terkaj, W. and Urgo, M. (2013). Integrated virtual platform for manufacturing systems design, *Procedia CIRP* **7**(2013): 425–430.

Freiberg, F. and Scholz, P. (2015). Evaluation of investment in modern manufacturing equipment using discrete event simulation, *Business Economics and Management 2015 Conference*, 13 April - 02 May, Ephesus, Turkey, pp. 217–224.

Gao, S. and Low, S. P. (2014). *Lean Construction Management: The Toyota Way*, [Electronic], Singapore: Springer.

Gartner (2018a). Advanced analytics, Gartner IT Glossary www.gartner.com/it-glossary/advanced-analytics/. (May. 03, 2018).

Gartner (2018b). Digitalization, Gartner IT Glossary, www.gartner.com/it-glossary/digitalization/. (Jan. 31, 2018).

Gerdin, S. (2016). The making of a smart industry, *Evolution* . 23 June.

Gubbi, J., Buyya, R., Marusic, S. and Palaniswami, M. (2013). Internet of things (IoT): A vision, architectural elements, and future directions, *Future generation computer systems* **29**(2013): 1645–1660.

Guion, A. L., Diehl, C. D. and McDonald, D. (2011). Conducting an in-depth interview, *University of Florida* pp. 1–3.

Hartig, F., Calabrese, J. M., Reineking, B., Wiegand, T. and Huth, A. (2011). Statistical inference for stochastic simulation models–theory and application, *Ecology letters* **14**(8): 816–827.

Hu, S. J. (2013). Evolving paradigms of manufacturing: from mass production to mass customization and personalization, *Forty Sixth CIRP Conference on Manufacturing Systems 2013*, 29-30 May, Setúbal, Portugal, pp. 3–8.

Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H., Lien, T., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N. and Shpitalni, M. (2011). Assembly system design and operations for product variety, *CIRP Annals-Manufacturing Technology* **60**(2011): 715–733.

Industrial Internet Consortium (2018). About us, *Industrial Internet Consortium*, www.iiconsortium.org/about-us.htm. (Jan. 31, 2018).

Ingalls, R. G. (2011). Introduction to simulation, *Proceedings of the 2011 Winter Simulation Conference*, 11-14 December, Phoenix, AZ, USA: Winter Simulation Conference, pp. 1379–1393.

Johansson, B. (2006). *On Virtual Development of Manufacturing Systems -Proposal for a Modular Discrete Event Simulation Methodology.* Gothenburg: Chalmers University of Technology. (PhD Thesis at Industrial and Materials Science. Production Systems).

Kagermann, H., Helbig, J., Hellinger, A. and Wahlster, W. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry*, Munich, Germany: acatech.

Koren, Y. (2010). *The global manufacturing revolution: product-process-business integration and reconfigurable systems*, Hoboken, New Jersey: John Wiley & Sons.

Kvale, S. and Brinkmann, S. (2014). *Den Kvalitativa forskningsintervjun*, 3rd edn, Lund: Studentlitteratur.

Kühn, W. (2006). Digital factory - simulation enhancing the product and production engineering process, *Proceedings of the 2006 Winter Simulation Conference*, 3-6 December, Monterey, CA, USA, pp. 1899–1906.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T. and Hoffmann, M. (2014). Industry 4.0, *Business & Information Systems Engineering* **6**(4): 239–242.

Leclercq-Vandelannoitte, A. (2015). Managing BYOD: How do organizations incorporate user-driven it innovations?, *Information Technology & People* **28**(1): 2–33.

Liker, J. K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*, New York: McGraw-Hill.

Liker, J. K. and Hoseus, M. (2008). *Toyota Culture: The Heart and Soul of the Toyota Way*, New York: McGraw-Hill.

Lindskog, E., Berglund, J., Vallhagen, J., Berlin, R. and Johansson, B. (2012). Combining point cloud technologies with discrete event simulation, *Proceedings of the 2012 Winter Simulation Conference*, 9-12 December, Berlin, Germany, pp. 1–10.

McAfee, A., Brynjolfsson, E., Davenport, T. H., Patil, D. and Barton, D. (2012). Big data: the management revolution, *Harvard business review* **90**(10): 60–68.

Nohrstedt, L. (2018). Den digitala tvillingen avslöjade läckaget i kärnkraftverket, *NyTeknik* . 19 February.

Platform Industrie 4.0 (2018). What is industrie 4.0?. *Platform Industrie 4.0*, www.plattform-i40.de. (Jan. 31, 2018).

Premier of the State Council of China and Li, K. Q. (2015). Report on the work of the government, *Proceedings of the 3rd Session of the 12th National People's Congress.* 08 March, Beijing, China.

Produktion 2030 (2017). *Make in Sweden 2030*, Stockholm: Teknikföretagen Communications.

Quinn Patton, M. (2002). *Qualitative research and evaluation methods*, Thousand Oaks, CA: Sage.

Rajkumar, R. R., Lee, I., Sha, L. and Stankovic, J. (2010). Cyber-physical systems: the next computing revolution, *Proceedings of the 47th design automation conference*, 13-18 June, Anaheim, CA, USA, pp. 731–736.

Rolstadås, A. (1995). *Benchmarking - theory and practice*, [Electronic], Boston, MA: Springer.

Saldaña, J. (2009). *The coding manual for qualitative researchers*, Thousand Oaks, CA: Sage.

Sargent, R. G. (2013). Verification and validation of simulation models, *Journal of simulation* **7**(1): 12–24.

Schleich, B. Anwer, N. M. L. and Wartzack, S. (2017). Shaping the digital twin for design and production engineering, *CIRP Annals - Manufacturing Technology* **66**(1): 141–144.

Schönsleben, P. Fontana, F. and Duchi, A. (2017). What benefits do initiatives such as industry 4.0 offer for production locations in high-wage countries?, *The 50th Conference on Manufacturing Systems*, 3-5 May, Taichung City, Taiwan, pp. 179–183.

Schuh, G., Anderl, R., Gausemeier, J. and Michael, H. (2017). *Industrie 4.0 Maturity Index*, Munich, Germany: acatech.

SKF Group (2014a). SKF receives 2013 excellent quality supplier award from hino motors, a Toyota Group company, SKF. www.skf.com/ca/en/news-and-media/. (Jan. 23, 2018).

SKF Group (2014b). SKF receives 2013 quality gold award from Yamaha, SKF. www.skf.com/ca/en/news-and-media/. (Jan. 23, 2018).

SKF Group (2015). SKF invests sek 190 million in gothenburg production channels, SKF. www.skf.com/group/investors/press-releases/. (Jan. 24, 2018).

SKF Group (2017a). Goldstar Paper Tech Ltd – SKF FX Transmission Bushings demonstrate superior quality and performance, SKF. www.skf.com/group/news-and-media/. (Jan. 23, 2018).

SKF Group (2017b). Major chinese steelmaker achieves cost, quality and environmental performance improvements with skf ConRo roll line units, SKF. www.skf.com/group/news-and-media/. (Jan. 23, 2018).

SKF Group (2017c). SKF enters the world of manufacturing using world-class digital technology, SKF. www.skf.com/group/news-and-media/. (Jan. 24, 2018).

SKF Group (2017d). *A World of Reliable Rotation Annual Report 2017*, Gothenburg, Sweden: SKF.

SKF Group (2018). About SKF, http://www.skf.com/group/our-company/index.html. (Jan. 24, 2018).

Skoogh, A., Perera, T. and Johansson, B. (2012). Input data management in simulation–industrial practices and future trends, *Simulation Modelling Practice and Theory* **29**(2012): 181–192.

Smart Factory Task Group (2017). *Smart Factory Applications in Discrete Manufacturing*, Needham, MA: Industrial Internet Consortium White Paper.

Terkaj, W., Tolio, T. and Urgo, M. (2015). A virtual factory approach for in situ simulation to support production and maintenance planning, *CIRP Annals-Manufacturing Technology* **64**(2015): 451–454.

Veza, I., Mladineo, M. and Gjeldum, N. (2015). Managing innovative production network of smart factories, *IFAC-PapersOnLine* **48-3**(2015): 555–560.

Wallén, G. (1996). *Vetenskapsteori och forskningsmetodik*, 2nd edn, Studentlitteratur, Lund.

Wang, S., Wan, J., Li, D. and Zhang, C. (2016). Implementing smart factory of industrie 4.0: an outlook, *International Journal of Distributed Sensor Networks* **12**(1): 1–10.

Yang, X., Malak, R. C., Lauer, C., Weidig, C., Hagen, H., Hamann, B., Aurich, J. C. and Kreylos, O. (2015). Manufacturing system design with virtual factory tools, *International Journal of Computer Integrated Manufacturing* **28**(1): 25–40.

A

Interview template

This document served as the foundation of the interviews. Since a semi-structured methodology was chosen this questionnaire was often expanded through follow-up questions regarding subjects of interest.

A.1 The questionnaire

A. Introduction
    I. Can we record this interview?
        i. This recording will be used internally to support us in writing our thesis report. We will take notes simultaneously, for the same reason.
    II. The interview will treat three themes on the topic of digitalization at SKF, more specifically about virtual factories. It will take approximately 45 min.
    III. Do you want to be anonymous in the study?
        i. Yes: Can we use your title/department as ID?
        ii. No: What is your name?
        iii. No: What is your work title?
    IV. Which department do you work for?
    V. Which departments do you most commonly collaborate with?
    VI. How long have you worked in your current role?
    VII. Are you interested in technology?
        i. Why?
B. General information
    I. Background to the project
        i. We are Amanda and Marcus. We are from Production Engineering at Chalmers University of Technology and we're currently doing our master's thesis here at SKF and Process Development.
    II. Scope of the project
        i. We want to evaluate the value of using digital solutions, such as virtual factories. Also, we want to explore how these could be used on a daily basis in the organization.
    III. Scope of the interview
        i. A first step is to map the needs of different user groups at SKF. The information will be consolidated in a report as well as a presentation for SKF stakeholders.
C. Readiness

I. In general, with your role and experience in mind, what does digitalization mean to you?
II. Do you think such solutions and tools can generate manufacturers such as SKF competitiveness in the future?
III. In your role, do you use/see simulation?
    i. Which kind of simulation?
    i. In what context?
IV. Example: Show movie of a 3D simulation of the E-factory.
    i. From our perspectives, simulation is a digital model of the reality. We will now show an example of what this could look like in a factory setting. This short movie depicts a part of the E-factory.
    i. -Show movie-
V. Does this simulation align with your perception of simulation?
    i. No: Why not?
VI. Have you heard of/used a virtual factory before this session?
    i. Yes: Tell us more.
VII. Explain our vision
    i. We consider it to be an environment similar to the one in the short movie, but extended with data from the real factory. In other words, it's a very small or no difference in the behavior of the virtual factory and the real factory.

D. Acceptance
I. What potential do you see considering the utilization of a virtual factory?
II. Do you see any obstacles in using the technology?
    i. No: Do you consider SKF to have reached a high organizational level of maturity?
III. If a virtual factory could be established tomorrow, what would make you use it?

E. Needs
I. In short, describe a normal day at work.
II. Which, do you believe, are your most important work tasks in day-to-day activities?
III. Is there anything you consider a bit bothersome, are there any "necessary evils" in your work?
    i. Do you believe any of these issues could be partly or completely resolved by a virtual platform such as a virtual factory?
IV. Let's say that you get proper orientation and education to be able to use the virtual factory, is there any specific functionality that you think would make your day-to-day activities easier?
V. Many development projects and similar activities require many involved parties. Do you see any challenges working in large groups of people in projects of a considerable size?
    i. Do you believe a virtual factory could be used to partly or completely resolve some of these challenges?

F. Sum-up
I. Summing up this interview,

i. Is there something else that you want that we take with us in out future work?
ii. Do you think we missed something in this interview?
iii. Is there anyone that you want us to talk to?

II. To confirm, we will ask you once more,
    i. Do you want to be anonymous?
III. As previously stated, the information gathered through these interviews will be consolidated in a report and presentation. You are welcome to take part in both.
IV. Thank you for your time.

B

Interview coding scheme

This document served as the basis for coding the interview notes which enabled analysis of the spoken context.

B.1 Category: Readiness

This category depicts the interviewees' technical knowledge about; virtual factory, simulation and digitalization. Table B.1 serves as the basis for the grading.

Table B.1: The used coding scheme for the category readiness.

Group	Criterion	Grade
A	No knowledge about the subject	-1
B	Heard of the subject, can give brief explanation	0
C	Involved in the subject, can explain and give examples of its application	1

B.1.1 Examples of answers for each group

A. No knowledge about the subject
    I. Virtual factory
        i. I have never heard of it.
        ii. It the use of VR glasses in production.
    II. Simulation
        i. I have never seen a simulation model.
        ii. It is a 2D depiction of a real object.
    III. Digitalization
        i. It is the use of computers instead of paper and pen.
        ii. It is about automation and robots.
B. Heard of the subject, can give brief explanation
    I. Virtual factory
        i. I have read about it in trade press.
        ii. It is a detailed data model of the real factory.
    II. Simulation
        i. My team are using simulations in the project I work on.
        ii. I have used simulation software for layout planning.
    III. Digitalization

i. It is about using data from the factory.
ii. It is about building a smart product by the use of data.

C. Involved in the subject, can explain and give examples of its application
  I. Virtual factory
    i. It is a simulation model which uses data from the real factory.
    ii. It is a digital concept which enables what-if testing in a representative environment.
  II. Simulation
    i. It is an animation of the reality based on data which represents certain processes or resources.
    ii. It is a model of the real world with the ability to model time dependent behavior.
  III. Digitalization
    i. It is about using the data retrieved from products and production to create a new business model.
    ii. It is based on the transformation of data into information, so that systems and products could be made smarter by providing an intelligence.

B.1.2 Weighted sum

Since the category readiness consist of three subcategories a weighted sum is used as the final grade. The weights are as follows; 0,50 for subcategory virtual factory, 0,25 for subcategory simulation, 0,25 for subcategory digitalization. This is further described in equation B.1 where a_i is the individual grade for each subcategory. The magnitude of the weights is based on firstly the scope of the thesis, virtual factory, and secondly on their relation the main subject. Due to virtual factory being the scope and the main technology it was designated the largest weight; 0,50. Both simulation and digitalization are treated as necessary supporting technologies for the development, as well as the understanding, of a virtual factory. Consequently, they were both assigned the weight 0,25. The grading only constitutes of integers and therefore is the weighted sum complemented with a floor function, rounding down (see equation B.2). This approach was chosen due to a conservative perspective and to remain critical throughout the analysis.

$$a_{\text{sum}} = \sum_{i=1}^{3} w_i a_i = 0.5a_{\text{VF}} + 0.25a_{\text{sim}} + 0.25a_{\text{digi}} \tag{B.1}$$

$$a_{\text{final}} = \lfloor \sum_{i=1}^{3} w_i a_i \rfloor = \lfloor 0.5a_{\text{VF}} + 0.25a_{\text{sim}} + 0.25a_{\text{digi}} \rfloor \tag{B.2}$$

B.2 Category: Acceptance

This category depicts the interviewees' acceptance of implementing and using a virtual factory. Table B.2 serves as the basis for the grading.

Table B.2: The used coding scheme for the category acceptance.

Group	Criterion	Grade
A	Against using a virtual factory	-1
B	Neutral about using a virtual factory	0
C	Positive about using a virtual factory	1

B.2.1 Examples of answers for each group

A. Against using a virtual factory
   i. I cannot see myself using such a product.
   ii. I don't believe it can provide any use for me or my colleagues.
B. Neutral about using a virtual factory
   i. I could see myself using such a product.
   ii. I can't see any real application for me, but I do think my colleagues could benefit from using a virtual factory.
C. Positive about using a virtual factory
   i. I could definitely see myself using such a product.
   ii. I can see many potential benefits from using this product in my team.

C

Benchmarking interview template

This document served as the foundation of the benchmarking sessions. This questionnaire was often expanded through follow-up questions regarding subjects of interest.

C.1 The questionnaire

Technical aspects

A. Goal and vision
   i. Background
      i. When did the vision of a virtual factory start?
   ii. Current state
      i. What is the current maturity of the virtual factory?
   iii. Future state
      i. What is considered the next step, What is currently under development?

B. Level of detail
   i. What parameters are currently being analyzed? what is the current level of detail?
   ii. Is the human in production or operators included in these parameters?
   iii. Does the presented level of detail vary across different user groups, e.g. considering project management or analysis of operations?
   iv. Does the model's level of detail ease ramp-up phases by generating a holistic perspective for different user groups?

C. Software
   i. How is compatibility between different software managed?
   ii. Which systems are in place today to counteract this, how do you choose designated sub-systems?
   iii. What are your recommendations considering developing tools in-house or utilizing commercially available tools?
   iv. Should the model have an online presence, being more easily reached across different networks?

D. Model use
   i. How is shared use of the model across different departments and use of different modules considered?
   ii. What modules are established today?

   iii. Who is the user of the model and the input data it depends on?
   iv. How is use of the model considered for educating new personnel?
   v. Have certain aspects of the production preparation process been automized, e.g. optimal routing?
E. Usability
   i. What has been tested considering usability aspects today?
   ii. Are some aspects considered to have been particularly successful?
   iii. Do you have any general advice for such aspects?
F. Calculation of cost
   i. Are there cost calculations being performed today?
   ii. Is the model used for such calculations or are data exported to other software?
   iii. More specifically do you perform cost calculation relating to:
      i. Routing
      ii. Investment options
      iii. Customer quotations and different product alternatives
G. Validation
   i. How is quality of the collected data measured?
      i. In theory (data as compared to reality)?
      ii. Practically (procedures, tools)?
   ii. What routines and work methods is there for working with data?
   iii. How up-to-date is the data that the model is based on?

Organizational aspects

A. Education and training
   i. What type of competences are required to use the virtual factory as well as for using the data it generates?
   ii. Is there any official division of user groups?
      i. How is the training designed for the user groups?
      ii. Is designated time given for training or is a trial-and-error methodology applied?
   iii. Is the training viewed as a continuous process or is the user expected to learn by themselves?
B. Implementation
   i. Based on your experience, is there any part of the virtual factory that should be implemented first?
   ii. Are pilot studies a successful concept in these types of projects?
      i. What should be prioritized as a pilot study?
   iii. How important is it to involve key stakeholders in the implementation?
   iv. Are there any specific requirements for leadership?
   v. How is the generated value from implementing the virtual factory concretized?
      i. How was the initial investment motivated?
   vi. Which success stories and lessons learned do you bring to the next implementation project?
C. Work methods and organizational structure

   i. Have you established standardized work methods for the use of the virtual factory?
      i. Have the required administration increased after the implementation?
      ii. How do you guarantee that the virtual factory is used on a daily basis?
      iii. In which project phases is the virtual factory used today?
   ii. How have you structured the work required for maintenance of the model and for collection of data?
      i. How do you work to ensure a living, up-to-date model?
   iii. Concerning support, how do you reason about local versus global support functions?
   iv. In what ways do the establishment of a virtual factory imply new requirements on an organization?
      i. Have any new work roles emerged, or been replaced?

D. Replicability
   i. Have you taken replicability into account when developing the system?
      i. Can the model be generalized to other factories, in other countries?

E. Results and effects
   i. How can the user trust the presented data?
   ii. Can you provide any hard numbers on the success related to the virtual factory?