JÖNKÖPING UNIVERSITY
School of Engineering

Implementation framework to realize the Smart Factory

Development of a practical framework to leverage the organizational implementation of the Smart Factory

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Abstract

Purpose Global megatrends and the resulting challenges for manufacturing companies, have brought up the concept of Industry 4.0 (I4.0) and its heart the Smart Factory (SF). Through I4.0 and the application of SF companies can increase their creation of value, however the degree of value depends on the way of implementation. Scholars and studies of successful SF implementation are still in an infant stage, and companies find little guidance in literature. Therefore, research question one targets on how to implement the SF and research question two on the investigation of success factors, challenges and outcomes of the successful SF implementation.

Method The literature review included 216 scholars in the field of SF implementation. On this basis, a theoretical proposition was developed, to guide data collection and analysis. For development of the practical framework, multiple case studies have been chosen. Through an orientation study, seven cases in a multinational manufacturing company have been selected for the research. The developed framework has been validated again with the experts in the company.

Results and analysis The developed implementation framework consists out of two parts. A strategic implementation process, including a SF maturity model to support the gradual advancement towards the SF and an operational implementation process for SF technologies, to advance to the higher maturity level. The framework represents a step-by-step approach including key activities, success factors and challenges of each phase. To justify an implementation, different outcomes have been clustered and organized to provide an overview.

Theoretical implications As this work is based on the current advancement of the research field, it first provides a condensed summary of SF implementation and second, through answering RQ1 and RQ2 closes research gaps. Hence, it contributes to the further advancement of the research field by providing a clear framework on the implementation approach and key factors, as well as a starting point for further research.

Managerial implications With the SF implementation framework, this work provides the missing connection between a directed strategic approach and new technology implementation with a step-by-step guideline to facilitate the implementation of SF. The framework represents a guideline, to be used by managers, including the most important aspects to consider.

Keywords Smart Factory, Industry 4.0, Implementation, Maturity Model, Framework, Case Study

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CAD	Computer aided design
CPPS	Cyber-Physical-Production-Systems
CPS	Cyber-Physical-Systems
ERP	Enterprise resource planning
I4.0	Industry 4.0
IIoT	Industrial internet of things
IoS	Internet of Services
IoT	Internet of things
KPI	Key performance indicator
M2M	Machine – to – machine
MES	Manufacturing execution system
MVP	Minimum viable product
PLC	Programmable logic controller
PM	Project management
RFID	Radio-frequency identification
ROI	Return on investment
SCADA	Supervisory control and data acquisition
SF	Smart Factory

1 Introduction

This chapter will introduce the topic with the background based on current research. On this basis the underlying problem will be elaborated, which then evolves into the formulation of the research questions. In the last part, an overview over the proceeding of this work is given.

1.1 Background

Societal problems and megatrends, such as reduced labor force, due to aging, demand for more and more shorter development times, stronger interconnections and dependencies and demanded resource efficiency have driven the development of e.g. Cyber-Physical-Systems (CPS) and the Internet of Things (IoT) (Hozdić, 2015; Schröder *et al.*, 2015; Qin, Liu and Grosvenor, 2016; Wang, Wan, Li, *et al.*, 2016). Production plants become more and more complex, which in turn results in longer planning phases and longer time-to-market (Zuehlke, 2010). Through these challenges, a new concept called Industry 4.0 (I4.0), has been introduced in Germany at the Hannover Fair 2011. This symbolized the beginning of the fourth industrial revolution (Qin, Liu and Grosvenor, 2016; Wang, Wan, Li, *et al.*, 2016). Each industrial revolution has brought fundamental changes, economically, socially and in the way of working and manufacturing. The complexity and automatization has steadily increased, which in turn has led to higher productivity and prosperity (Kelkar, 2014; Hozdić, 2015; Qin, Liu and Grosvenor, 2016). An illustrative overview of the industrial evolution is given below in Figure 1.

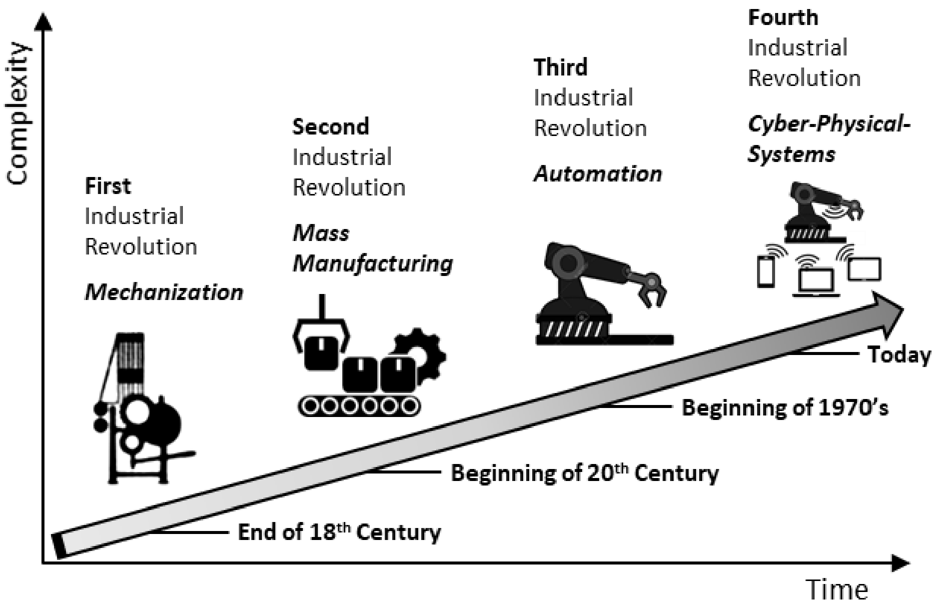

Figure 1: From the first to the fourth industrial revolution, adapted from Kelkar (2014) and Hozdić (2015)

The first industrial revolution was evoked through the mechanization, enabled through steam- and waterpower, during the second half of the 18th century. While prior, manufacturing happened in households, it then was performed in factories. Mass manufacturing was the second industrial revolution, beginning in the end of the 19th century and characterized through assembly lines and work-sharing, also known as Fordism. Through automation and robots during the 1970's the third industrial revolution evolved. Central to this revolution were programmable logic controllers (PLCs), which facilitated the controlling of machines and assets (Kelkar, 2014; Hozdić, 2015). The latest revolution represents the fourth and current revolution with CPS as central element.

I4.0 offers new opportunities to radically improve quality, productivity and efficiency, but it requires entrepreneurial courage and the will for innovation. Users of I4.0 see high potential in harvesting the potentials, while providers see the high potential of new businesses (Jäger *et al.*, 2016). Also, other countries have announced their digital manufacturing strategies, such as China with the "Made-in-China 2025" strategy (Li, 2018), USA with Smart Manufacturing (Davis *et al.*, 2012) and Japan with Industry 4.1J (Kagermann *et al.*, 2016). All strategies focus on the use of the industrial IoT (IIoT), creating smart manufacturing systems, including horizontal and vertical integration among tiers and creating a highly responsive, innovative and competitive global manufacturing system (Li, 2018; Pérez-Lara *et al.*, 2018).

Through realizing I4.0 in manufacturing, also called the Smart Factory (SF), flexibility and productivity increases, resource and energy can be used more efficient and better transparency over the manufacturing processes and equipment can be gained. In addition, the integration of equipment and processes can be enabled, as well as profitability increased, and staff can be released from routine tasks (Wang, Wan, Li, *et al.*, 2016).

Manufacturing operates in the field of tension of everchanging customer needs while opening new markets. Customization is becoming more and more important as a differentiator against competition. However, customer requirements differ depending on the type of customer, which in turn leads to the necessity to be able to produce small lot sizes. Another point is, the shortening of product life cycles, demand for a responsive and flexible manufacturing systems (Dotoli *et al.*, 2019).

So far, average realized overall production gains from smart factories range from 22% in the pharma, life science and biotec industry up to 29% in industrial manufacturing (Ludbrook *et al.*, 2019). This sector development and improvement of productivity, due to I4.0 is estimated to continue (Rüßmann *et al.*, 2015). Digital adopters are foreseen to have the biggest growth of revenue in the next three years (Ludbrook *et al.*, 2019). Also, general employment will increase and the demand for mechanical engineering sector may rise even more. However, short term low-skilled labor jobs will become obsolete due to the greater automatization (Rüßmann *et al.*, 2015).

Digitalization and globalization force enterprises to strategically realign their business models in the face of international competition. In the future, the perceived success factors are intelligent products, services and their connection, customer orientation, efficient use of data and optimization of products and technologies (Schröder *et al.*, 2015).

Future technologies need to accelerate planning and setup of production equipment, and need to enable production systems with the ability to make rapid product changes during operation and reduce the planning effort (Zuehlke, 2010). Production plants become more and more complex, which leads to longer planning phases (Zuehlke, 2010). Already in 2010, Zuehlke suggested to develop more technologies for the human.

Today these technologies in the production are aggregated under the term SF. The SF represents a key feature of I4.0 (Drath and Horch, 2014). While the term SF was first introduced by Zuehlke (2010), it then became common use for governmental initiatives in Europe (Strozzi *et al.*, 2017). SF is seen as a concept, which covers the entire supply chain, focusing on different tiers of production and supply chains, in order to deploy its full potential (Strozzi *et al.*, 2017). Inside the production facility, the physical flow is tracked on digital platforms continuously to enable this communication among tiers (Alcácer and Cruz-Machado, 2019). Such a holistic approach is necessary to avoid the development of "island-solutions" for the SF (Strozzi *et al.*, 2017). Further, SF refers to the integration of communication technology and information, which creates the connection of machines, equipment, transportation vehicles, products and humans for information exchange in real-time (VDI, 2019). VDI (2019) defines SF as a *"factory, whose degree of integration has reached a level, which makes self-organizing functions possible in production and in all business processes relating to production."* Intelligent decision making is enabled through the virtual representation of the factory, with the aim to increase efficiency, effectiveness, flexibility and or adaptability (VDI, 2019).

1.2 Problem description

SF implementation is a process innovation, which affects other subsystems and processes. The implementation will lead to unanticipated technological challenges, requires new skills and significantly changes the way of working. Through this extensive complexity, guidance becomes even more important. However, literature and studies of successful SF implementation are still in an infant stage, and companies find little guidance in literature. Therefore, also the knowledge about success factors, key challenges and activities within the process remain undiscovered (Sjödin *et al.*, 2018). In order to be able to cope with the rapid and immediate change in the production environment it is necessary to define development strategies and policies of its realization (Hozdić, 2015).

Through I4.0, IoT and the application of SF a company can increase the creation of value (Wang, Wan, Li, *et al.*, 2016; Moeuf *et al.*, 2018; Rub and Bahemia, 2019). Although, it can be argued, that the degree of value is dependent on the way of implementation in a firm (Rub and Bahemia, 2019). Due to the fact, that different companies, create their SF according to their needs, the complexity of it and its implementation arises (Rub and Bahemia, 2019). Research in the field of SF is not homogenous and unequally advanced (Osterrieder, Budde and Friedli, 2019). The SF research model by Osterrieder, Budde, and Friedli (2019) identified eight pillars in the current research field, which are related to CPS, data and infrastructure, however there is no pillar of implementation.

Further, different practitioners showed, that the current research provides a big number of different models, frameworks and architectures related to the implementation of the SF, but rarely real cases and lessons learned from practice are described and discussed.

It is still a high uncertainty among manufacturers, how to implement I4.0 and what the basic requirements are (Oztemel and Gursev, 2020). The quantity of case studies and success stories on implementing SF is not enough to be used as a guidance, as most publications in the field of SF, are often single use cases with low generalizability (Osterrieder, Budde and Friedli, 2019; Sony and Naik, 2019). An application of a general implementation model would enrich the understanding of the SF and in which ways it can be implemented (Kagermann *et al.*, 2016; Strozzi *et al.*, 2017; Moeuf *et al.*, 2018). Further, a general implementation model can illuminate the benefits of I4.0 more concrete and make them visible for companies to reduce further implementation doubt (Kagermann *et al.*, 2016; Liao *et al.*, 2017).

Another point is, that the vertical integration among manufacturing processes doesn't fit into the traditional automation pyramid, as it focuses on distributed and collaborative architectures (Alcácer and Cruz-Machado, 2019). But in the SF of the future, the central technology are CPS and only through vertical integration the SF is enabled of being connected (Liu and Xu, 2016). Therefore, Chen and Muraki (1997) suggests the further improvement and development of software tools in manufacturing to support vertical integration. Additionally, it is suggested to investigate more use cases for software tools and digital applications in manufacturing systems and throughout the SF and increase in this way the body of knowledge (Azadegan *et al.*, 2011; Syberfeldt *et al.*, 2016; Osterrieder, Budde and Friedli, 2019).

1.3 Purpose and research questions

On an overall level, there is a need to investigate the implementation process of the SF. Therefore, the leading research questions of this thesis are depicted below, to advance the body of knowledge of current research.

> *RQ1: How can the SF be implemented in practice?*

The development of an implementation framework for SF and SF projects underlies research question one. This should be based on the current research, followed by the proof of the framework in real case environment, to enhance the body of knowledge and contribute to further understanding of the use of an implementation framework. This can be seen as one step towards an applicable guideline for implementation (Hozdić, 2015; Kagermann *et al.*, 2016; Liao *et al.*, 2017; Strozzi *et al.*, 2017; Moeuf *et al.*, 2018; Sony and Naik, 2019; Oztemel and Gursev, 2020).

As for realizing the SF, software tools, digital application and IT systems are the foundation and account for the biggest leverage, a proof of the SF project implementation framework in this context matches the direction of necessary advancement (Chen and Muraki, 1997; Azadegan et al., 2011; Liu and Xu, 2016; Syberfeldt et al., 2016; Sony and Naik, 2019).

> *RQ2: What are success factors, challenges and outcomes of an implementation of SF?*

The second research question aims on investigating the challenges, pinpoints, lessons learned, and benefits of an implementation (Liao *et al.*, 2017; Oztemel and Gursev, 2020). Another insight, which is gained, is the "how" a SF implementation can be successful. Additionally, it targets on the connections with the production system context and how the necessary change can be performed, to cope with the requirements (Hozdić, 2015; Kagermann *et al.*, 2016; Strozzi *et al.*, 2017; Moeuf *et al.*, 2018; Rub and Bahemia, 2019; Sony and Naik, 2019; Oztemel and Gursev, 2020).

1.4 Delimitations

The framework will be delimited by neither considering specific technology implementations, nor the technical implementation of the SF. This means the different technologies, which belong to the field of I4.0 and SF will neither be elaborated detailed, nor the technical implementation, such as "how to set up and develop the structure of an I4.0 architecture", will be elaborated. This has already been focused by several other scholars.

Additionally, the framework will not apply for small and medium sized companies, as special circumstances and restrictions must be considered in this context and already other scholars, such as Pinto *et al.* (2019), have provided guidance in this field.

1.5 Outline

This thesis is divided into six chapters. The first chapter has introduced the topic of SF and I4.0 and current challenges within this field regarding the implementation, leading into the definition of the research questions. The second chapter provides the theoretical background in the area of I4.0 and SF implementation. At first, the general concept of SF and I4.0 is briefly outlined, followed by the distinct focus on *RQ1* with the implementation process and on *RQ2* with the key factors of SF implementation and the maturity model. The third chapter depicts the research approach, which has been undertaken. This contains the outline of the systematic literature review, including the literature search, as well as the elaboration of the case study with the overview of the case company and the different cases focused. Further, the gathering and the analysis of investigation data are outlined. In the fourth chapter findings out of the case studies are presented with the process of implementation, the maturity model and the key factors. The findings chapter follows the same structure as chapter two with the distinct focus on both research questions. The analysis and the developed framework are outlined in the chapter five. This chapter, in contrast to the theoretical background and the findings, is structured in a combination of *RQ2* and *RQ1*, as it turned out that both research questions are highly interdependent and connected. Therefore, the different sub-chapters focus on the strategic SF implementation, supported by a maturity model, the operational SF implementation and the overall resulting outcomes of the SF implementation. The final chapter sums up and discusses critically the developed SF implementation framework. Additionally, contribution to academia and industry are summarized and further research suggestions based on the results are outlined.

2 Theoretical framework

The following section is divided into three parts. First, an introduction into the characteristics and contents of SF and briefly of the superordinate context I4.0 will be given. The consecutive chapter provides an overview how to facilitate and ascend towards the SF. Therefore, the strategic and operational implementation process will be depicted (RQ1). To successfully proceed the implementation, the third chapter focuses on the success factors, challenges and outcomes and different maturity models of the SF implementation (RQ2).

2.1 Industry 4.0 and Smart Factory

SF is the heart of I4.0, which was presented as the German manufacturing strategy to maintain the leading position in global manufacturing. Through I4.0 and the technologies around, the manufacturing industry changes through the digital transformation. The aim of I4.0 is achieving higher productivity and efficiency through a connection of the physical and the virtual world (Qin, Liu and Grosvenor, 2016; Wang, Wan, Li, *et al.*, 2016; Alcácer and Cruz-Machado, 2019). This connection is enabled through horizontal, vertical and end-to-end engineering integration (Wang, Wan, Li, *et al.*, 2016; Pérez-Lara *et al.*, 2018).

The key aspects of I4.0 are data (for digitalization, visualization, analytics), connectivity (enable connection of networks, integration, web-services), services (for data access, security, collaboration) and devices (machines, control, IoT sensors) (Harrison, Vera and Ahmad, 2016). Key technologies of I4.0 are the industrial IoT, cloud computing, big data, simulation, augmented reality, additive manufacturing, horizontal and vertical systems integration, autonomous robots and cybersecurity (Rüßmann *et al.*, 2015; Pérez-Lara *et al.*, 2018; Alcácer and Cruz-Machado, 2019).

Smart Factory

SF is defined by VDI (2019) as a *"factory whose degree of integration has reached a level which makes self-organizing functions possible in production and in all business processes relating to production."* The SF is the heart of I4.0, wherein CPS, IoT and Internet of Services (IoS) are the foundation components. These technologies are the base to enable the three different kinds of integration by connecting all manufacturing resources (sensors, machines, robots, conveyors) and evolve not only the concept of the decentralized production system, but also integrating consciousness and intelligence into the factory, to predict and maintain machines, control the production and manage the factory system (Hozdić, 2015; Qin, Liu and Grosvenor, 2016; Wang, Wan, Li, *et al.*, 2016; Alcácer and Cruz-Machado, 2019; VDI, 2019). Through this, it is possible to produce customize and small-lot products efficiently and profitably (Wang, Wan, Li, *et al.*, 2016; Xu and Hua, 2017).

Radziwon *et al.* (2014) defines the features of a SF based on various sources, as being flexible and reconfigurable, low cost, adaptive or transformable, agile and lean. This could be achieved through a modular structure of both product and process technology and organization (Radziwon *et al.*, 2014).

Smart Factory Architecture

The concept SF can be understood as a four-layer model with distinct activities. These are physical, network / data, cloud & intelligence and control layer, as depicted in Figure 2.

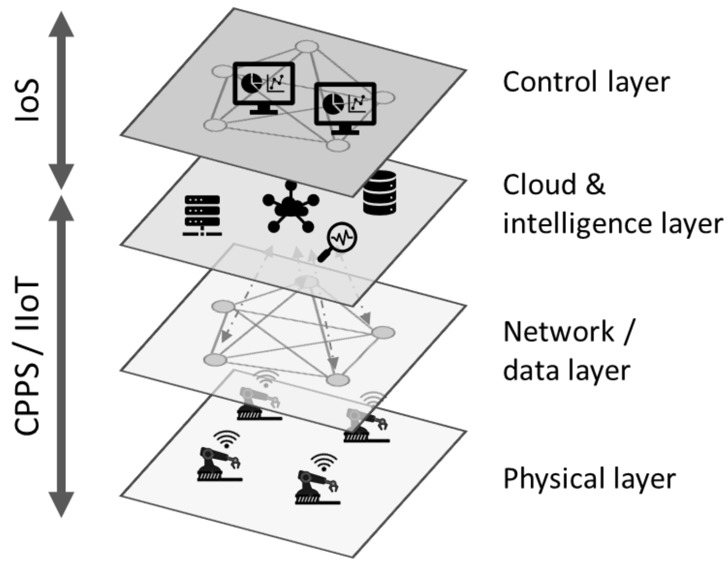

Figure 2: SF layer concept, adapted from Wang *et al.* (2016), Chen *et al.* (2017), Davies, Coole and Smith (2017) and Zuehlke (2010)

The physical layer contains all machines, terminals and manufacturing resources. This layer represents the foundation for intelligent manufacturing (Zuehlke, 2010; Davis *et al.*, 2012; Chen *et al.*, 2017). The data layer enables the integration and connection of various network technologies. Data transfer and information sharing is enabled between the physical layer through sensors and the intelligence layer, by controlling the type and variety of data and the rate by software. Through technologies, such as edge computing and standardized OPC-UA interconnection, security and real-time transfer can be realized (Davis *et al.*, 2012; Wang, Wan, Li, *et al.*, 2016; Chen *et al.*, 2017). The data is then stored in the cloud and processed through analytics. The goal is to realize intelligent manufacturing by discovering knowledge through data mining technologies (Chen *et al.*, 2017). The top layer represents the visualization and supervision of the data essence. This enables control activities of the production system when necessary (Zuehlke, 2010; Davis *et al.*, 2012; Wang, Wan, Li, *et al.*, 2016).

Cyber-Physical Systems

CPS are the connection of "cyber" as electronic systems with "physical" things. The cyber component enables the physical component, through a created virtual copy, to interact with other virtual copies. Therefore, in CPS information about the physical environment is processed. CPS are a range of transformative technologies, which enable the managing of interconnected software and hardware capabilities. (Hozdić, 2015; Alcácer and Cruz-Machado, 2019).

Smart elements in a factory are enabled by CPS. Through connection they have the ability to communicate with each other and contribute to tasks, such as planning, or non-repetitive tasks (Alcácer and Cruz-Machado, 2019). Further features, such as dynamic routing, self-organization and big data is enabled (Wang, Wan, Li, *et al.*, 2016). CPS consist mainly out of three components. Communication, computation and control and handling and monitoring. Through communication CPS connect to higher or lower levels of control systems or production entities. In computation and control the intelligence is embedded with the exchange of information and measures. Sensors are used, in order to monitor physical components, which then are connected to the physical world through the CPS, by the handling and monitoring component (Harrison, Vera and Ahmad, 2016; Chen *et al.*, 2017; Alcácer and Cruz-Machado, 2019). CPS are the foundation of the SF, structured as Cyber-Physical-Production Systems (CPPS), compare Figure 2. The interaction of CPPS with the virtual world enables the manufacturing IoT, the IIoT. Further, CPPS enable the real-time management in manufacturing. CPPS change the automation pyramid drastically from a hierarchical to a decentralized approach with smart objects and a direct interconnection of the different hierarchies (Hozdić, 2015; Harrison, Vera and Ahmad, 2016; Chen *et al.*, 2017; Alcácer and Cruz-Machado, 2019; VDI, 2019).

Internet of Services

The concept of Internet of Services is the idea, that services are accessible through the internet, in order to create, combine and offer new value-added services by companies. Therefore, the product-oriented manufacturing industry is shifting more and more towards service-oriented business models (Alcácer and Cruz-Machado, 2019). However in the internal SF context, IoS facilitate the collection of production information for improving product and service quality and being able to access these via internet for maintenance, decision makers and implementers, which is also displayed in Figure 2 (Wang, Wan, Li, *et al.*, 2016; Chen *et al.*, 2017; Alcácer and Cruz-Machado, 2019).

2.2 Implementation of Smart Factory

In the following the focus is applied to the implementation process of SF and SF projects, to support RQ1 of how the SF can be implemented in practice.

The implementation process can be divided into two parts. The strategic implementation process and the operational implementation process of a SF technology. Different authors suggest having a distinct strategy and roadmap, thus supporting the differentiation between strategic and operational implementation (Trost, 2015; VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Huber, Henkel and Kranz, 2019; Sony and Naik, 2019). The predominant process steps found in scholars are outlined below in Table 1.

Table 1: Implementation process SF

	Phases	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Strategic	Assessment of readiness				X	X			X	X
	Definition of Maturity				X			X		X
	Strategy & Vision			X		X		X		X
	Identify technologies	X	X	X	X	X	X	X	X	
	Develop use cases & scope		X	X	X	X	X	X	X	
	Roadmap				X	X		X		
Operational	Connect / integrate	X		X		X	X	X	X	
	Examine / validate			X		X		X	X	
	Develop business case		X	X	X	X		X	X	
	Execute / implement		X	X	X	X		X	X	
	Scale		X	X		X			X	

Note: (1) Bauer, Jendoubi and Siemonheit (2004); (2) Cooper (2008); (3) Iansiti and Lakhani (2014); (4) VDMA Industrie 4.0 Forum (2016); (5) Illa and Padhi (2018); (6) Sjödin et al. (2018); (7) Huber, Henkel and Kranz (2019); (8) Pinto et al. (2019); (9) Sony and Naik (2019)

Both processes and the different phases will be elaborated in the following chapters.

2.2.1 Strategic implementation

Assessment of readiness

Before deciding to implement I4.0, the *readiness* for it should be assessed. This includes how ready the organizational strategy is for I4.0, the degree of digitalization in the organization and in the supply chain, how smart current products and services are, if employees are adaptable to I4.0, the degree of management commitment on I4.0 and the dependencies of different processes (Pinto *et al.*, 2019; Sony and Naik, 2019). A key factor can be the readiness of the equipment, as machines should be able to communicate though standard industry protocols as the retrofitting can be quite challenging. Also, the expertise for implementation and managing of IoT solutions should be internally available (VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018).

Definition of maturity

The *definition of the maturity* represents the major part of the assessment. A maturity model is suggested, to get a clear picture of the current state and the effort of the implementation (VDMA Industrie 4.0 Forum, 2016; Sony and Naik, 2019). The maturity level is assessed out of the corporate strategy, the process landscape, the prior assessment and possible already running use cases (VDMA Industrie 4.0 Forum, 2016; Huber, Henkel and Kranz, 2019). This will account for a starting basis for the strategy and technology identification (VDMA Industrie 4.0 Forum, 2016).

Strategy & vision

Having a *I4.0 / SF strategy* is one of the main drivers, in order to succeed in the implementation (Illa and Padhi, 2018; Sony and Naik, 2019). Further the choice of possible new technologies can be directed correctly (Iansiti and Lakhani, 2014). In this step, with the help of e.g. strategy workshops, an overall and a department specific target vision is created. Out of this strategy, field of actions are identified, evaluated and prioritized regarding their benefits. Different framework conditions such as the IT landscape are taken into account (Huber, Henkel and Kranz, 2019).

Identification of technology

In the phase of *technology identification* a digital lens is applied to discover, review and analyze existing processes in the strategic fields of action, which have been identified prior in the strategy and maturity assessment (Cooper, 2008; Iansiti and Lakhani, 2014; Sjödin *et al.*, 2018; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019). This includes the decomposition of processes into tasks and looking for the most challenging process, which can be digitalized or to identify scalable processes with little dependencies (Iansiti and Lakhani, 2014; Pinto *et al.*, 2019). This makes it easier to evolve to other similar processes or leverage the advantage (Iansiti and Lakhani, 2014; Pinto *et al.*, 2019). Only a clever selection of the fitting technologies will release the benefits (VDMA Industrie 4.0 Forum, 2016). Therefore, the consecutive step is to identify and discover suitable technologies and discuss the compatibility of the new technology with the existing system (Cooper, 2008; Pinto *et al.*, 2019) cooper). The generated ideas and technologies will be further discussed and developed into concepts (VDMA Industrie 4.0 Forum, 2016). Generally when starting, important use cases with fast payoff or “low-hanging fruits” should be favored (Illa and Padhi, 2018).

Development of use cases & scope

During the further *development of use cases* the concepts will be assessed for their potential and benefits, as well as for their needed resources and costs (VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Huber, Henkel and Kranz, 2019). For assessing this, a business case is created including an assessment of interdependencies of the existing system, the design structure and complexity (Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019). Within this process old and new technologies are mapped to provide direction for the implementation and an implementation and control strategy is set up to ensure a successful implementation (Sjödin *et al.*, 2018; Huber, Henkel and Kranz, 2019). To define the specific new-value, processes need to be rethought from big data and new value-capturing modes (Iansiti and Lakhani, 2014). The target is to have delimited use cases with a distinct scope to identify the concepts with a high potential and low resource input (Cooper, 2008; VDMA Industrie 4.0 Forum, 2016).

Roadmap

Through the creation of the *roadmap*, all use cases are visualized regarding time and content dependencies (VDMA Industrie 4.0 Forum, 2016; Huber, Henkel and Kranz, 2019). This will facilitate the implementation and the transformation into suitable projects, which are able to be implemented (VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018).

2.2.2 Operational implementation

The operational implementation represents the project organization of a specific prior defined use case.

Connect / integrate

The *connect / integrate phase* comprises out of the integration of the new technology to search for synergies across the company and get the technology running (Iansiti and Lakhani, 2014; Sjödin *et al.*, 2018; Huber, Henkel and Kranz, 2019). Prior to the integration, it is suggested to have a kind of project kick-off with the employees affected and to set up an integration proceeding (Huber, Henkel and Kranz, 2019).

Examine / validate

The phase of *examination and validation* comprises out of the development of the operating concept or pilot, as well as the evaluation of improvements through the new technology. This can contains the assessment of the new value creation, which makes it possible to also assess if further possible value can be created with the solution (Iansiti and Lakhani, 2014; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019).

Develop business case

The *development of the business case* is done based on the prior phase, on the pilot developed, through which a clear picture of the value creation was gained. This will be quantified and the return on investment is calculated (Cooper, 2008; Iansiti and Lakhani, 2014; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019).

Execute / implement

After the release of the project into the *implementation*, the technology will be fully tested, developed and implemented (Cooper, 2008; Illa and Padhi, 2018; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019). Once the results and the value creation are achieved, in the defined area, the project can be handed over to the last phase (Iansiti and Lakhani, 2014; Illa and Padhi, 2018).

Scale

The final *phase of scaling* includes the rollout and the launch of the solution (Cooper, 2008; Pinto *et al.*, 2019). This means evolving to similar processes, use cases and to more complex processes as an evolution stage (Illa and Padhi, 2018; Pinto *et al.*, 2019).

Success factors of SF project implementation

A common mentioned success factor is the use of agile methods and elements in the project implementation for SF (Yusuf, Sarhadi and Gunasekaran, 1999; Vinodh, 2011; Radziwon *et al.*, 2014; Pérez-Lara *et al.*, 2018; Sjödin *et al.*, 2018; Di Fiore, West and Segnalini, 2019; Sony and Naik, 2019). This enables project teams to react and adapt quickly to new circumstances, free capacity through less reporting effort and bring technologies faster to market, while facing high uncertainties in the implementation of a new technology (Yusuf, Sarhadi and Gunasekaran, 1999; Vinodh, 2011; Radziwon *et al.*, 2014; Pérez-Lara *et al.*, 2018; Di Fiore, West and Segnalini, 2019). Generally, change needs to be incorporated by organizations as a core competence, in order to reach their strategic objectives and to enable fast transformations (Yusuf, Sarhadi and Gunasekaran, 1999; Radziwon *et al.*, 2014; Pérez-Lara *et al.*, 2018)

Further, it was outlined as important to use a stage-gate model, in order to have well-defined targets, but using agile methodologies within each stage to benefit from both approaches (Cooper, 2008; Sjödin *et al.*, 2018). This comprises out of the recruitment of a product owner and scrum master, setting up of cooperation and cross-functional teams and a guideline on how to handle delays (Sjödin *et al.*, 2018). It has to be mentioned, that some companies transform stage-gate models into processes full of bureaucracy, although the initial intention of the stage-gate project model matches the requirements of an agile process, with being a well-defined and efficient system, that speeds time to market (Cooper, 2008). A stage-gate model with agile elements matches also the implementation models, which were elaborated already.

2.3 Key factors of the introduction of Smart Factory

In the following an overview of the literature on the question regarding success factors, challenges and outcomes of the SF introduction of different authors are presented. This supports RQ2, in order to be able to consider the respective key factors within the implementation. Criteria have been clustered for better accessibility. Additionally, maturity models are depicted to support the research question and display success factors based on the maturity.

2.3.1 Success factors

The most important factors to consider within the implementation of a SF, in order to be successful, are elaborated in the following.

Success factors within the SF introduction have been clustered and are depicted below in Table 2. These are data acquisition / transfer / use, IT architecture (hard- / software), use case considerations, culture development, initial assessment, Smart Factory property, organizational processes, competency / skill enhancement and external collaboration / networking.

Table 2: Topic cluster success factors of SF implementation

Topic cluster	No. of success factors
Data acquisition / transfer / use	24
IT architecture (hard- / software)	21
Use case considerations	20
Culture development	19
Initial assessment	16
Smart Factory property	15
Organizational processes	14
Competency / skill enhancement	11
External collaboration / networking	3

The number of success factors represents the quantity of mentioning success factors in current research, related to the distinct category. These have been outlined as well, as they provide an indication of the importance of each category in the current literature. Success factors related to technical aspects like data acquisition / transfer / use and IT architecture, as well as use case considerations and culture development have the highest focus, where organizational processes, competency and skill enhancement and external collaboration are not as focused.

The complete literature overview on success factors can be found in Appendix 1 – Success factors of SF implementation. The success factors are elaborated in the following.

Data acquisition / transfer / use

The acquisition, transfer and the use of data has been given the highest focus. Important have been found to focus on aiming for and increasing data quality. This means to strive for large, real-time, reliable and usable data (Yao, Jin and Zhang, 2015; Jäger *et al.*, 2016; Mabkhot *et al.*, 2018; Sjödin *et al.*, 2018). The basis for this, is data acquisition with setting up automated processes for mining and sharing of data (Davis *et al.*, 2012; Lee and Lee, 2015; Chen *et al.*, 2017; Sjödin *et al.*, 2018). This enables the detection of potentials based on high quality data, real-time performance analysis and the resulting visualization of critical operational analytics (Davis *et al.*, 2012; Chen *et al.*, 2017; Mabkhot *et al.*, 2018; Sjödin *et al.*, 2018). Through this, it is possible to integrate the gained data-based results into decision making (Mabkhot *et al.*, 2018; Sjödin *et al.*, 2018). The reliability and validity of the dataset can be further increased through enlarging it, with creating data flow of already existing processes, data sources (e.g. sales and quality data) and the integration of digital systems from tiers and knowledge sharing with suppliers, users and shareholders. This whole set of success factors enables control and heal-ability of the system as a whole, including supply chain predictability (Chen *et al.*, 2017; Mabkhot *et al.*, 2018; Sjödin *et al.*, 2018).

IT architecture (hard- / software)

The highest importance is seen in having a defined IT architecture, in order to be able to connect all new technologies (Davis *et al.*, 2012; Mabkhot *et al.*, 2018; Sony and Naik, 2019). Within the setup, data centricity, vertical integration, as well as cloud computing and connection need to be considered. Further, the IT architecture needs to enable plug and play of components and a decentralized and modular control. However, only with secure communication between all elements a robust and reliable basis can be achieved (Davis *et al.*, 2012; Illa and Padhi, 2018; Mabkhot *et al.*, 2018; Frank, Dalenogare and Ayala, 2019; Huber, Henkel and Kranz, 2019). Although success factors as improving sensor technology, providing enough data storage, enable traceability, virtualization and energy management and using embedded computers and virtual interfaces with CPS might have a relative lower importance, they should not be neglected (Davis *et al.*, 2012; Lee and Lee, 2015; Mabkhot *et al.*, 2018; Frank, Dalenogare and Ayala, 2019). Other important factors were the selecting of the right platform and the right integration partner (Illa and Padhi, 2018).

Use case considerations

The most important factor, is to generally identify company fitting use cases and technologies (Jäger *et al.*, 2016; VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Sjödin *et al.*, 2018; Pinto *et al.*, 2019). The use cases should focus on optimization of small and independent areas, but still should consider consecutive scalability, as well as focusing on rapid implementation of the pilot projects to ensure a successful start. Dependencies to other topics and the integration into pre-existing information systems need to be outlined and considered (Jäger *et al.*, 2016; Huber, Henkel and Kranz, 2019; Masood and Egger, 2019; Pinto *et al.*, 2019). To make the new use cases tangible, a business case focus with an ROI calculation and prediction should be applied and the benefits of each project stage be quantified. To ease the realization, use cases with moderate investment and training effort should be favored (VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019).

The investment for the overall IT architecture should be strategically managed and not be one additional use case, as it should be considered as the basis for all use cases (Sony and Naik, 2019).

Culture development

To develop into a culture, which supports the SF implementation, first an open smart manufacturing culture and the incorporation of the lean philosophy needs to be realized (Zuehlke, 2010; Mittal, Romero and Wuest, 2018; Sjödin *et al.*, 2018; Büchi, Cugno and Castagnoli, 2020). Further key factors are to create cross-departmental collaboration and proactive knowledge-sharing, also of the production staff (Illa and Padhi, 2018; Mabkhot *et al.*, 2018; Mittal, Romero and Wuest, 2018; Sjödin *et al.*, 2018; Huber, Henkel and Kranz, 2019). This can be enabled through cross-functional digitalization networks and the decentralization of decisions and the decision process (Davis *et al.*, 2012; Sjödin *et al.*, 2018). In return, organizational agility and continuous smart innovation through innovative active employees can be triggered (Mittal, Romero and Wuest, 2018; Sjödin *et al.*, 2018; Masood and Egger, 2019; Sony and Naik, 2019). To create a connection between the shop floor and the business environment and vice versa, a direct relationship of the management and the worker should be enabled (Davies, Coole and Smith, 2017). For a further support of the cultural development, it is important to keep the organization up to date with the latest smart manufacturing trends (Mittal, Romero and Wuest, 2018).

Initial assessment

Assessing the readiness of the factory and the equipment was outlined as essential. The assessment includes the degree of intelligent manufacturing, in order to get an indication of the effort for the SF implementation (Qin, Liu and Grosvenor, 2016; Chen *et al.*, 2017; Illa and Padhi, 2018; Sony and Naik, 2019). A further point is ensuring top management support and commitment and an approved budged for the initiative (Trost, 2015; Illa and Padhi, 2018; Huber, Henkel and Kranz, 2019; Li, Peng and Xing, 2019; Masood and Egger, 2019; Sony and Naik, 2019). Further, including IoT infrastructure and data related aspects, as well as organizational and human issues in the assessment have been outlined as important (Li, Peng and Xing, 2019). Of further importance are the degree of product smartness and automation, as well as solid governance (Illa and Padhi, 2018; Mabkhot *et al.*, 2018; Frank, Dalenogare and Ayala, 2019).

Smart Factory property

The criteria included in this cluster can be understood as the properties of the target state “the SF.” Important is, that technologies, interfaces and dashboards are designed for humans and modular and reconfigurable fixtures and tools are incorporated (Zuehlke, 2010; Davis *et al.*, 2012; Mabkhot *et al.*, 2018). Machines are connected through intelligent production and transport systems to enable a self-adopting, decentralized and flexible structure with the self-organization of the system. Through simulation and virtual systems, a proactive production planning and forecasting is realized. Customers are delighted by I4.0 solutions, through offering core processes as services and increased focus on after-sales services (Zuehlke, 2010; Jäger *et al.*, 2016; Mabkhot *et al.*, 2018; Sjödin *et al.*, 2018; Frank, Dalenogare and Ayala, 2019; Sony and Naik, 2019).

Organizational processes

Of high importance is the factor of the gradual implementation and progressive adaption towards the SF (Qin, Liu and Grosvenor, 2016; VDMA Industrie 4.0 Forum, 2016; Mittal, Romero and Wuest, 2018; Sjödin *et al.*, 2018; Frank, Dalenogare and Ayala, 2019; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019). This needs to be supported with the development and with the guidance of an I4.0 strategy, vision and roadmap (Trost, 2015; VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Huber, Henkel and Kranz, 2019; Sony and Naik, 2019). Both previously mentioned success factors are shaped in a formal implementation process and an I4.0 strategy framework with the capabilities and use-cases (VDMA Industrie 4.0 Forum, 2016; Sjödin *et al.*, 2018; Huber, Henkel and Kranz, 2019). Of further importance are to create specialized roles for predictability and a defined project organization for the implementation of the use cases (Sjödin *et al.*, 2018; Huber, Henkel and Kranz, 2019).

Competency / skill enhancement

Of major importance as a basis, also in an overall relation to other categories, has the building up of internal expertise and the training of employees (Davis *et al.*, 2012; Lee and Lee, 2015; Trost, 2015; VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Mabkhot *et al.*, 2018; Sjödin *et al.*, 2018; Li, Peng and Xing, 2019; Mittal *et al.*, 2019). Only with this, the factory is equipped with the necessary digitalization knowledge, which can be supported additionally through recruiting data scientists and analysts (Sjödin *et al.*, 2018).

External collaboration / networking

External related success factors are established personal networks and market observations, as well as a process for the inclusion of partners and technology partnerships (Jäger *et al.*, 2016; Illa and Padhi, 2018; Sjödin *et al.*, 2018).

2.3.2 Challenges

The most important challenging factors to consider within the implementation of a SF, in order to be able to encounter these, are elaborated in the following.

The topic cluster of challenges depicted below in Table 3, are technical, organizational and external challenges.

Table 3: Topic cluster challenges of SF implementation

Topic cluster	**No. of challenges**
Technical	20
Organizational	19
External	4

Through the indication of no. of challenges, the equal focus on technical and organizational challenges can be identified. The complete literature overview on challenges can be found in Appendix 2 – Challenges of SF implementation. The challenges of the different topic clusters will be elaborated in the following.

Technical challenges

The biggest challenge is seen in ensuring IT security and safety, as well as in arising privacy issues (Bauer, Jendoubi and Siemonheit, 2004; Lee and Lee, 2015; Jäger *et al.*, 2016; Kagermann *et al.*, 2016; Wang, Wan, Li, *et al.*, 2016; Mueller, Chen and Riedel, 2017; Huber, Henkel and Kranz, 2019; Li, Peng and Xing, 2019). In addition, the setting up of an appropriate infrastructure including CPS and sensors, as well as to create a robust system are highlighted to be possible challenges (Iansiti and Lakhani, 2014; Lee and Lee, 2015; Jäger *et al.*, 2016; Kagermann *et al.*, 2016; Mueller, Chen and Riedel, 2017; Li, Peng and Xing, 2019). Further challenges outlined are managing and controlling of the machines, the high complexity, the introduction of intelligent decision making and negotiation mechanisms, manufacturing specific big data and analytics, as well as flexible conveying for adaptable routing (Iansiti and Lakhani, 2014; Wang, Wan, Li, *et al.*, 2016; Mueller, Chen and Riedel, 2017).

Organizational challenges

The biggest organizational challenge outlined is, to develop the necessary employee skills and get qualified personal and the knowledge of organizational implementation (Bauer, Jendoubi and Siemonheit, 2004; Jäger *et al.*, 2016; Kagermann *et al.*, 2016; VDMA Industrie 4.0 Forum, 2016; Huber, Henkel and Kranz, 2019; Li, Peng and Xing, 2019). Another major challenge is the necessity of high initial investment for the IT infrastructure. Further encountered challenges are, the cooperation and information sharing between departments, the system modelling and analysis and the missing capacity for implementation (Lee and Lee, 2015; Jäger *et al.*, 2016; Kagermann *et al.*, 2016; Wang, Wan, Zhang, *et al.*, 2016; Mueller, Chen and Riedel, 2017; Huber, Henkel and Kranz, 2019; Masood and Egger, 2019). Within the initial phase of the implementation challenges are, limited financial resources, if the budget was not managed holistically, as well as unsuccessful projects, which could lead to higher resistance against the implementation of the SF (Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019).

External challenges

External related challenges are new competitors, technologies and business models, as well as legal certainty (Jäger *et al.*, 2016; Kagermann *et al.*, 2016).

2.3.3 Outcomes

The topic cluster of outcomes depicted below in Table 4, are business impact and direct result of technology. While direct result of technology is more detailed and refers to the direct outcome an implemented technology has on the process, product or system, the business impact refers to the consequential impact on the overall business. This means, business impact accounts for the higher level, to which the result of technology leads, e.g. a more responsive supply chain (direct result) leads to increased flexibility (overall business).

Table 4: Topic cluster outcomes of SF implementation

Topic cluster	No. of outcomes
Business impact	29
Direct result of technology	14

Through the indication of the no. of challenges, a greater focus can be observed on the business impact, where distinct technology results have not been investigated to the same extend. The complete literature overview on challenges can be found in Appendix 3 – Outcomes of SF implementation. The outcomes of both topic clusters will be elaborated in the following.

Business impact

The highest business impact of an implementation of SF is increased efficiency, increased flexibility and improved (product) quality (Jäger *et al.*, 2016; VDMA Industrie 4.0 Forum, 2016; Sjödin *et al.*, 2018; Sony and Naik, 2019; Büchi, Cugno and Castagnoli, 2020). Further outcomes are, increased effectiveness, increased speed (of innovation), improved (product) safety, better sustainability and lower cost (Davis *et al.*, 2012; Trost, 2015; Jäger *et al.*, 2016; VDMA Industrie 4.0 Forum, 2016; Sjödin *et al.*, 2018; Sony and Naik, 2019; Büchi, Cugno and Castagnoli, 2020). Additionally, the risk of decisions is increased, fast ROI is gained, larger product variety is possible, insurance cost can be reduced and higher margins through direct sales can be generated. Additionally, strategic decision making can be improved, as well as market strength be increased and competitive advantage can be reached, through meeting customer needs better (Trost, 2015; Wang, Wan, Li, *et al.*, 2016; Pagnon, 2017; Sony and Naik, 2019; Büchi, Cugno and Castagnoli, 2020).

Direct result of technology

A direct outcome of technology implementation is, the removal of human error and injuries (Pagnon, 2017; Büchi, Cugno and Castagnoli, 2020). Further, the decentralization of data analytics and IT skills, cheaper production of custom products, through optimization and the detection and prevention of breakdowns can be achieved. Additional outcomes impacting on the supply chain are real-time traceability, increased capacity, decreased logistics effort through a more responsive and optimized supply chain. Employee related outcomes are increased workers health and overall lower cost management. Even manufacturing innovation and manufacturing intelligence can be increased through the implementation of SF technologies and initiatives (Davis *et al.*, 2012; Trost, 2015; Pagnon, 2017; Sony and Naik, 2019; Büchi, Cugno and Castagnoli, 2020).

As an interim conclusion it is visible, that the same criteria can be found in either success factors or challenges, depending on the subjective perception. However, the most frequently mentioned success factors, challenges and outcomes are depicted in Table 5. This represents a status and will be further validated with the use cases.

Table 5: Success factors, challenges and outcomes of SF implementation

Success factors	Challenges	Outcomes
• Employee training • Gradual implementation • Top management commitment • Company specific technologies • I4.0 strategy and roadmap • Data quality • Automated data mining and sharing • Open SF culture • Defined IT architecture • Real-time performance analysis • Cross department collaboration	• IT security and safety • Develop employee skills • Organizational implementation • High investment • IT infrastructure • Robust system	• Increased efficiency • Increased flexibility • Improved quality • Increased effectiveness • Increased speed • Less errors • Better sustainability • Improved safety • Lower cost

During the review it turned out, that the gradual implementation of a SF is a major success factor, as well as the different success factors and challenges to be considered, do not account generally for application, but depend on the maturity of the SF (Qin, Liu and Grosvenor, 2016; VDMA Industrie 4.0 Forum, 2016; Mittal, Romero and Wuest, 2018; Sjödin *et al.*, 2018; Frank, Dalenogare and Ayala, 2019; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019). Therefore, to provide an implementation framework (RQ1), it is necessary to detail the key factors into stages to be applicable. To support this, the next chapter will depict maturity models in more detail.

2.3.4 Maturity models

Different authors suggest the gradual implementation of the SF, based on an I4.0 strategy and roadmap (Trost, 2015; Qin, Liu and Grosvenor, 2016; VDMA Industrie 4.0 Forum, 2016; Illa and Padhi, 2018; Mittal, Romero and Wuest, 2018; Sjödin *et al.*, 2018; Frank, Dalenogare and Ayala, 2019; Huber, Henkel and Kranz, 2019; Pinto *et al.*, 2019; Sony and Naik, 2019). Also, the other most frequently mentioned success factors, such as data quality, automated data mining and sharing, real-time performance analysis and open SF culture are not set up at once but are evolved out of a maturity process. Therefore, a maturity model can represent this gradual approach and facilitate the understanding of the path with the underlying factors towards the goal SF.

An overview over the found maturity models is displayed in the following in Table 6.

Table 6: Maturity models

Author	Model	Characteristics
Frank, Dalenogare and Ayala (2019)	3-stage maturity model	Stage 1: Vertical integration, energy management, traceability; Stage 2: Automation, virtualization; Stage 3: Flexibilization
Sjödin *et al.* (2018)	4-stage maturity model	Level 1: Connected technologies; Level 2: Structured data gathering and sharing; Level 3: Real-time process analytics and optimization; Level 4: Smart and predictable manufacturing
Mittal, Romero and Wuest (2018)	5-stage maturity model	Tools boxes with maturity levels of manufacturing / tools, design / simulation, robotics / automation, sensory / connectivity, cloud / storage, data analytics, business management
VDMA Industrie 4.0 Forum (2016)	5-stage maturity model	Maturity categories of data processing, machine-to-machine communication, company wide networking with production, ICT infrastructure in production, man-machine interfaces, efficiency with small batches
Odwazny, Cyplik and Szymanska (2018)	3-stage maturity model	Stages of aspiration, maturity and SF with criteria for human factor, technical / organizational and management

To establish a common maturity model, each model was broken up into its detailed criteria and mapped into a five-stage maturity model, as this was the common denominator of the level of detail. The stages range from no focus, over aspiration, early and late maturity to SF. To facilitate the assessment, different clusters, which account for a common category have been created. The complete overview of criteria with the mapping into the respective maturity level and category can be found in Appendix 4 – Criteria maturity models. All categories are based on the models set up by VDMA Industrie 4.0 Forum (2016), Mittal, Romero and Wuest (2018), Odwazny, Cyplik and Szymanska (2018), Sjödin *et al.* (2018) and Frank, Dalenogare and Ayala (2019). In the following each topic with the respective maturity levels will be elaborated.

Automation / robotics

The category of automation / robotics advances from manually operated machines and the use of hand-tools over to the use of robots, non-programmable machines, and the automation of single processes, to programmable machines and automatic non-conformities identification in the early maturity. The late maturity stage consists out of collaborative robots and an order-based processing, where the target SF state represents collaborative robots, based on AI and the automation, based on sustainability aspects. Table 7 provides the overview of the category.

Table 7: Category Automation / robotics

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
Manually operated machines and use of hand-tools	Automation of single processes	Programmable machines, automatic NC identification	Collaborative robots and automation of order processing	Collaborative robots (AI) and sustainability driven automation

Design and simulation

The lowest stage represents paper-based design, followed by the computer aided design (CAD), where environment and the model are software supported. Early maturity is the incorporating of simulation software and models into decisions and production steering. Virtual commissioning, the simulation-based testing, 3D-prototyping and optimization of the digital factory account for late maturity. The SF state is the use of additive manufacturing, augmented and virtual reality, as well as the use of simulation models for all decision processes. Table 8 represents the overview of the category.

Table 8: Category design and simulation

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
Paper based design	Computer aided design (CAD)	Simulation software and models used for decision making	Virtualization (simulation to test, prototype, optimize)	AM, simulation used in all decisions, AR & VR

IIoT (connectivity / traceability)

No asset communication represents the level of applying no focus on IIoT. In the aspiration state, sensors, actuators, PLCs and field bus interfaces are partly equipped in the machine park. Early maturity represents the gradual implementation of IoT, with the inclusion of further elements. RFID or a similar technology is widely used in the factory. This enables the conversion of signals into readable formats and traceability. The late maturity state represents full traceability of raw materials and products and the connection of all machines to the database. Connectivity on the SF level is the full integration of all tools and technologies and enabling machine to machine (M2M) communication and the use of web-services. Table 9 depicts the overview of the category.

Table 9: Category IIoT (connectivity / traceability)

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
No communication	Sensors, PLCs, field bus interfaces available	Gradual connection of assets, tracking of products	All assets are connected tracking of raw materials	M2M communication, full connection of tools and technologies

Data storage / integration

No focus on data storage and integration is characterized using registers, logbooks and spreadsheets, as well as the information exchange via mail or telephone. The first advancement is to have sufficient technology and IT solutions, such as an ERP system and central data servers in production. In the aspiration state, existing applications should be connected to create data flow. An early maturity represents the use of an MES, which also stores sensor data, a full integrated software and data system, as well as uniform data formats and rules for data exchange. Late maturity represents the use of a cloud, interdivisional linked data servers and an automated information exchange. By using a fog (a cloud with reduced network congestion and latency), the efficient storage is ensured in the SF state. Further, the data base is fully secured, as well as IT solutions are fully networked, inter-divisional and suppliers and customers are integrated into the process design. Table 10 represents the overview of the category.

Table 10: Category data storage / integration

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
Manual info exchange, spreadsheet, registers	ERP, connect applications, central data servers	MES, uniform data format, software and systems integrated	Storage of sensor data, cloud, automated data exchange	Secured data base, inter-divisional & networked IT solutions

Data processing

The state of no focus is no processing of data. The aspiration level represents the use of a supervisory control and data acquisition (SCADA) system, storing data for documentation, as well as aspiring to aggregate available data efficiently, including cleaning. Early maturity represents data integration of different sources, the build-up of automated processes for data mining, analyzing, monitoring and sharing across production functions. The concept of big data is in the first steps of introduction and the accuracy of data collection is increased. Late maturity represents the use of AI in maintenance and production, big data and using optimization and real-time analysis to streamline operational processes. In the SF data aggregation, analysis and interpretation is world class. Data is important, valid, up-to-date, real-time and allows active production steering. Proactive processes for forecasting and planning scenarios are implemented and a system analysis, monitors and visualizes critical operational processes. Process planning and control are automatized. Table 11 shows the overview of the category.

Table 11: Category data processing

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
Data collection but no processing	Data for documentation, data cleaning, SCADA	Big data introduction, mining processes and monitoring of assets	AI (maintenance & production), real-time analysis and optimization	World class data aggregation, analysis and interpretation

Man – machine interface

When no information is exchanged between the user and the machine, no focus of SF is given to man – machine interfaces. Using local user interfaces represents aspiration, while centralized production monitoring and control represents early maturity. The advancement to late maturity characterizes remote operation and the use of mobile interfaces. The ability to be operated through interfaces and the use of augmented and assisted reality characterizes the SF state. Table 12 depicts the overview of the category.

Table 12: Category man - machine interface

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
No information exchange between machine and user	Local user interfaces	Remote / centralized monitoring	Remote operation / use of mobile interfaces	Operation via interface, Augmented and assisted reality

Small batch production

Having no focus is characterized by a rigid production system and a small proportion of identical parts. Aspiration is seen in using a flexible production system and using the existing identical parts. The maturity in an early stage is characterized through using a flexible production system and a modular product design, where the late maturity is additionally component driven. The SF state represents a flexible production system with flexible lines and a component-driven modular production embedded in value-adding networks with tiers. Table 13 depicts the overview of the category.

Table 13: Category small batch production

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
Small proportion of identical parts	Use of flexible production systems and identical parts	Flexible production system and modular product design	Component-driven flexible production of modular products	Component-driven flexible production in value-adding networks

Horizontal integration

Regarding the maturity of horizontal integration, a no focus criteria was not found within the references. The aspiration state represents the readiness to cooperate with other departments inside the company. The advancement is the execution with full cooperation between departments, the use of digital platforms with other units, as well as the readiness to cooperate with other companies in the supply chain. Late maturity is the execution of the cooperation among tiers, organizing knowledge-sharing sessions with suppliers, customers, users and other stakeholders, as well as the use of digital platforms with suppliers. The SF state characterizes the full collaboration with suppliers and customers, by being an integral element in the supply chain, customize products according market demand, being digitally connected with customers and suppliers to enable demand driven planning based on single orders. Table 14 represents the overview of the category.

Table 14: Category horizontal integration

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
-	Cooperate with other departments	Full cooperation and digital platforms with other departments	Digital platforms with suppliers, collaboration with customer / supplier	SC integration and collaboration, demand driven planning

Digital culture

The no focus state, which represents the base for the consecutive stages is the implementation of lean philosophy and the reduction of waste. Aspiration characterizes having the same values and beliefs, as well as the creation of an inclusive culture for SF implementation through the involvement of the workforce. In the aspiration stage employees apply a digital lens to existing processes and technologies to develop a target state. Early maturity represents the employee involvement outside of R&D and the build-up of cross-functional digitalization networks, to facilitate knowledge sharing.

Late maturity was not characterized, while the SF state represents the creation of a continuous SF innovation culture. Table 15 represents the overview of the category.

Table 15: Category digital culture

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
Lean thinking	Same values / beliefs and inclusive culture, apply digital lens	Cross-functional digitalization networks, employee involvement	-	Culture of continuous SF innovation

Cross-departmental collaboration

Having no focus on cross-departmental collaboration is characterized through no networking of the production with other business units. While in the aspiration state individuals are capable to work in teams and information is exchanged via mail or telephone, in the early maturity teams gain autonomy and can easily work with others as well as are using shared internet-based data portals with other departments. Late maturity was not characterized. The SF state represents a high level of autonomy of teams and individuals and decentralization. Table 16 depicts the overview of the category.

Table 16: Category cross-departmental collaboration

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
No networking with other departments	Individuals capable to work in teams	Autonomous teams and cooperation portals for sharing data	-	High level of autonomy and decentralization

Organization

In the category of organization, no criteria were found for having no focus. In the aspiration state the SF implementation process and a process for involving external actors needs to be formalized. The early maturity characterizes the revision of production staff roles to proactively coordinate digital insights and knowledge sharing, where in the late maturity employees only control the processes and react to system warnings if necessary. The SF state is characterized by investment pressure in R&D area, no operational employees in the machine park and the presence of specialized roles and responsibilities towards predictable production. Table 17 represents the overview of the category.

Table 17: Category organization

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
-	Formal implementation processes of SF and external involvement	Revise production roles to share digital insights and knowledge	Employees control processes and react to changes	Specialized roles towards predictable production

Skills / know-how

In the skills and know-how category no criteria for no focus category was found. The aspiration characterizes the recruitment of people with digitalization knowledge and the presence of qualified individuals, including IT specialists and automation engineers. In the early maturity the focus is on educating people to develop the ability to exploit the connected data systems and to be able to analyze and operate them. In the late maturity dedicated data analysts and scientists are recruited to optimize production. In the SF state, staff consists out of digitalization experts and employees are moved from shop floor to other departments if possible, as additional skill and knowledge is demanded. Table 18 represents the overview of the category.

Table 18: Category skills / know-how

No focus	Aspiration	Early Maturity	Late Maturity	Smart Factory
-	Qualified employees and IT specialists	Operational employees have / are educated in digitalization skills	Recruit data analysts and scientists to optimize production	Staff consists out of experts

Each category sums up the theory and will be further detailed with case studies.

3 Method and implementation

This chapter outlines the methodology applied in this study. First, the overall research approach is explained and elaborated. This is followed by the depiction of the detailed proceeding of the literature review, including review principles, as well as the presentation of the use cases. This includes the introduction to the focal case company, data collection and the analysis.

3.1 Research approach

The research process can be divided in four parts, which are literature review, orientation study, main study and validation. The literature review was carried out according to the PRISMA statement, as it provides a transparent process and accounts for a guideline in article selection (Moher *et al.*, 2009).

The research follows the suggested procedure of Yin (2009), to develop prior a theoretical proposition, which then guides data collection and analysis. This represents the implementation process of SF in chapter 2.2, the success factors, challenges and outcomes in chapter 2.3 and the maturity model categories in chapter 2.3.4.

To develop the theory further, case studies were chosen. This qualitative research method was chosen, as the research questions target at a very current issue of the manufacturing industry, as well as the fact, that a sound description of the requirements are necessary for the evaluation of different solutions and these are highly context dependent (Yin, 2009). Further, case studies are the most appropriate methodology in early stages of research in the field, as well as theory developed out of case studies are likely to have novelty, testability and empirical validity (Eisenhardt, 1989). To enhance the validity of multiple data sources in case studies are used (Williamson, 2002). Multiple case studies allow a more thorough exploration of the field of research. A multiple case study has the advantages to produce robust, in-depth insights and higher generalizability in contrast to single case studies (Eisenhardt and Graebner, 2007). The selection of the methodological instruments was based on the case study. These are observations, semi-structured interviews and printed and qualitative data, to ensure research triangulation (Yin, 2009).

Trade-offs of theory building from cases are, that empirical evidence leads to outcomes, high in detail, but lacks simplicity of an overall perspective (Eisenhardt, 1989). To counteract this, questions related the most important factors and challenges are included in the questionnaire, to still be able to create a higher level of perspective, even with a detailed foundation.

Another weakness of theory building from cases is, although it might be very novel and empirically valid, generalizability is lacking, due to the bottom up approach. However, this can be counteracted through a combination of multiple studies and theory-testing (Eisenhardt, 1989). Therefore, the three phased research approach was chosen. First, conducting an orientation study, where appropriate cases are selected, followed by a main study, where knowledge is gained and a closing validation phase, where the developed framework again is discusses with the experts in the company.

3.2 Literature review

3.2.1 Systematic literature review method

The aim of the systematic literature review is to provide a neutral data collection and analysis. As the research outcome depends on what was done, what was found and how transparent the process was, a systematic and comprehensible process is necessary (Moher *et al.*, 2009).

For this study the PRISMA statement was chosen, due to the transparent process and guideline from identification to the rationale inclusion of appropriate articles, which it provides (Moher *et al.*, 2009). The PRISMA flow chart below in Figure 3, provides an overview over the different phases.

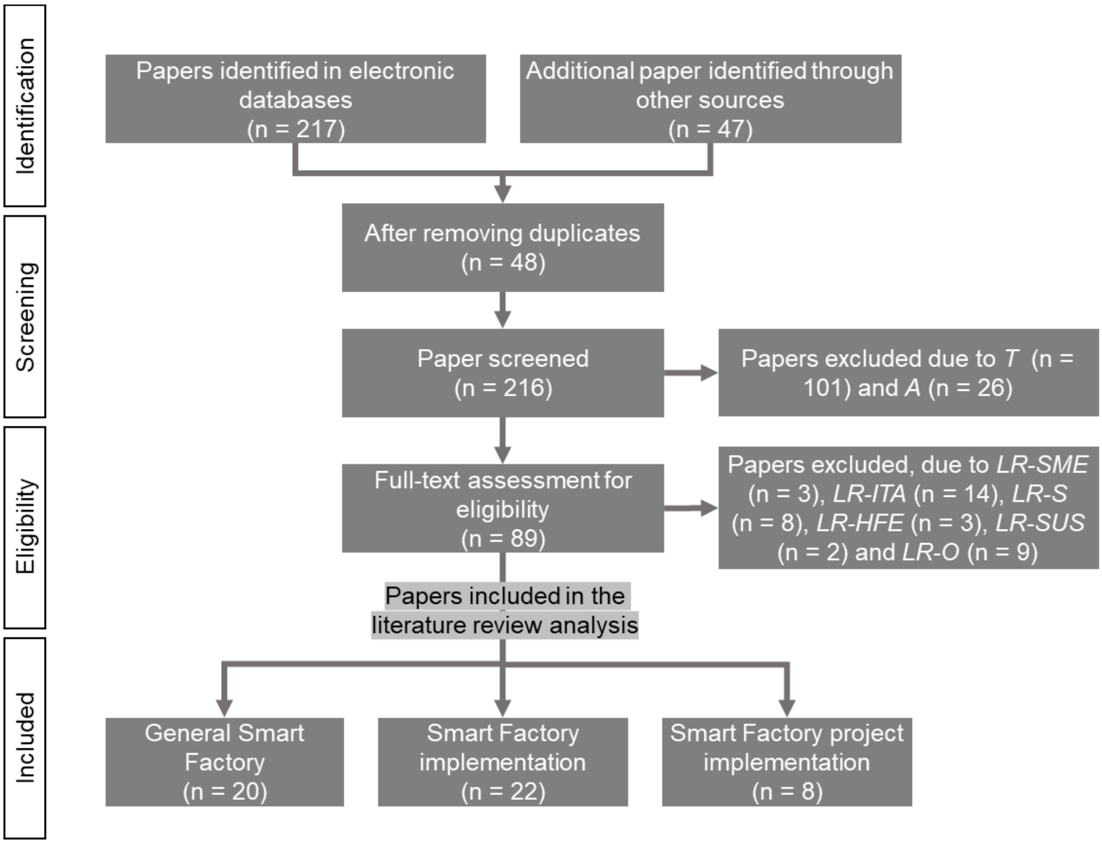

Figure 3: Systematic literature review, adapted from Moher et al. (2009)

The abbreviations of the exclusion criteria are depicted in Table 19 and further elaborated in the following chapter 3.2.2.

3.2.2 Literature search

For the literature search, only papers published in English and published between 2007 and 2020 are considered. This time frame was selected, as the focus on the topic increased due to governmental efforts to gain speed in the implementation (Strozzi *et al.*, 2017). For searching suitable literature, two databases and search engines were used. Namely, they are Science Direct and Primo, the library search engine of Jönköping University. Further in order to enhance validity only peer-reviewed articles in English were considered. The literature study, both research questions, RQ1 and RQ2, could be addressed through the same search terms, as it was not possible to distinguish in the literature search between the implementation of the SF in the sense of implementing the framework and implementing a SF project.

In Science Direct the search was conducted using for *title, abstract or author-specific keywords "Smart Factory implementation"* and filtering for *research articles* and *case reports between 2007 and 2020*.

In Primo the search was conducted using for *subject "Smart Factory"* AND for *any field "Smart Factory implementation"* and filtering only *full text* or *peer-reviewed* or *open access articles* in *English between 2007 and 2020*.

The search resulted in 217 identified papers (Science Direct n = 115, Primo n = 102). For getting an initial understanding of the topic and validating the research questions, two review articles provided a direction for further research on SF and I4.0, which were published recently. Both, Osterrieder, Budde and Friedli (2019) and Rub and Bahemia (2019), provided an initial overview over the field of SF implementation and the concepts developed in the last years. Therefore, based on these two reviews 47 articles were identified to be included as well.

In order to provide a transparent review process, the criteria for excluding papers should be explicitly outlined (Moher *et al.*, 2009; Liao *et al.*, 2017). In Table 19, the main exclusion criteria with their reasons for exclusion are depicted.

Table 19: Exclusion criteria and explanation

Criteria	Criteria explanation
Title (*T*)	Title not connected to implementation of SF, SF project implementation or generally on SF (n = 101)
Abstract (*A*)	Abstract does not display content of SF implementation, SF project implementation or generally on SF (n = 26)
Loosely related (*LR*)	Not focusing on the implementation of SF, but
	LR-SME: Assessing I4.0 in the context of SMEs (n = 3)
	LR-ITA: Developing of IT-architecture for I4.0 (n = 14)
	LR-S: Developing of software or hardware for I4.0 (n = 8)
	LR-HFE: Assessing human factors in the context of I4.0 (n = 3)
	LR-SUS: Focusing on chances with I4.0 on sustainability and re-manufacturing (n = 2)
	LR-O: Other (evaluation research trends, technology selection, management and impact on lean manufacturing) (n = 9)

The review process started first with the removal of duplicates (n = 48). The first screening process was carried out by reviewing the title (*T*) and where in doubt, briefly the abstract (n = 101). After the initial screening, all articles were assessed by their abstracts and keywords, where in doubt, briefly reading their contents (n = 26). Through this second screening process, articles were excluded, due to focusing not on aspects of implementation of SF, SF project implementation or generally on SF. Instead the focus of research was IT-Architectures (n = 13), future workforce skills (n = 9) and smart product implementation (n = 4). The next step covered the full text assessment for eligibility. During this step, further articles were excluded due to assessing I4.0 only in SMEs (n = 3), development of IT-architecture for I4.0 (n = 14), development of software and hardware solutions for I4.0 (n = 8), the assessment of human factors in the context of I4.0 (n = 3), the focus on potentials with I4.0 in sustainability and remanufacturing (n = 2) and others (n = 9). The result, after the full text assessment, was the categorization of articles into general SF articles (n = 20), SF implementation (n = 22) and SF project implementation (n = 8) for inclusion in the literature review.

3.3 Case Study

3.3.1 Case company

The headquarter of Company A is located in western Europe and was founded during the 1950s. The competence lies in the construction industry for professionals. In 2019 an overall turnover of >5 billion € was reached. In total 25.000+ employees in more than 120 countries are employed at Company A. Despite the size, all shares of Company A are held by the family of the founder. Company A’s DNA is manifested in innovation, which is quantified in a high expense on R&D and 40+ annual product patents. The corporate strategy is driven by creating high customers value and building a better future. The product portfolio ranges from intangible products such as consulting and services in the respective business field over the tangible products, such as machines onto consumer products. The case studies have been conducted in three different production plants of Company A, hereinafter referred to as Production A, B and C. The topic of SF is not new to Company A, as they started to focus on initiatives already.

Production Site A

Production A is subdivided into three production units on 20.000 m^2 production area. In total 360 people are employed. Each unit concentrates on different consumer goods. Within these production units, standard technology is combined with business leading technology for manufacturing for providing highest performance and quality. Technology ranges from different forming processes (hot and cold forming), as well as stamping and bending, over heat treatment and granulate production, to automated assembly.

Production Site B

In Production B different construction products and construction chemicals, as well as motors for machines are manufactured. In four specialized production units, different industry leading manufacturing technologies such as thread- and hot-forming and technologies for portioning of chemicals are operated. In total 500 people are employed.

Production Site C

Production C and the location is specialized in the development and manufacturing of plastics technology. Plastic products for machines and consumer products for the construction sector are produced with different technologies such as injection molding and complementary technology, as well as the assembly of consumer goods and machines on an area of 11.000 m^2. At the location currently 220 people are employed.

Despite all cases are conducted from Company A, the company provides valuable and heterogenic cases as the business field and manufacturing technology differ from production site to production site. Ranging from consumption goods, over machines and closed loop services of these machines.

3.3.2 Case selection

Out of the research gap, it is suggested to focus on cases of, software tools, digital application and IT systems, as they are the foundation of SF functionality and account for the biggest leverage. A proof of the framework in this context matches the direction of necessary advancement (Chen and Muraki, 1997; Azadegan *et al.*, 2011; Liu and Xu, 2016; Syberfeldt *et al.*, 2016; Sony and Naik, 2019). Therefore, a focus will be on such case studies, however also other technology implementations should be considered in order to provide a framework with generalizability.

For selecting appropriate cases, it is important to assessment the potential data, whether to interview people, review documents or records or make observations in the field. For choosing the cases, these that will most likely "illuminate" the research questions. should be favored (Yin, 2009). Therefore, the research starts with a pre-study of different cases, to assess the potential data, that can be gathered and chose the most appropriate. This increases the likelihood of success of the study (Bickman and Rog, 2013). The interview guideline for the orientation study can be found in Appendix 5 – Orientation study interview guideline.

Different recommendations regarding the quantity of case studies are given. Eisenhardt (1989) suggests four to ten, while Meredith (1998) suggests between two and ten case studies. Therefore, seven case studies have been identified in the orientation study to be used for theory development. In Table 20, a short description of the cases is displayed.

Table 20: Description case studies

Case	Plant	Description
ERP System user interface (EUI)	A	Introduction of front-end user experience improved apps for the ERP system
Condition Monitoring (COM)	A	Transparency of machine condition and visualization to enable preventive maintenance
Machine connectivity (MAC)	A	Machine connection to cloud and data collection
Robot implementation and integration (RII)	B	Implementation of palletizing robots and the integration into the system
Tracking consumables (TRC)	B	Implementation of a digital twin to ensure traceability for finished products
Automated guided vehicles (AGV)	C	Introduction of AGVs for intralogistics
AI in production process (AIP)	C	Process monitoring and process improvement through parameter optimization with AI algorithms

3.3.3 Data collection

Interviews

As a tools, semi-structured interviews were chosen for the main study, as they allow to investigate the knowledge and the working experience of the individuals in a more thorough and completer way (Williamson, 2002). For case studies it is required to control the environment of data gathering, where interviews are more suitable to (Eisenhardt, 1989). Another point is the high complexity of the topic and therefore the quantity of questions to investigate the topic. Through semi-structured interviews, it is possible to understand the reasons for attitudes, opinions and decisions taken. Additionally, they provide the opportunity to investigate areas of significant interest, which were not considered earlier (Saunders, Lewis and Thornhill, 2009). All interviews have been conducted face-to-face, as phone interviews lack the possibility to grasp other evidences, such as expressions and gestures. Also, to reduce potential perception gaps between plant and headquarter multiple cases or interview partners of each entity were considered in the selection. The same applies for hierarchies and functions (Eisenhardt and Graebner, 2007). Therefore, in selecting the interview partners of each case, both different hierarchies and functions were considered, e.g. Project Manager, SF responsible and unit head. In Table 21 below, the overview of interview partners and the respective phase of research is depicted.

Table 21: Overview interviews orientation study, main study and validation

Position	Company Site / Responsibility	Duration	Orientation / main study / validation
Program Manager I4.0	Global	50 min	Orientation
Head of Lean & SF	A	50 min	Orientation
Project Manager I4.0	B	0 min”	Orientation
Project Manager Digitalization	C	50 min	Orientation
IT Process Consultant I4.0	Global	35 min	Main study
Head of Maintenance	A	30 min	Main study
Project Manager (EUI)	A	35 min	Main study
Project Manager (COM)	A	30 min	Main study
Project Manager (MAC)	A	25 min	Main study
Project Manager (RII)	B	25 min	Main study
Project Manager (TRC)	B	25 min	Main study
Project Manager (AGV)	C	30 min	Main study
Project Manager (AIP)	C	50 min	Main study
Program Manager I4.0	Global	15 min	Validation
Head of Lean & SF	A	15 min	Validation
Project Manager I4.0	B	10 min	Validation
Project Manager Digitalization	C	15 min	Validation

**not available for interview, but suggestion of valuable cases at company site B*

In the opening of a semi-structured interview, the aim is to gain the interviewee's confidence through erasing uncertainties. This can be done by explaining the purpose and background of the study and the proceeding, stressing the anonymity and confidentiality, the right not to answer, the offer to provide a summary of the research findings and the request to record the interview electronically (Saunders, Lewis and Thornhill, 2009).

Questions should be clearly phrased and through open questions bias can be avoided and can be followed up through explicit exploring questions to create a full understanding. When using special terminology, it should be ensured that both the interviewee and the interviewer have the same understanding. To gather the participants experiences, critical incident technique was considered, in constructing the questions. This means, participants are given the opportunity to describe a critical incident, which is key to the research question (Saunders, Lewis and Thornhill, 2009).

Another point, which was considered in conducting the interviews was trust. Trust first, needs to be established in an interview, so that interviewees reveal their true perception, the first questions were rather general, then progressing in the level of sensitivity (Saunders, Lewis and Thornhill, 2009). The interview guideline of the main study can be found in Appendix 6 – Main study interview guideline.

Observation

Observations involve the systematic observation, recording, description and analysis of people in their natural setting. It has the aim to investigate, the root of what is going on (Saunders, Lewis and Thornhill, 2009). However, this method is used mainly in combination with other tools, such as interviews and other sources, as observations enhance the triangulation of case studies and are suitable to identify the more subtle factors of influence (Meredith, 1998; Saunders, Lewis and Thornhill, 2009).

Observations, in this study were carried out in knowledge-sharing meetings, regular gatherings and project meetings. The researcher took different roles during observations. Two roles of the researcher were overtaken occasionally. On the one hand, the role of the complete participant was overtaken, in case of own led project meetings for SF projects. On the other hand, the role of the participant as an observer. This means in both roles, the researchers' identity was revealed, as the researcher was member of the organization (Saunders, Lewis and Thornhill, 2009).

Printed and qualitative data

To enhance the validity, additional printed and qualitative data where considered to complement and enrich the findings of observations and interviews. The data included annual reports, internal presentations and guidelines, business plans and strategy papers, as well as project descriptions and status reports. The data was possible to access in the internal network, where only project descriptions and status reports where shared by the interviewees. Data of relevance was added to the case descriptions. However, no further statistical methods or content analysis was applied on the data.

3.3.4 Data analysis

To grasp the complete information of each case write-ups were used, as the importance of developing a rich familiarity with each case is outlined by Eisenhardt (1989). To further enhance the data quality and the completeness, interviews have been recorded, in order to enable a reassessment after conduction. This helps to grasp every detail. The approach for data analysis was first, summarizing and combining the findings according to the process outlined in chapter 2.2 and the maturity model in chapter 2.3.4. Secondly, the recorded interviews have been reassessed and the missing parts have been added. Thirdly, cross-case search for patterns was used, in order to avoid information-processing biases, such as limited data, relying more elite respondents or ignoring statistical properties. To avoid these biases, the key is to look at the data in different ways (Eisenhardt, 1989). The used strategies were twofold. The first strategy was, the division of source by data and searching for same pattern. When the same pattern from one data source, e.g. interviews, matches with one form another, e.g. observations, the finding is stronger and better grounded. The second strategy was the selection of different cases and the listing of similarities and differences between them. Through this, researchers focus on the subtle similarities and differences between the cases (Eisenhardt, 1989). Through these strategies the probability to grasp novel findings in the data is higher, as well as a higher accuracy and reliability is achieved (Eisenhardt, 1989).

3.4 Reliability and validity

Validity and reliability is especially important for qualitative research, in order to ensure the integrity of the study (Williamson, 2002). Through interviews of different departments and different responsibility levels, the internal validity of this study was ensured. Further, through the orientation study, valid cases were selected, and the gained insights from the case studies again checked with the internal experts. The data, which was collected at the company, is the foundation of the internal validity. The results of the study can directly be applied in the case company. External validity and reliability of this study was achieved through extensive research and review of articles in the respective field, including a comparison with the findings. Through observations and semi-structured interviews, method triangulation was used, which further ensures validity, as well as reliability of the study (Williamson, 2002).

Summarized the expected reliability and validity of this study is high, as different actions were undertaken, in order to improve both reliability and validity. However, the results can never account for complete generalizability in very differing contexts, although it tries to achieve it in a comparable context.

4 Findings

This chapter outlines the findings at Company A, gathered through 13 interviews, continuous observation and qualitative data. This chapter is structured according to the same logic as chapter 2 Theoretical framework. In the first sub-chapter, findings supporting RQ1: "How can the SF be implemented in practice?" are displayed, followed by findings targeting on RQ2: "What are success factors, challenges and outcomes of an implementation of SF?"

4.1 Implementation of Smart Factory

4.1.1 Strategic implementation

The strategic implementation of the SF was developed according to no official strategy process. The SF program evolved out of a bottom-up approach including the anticipation of the future state. However, the sequence was the strategy set up, set up of the roadmap and the revision of strategy and roadmap. The strategy comprises out of five enablers, which are digitalization, people and change, tools, technology and IT infrastructure.

4.1.2 Operational implementation

SF projects emerge in two ways and in a hybrid of both. One way is bottom-up, e.g. through work analysis and identification of high manual work tasks or tasks with little know-how required or cost reduction workshops or initiatives. The second way is the top-down initiation of SF projects through either the SF strategy, the corporate strategy and management or out of the department strategies. The close connection and alignment with the strategy was found in targeting on the same strategic measures in projects and overall.

On the operational level SF projects are organized according to the stage-gate time-to-market (TTM) process, with the phases of ideation, focusing, prototype, pilot, validation and scale.

In the *ideation* phase, the project idea and vision are developed. The set-up of the project organization, the requirement specification and the project plan are performed in the *focusing* phase, closing with the project order. The *prototype* phase has the goal to build a minimum viable product (MVP). Therefore, a prototype is created, vendors are evaluated, the solution is specified, and testing, training and change management is planned. After the MVP, the pilot is developed with setting up the system and solution, which includes a testing in real working environment. Also, the planning of testing, training and change management is refined. The phase closes with the management presentation and in a positive case, in the release into the *validation* phase. At this point then, the cut-over plan is finalized, and intensive care support is planned. The validation phase also includes the cut-over and the implementation of the change. The phase is closed with the validation of the implementation together with the management. If the solution achieves the targets, it is ready to be scaled. The *scale* phase includes the rollout of the solution, the handover to standard support, the analysis of the bottom-line impact and the setup of reporting and controlling including feedback loops. With the termination of the sale phase the project is terminated as well and in an operate state.

4.2 Key Factors of the introduction of Smart Factory

The content of this chapter is clustered according to the same topics as in chapter 2.3.

4.2.1 Success factors

The overview of success factors is displayed in Table 22. In total 71 success factors have been investigated, which will be elaborated in the following.

Table 22: Success factors SF introduction Company A

Topic cluster	**No. of success factors**
Organizational processes	32
Smart Factory property	8
Use case considerations	7
Culture development	6
Competency / skill enhancement	5
Initial assessment	4
Data acquisition / transfer / use	4
External collaboration / networking	3
IT architecture (hard- / software)	2

A visible shifted distribution of the no. of success factors towards organizational processes can be observed. According to the findings in Company A, success factors of SF implementation are mainly related to organizational processes and not as much to technical, use case or cultural aspects. This highlights the necessary focus and relevance of this thesis on the implementation process of SF with *RQ1* as many key factors to be consider have been investigated.

Organizational processes

The cluster of organizational processes has been again sub-clustered for a better accessibility into *strategy implementation, project communication, project management, team composition technology selection, user-integration and change management*.

Success factors regarding *strategy implementation* were the development of the SF strategy and vision by a global department, defined use-cases and global projects connected to the SF strategy and the manufacturing strategy, considering always a global perspective within the implementation, as well as a close collaboration between company sites to ensure the best solution for the overall company. Further, the coordination of SF initiatives through the Lean department, to have the connection to continuous improvement process and vice versa. To define actions and projects a maturity model supported and to establish strategy-supporting key performance indicators. Another point was the project steering and reporting via meetings on plant level and on a global level, shareholder management with considering the SF impact and internal communication supported by technology clusters.

Within the *project communication* regular meetings with the management, to ensure a regular communication and to consider all stakeholders, as well as ensuring a continuous communication in joint development with the vendor and having an open discussion concerning the target have been outlined as important.

Success factors in *project management (PM)* have been mainly twofold. On the one hand, connected to a sound project management, which means to have aligned project goals and scope, responsibilities, an effective communication and management support. On the other hand, connected to the use of Agile PM methods and the use of e.g. Scrum or Kanban, which degree depends highly on the novelty, complexity and uncertainty of the technology. Additionally, the more the project is shifted to Agile PM methods, the less important the milestones become.

Within the *team composition* of a project dedicated and defined resources (owner, leader, team), the formation of a core and expert team and the right IT and technical skills and knowledge within the team were important.

Regarding the *technology selection*, a sound market overview of different systems, solutions and vendors is of importance, resulting then in a selection of the appropriate fitting partner and technology. Further, the proof of concept should be in a small and delimited area, however also a sustainable solution needs to be ensured.

Of importance during the whole project is *user-integration*. This includes the involvement of employees with the right knowledge at an early stage, regular workshops with production employees, as well as the user integration into solution development, analysis and testing and the training and alignment of employees.

An often-mentioned success factor or point of improvement was *change management*. This means, setting up a change management strategy in the early project stages, as well as to carry out change management within the project, which includes the information, motivation, empowerment, the revealing of potential and education of employees.

Smart Factory property

The properties of the target state SF is seen in connectivity through vertical and horizontal communication with CPS, regional and global collaboration with smart devices and processes, automation of administrative, technologic and logistic processes, transparency of current processes and further insights, adaptability of machines and processes to change and predictability with data analytics and AI. On the non-technology side, involvement of stakeholders, embracing of smart innovation and easy process improvements based on data, are outlined.

Use case considerations

Important to consider within use-cases is to have a clearly defined vision and scope for the change, to think of new potential with the new technology and the standardization potential, consider regulations of e.g. work safety, as well as to keep the management attention until the end of project and the alignment with IT project management and IT security.

Culture development

Within establishing a culture of SF innovation, it was mentioned as important to create enthusiasm from beginning on, create communities on plant and between plants, create sensibility and an “eye” for digital technologies and requirements, ensure a good team collaboration and a common understanding of terminology. An addition was made, that the already introduced MES system helped to develop a digital mindset and created possibilities to use data.

Competency / skill enhancement

To develop the necessary skills and competencies for the SF new and different skills are necessary, as well as user trainings are critical. Further, the project teams need to have the fitting skills and knowledge of IT systems, IIoT landscape and the technical knowledge of production. To achieve this, two approaches have been made. Once many trial-and-error use-cases have been performed to explore the SF field and a digitalization team on plant level was set up.

Initial assessment

Before starting with the introduction, top management commitment and support, as well as the structures to maintain attention needs to be ensured. Further, an external view needs to be applied through benchmarking of other players and other plants.

Data acquisition / transfer / use

Enabling data acquisition, transfer and use is seen as the basis of connectivity and CPS. Only through high data quality, standardization and data integration advanced data analytics and the SF is possible to be realized. A major impact on success has the introduction of an MES.

External collaboration / networking

In order to get “fresh” inputs, external conferences and in the industry newly discussed technologies influence the internal implementation and broaden the horizon.

IT architecture (hard- / software)

A global defined IIoT architecture and the compatibility with existing ERP systems and software was pointed out to have a major impact on success.

4.2.2 Challenges

In total 32 investigated challenges have been clustered according to the topics of technical, organizational and external challenges, which are displayed in Table 23.

Table 23: Challenges SF introduction Company A

Topic cluster	No. of challenges
Organizational	20
Technical	11
External	1

The overview of the no. of challenges follows the distribution towards organizational related key factors, similar as outlined in the previous chapter 4.2.1. The challenges will be elaborated in the following.

Organizational

Challenges within the *PM* in a project, connected to a lack of sound PM have been unclear communication of tasks, duties and operational changes, an unclear scope, which resulted in different interests and unspecific phases, gates and deliverables including terminology. Additionally, the missing of dedicated IT resources, the dependency on other projects in terms of resources, as well as general limited resources for bottom-up projects and missing support from other departments

These challenges are also connected to *change management*, in detail a lacking communication strategy and blocking of employees against change.

Challenges regarding *skills and know-how* were the missing of know-how and experience and fluctuation of employees. Generally, the intra-project organization work and implementation are perceived not as interesting as the technical realization.

Challenges on the *overall implementation* have been different local approaches of the SF program, high effort on alignment and discussions within the set-up, different maturity levels of plants, resulting in reduced scalability and further potential of distinct projects. Additionally, challenges have been to find measures towards a successful implementation, as well as the adaptability of own developed processes to new technologies.

Technical

Challenges with technical aspects with the *integration of new technology* have been the integration of robotics and digital technology into old production processes, the integration into an existing and inflexible layout, while considering safety regulations, and the little standardization of resources, different machines and equipment, which results in varied interfaces, controls, network connections and syntax.

Other challenges are related to the *evaluation and quantification of the use case*. Specifically, the evaluation of the system and the choice of hardware, as the importance of different new features are unclear. Also, the quantification of the exact business benefit and cost savings, due to incomplete data and the calculation with subjective factors has been challenging, as these factors are often included and are not completely reliable.

Dependency on hardware set-up and invest and on digitalization pilots have been mentioned as well, in line with the immature technologies, such as different AI technologies, which are still in a development phase. Also, commonly many factors, which are necessary in a productive environment are not considered in the pilot.

External

The challenge of new guidelines and regulations, which need to be considered within a project, was mentioned solely as externally evolved.

4.2.3 Outcomes

The topic cluster of outcomes of the SF introduction are displayed below in Table 24 and will be elaborated in the following.

Table 24: Outcomes SF introduction Company A

Topic cluster	No. of outcomes
Direct result of technology	21
Business impact	10

Outcomes of the SF implementation have been found to be mainly connected to a distinct technology.

Direct result of technology

Direct outcomes of a technology introduction were the transparency of process parameters, machine condition and lifetime, error codes and material flow.

Outcomes related to *lower maintenance effort* were decreased machine stop time, better spare parts timing, enabling of condition-based maintenance (increased planned maintenance / decreased serial inspection) and preventive maintenance, resulting in the avoidance of machine crashes and consecutive damages through early detection of possible breakdowns.

Related to *improved usability*, outcomes were improved and more intuitive user interfaces, less time for training, enabling of mobile and remote working and control and decision support and decision making with the help of data visualization and the integration of further data from other systems. Further, new technologies can be implemented to be a part of future adaptability and increase the systems robustness.

Another outcome of SF projects is *standardization*. Through rethinking of processes and adapting of existing premises software, equipment and interfaces are standardized through the common connection.

Additional outcomes are the elimination of physical strain, the reduction of trails and sample inspections, increased logistics speed, lower cost and shorter time replacements in case of quality issues, which results in containment of reputation loss.

Business impact

Outcomes of the SF introduction, which impacted the overall business were improved quality, lower cost, higher delivery performance, increased efficiency, higher productivity, higher work safety, higher trust in technology, traceability of materials and increased transparency.

4.2.4 Maturity Model

The existing maturity model in Company A is based on the 5-stage maturity model by VDMA Industrie 4.0 Forum (2016) also displayed in chapter 2.3.4 and extended with company specific criteria of strategic importance. Further, all criteria have been grouped into categories according to enablers, which are *digitalization, people and change, digital processes, technologies and IT infrastructure*. The maturity levels of all company specific criteria are not detailed elaborated, but are rated according to the degree of achievement, e.g. digitalization of process X, level one 0-20%, level two 20-40%, level three 40-60% etc. Therefore, in the following only the criteria additionally incorporated by the company into the maturity model by VDMA Industrie 4.0 Forum (2016) will be displayed.

In the category of *digitalization*, criteria are the implementation of SF roadmap, availability of investments and resources, established KPIs to reach the goal, the assignment of employees to specific SF topics and digital transformation with being a global driven topic, to be able to use scaling effects.

The criteria of the category *people and change* are communication channels for SF and digital transformation, documentation of SF activities, competency enhancement to skill up employees, acceptance of digital transformation through communication, the digital interconnection of employees and machines and the interaction between operator and machine.

The *digital process* category is divided into different supply chain areas, where the degree of digitalization is used as evolution.

In the category of *technology* data quality, a standardized data format and production data from machines are depicted. A larger company specific topic is the criteria of performance measurement, which is intended to be enabled through the SF. This includes the implementation of an overall equipment efficiency performance indicator and specific measures towards the implementation.

The category of *IT infrastructure*, criteria are the creation of data and IT security awareness, integration of different systems across units and with piers and network coverage and modularity of IT components.

5 Analysis and Smart Factory implementation framework

This chapter represents the result of this thesis, on basis of the literature review depicted in chapter 2.2 and chapter 2.3, synergized with the findings at Company A, displayed in chapter 4. Within this chapter RQ1: "How can the SF be implemented in practice" was combined with RQ2: "What are success factors, challenges and outcomes of an implementation of SF", as they are highly related to each other and interconnected. Success factors and challenges of the introduction (RQ2) are structured into the distinct process phases of the SF implementation process (RQ1). The sub-chapter one focuses on the strategic SF implementation with its key activities, success factors and challenges, where sub-chapter two focuses on the operational SF implementation. The outcomes of the SF implementation (RQ2) are elaborated in sub-chapter three. For a better understanding, the structure of this chapter is visualized in Figure 4.

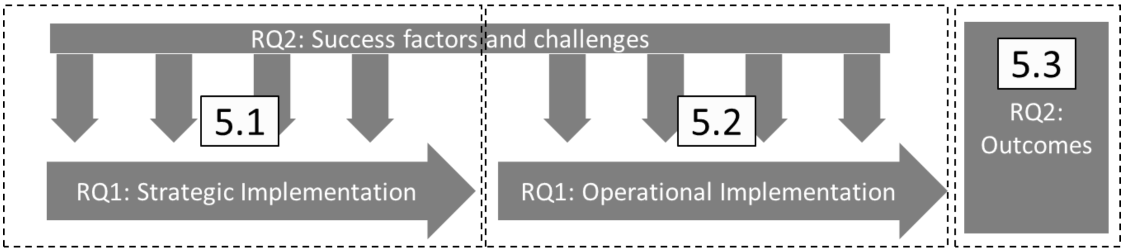

Figure 4: Structure of the chapter analysis and implementation framework

5.1 *RQ1 & RQ2:* Strategic Smart Factory implementation

In order to implement the SF a major success factor found in both, theory and in the case company is, the defining and deriving of a global company-wide SF strategy and vision out of the overall manufacturing strategy. This includes a distinct company fitting roadmap with use cases towards the goal SF. Further, the gradual implementation of the SF together with the help of a maturity model have been a valuable aid to guide and communicate the change. These major success factors underline again the importance to answer *RQ1* and to provide a comprehensive step-by-step approach for the implementation. This framework for implementation will be elaborated in the following.

5.1.1 Strategic Smart Factory implementation process

The condensed step-by-step framework with the key activities of the strategic SF implementation process can be found in Appendix 7 – Strategic SF Implementation Framework. Additionally, the success factors and challenges of each step are outlined. The theoretical strategic implementation process, outlined in chapter 2.2.1, was connected to the success factors of initial assessment, organizational processes, culture development and use-case considerations of the theory and investigated in the case company.

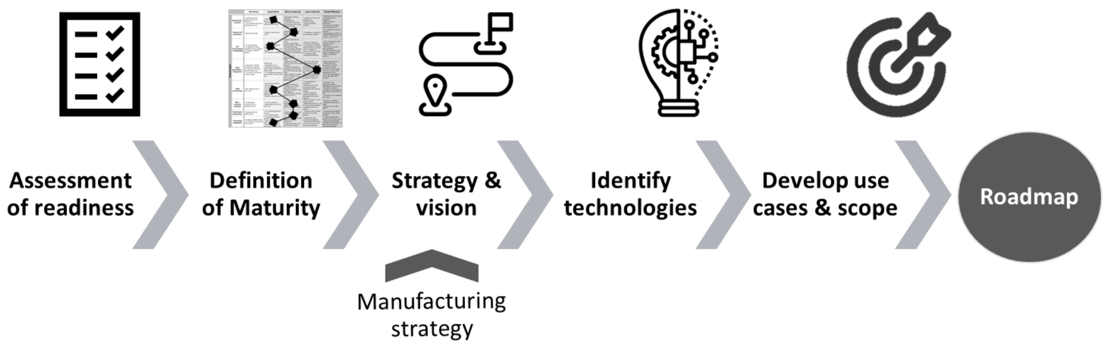

Figure 5: Strategic SF implementation process

An overview of the process provides Figure 5, which will be elaborated in the following.

Assessment of readiness. With the first step, the status quo is assessed. This contains the degree of digitalization, the smartness of current products and services, adaptability of employees to I4.0, dependencies to other projects and the expertise and know-how for I4.0. Overall management commitment must be ensured for starting the journey towards the SF. This step has the goal to establish a first idea of the current status. Success factors at this point are, to have a project owner for the strategy process, who is supported by a project team, to apply a global, company overarching perspective and to set up SF communities or networks.

Definition of Maturity. The definition of the SF maturity is established as a summary of the assessment. The maturity level definition is performed by mapping the current capabilities into each category of the maturity model, as each level represents a checklist. The definition of the current state provides an indication of the effort for implementation. Success factors in general, are the gradual implementation, which represents the different maturity levels and in case of having several production sides, performing distinct maturity assessments, as maturity can vary greatly. The developed maturity model is further elaborated in chapter 5.1.2.

Strategy and Vision. On the base of the maturity and the manufacturing strategy a global SF strategy and vision is defined. This can be done through e.g. workshops. Further, the specific fields of action based on the maturity model and the prioritization is worked out. Out of these, the SF department strategies are derived. The establishing of strategy supporting KPIs and the strategically managing of the architecture investment are major success factors. Challenging can be different SF approaches in different plants and the actual measuring of success.

Identify technology. In order to implement new technologies, fields of best application need to be found. This is performed through the review and analysis of existing processes in the field of action and the decomposition of tasks and processes. On this basis, the fitting technologies can be selected and then be developed into concepts. In the beginning of the SF journey it is important, to start with small and independent use cases, which provide a fast payoff and require little training effort, to not slow down the implementation through higher resistance from employees.

Develop use cases and scope. The prior developed technology concepts are in this step assessed for their potential and benefits, resulting in a brief business case creation. Interdependencies can be assessed through the mapping of old and new technologies. To set up an implementation and control strategy ensures the successful execution of the project. Within this step it is important, to clearly define the project vision and scope, as well to include an ROI prediction. A challenge can be the limited scalability potential, due to different maturity levels of different plants.

Roadmap. The roadmap represents the summary of the outlined use-cases, on basis of the SF strategy and vision. This provides guidance and an overview of the time and content dependencies, to encounter resource scarcity within the implementation.

5.1.2 Smart Factory maturity model

In order to implement the SF different success factors, challenges and technologies are mandatory to implement or to consider. The investigation at the case company further pointed out the importance of a maturity model. With the help of the maturity model as a strategic tool, companies can advance step-by-step towards the SF. This tool is applied, as mentioned in the last chapter, in the definition of the maturity phase of the strategic SF implementation process and provides guidance in the phase of the strategy and vision development and while identifying suitable technologies.

The proposed maturity model contains more detailed information than the theoretical proposition, outlined in the theoretical background. The reason is, that several interview partners pointed out the importance of the model of being self-explaining and comprehensible. The model accounts for a synergized approach between theory (chapter 2.3.4) and findings (chapter 4.2.4), as well as inclusion of further success factors, which are related to specific levels of the SF evolution (chapter 2.3.1). The success factors incorporated in the maturity model are out of the categories of SF property, Data acquisition / transfer / use, IT architecture (hard / software), as well as culture development and competency / skill enhancement. The developed maturity model is depicted in the following in two parts of technology (Figure 6) and people and organization (Figure 7), only due to the size and readability. However, it needs to be understood application-wise as one template and tool in the strategic SF implementation, comparable to the morphologic box.

Technologies	No focus	Aspiration	Early maturity	Late maturity	Smart Factory
Automation / robotics	- Manually-operated machines and use of hand-tools - Non-standardized and non-automized processes	- Automation of single processes - Mainly manual operation with unstructured data	- Programable machines - Automatic NC identification - Automation of repetitive rule-based processes using unstructured data	- Collaborative robots and automation of order processing - Largely automated workflows	- Collaborative robot (AI) and sustainability driven automation - Digital assistants implemented - Autonomous controlling and steering processes
Design and simulation	- Paper-based design	- Computer aided design (CAD)	- Simulation software and models used for decision making	- Virtualization (simulation to test, prototype, optimize)	- AM, simulation used in all decisions - Implementation of AR & VR - Real-time OEE displaying on machine / mobile device
IIoT (connectivity / traceability)	- No communication - No digital networking capability for data exchange - No interface standard defined	- Sensors, PLCs, fieldbus interfaces available - No data connections to other systems - IIoT architecture defined	- Gradual connection of assets - Extensive networking options (fieldbus / ethernet) - Tracking of products - Data connection with other systems possible, but with high effort (non-standardized interfaces) - IIoT architecture implemented	- All assets connected - Tracking of raw materials - Some machines networked with other objects via cloud or have a digital twin - Data connections to other IT systems possible - Standardized interfaces	- M2M communication (and with other objects) - Digital twin concept realized - Full connection of tools and technologies - Network connections with other IT systems possible - Highly standardized interfaces
Data generation / integration	- Manual info exchange, spreadsheets, registers - No data generation from production processes - IT systems not protected, no data security	- ERP System implemented - Central data servers - Generation and usage of data not fully automated with manual steps - Uncoordinated precautions, no systematic coverage of all risks	- MES implemented - Uniform data formats - Software and systems partly integrated - Automatic generation of operating or usage data, but not at all relevant measuring points - Safety guidelines available - Basic security processes and technologies implemented	- Storage of sensor data - Cloud implementation - Automated exchange and generation of operating or usage data at all relevant measuring points, but not real-time - Roles and responsibilities are formally defined and assigned to employees	- Fully secured database - Interdivisional and networked IT solutions - Automatic real-time generation of relevant data - Processes are part of the management system - Roles and responsibilities are formally defined and assigned
Data processing	- Data collection, but no processing	- Data for documentation - Data cleaning - SCADA system implemented - Descriptive analytics (What has happened?) - Data aggregation and mining - Manual evaluation of data	- Big data introduction - Mining processes and monitoring of assets - Diagnostic analytics (Why did it happen?) - Semi-automatic evaluation of data (e.g. Excel)	- AI (maintenance & production) - Real-time process data monitoring, analysis, optimization and long-term learning - Predictive analytics, statistical models and forecasting (What could happen?)	- World class data aggregation, analysis and interpretation in real-time - Prescriptive Analytics - Optimization and simulation algorithms (What should we do?) - Automatic process planning and control
Man – machine interface	- No information exchange between machine and user	- Local user interfaces - Opportunities are present but no use	- Remote / centralized monitoring - Digital interconnections with IT systems are realized	- Remote operation / use of mobile interfaces - Digital interconnection with IT systems and possibilities with digital services are	- Operation via interface - Augmented and assisted reality - Digital services are fully realized
Flexible production	- Small proportion of identical parts	- Use of flexible production systems - Use of identical parts	- Flexible production system - Modular product design	- Component-driven flexible production of modular products	- Component-driven flexible production in value-adding networks
Horizontal integration	- No linking of different units - No integration of production with externals	- Cooperation with other departments - Information exchange via mail / telecommunication - Selected integration of production with other units	- Full cooperation and digital platforms with other departments - Uniform data formats and rules for data exchange	- Collaboration with customers and suppliers - Interdivisional linked data servers and systems with externals and internals	- Complete Supply Chain integration and collaboration - Demand-driven planning - Real-time exchange between all IT-Systems and users (external and internal)

Figure 6: Maturity model technologies

People & Organization		No focus	Aspiration	Early maturity	Late maturity	Smart Factory
	Digital culture	- Lean philosophy implemented - No communication concept for Smart Factory - No explicit skill development for digital transformation	- Same values / beliefs and inclusive culture - Apply digital lens - Top-down communication - Reactive skill development for project-dependent skill gaps	- Cross-functional digitalization networks and initiatives - Employee involvement - Direct communication to employees	- Different communication channels are actively used - Specific collaborations for skill development	- Culture of continuous SF innovation - Communication concept implemented and regularly revised - SF initiatives are continuously measured and improved - Decisions are partly automated
	Cross-departmental collaboration	- No networking with other departments - Opportunities not defined	- Individuals capable to work in teams - Awareness of technical and business opportunities of Smart Devices but no use	- Autonomous teams and cooperation, portals for data sharing - Partly digital interconnections with other employees via Smart Devices	- Interconnection of employees with other employees implemented - Realizing of digital services	- High level of autonomy and decentralization - Digital interconnection of employees with IT systems and other employees - Expanded services and functionalities
	Organization	- Topic of Smart Factory is not present - No documentation of Smart Factory activities	- Changes on roles and tasks are communicated - Only local and not completely documentation	- Revise production roles to share digital insights and knowledge - New roles and tasks are defined with a training plan - Smart Factory activities are completely documented	- Employees control processes and react to changes - New roles are implemented and further development offered - SF activities are documented with global access for communities	- Specialized roles towards predictable production - Human fully integrated in digital systems - SF activities are aligned with the implementation process and documentation
	Smart Factory processes	- No SF roadmap defined / barely no digital activities - Topic of Smart Factory is not present - No KPIs defined	- Formal implementation processes of SF and external involvement - Basic plan to implement strategy - SF terminology defined - KPIs are collected and used	- Global manufacturing strategy and local Smart Factory communities are aligned - Some KPIs are showing positive trends	- Robust roadmap of Smart Factory aligned with other strategic initiatives - Majority of KPIs are showing positive trend	- Sustainable roadmap defined - Digital strategy is defined and revised regularly - All KPIs show positive trend
	Skills / know-how	- Awareness of missing competencies but no training	- Qualified employees and IT specialists - Trainings are offered but barely used	- Operational employees have / are educated in digitalization skills - Some employees can train others on tasks - Digitalization team at plant	- Recruit data analysts and scientists to optimize production - Task related trainings are standardized and done	- Staff consists out of experts - Open learning platform to access material

Figure 7: Maturity model people and organization

In the following, only a brief elaboration of the development of each category will be given, as the categories and the criteria for each stage itself can be captured in the maturity model.

Technology categories

Automation / robotics. This category depicts the advancement from manually operated machines and non-standardized processes towards collaborative robots based on AI, digital assistants and autonomous controlling and steering processes. The evolution of overall process automation has been stronger incorporated, as it was pointed out as the basis for the SF in the cases.

Design and simulation. This category has mainly not changed to the theoretical proposition, except the inclusion of manufacturing KPI depiction as decision support at the point of interest.

IIoT (connectivity / traceability). This category has been extended with further inclusion of interfaces and network options between machines and with the network. Aspects regarding the IIoT architecture have been incorporated from success factors. The original categories have been found exactly in the maturity model of Company A.

Data generation / -integration. The automatic real-time data generation as a SF state with its evolution steps have been added, including network security and roles and responsibilities. Again, the categories of the theoretical proposition have been found implemented in the model at the case company. The change of content lead consequently to the change of the category name, which was previously data storage /-integration.

Data processing. The original category was again found in the existing maturity model, although synergy includes a more detailed description of the data analysis to facilitate a better understanding.

Man - machine interface. Digital connections with IT systems and the realization of digital services to enhance the interaction between operator and machine have been added to this category. They further detail the levels of maturity.

Flexible production. These criteria have only been partly found in the present maturity model. However, the flexible aspect has been stated with a higher importance. Due to this fact and as flexible covers more properties of the flexible and adaptable production, the category name has been changed from prior “small batch production.”

Horizontal integration. Aspects regarding the linkage of different units, transfer of data between departments and tiers, as well as the integration into the respective systems have been further detailed with the findings.

People and organization categories

Digital culture. This category has been enlarged with the aspects of communication of the SF strategy and digital transformation, as well as explicit collaboration for skill development. The aspects of the theoretical proposition have been found in the findings as well.

Cross-departmental collaboration. As the original category was found implemented as well, aspects of smart device opportunities and the digital connection of employees with each other and IT systems have been included and more detailed.

Organization. This category originally was summarized with the following category of Smart Factory processes. However, during the interviews and the investigation the importance and the quantity of organizational aspects and formal SF processes to be considered became clear. Therefore, this category contains all aspects regarding the change of roles and tasks, as well as the documentation and alignment of SF activities.

Smart Factory processes. Within this category the formal process aspects regarding an aligned SF strategy and roadmap are considered, whose importance were already stated in the beginning of this chapter. Hence, the separate category and additional focus is justifiable. This contains the global perspective, as well as supporting KPIs. This was outlined by the interviewees as necessary to control the process.

Skills / know-how. The aspects out of the theoretical proposition have only been partly found incorporated. However, additional aspects regarding the attention and sensibilization of the need for training, as well as standardized training have been present in the model at company A. Therefore, this was included, as well as success factors of competency / skill enhancement out of the findings.

In the following the operational SF implementation will be elaborated.

5.2 *RQ1 & RQ2*: Operational Smart Factory implementation

The question of how to advance in the level of maturity remains still. This specific topic is addressed in this chapter with the operational SF implementation.

In the operational implementation of the SF it became clear in both, theory and in the findings, that **top management commitment and attention**, facilitated e.g. through regular meetings, is essential to success and the proceeding. Additionally, all stakeholders need to be regularly updated and kept in the communication loop.

Regarding the PM approach, several authors, as well as interview partners pointed out the importance to use **agile project management**, including the “fail early, fail often and fail cheap” way of thinking in the beginning. However, depending on the novelty, complexity and uncertainty of SF technology projects, the PM approach should be adapted. This adaption is pointed out in Figure 8.

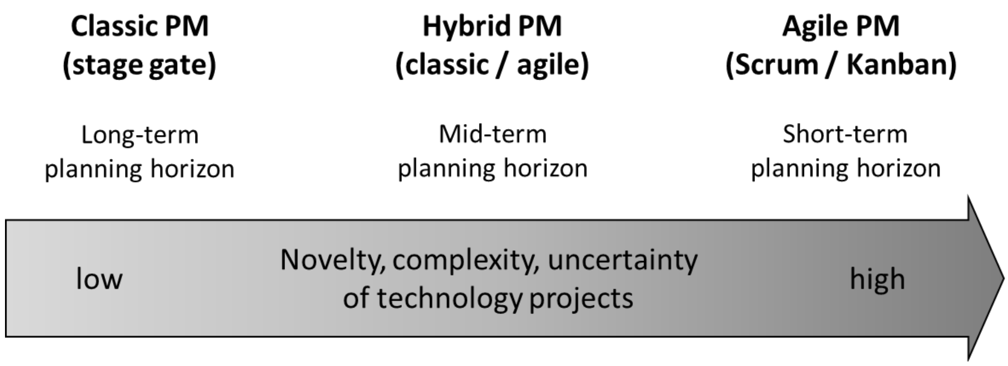

Figure 8: SF technology PM approach

This means, in high complex, new and uncertain projects a short-term planning horizon, combined with the Scrum / Kanban methodology should be chosen to handle occurring challenges. In this case, the in the following suggested stage-gate process will be of minor importance, but the milestones represent orientation points. On the other hand, while implementing a mature technology a more long-term planning and a rather defined stage-gate process can be applied.

Another outlined major point of success is **change management**. Although this is not only specifically important for SF projects, but for projects in general, it has a strong impact. Change management in SF projects needs to be considered in every project phase. This targets especially on information of the planned change and proceeding, motivation of employees and empowerment, revealing of the specific potential, as well as the education of employees. Also, it is highly important to ensure the integration of users and ensure a continuous communication.

The main challenges within projects, are found to be mostly related to missing know-how and experience, as well as limited capacity and project resources, due to other projects.

For the operational implementation a stage-gate process with agile elements, depicted in Figure 9, is proposed. The condensed process with key activities, success factors and challenges can be found in Appendix 8 – Operational SF Implementation Framework..

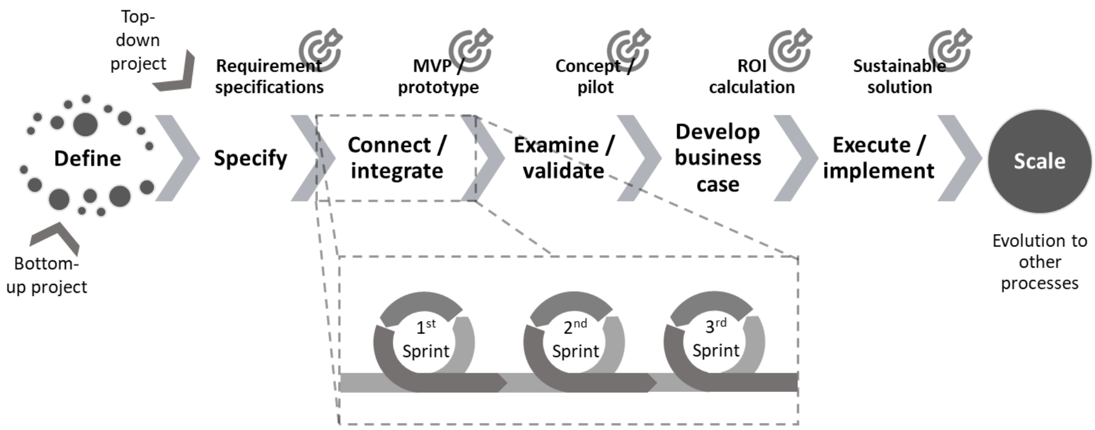

Figure 9: Agile stage-gate process for operational SF implementation

The process was developed out of the theoretical background, synergized with the process, success factors of the categories external collaboration / networking, IT architecture (hard-/software), organizational processes and use-case considerations and challenges found at the case company. The process will be elaborated in the following.

Define. At first, the project scope and vision are defined. This phase is applicable only for bottom-up projects, as top-down projects and use-cases are already defined in the strategy process. However, the importance to include this phase in the process was pointed out, as through conferences, networks, market observations and technology partnership ideas for new application of SF technologies evolve.

Specify. The phase of specification starts with the setup of the project organization and the project plan. Further, an official kick-off with all project members is conducted.

Important is, that all members incorporate together technical and IT skills and knowledge and a core and expert team is formed. The phase has the target to provide the requirement specification for the project. Critical success factors in this phase are the alignment of the project scope and target with all project members, as well as the definition of goals and responsibilities. Further, it is essential to set up the change management strategy. While ensuring this, challenges such as lack of PM skills and deviating interests can be encountered. Also, legal certainty can be a challenge in this phase.

Connect / integrate. This phase has the goal to create an MVP or a prototype. To reach this, first, if applicable, different vendors need to be evaluated, to choose the right technology. On the one hand, a market overview of different systems, solutions and vendors, the inclusion of employees with the right knowledge, as well as ensuring the compatibility with existing systems and IT are successful practices. Of great influence is the selection of the platform and integration partner. On the other hand, the integration of new technology into existing processes and to know the importance of new technology features might be challenging. The new technology needs to be implemented afterwards. Further employees, which are blocking the change can be a challenge. Through the MVP the final system solution can be finally specified. In addition, a plan for testing, training and change management needs to be established.

Examine / validate. After the deployment of the MVP, the technology is developed into the concept or pilot. Successful projects have been conceptualized in a small and delimited area first. The proof of concept needs to be evaluated and tested and the new value through technology needs to be assessed. A sustainable solution and scalability are important to consider, as well as all operating factors and a correct evaluation of the system. Challenging can be the adaptability of existing processes into the new technology. In this phase the planning, training and change management needs to be refined.

Develop business case. To quantify the new value, the new improvements and the ROI it is important to consider possible flexible usage and standardization potential. However, this might be challenging to exactly quantify cost savings and benefit, as it might not be completely reliable, due to the human factors in the process. Further, the cut-over plan and the change implementation need to be managed. Important is the training and the alignment with the employees before the cut-over.

Execute / implement. With the release of the business case the development and implementation at full scale starts. The bottom-line impact needs to be analyzed and compare to the predicted value generation. To achieve sustainable results, reporting and controlling methods need to be implemented. A success factor is to keep the management attention after the implementing of the solution until the sustainable solution is reached, as the organizational implementation is perceived not as interesting as the technical realization. After sustaining and proving the results in the operating state, a roll-out of the solution can be focused.

Scale. The sustainable solution can be evolved to other similar processes and applications, as well as to other more complex processes.

5.3 *RQ2:* Outcomes of Smart Factory implementation

The structure of outcomes has been re-worked after the synergy of theory and findings. Below in Figure 10, the main outcome categories are depicted. This accounts for a combined summary of the of both, theory and findings.

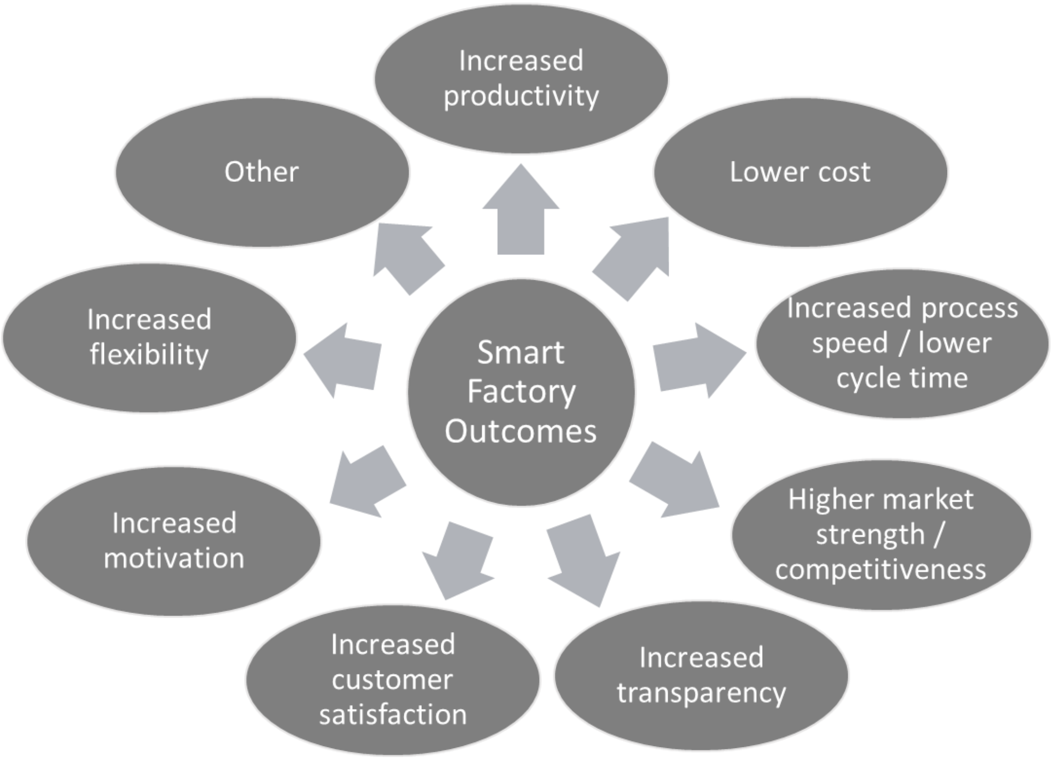

Figure 10: Outcomes of SF implementation

Each category will be elaborated in the following.

Higher productivity. Outcomes of the SF implementation, which in turn resulted into higher productivity, were increased efficiency, increased effectiveness, optimization and standardization. Increased effectiveness contained, improved (product) quality, improved (product) safety and removal of errors. Detailed results of optimization have been a more responsive and optimized supply chain, manufacturing intelligence and decreased logistics effort. Improvements with the result of standardization have been the reduction of different software and 5S improvements.

Lower cost. Overall lower cost has been the result of lower costs for check and replacement (quality issues), higher margins through direct sales and less distributors, reduction of insurance cost, better spare parts timing (lower inventory), reduction of trails and sample inspection, lower cost management and cheaper production of custom products.

Increased process speed / lower cycle time. Theory, as well as findings, pointed out the outcome of increased speed or lower cycle times through the enabling of mobile or remote working and control, detection and prevention of breakdowns and decrease of machine stop time. Additionally, less time for training, also due to an improved and more intuitive user interface and enabling of preventive maintenance results in the increase of planned maintenance and the decrease of serial inspection effort.

Higher market strength / competitiveness. With the target to improve the competitive and market position of an enterprise, introducing the SF can be supportive as well. The introduction leads to better strategic decision making, meeting customer needs better, manufacturing innovation, containment of reputation decrease, better sustainability and increased speed of innovation.

Increased transparency. To the transparency enhancement, the SF introduction contributes through enabling traceability of processes and material flows and real-time traceability, as well as through gaining transparency of parameters, lifetime and of machine condition and errors.

Increased flexibility. With SF technologies, larger product variety is possible, increased capacity can be realized and the usability of technical resources for future application can be ensured.

Increased motivation. Even motivation can be boosted with the SF introduction. This is achieved through the decentralization of data analytics and IT skills, the higher trust in technology, as well as increased workers health.

Increased customer satisfaction. The SF introduction contributes with higher delivery performance to increase customer satisfaction.

Others. Further outcomes, which have not been mapped to a category are the increased risk of decisions, a fast ROI of new technologies and the integration of different systems.

6 Discussion and conclusions

In this chapter at first, the method regarding its strength and weaknesses is assessed. This is followed by a reflection on the developed framework and the results including addressing contribution to academia and industry. As closure, directions of further research are elaborated.

6.1 Discussion of method

The methodology applied in this thesis was described in chapter 3.1. First, a literature review was performed, followed by a development of a theoretical proposition, which then was synergized and further developed with a multiple case study.

The systematic literature review by Moher *et al.* (2009) was chosen as it provides a transparent process of exclusion and proceeding, as well as a guideline for conduction. The benefits have been clearly realized. Although the effort to conduct the whole literature review was high, after the completion a sound and reliable overview over the current field of research was gained. Through this, already performed work, such as the purpose and research questions could be changed once slightly, in order to advance in the exact direction. This also improved the communication with the supervisors, as a clear target could be defined. Further, using the PRISMA statement improved the comprehensibility of the review process as the exact criteria of exclusion have been outlined.

As Yin (2009) suggested and outlined as a valuable aid, the development of the theoretical proposition was very helpful to communicate the idea of the maturity model and the implementation process within the interviews. It can be assumed that without this, the findings would have been less focused and less applicable for the framework development.

With the choice of a multiple case study, as a qualitative investigation method, the target to gain a sound description of the requirements and influencing factors was achieved. As Eisenhardt (1989) pointed out, results were of high novelty and validity. Important was the use of multiple case studies, as the field of SF implementation corresponds to a variety of technologies. Only through this it was possible to attempt a framework with generalizability, through comparison and synergizing of the finding from different cases. With the help of the different interview phases (orientation, main, validation), as well as interview partners from different hierarchies, valuable cases and a high internal validity and reliability were achieved. The use of observations and qualitative data as supportive methods suited the approach very well, as the author participated in several SF projects and aspects, which were of minor importance for the interview partners were detected and investigated in this way.

However, it must be mentioned, that within the development of the strategic SF implementation framework only one case was considered in the findings, as all technology implementations were from one company. Although the implementation framework was validated with experts, who also have experience from other companies, the generalizability might be slightly lower compared to the operational SF implementation.

In total, the elaborated method made it possible to approach both research questions in a sound and systematic way, with inclusion of the important aspects. Consequently, both research questions were answered extensively and comprehensively.

6.2 Discussion of findings

6.2.1 Discussion of Smart Factory implementation framework

The purpose of this thesis was twofold. First, the need to investigate the implementation process, with the leading research question one "how can the SF be implemented in practice?" and second, to investigate challenges, success factors, lessons learned and benefits of an SF introduction, with the leading research question two "what are success factors, challenges and outcomes of an implementation of SF?"

Both research questions have been addressed with the developed SF implementation framework.

Research question one was answered with the formal process of the strategic and the operational SF implementation, as well as with the maturity model when advancing in the implementation. The models of current research have only developed parts of the proposed framework. The approaches of Iansiti and Lakhani (2014), Illa and Padhi (2018), Huber, Henkel and Kranz (2019) and Pinto *et al.* (2019) have been developed in the same direction, however lacking few steps and details, such as a dedicated project phase for bottom-up projects, the evaluation of vendors and a tool, such as a maturity model, to advance and guide the evolution towards SF. Another important point is the inclusion and alignment of the maturity model with the strategic introduction process. The above-mentioned researchers have not incorporated such a method to guide the overall SF implementation. The developed maturity model in detail represents a more complete and overall approach, which covers also the organizational and employee related aspects. These have not been fully incorporated by the existing models, such as VDMA Industrie 4.0 Forum (2016) and Frank, Dalenogare and Ayala (2019), as the focus is only on technology advancement or such as Odwazny, Cyplik and Szymanska (2018) and Sjödin *et al.* (2018), which don't provide continuous levels of specific categories high in detail.

A point of improvement and further research could be to reveal different dependencies within the maturity model, such as which stage of category A needs to be reached, in order to realize a certain stage of category B. This was not incorporated in this model, but could be interesting within the implementation, as success factors, like having the right skillset inside the company and an open organization, have been outlined.

Research question two was answered within the outline of the implementation process. Authors such as Li, Peng and Xing (2019) and Sony and Naik (2019), have collected and depicted various success factors and challenges, however have not mapped them into a specific phase or evolution step. However, it became clear, that only through this they become applicable. This was also the main reason of combining *RQ1* and *RQ2*. Through this, it was possible to connect the specific implementation phase to the key factors, hence providing a sound and overall implementation process. As a conclusion, outcomes of various scholars, synergized with the outcomes from the cases have been categorized, which represent a condensed picture of the benefits of the SF implementation.

6.2.2 Contribution to academia and industry

The developed implementation framework enhances the body of knowledge and contributes to further understanding of the "how" to implement the SF. The developed framework represents the next step towards an applicable guideline for implementation, which was pointed out as necessary advancement (Hozdić, 2015; Kagermann *et al.*, 2016; Liao *et al.*, 2017; Strozzi *et al.*, 2017; Moeuf *et al.*, 2018; Sony and Naik, 2019; Oztemel and Gursev, 2020). Further, the framework was developed out of different implementation cases of software tools and digital applications and therefore matches the necessary context, in order to be applicable. A framework developed in this context was outlined as the necessary advancement, as digital tools and IT systems account for the biggest leverage in SF implementations (Chen and Muraki, 1997; Azadegan et al., 2011; Liu and Xu, 2016; Syberfeldt et al., 2016; Sony and Naik, 2019).

In addition, this thesis elaborates the necessary change, connections with the production system and how to cope with the requirements within the implementation. Additionally, success factors, challenges and outcomes of current field of research including first-hand practical key factors are elaborated, which were outlined as consecutive fields of research by Hozdić (2015), Kagermann *et al.* (2016), Strozzi *et al.* (2017), Moeuf *et al.* (2018), Rub and Bahemia (2019), Sony and Naik (2019) and Oztemel and Gursev (2020).

As already stated, the framework is a hands-on implementation process, which can be implemented and taken as a guideline. Due to the broad basis, which was considered throughout the theoretical framework and the variety of use-cases this approach ties to apply for generalizability. This framework facilitates the implementation of the SF from the very first step, until the last maturity stage of every aspect, until the SF is reached. Also, an implementation process and PM approach to advance in the level of SF, including deliverables was outlined. Hence, a complete approach is provided.

6.3 Further research

This thesis emphasizes the need to incorporate a strong change management and organization development within the implementation of SF. Further, valuable advancements in research could target at this specific issue. Applying the operational implementation framework also for organizational and employee specific projects might point out further success factors.

Also, to apply and proof the implementation framework and the maturity model in further companies and in various industries would be interesting to see, if the success factors, challenges and steps are applicable in these contexts as well. This advancement would also further prove and support the generalizability of the strategic SF implementation framework.

As already stated in the delimitations, the underlying technical challenges of a distinct technology and to advance from one maturity level to the consecutive were excluded in this study. Therefore, further studies might apply this detailed focus to complete the overall big picture and provide guidance within every category of SF.

Connected to the latter another direction of further investigation could be towards revealing different dependencies between the category stages, such as which stage of category A needs to be reached, in order to realize a certain stage of category B. Although this would be a very effortful investigation, due to the high level of detail, it could lead to an ever more thorough approach of the SF implementation.

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8 Appendices

8.1 Appendix 1 – Success factors of SF implementation

Criteria	Maturity model	Topic cluster	Qin, Liu and Grosvenor (2016)	Pinto *et al.* (2019)	VDMA Industrie 4.0 Forum (2016)	Jager *et al.* (2016)	Masood and Egger (2019)	Li, Peng and Xing (2019)	Trost (2015)	Yao, Jin and Zhang (2015)	Mittal, Romero and Wuest (2018)	Lee and Lee (2015)	Sony and Naik (2019)	Zuehlke (2010)	Mittal *et al.* (2019)	Davis *et al.* (2012)	Buchi, Cugno and Castagnoli (2020)	Chen *et al.* (2017)	Sjödin *et al.* (2018)	Davies, Coole and Smith (2017)	Mabkhot *et al.* (2018)	Ilia and Padhi (2018)	Huber, Henkel and Kranz (2019)	Frank, Dalenogare and Ayala (2019)	Total mentions
- Increase / aim for data quality (large, real-time, reliable, usable)	X	Data acquisition / transfer / use				X				X									X		X				4
- Automated processes for mining and sharing	X	Data acquisition / transfer / use										X				X		X	X						4
- Implement real-time performance analysis	X	Data acquisition / transfer / use														X			X		X				3
- Data acquision as basis	X	Data acquisition / transfer / use																X	X						2
- Process to detect potential based on data	X	Data acquisition / transfer / use																X	X						2
- Integration of data into decision making	X	Data acquisition / transfer / use																	X		X				2
- Visualisation of critical operational analytics	X	Data acquisition / transfer / use																	X		X				2
- Integration of data resources (sales / quality)		Data acquisition / transfer / use																X							1
- Create data flow of already exisitng applications	X	Data acquisition / transfer / use																	X						1
- Control and heal-ability		Data acquisition / transfer / use																			X				1
- Knowledge sharing with suppliers, users and stakeholder	X	Data acquisition / transfer / use																	X						1
- Integrate digital systems from tiers for Supply Chain predictability	X	Data acquisition / transfer / use																	X						1
- Defined IT architecture		IT architecture (hard- / software)											X			X					X				3
- Shared infrastructures towards plug and play		IT architecture (hard- / software)														X									1
- Enough data storage		IT architecture (hard- / software)										X													1
- Improved sensor technology		IT architecture (hard- / software)														X									1
- Secure communication		IT architecture (hard- / software)																			X				1
- Cloud computing		IT architecture (hard- / software)																			X				1
- Cloud connection		IT architecture (hard- / software)																			X				1
- Focus on data centricity		IT architecture (hard- / software)																					X		1
- Vertical integration	X	IT architecture (hard- / software)																						X	1
- Energy management	X	IT architecture (hard- / software)																						X	1
- Traceability	X	IT architecture (hard- / software)																						X	1
- Virtualisation	X	IT architecture (hard- / software)																						X	1
- Embedded computers		IT architecture (hard- / software)																			X				1
- Modular and decentralized control architecture		IT architecture (hard- / software)																			X				1
- Virtual interfaces with CPS		IT architecture (hard- / software)																			X				1
- Standardized virtual modelling language		IT architecture (hard- / software)																			X				1
- Robust infrastructure		IT architecture (hard- / software)																				X			1
- Selecting the right platform and integration partner		IT architecture (hard- / software)																				X			1
- Selecting the right integration partner		IT architecture (hard- / software)																				X			1
- Identify company fitting use cases and technologies	X	Use case considerations		X	X	X													X			X			5
- ROI calculation / prediction		Use case considerations																				X	X		2
- Use case implementation for optimization	X	Use case considerations																	X				X		2
- Scaleability		Use case considerations		X			X																		2
- Rapid implementation of pilot projects		Use case considerations		X																			X		2
- Quantifiable benefits of each stage		Use case considerations			X																				1
- Strategically manage investment for architecture		Use case considerations											X												1
- North star framework (dependencies and business case)	X	Use case considerations																					X		1
- Integration with pre-existing information systems		Use case considerations		X																					1
- Start successfully		Use case considerations		X																					1
- Start with moderate investment and training effort		Use case considerations		X																					1
- Start with small and independent use cases		Use case considerations				X																			1

Appendix 1 – Success factors SF implementation continued:

Criteria	Maturity model	Topic cluster	Qin, Liu and Grosvenor (2016)	Pinto *et al.* (2019)	VDMA Industrie 4.0 Forum (2016)	Jäger *et al.* (2016)	Masood and Egger (2019)	Li, Peng and Xing (2019)	Trost (2015)	Yao, Jin and Zhang (2015)	Mittal, Romero and Wuest (2018)	Lee and Lee (2015)	Sony and Naik (2019)	Zuehlke (2010)	Mittal *et al.* (2019)	Davis *et al.* (2012)	Büchi, Cugno and Castagnoli (2020)	Chen *et al.* (2017)	Sjödin *et al.* (2018)	Davies, Coole and Smith (2017)	Mabkhot *et al.* (2018)	Illa and Padhi (2018)	Huber, Henkel and Kranz (2019)	Frank, Dalenogare and Ayala (2019)	Total mentions
- Cross departmental collaboration / knowledge sharing		Culture development																			X	X	X		3
- Open smart manufacutring culture	X	Culture development									X						X		X						3
- Proactive knowledge sharing of production staff	X	Culture development									X								X						2
- Lean culture implementation	X	Culture development									X			X											2
- Organisational agility		Culture development					X						X												2
- Continuous smart innovation	X	Culture development											X						X						2
- Decentralized decisions / decision process change (from mgmt. to worker)		Culture development														X									1
- Cross functional digitalization networks	X	Culture development																	X						1
- Innovative active employees	X	Culture development									X														1
- Keeping organisation up to date with latest SM trends	X	Culture development									X														1
- Direct relationship of management and worker to understand situation		Culture development																		X					1
- Top management support / commitment / approved budget		Initial assessment					X	X	X				X									X	X		6
- Assessment of readiness		Initial assessment	X										X												2
- Equipment readiness / intelligent manufacturing equipment		Initial assessment																X				X			2
- Include IoT infrastructure and data related aspects into analysis		Initial assessment						X																	1
- Consider organisational issues		Initial assessment						X																	1
- Consider human issues		Initial assessment						X																	1
- Smart products		Initial assessment																			X				1
- Solid governance		Initial assessment																				X			1
- Automation	X	Initial assessment																						X	1
- Technologies for humans / human centred interfaces and dashboards		Smart factory property												X		X									2
- Modular and reconfigurable fixtures / tools		Smart factory property												X							X				2
- Connection of machines through intelligent production and transport systems		Smart factory property				X																			1
- Delight customers with I4.0		Smart factory property											X												1
- Self-adopting decentralized structures		Smart factory property												X											1
- Self-organisation of the system		Smart factory property												X											1
- Use of simulation	X	Smart factory property																	X						1
- Proactive production planning and forecasting	X	Smart factory property																	X						1
- Flexibilisation	X	Smart factory property																						X	1
- Virtual system builder		Smart factory property																			X				1
- Virtual reader		Smart factory property																			X				1
- After-sales services		Smart factory property																			X				1
- Offering core processes as services		Smart factory property																			X				1
- Gradual implementation / progressive adaption		Organisational processes	X	X	X						X								X				X	X	7
- Deriving I4.0 strategy vision and roadmap	X	Organisational processes			X				X				X									X	X		5
- Formal implementation process	X	Organisational processes																	X				X		2
- I4.0 strategy framework (capabilities and use-cases)	X	Organisational processes			X																		X		2
- Specialized roles for predictability	X	Organisational processes																	X						1
- Defined project organisation		Organisational processes																					X		1
- Employee training / build internal expertise	X	Competency / skill enhancement			X			X	X			X			X	X			X		X	X			9
- Equip factory with digitalization knowledge	X	Competency / skill enhancement																	X						1
- Recruit data scientists and analysts	X	Competency / skill enhancement																	X						1
- Personal networks and market observations		External collaboration / networking				X																			1
- Process for inclusion of partners	X	External collaboration / networking																	X						1
- Technology partnerships		External collaboration / networking																				X			1

8.2 Appendix 2 – Challenges of SF implementation

Criteria	Topic cluster	Pinto *et al.* (2019)	VDMA Industrie 4.0 Forum (2016)	Jäger *et al.* (2016)	Kagermann *et al.* (2016)	Masood and Egger (2019)	Li, Peng and Xing (2019)	Mueller, Chen and Riedel (2017)	Iansiti and Lakhani (2014)	Wang *et al.* (2016)	Lee and Lee (2015)	Bauer, Jendoubi and Siemonheit (2004)	Huber, Henkel and Kranz (2019)	Total mentions
IT security, safety and privacy issues	Technical			X	X		X	X		X	X	X	X	**8**
Set up of appropriate infrastrucutre, CPS and sensors	Technical			X	X		X	X						**4**
Create robust system	Technical			X					X		X			**3**
Achieve coordination and management of machines	Technical							X						**1**
High complexity	Technical								X					**1**
Intelligent decision making and negotation mechanism	Technical									X				**1**
Manufacturing specific big data and analytics	Technical									X				**1**
Flexible conveying for adaptable routing	Technical									X				**1**
Develop necessary employee skills / change skillset / qualified personnal	Organisational			X	X		X					X	X	**5**
Knowledge of organisational implementation	Organisational		X	X	X								X	**4**
High investment necessary	Organisational			X	X	X					X			**4**
Cooperation and information sharing between departments	Organisational							X					X	**2**
Limited financial resources	Organisational	X												**1**
System modelling and analysis	Organisational									X				**1**
Unsuccessful projects	Organisational												X	**1**
Capacity for implementation	Organisational												X	**1**
New competitors, technologies and business models	External			X	X									**2**
Legal certainty	External			X	X									**2**

8.3 Appendix 3 – Outcomes of SF implementation

Criteria	Topic cluster	VDMA Industrie 4.0 Forum (2016)	Jäger *et al.* (2016)	Trost (2015)	Wang *et al.* (2016)	Pagnon (2017)	Sony and Naik (2019)	Davis *et al.* (2012)	Büchi, Cugno and Castagnoli (2020)	Sjödin *et al.* (2018)	Total mentions
Increased efficiency	Business impact	X	X				X			X	**4**
Increased flexibility	Business impact	X	X						X		**3**
Improved (product) quality	Business impact						X		X	X	**3**
Increased effectiveness	Business impact	X	X								**2**
Increased speed of innovation / speed	Business impact			X					X		**2**
Improved (product) safety	Business impact						X			X	**2**
Better sustainability	Business impact							X		X	**2**
Lower cost	Business impact								X	X	**2**
Increased risk of decisions	Business impact			X							**1**
Fast ROI	Business impact					X					**1**
Larger product variety possible	Business impact					X					**1**
Reduction of insurance cost	Business impact					X					**1**
Higher margins through direct sales	Business impact					X					**1**
Better strategic decision making	Business impact				X						**1**
Increased market strength	Business impact					X					**1**
Competitive advantage	Business impact						X				**1**
Meeting customer needs better	Business impact								X		**1**
Removal of human error and injuries / of errors	Direct result of technology					X			X		**2**
Decentralisation of data analytics and IT skills	Direct result of technology			X							**1**
Cheaper production of custom products	Direct result of technology					X					**1**
Detection and prevention of breakdowns	Direct result of technology					X					**1**
Real-time traceability	Direct result of technology					X					**1**
Optimizaiton	Direct result of technology					X					**1**
Manufacturing innovation	Direct result of technology						X				**1**
More responsive and optimized supply chain	Direct result of technology						X				**1**
Decreased logistics effort	Direct result of technology						X				**1**
Increased workers health	Direct result of technology						X				**1**
Lower cost management	Direct result of technology							X			**1**
Manufacturing intelligence	Direct result of technology							X			**1**
Increased capacity	Direct result of technology								X		**1**

8.4 Appendix 4 – Criteria maturity models

(1) Odwazny, Cyplik and Szymanska (2018); (2) VDMA Industrie 4.0 Forum (2016); (3) Mittal, Romero and Wuest (2018); (4) Sjödin et al. (2018); (5) Frank, Dalenogare and Ayala (2019)

Stage	Maturity	Criteria	Source	Cluster
1	No focus	Raw materials (hand-tools)	(3)	Automation / robotics
1	No focus	Manually-operated machines	(3)	Automation / robotics
2	Aspiration	Automation - Industrial Robots	(5)	Automation / robotics
2	Aspiration	Energy (pneumatic / electric machines)	(3)	Automation / robotics
2	Aspiration	Non-programmable machines	(3)	Automation / robotics
2	Aspiration	Automation and robotics of single processes.	(1)	Automation / robotics
3	Early maturity	Automation - Automatic nonconformities identification	(5)	Automation / robotics
3	Early maturity	Parts (NC-machines)	(3)	Automation / robotics
3	Early maturity	Programmable machines	(3)	Automation / robotics
4	Late maturity	Collaborative robots	(5)	Automation / robotics
4	Late maturity	Orders (manufacturing information system / MES)	(3)	Automation / robotics
4	Late maturity	Collaborative robot (mimic human)	(3)	Automation / robotics
5	Smart Factory	Sustainable resources	(3)	Automation / robotics
5	Smart Factory	Collabrative robot (based on AI)	(3)	Automation / robotics
1	No focus	Paper-based design	(3)	Design and simulation
2	Aspiration	Environment & model (CAD)	(3)	Design and simulation
3	Early maturity	Simulation software	(3)	Design and simulation
3	Early maturity	Simulation models are used in decision process and production steering.	(1)	Design and simulation
4	Late maturity	Virtualization - Virtual commissioning	(5)	Design and simulation
4	Late maturity	3D prototypes	(3)	Design and simulation
4	Late maturity	Implement simulation systems to test, prototype, and optimize the digital factory	(4)	Design and simulation
5	Smart Factory	Additive manufacturing	(5)	Design and simulation
5	Smart Factory	Augmented & virtual reality	(5)	Design and simulation
5	Smart Factory	Configurators (interfaces)	(3)	Design and simulation
5	Smart Factory	Simulation models used for all decision required processes	(1)	Design and simulation
1	No focus	Source available (raw materials / tools)	(3)	IIoT (Connectivity / traceability)
1	No focus	No communication	(2)	IIoT (Connectivity / traceability)
2	Aspiration	Sensors available	(3)	IIoT (Connectivity / traceability)
2	Aspiration	Part of the machine park is equipped in PLC steering.	(1)	IIoT (Connectivity / traceability)
2	Aspiration	Sensors / actuators / PLCs	(5)	IIoT (Connectivity / traceability)
2	Aspiration	Field bus interfaces	(2)	IIoT (Connectivity / traceability)
3	Early maturity	Traceability of final products	(5)	IIoT (Connectivity / traceability)
3	Early maturity	Internet of Things	(5)	IIoT (Connectivity / traceability)
3	Early maturity	Internet of Things is implemented gradually. More elements are included in the net	(1)	IIoT (Connectivity / traceability)
3	Early maturity	RFID (or similar technology) is widely used in the factory for track and trace	(1)	IIoT (Connectivity / traceability)
3	Early maturity	industrial ethernet interfaces	(2)	IIoT (Connectivity / traceability)
3	Early maturity	Signals are converted into readable formats	(3)	IIoT (Connectivity / traceability)
4	Late maturity	Traceability of raw materials	(5)	IIoT (Connectivity / traceability)
4	Late maturity	Machines have access to internet	(2)	IIoT (Connectivity / traceability)
5	Smart Factory	Automation - M2M communication	(5)	IIoT (Connectivity / traceability)
5	Smart Factory	Full integration of all installed tools and technologies	(1)	IIoT (Connectivity / traceability)
5	Smart Factory	Web-services (M2M software)	(2)	IIoT (Connectivity / traceability)
1	No focus	Register, logbooks, spreadsheets	(3)	Data storage / integration
1	No focus	Information exchange via mail / telecommunication	(2)	Data storage / integration
2	Aspiration	ERP	(5)	Data storage / integration
2	Aspiration	Built in HDs	(3)	Data storage / integration
2	Aspiration	Sufficient technology is available: including IT solutions	(1)	Data storage / integration
2	Aspiration	Connect existing technological applications to create data flow.	(4)	Data storage / integration
2	Aspiration	Central data servers in production	(2)	Data storage / integration
3	Early maturity	MES	(5)	Data storage / integration
3	Early maturity	Shared HDs (flash drive, intranet)	(3)	Data storage / integration
3	Early maturity	Software and systems are fully integrated data wise.	(1)	Data storage / integration
3	Early maturity	Uniform data formats and rules for data exchange	(2)	Data storage / integration
3	Early maturity	Storage of sensor data	(3)	Data storage / integration
4	Late maturity	Cloud	(5)	Data storage / integration
4	Late maturity	Cloud	(3)	Data storage / integration
4	Late maturity	Uniform data formats and interdivisionally linked data servers	(2)	Data storage / integration
4	Late maturity	Automated information exchange (e.g. order tracking)	(2)	Data storage / integration
5	Smart Factory	Fog (able to reduce network congestion / latency)	(3)	Data storage / integration
5	Smart Factory	Aggregated data is effectively stored	(1)	Data storage / integration
5	Smart Factory	Data base is fully secured	(1)	Data storage / integration
5	Smart Factory	Inter-divisional, fully networked IT solutions	(2)	Data storage / integration
5	Smart Factory	Suppliers / customers are fully integrated into the process design	(2)	Data storage / integration

Continued Appendix 4 – Criteria maturity models

Stage	Maturity	Criteria	Source	Cluster
1	No focus	Data collection	(3)	Data processing
1	No focus	No processing of data	(2)	Data processing
2	Aspiration	SCADA	(5)	Data processing
2	Aspiration	Data cleaning	(3)	Data processing
2	Aspiration	Enterprise aspires to aggregate available data effectively	(1)	Data processing
2	Aspiration	Storage data for documentation	(2)	Data processing
3	Early maturity	Energy monitoring and improving	(5)	Data processing
3	Early maturity	Data integration (combination of different sources)	(3)	Data processing
3	Early maturity	Enterprise is implementing Big Data concept.	(1)	Data processing
3	Early maturity	Monitoring and cooperation is built within machine park	(1)	Data processing
3	Early maturity	Create insight-mining processes to support information gathering across departments	(4)	Data processing
3	Early maturity	Increase accuracy of data collection from technology	(4)	Data processing
3	Early maturity	Create automated processes for data mining and sharing across functions	(4)	Data processing
3	Early maturity	Analyzing data for process monitoring	(2)	Data processing
4	Late maturity	Virtualization - AI for maintenance (Predictive Maintenance)	(5)	Data processing
4	Late maturity	Virtualization - AI for production (Optimization	(5)	Data processing
4	Late maturity	Big Data	(5)	Data processing
4	Late maturity	Data reduction (only important data left)	(3)	Data processing
4	Late maturity	Use insight analysis and data interpretation to streamline operational processes	(4)	Data processing
4	Late maturity	Create processes for evaluating optimization opportunities	(4)	Data processing
4	Late maturity	Implement systems for real-time performance analysis	(4)	Data processing
4	Late maturity	Evaluation for process planning / control	(2)	Data processing
5	Smart Factory	Analytics	(5)	Data processing
5	Smart Factory	Data transformation (avoid redundancies)	(3)	Data processing
5	Smart Factory	World class in aggregation, analysis and data interpretation.	(1)	Data processing
5	Smart Factory	Data is valid, up to date and allows sufficient production steering	(1)	Data processing
5	Smart Factory	Monitoring of current state and real-time capability.	(1)	Data processing
5	Smart Factory	Develop processes for integrating data visualization into decision making	(4)	Data processing
5	Smart Factory	Create proactive processes for forecasting and planning future production	(4)	Data processing
5	Smart Factory	Create systems to monitor and visualize critical operational analytics	(4)	Data processing
5	Smart Factory	Automatic process plannnig / control	(2)	Data processing
1	No focus	No information exchange between user and machine	(2)	Man - machine interface
2	Aspiration	Use of local user interfaces	(2)	Man - machine interface
3	Early maturity	Remote monitoring	(5)	Man - machine interface
3	Early maturity	Centralized / decentralized production monitoring / control	(2)	Man - machine interface
4	Late maturity	Remote operation	(5)	Man - machine interface
4	Late maturity	Use of mobile user interfaces	(2)	Man - machine interface
5	Smart Factory	Able to be operated with interface	(3)	Man - machine interface
5	Smart Factory	Augmented and assisted reality	(2)	Man - machine interface
1	No focus	Rigid production systems and a small proportion of identical parts	(2)	Small batch production
2	Aspiration	Use of flexible production systems and identifcal part	(2)	Small batch production
3	Early maturity	Flexible production systems and modular designs for the products	(2)	Small batch production
4	Late maturity	Component-driven flexible production of modular products within the company	(2)	Small batch production
5	Smart Factory	Flexible lines	(5)	Small batch production
5	Smart Factory	Component-driven modular production in value-adding networks	(2)	Small batch production
2	Aspiration	Readiness to cooperate with other departments, within enterprise	(1)	Horizontal integration
3	Early maturity	Digital platforms with other companies units	(5)	Horizontal integration
3	Early maturity	Full cooperation between departments.	(1)	Horizontal integration
3	Early maturity	Readiness to cooperate with other companies in the supply chain and potential co-operators	(1)	Horizontal integration
4	Late maturity	Digital platforms with suppliers	(5)	Horizontal integration
4	Late maturity	Customer involvement (product design)	(3)	Horizontal integration
4	Late maturity	Organize sense-making sessions with suppliers, users, and other stakeholders	(4)	Horizontal integration
5	Smart Factory	Digital platforms with customers	(5)	Horizontal integration
5	Smart Factory	Collaboration (supplier involvement)	(3)	Horizontal integration
5	Smart Factory	Factory as integral element of SC cooperating with companies in the branch and outside	(1)	Horizontal integration
5	Smart Factory	High level of integration with clients	(1)	Horizontal integration
5	Smart Factory	Products highly customized according to market demand	(1)	Horizontal integration
5	Smart Factory	Demand driven planning according to single clients' order	(1)	Horizontal integration
5	Smart Factory	Integrate digital system insights from external partners to enable supply chain predictability	(4)	Horizontal integration
1	No focus	Lean thinking (waste elimination)	(3)	Digital culture
2	Aspiration	Organizational culture (same values / beliefs)	(3)	Digital culture
2	Aspiration	Create inclusive culutre for implementation by involving workforce in vision development	(4)	Digital culture
2	Aspiration	Apply a digital lens to map existing and new technologies.	(4)	Digital culture
3	Early maturity	Employee involvement (outside R&D)	(3)	Digital culture
3	Early maturity	Build cross-functional digitalization networks to facilitate knowledge sharing	(4)	Digital culture
5	Smart Factory	Create a culture of continuous smart factory innovation	(4)	Digital culture
1	No focus	No networking of produciton with other business units	(2)	Cross-departmental collaboration
2	Aspiration	Individuals are capable to work in teams.	(1)	Cross-departmental collaboration
2	Aspiration	Information exchange via mail / telecommunication	(2)	Cross-departmental collaboration
3	Early maturity	Teams gain autonomy and can easily cooperate with others	(1)	Cross-departmental collaboration
3	Early maturity	Internet-based portals with data sharing	(2)	Cross-departmental collaboration
5	Smart Factory	High level of autonomy and decentralization	(1)	Cross-departmental collaboration
2	Aspiration	Formalize hybrid smart factory implementation processes.	(4)	Organisation
2	Aspiration	Create process for involving external actors in development of connected platform.	(4)	Organisation
3	Early maturity	Revise production staff roles to proactively coordinate digital insights and knowledge sharing	(4)	Organisation
4	Late maturity	Employees are controlling the process and react to system warnings if necessary	(1)	Organisation
5	Smart Factory	No operational employees in the machine park	(1)	Organisation
5	Smart Factory	Big investment pressure in research and development area.	(1)	Organisation
5	Smart Factory	Create specialized roles and responsibilities geared toward predictable production	(4)	Organisation
2	Aspiration	Team has qualified individuals including IT specialists and automatics engineers.	(1)	Skills / Know-how
2	Aspiration	Recruit people with digitalization knowledge	(4)	Skills / Know-how
3	Early maturity	Operational employees have analytic skills and operate with available IT software	(1)	Skills / Know-how
3	Early maturity	Educate people to develop the ability to exploit connected data systems.	(4)	Skills / Know-how
4	Late maturity	Recruit data analysts and data scientists to optimize production	(4)	Skills / Know-how
5	Smart Factory	Staff consists of experts	(1)	Skills / Know-how
5	Smart Factory	Staff is being moved to other departments from shop floor if possible (skills and knowledge)	(1)	Skills / Know-how

8.5 Appendix 5 – Orientation study interview guideline

General Questions

- To improve the quality of the transcript, is it ok if the interview is recorded?
- Background information:
  - What is your position?
  - What are your tasks and responsibilities?
  - How long are you in the company?
  - What is Smart Factory for you?

Explorative Questions

Smart Factory Assessment / Maturity

- In which Smart Factory projects are you involved?
- Are there other Smart Factory projects than these on the overview list?
- How smart is the factory on a scale 1 - 5 and how do you determine it?

Smart Factory Strategy / Roadmap

- How was the Smart Factory strategy / program created?
- How do Smart Factory projects evolve?
- How are other plants working?
- Where are the focus areas of the Smart Factory program?
- How was the need for change identified to start the Smart Factory program?
- Who was the sponsor (budget)?
- How were the human resources for the initiative managed?
- What other process improvement activities are present and how are they connected to Smart Factory program?

Smart Factory Program Implementation

- Out of your experience, what worked well?
- What are / have been success factors?
- What are / have been challenges?
- What could have been improved?
- What are / have been the outcomes and benefits?
- Identified benefits from literature are: Increased efficiency, increased flexibility, improved quality, increased effectiveness, increased speed, less errors and better sustainability – can you confirm these?
- Theoretical Smart Factory implementation framework
  a. What are your thoughts and relevant experiences of this approach?
  b. How would you group the technologies clusters and why?
  c. Are the maturity stages senseful for you?

Smart Factory Project Implementation

- How are Smart Factory projects organized and why?
  a. Who is the project leader?
  b. How is the way of working (different phases / deliverables)?
- How is the process of technology implementation?
- Theoretical project implementation framework
  a. What are your thoughts and relevant experience of this approach?
  b. What challenges / success factors do you think each stage has?

Which projects are valuable cases in terms of size, implementation, benefits and challenges?

8.6 Appendix 6 – Main study interview guideline

General Questions

- To improve the quality of the transcript, is it ok if the interview is recorded?
- Background information:
  - What is your position?
  - What are your tasks and responsibilities?
  - How long are you in the company?
  - What is Smart Factory for you?

Explorative Questions

Smart Factory Overview

- In which Smart Factory projects are you involved?
- Are there other Smart Factory projects than these on the overview list?
- How are Smart Factory projects organized?
  a. Who is the project leader?
  b. How is the way of working?

Smart Factory Project

- Brief description of the Smart Factory project
- Out of your experience, what worked well?
- What are / have been success factors?
- What are / have been challenges?
- What are / have been the results and benefits?
- What could have been improved?
- Identified benefits from literature are: Increased efficiency, increased flexibility, improved quality, increased effectiveness, increased speed, less errors and better sustainability – can you confirm these?

Smart Factory Project Implementations

- How are Smart Factory projects organized?
- How is the process of implementation?
- How is the implementation framework used?
  a. How was the need for change identified?
  b. What was the scope of the project and how was it communicated?
  c. Who was the sponsor (budget)?
  d. How are human resources for project teams managed? What was crucial?
  e. What are the deliveries for each gate?
- Theoretical project implementation framework
  a. What are your thoughts and relevant experience of this approach?
  b. What challenges / success factors do you think each stage has?

8.7 Appendix 7 – Strategic SF Implementation Framework

Key activities	Success factors	Challenges
	Assessment of readiness	
Criteria: - Degree of digitalization - Smartness of current products and services - Adaptability of employees to I4.0 - Management commitment - Dependencies to other projects - Expertise and Know-how for I4.0	- Dedicated SF project owner with I4.0 expertise - Defined project team - Global perspective - SF communities / networks	
	Definition of Maturity	
- Use of maturity model - Definition of current state and indication of effort for implementation	- Maturity model to benchmark different production plants - Gradual implementation of SF	
	Strategy & Vision	
- Strategy workshops - Definition of overall strategy - Definition of department specific strategies - Driving of fields of actions on basis of the maturity model incl. Prioritization	- Establishing of strategy supporting KPIs - Strategically manage investment for architecture	- Different SF approaches in different plants - Measuring of success
	Identify technologies	
- Discover, review and analyze existing processes in the fields of action - Decomposition of tasks and processes - Selection of fitting technologies - Development of technology concepts	- In the beginning: start with small and independent use cases, with fast payoff and little training effort	
	Develop use cases & scope	
- Assessment of potential and benefits of technology concepts - Business case creation and assessment of interdependencies - Mapping of old and new technologies - Set up of implementation and control strategy	- Clear and defined project vision and scope - ROI prediction	- Different maturity levels of different plants (limited scalability)
	Roadmap	
- Visualization of all use cases - Overview of time and content dependencies		

8.8 Appendix 8 – Operational SF Implementation Framework

Key activities	Success factors	Challenges
	Define (only for bottom-up projects)	
- Define project scope and vision	- Origin bottom-up: Conferences, networks, market observations, technology partnerships	
	Specify	
- Project Kick-off - Set up project organization (team / resources) - Project plan - Requirement specifications	- Open discussion concerning the target - Aligned and defined project owner, goals, responsibilities, scope - Skills and knowledge of project members (IT & technical) - Formation of core and expert team - Set up change management strategy	- Lack of PM skills - Different interests in projects - Legal certainty
	Connect / integrate	
- If applicable evaluate vendors - Integration of new technology (Create MVP/prototype) - Plan testing, training, change management - Specify solution - Actively manage stakeholders	- Market overview of different systems, solutions & vendors - Employee involvement with right knowledge at the early stage - Selection of the right platform and integration partner - Compatibility existing systems (alignment with IT)	- Integration of new technology with existing layout, processes, and equipment (lack of standardization) - Importance of new technology features partly unclear, due to novelty - Blocking of employees against change
	Examine / validate	
- Development of operating concept / pilot - Evaluation and testing of improvements and new value through new technology - Refine planning, training and change management	- Proof of concept in small and delimited area - Ensure a sustainable solution and scalability	- Consider all operating factors - Evaluation of system - Adaptability of existing processes
	Develop business case	
- Quantification of new value and improvements - Calculation of the return on investment - Plan Cut-over - Manage Change	- Training and alignment of employees before cut-over - Consider flexible usage and standardization potential	- Quantification of exact cost savings and benefit - Not completely reliable, due to human factor
	Execute / implement	
- Development, implementation and full test - Analyze bottom line impact - Start reporting and controlling - Roll-out after achieving of results	- Keep management attention until project end	- Implementation perceived not as interesting as technical realization
	Scale	
- Evolving to other similar processes and use cases - Evolving to other more complex processes		