Organising the Implementation of Industry 4.0 in a High Value German Manufacturing Firm: A Complex Adaptive Systems Approach.

Julian Rüb

This thesis is submitted to Newcastle University in fulfilment of the requirements for the degree of

Doctor of Philosophy

Newcastle University Business School
Faculty of Humanities and Social Sciences
United Kingdom

September 2021

Dedicated to the ones giving

their dreams a chance.

Abstract

This thesis addresses an important research gap in empirical qualitative evidence regarding the organisational aspects of the implementation of Industry 4.0. Whereas there is a basic understanding of the technical implementation in the factory plant, the understanding of the implementation from an organisational perspective is limited. A holistic single case study with 35 semi-structured expert interviews enabled a deep exploration of an implementation in a real-world context at the firm level. The findings demonstrate how a high value German manufacturing company has implemented Industry 4.0, as well as why this firm implemented as it did. Several elements are thematically analysed, representing important examples of how manufacturing firms can organise the implementation of Industry 4.0 in praxis. Covering the three areas of actions, influences and relationships, the implications of the analysed elements are discussed in relation to six theoretical themes, namely centralisation vs. decentralisation, diffusion of new ideas, working in teams, trust, open innovation and path dependence. This thesis represents the first existing study that understands the implementation of Industry 4.0 as a Complex Adaptive System of interrelated system elements which continuously evolve over time. In this sense, a newly developed system model acknowledges important relationship characteristics that lead to a more comprehensive perspective on the complex implementation of Industry 4.0. This thesis contributes to the research field by being the first study to suggest a “dual approach” encompassing important decentralised as well as centralised implementation patterns for a successful process. It furthermore demonstrates how workforce concerns regarding job security significantly influence the emergence of system elements regarding change management during the implementation of Industry 4.0. The thesis offers academic contributions to the Industry 4.0 implementation literature, as well as organisational elements recommended for practitioners when organising the implementation of Industry 4.0.

Acknowledgements

I would like to thank my supervisors for critically reviewing my work during the Ph.D. journey at Newcastle University Business School in the United Kingdom. I especially thank Paul Richter, my former M.Sc. degree programme director at Newcastle University, for being a supportive mentor throughout the Ph.D. process. Our good conversation in 2015 may have been the trigger to pursue the Ph.D. a few years later. Furthermore, I thank Guido Baltes and his fantastic Ph.D. students Christoph, Christina, Chrissi and Nicolai, for offering me the infrastructure and environment to make the hard work of the Ph.D. much more enjoyable. In this sense I thank the University of Applied Sciences in Konstanz for being a trustful and stable institution and partner in Germany. I very specially thank my friend Kevin from Leipzig for mentoring me at the beginning of the second half of the Ph.D. and for providing important input on the systems thinking perspective. Our conversations and your valuable feedback supported my progress in this Ph.D. project.

I furthermore would like to thank the company “BERTLEI” and all its anonymous participating actors for their time and interest, and for everything I could learn from you by conducting the interviews for this thesis. I found that collecting the data and hence building an understanding of the implementation of Industry 4.0 in praxis was the most interesting part of this research project. In this sense I would like to highlight the supportive role of Sven from Stuttgart with whom I could exchange many valuable thoughts in this direction. I furthermore thank the members of the NITIM doctoral school and the ICE IEEE conference network, who each year provided an interesting and supportive critical perspective on my research. In the same way I thank my colleagues from Newcastle University, Nosheen, Meryem, Nuzhat, Saleh, Hugo, and more, for the companionship and the countless conversations and knowledge exchange throughout the previous years.

Finally, I want to heartfelt thank my family and good friends for being authentic and solid pillars in my life, supporting and encouraging me in most of the things I am doing. These social relations may be the most important thing that really count at the end, at least evaluated retrospectively. My academic career has been a test of endurance and character for me. I began this journey fearless and convinced, but had to learn and work through a contrary perspective in the later stages of it. Whether in academia or elsewhere, I dedicate this work to all those with open eyes and the aspiration to give their dreams a chance. I am looking forward to the exciting conversations and joint projects building on this period of my life.

Declaration and Statement of Copyright

Julian Rüb, September 30th 2021

Table of Content

List of Figures

List of Tables

List of Abbreviations

Acatech	German Academy of Science and Engineering
BERTLEI	Synonym for the firm of the case study of this thesis
BITKOM	German Association for Information Technology
CAS	Complex Adaptive Systems (theory)
CDDT	Central department for digital transformation
CDO	Chief digital officer
CEO	Chief executive officer
CPS	Cyber Physical Systems
DDS	Data protocol
D2D	Device to device
Et al.	et alia / and others
EtherCAT	Data protocol
e.g.	For example
FMCG	Fast moving consumer goods
GPS	Global positioning system
HR	Human resources
ICT	Information and communication technology
IEEE	Institute of electrical and electronics engineers
IIC	Industrial internet consortium
IIRA	Industrial internet reference architecture
Industrie 4.0	German name for Industry 4.0
Industry 4.0	The fourth industrial revolution
IoS	Internet of services
IoT	Internet of Things
IP	Interview participant
IT	Information technology
IVI	Industrial value chain initiative
i.e.	that means
I4.0	Industry 4.0
KPI	Key performance indicator
KRI	Key risk indicator

LISA	Line information system architecture
MES	Manufacturing execution system
NFC	Near field communication
OPC-UA	Open platform communication unified architecture
OSLC	Open services for lifecycle collaboration
RAMI	Reference architectural model industrie
RFID	Radio-frequency identification
ROI	Return of investment
RSBF	Resource sharing-based framework
SDIN	Software defined industrial network
SLR	Self-organising local relationships
TCE	Transaction Cost Economics (theory)
U.S.	United States
XYZ	Synonym for anything

Chapter 1. Introduction

1.1 Background and research context

Industry 4.0 refers to real time, intelligent, horizontal and vertical interconnectedness of people, machinery, objects and ICT-systems for the dynamic management of complex systems (Kagermann et al., 2013). The notion was first introduced in 2011 at the Hanover Industrial Fair and developed as part of the German high-tech strategy in 2013 (Kagermann et al., 2011; BMBF, 2014). Its main driver refers to emerging new technologies, such as cyber physical systems (CPS), the internet of things (IoT) and cloud computing. Governments, academics, industries and organisations are trying to make sense of the new phenomenon as well as their combined implementation, which makes Industry 4.0 an intensively discussed topic (Hartmann and Halecker, 2015). Industry 4.0 follows three previous industrial revolutions, which refer to 1.) the invention of the steam engine, 2.) the invention of conveyor belt production, and 3.) the invention of programmable machines (Acatech, 2013). The dates of the latest references of this thesis, such as Hoyer et al. (2020) and Veile et al. (2020), indicate that research on the implementation of Industry 4.0 is still very much a developing research field.

The aim of Industry 4.0 is to optimise the efficiency of value creating processes in terms of production optimisation, and hence customer value (Bauer *et al.*, 2014; Roth, 2016; Vachálek *et al.*, 2017). The literature consistently agrees that the implementation of Industry 4.0 can lead to the creation of value (Acatech, 2013; Westerlund *et al.*, 2014; Bauer *et al.*, 2014; Bauernhansl *et al.*, 2015; Burmeister *et al.*, 2016; Kiel *et al.*, 2017; Kusiak, 2018; Moeuf *et al.*, 2018; Buer *et al.*, 2018; Tuptuk and Hailes, 2018; Sjödin *et al.*, 2018) and is not just a "management fashion" (Madsen, 2019) that fails to gain consistent practical relevance due to the non-fulfilment of its promises. Scholars and research institutions, like *"BITKOM"* and *"FRAUNHOFER",* estimate the economic value of Industry 4.0 for Germany. They predict a rise from 76.8 to 99.8 billion Euro gross value added between 2013 and 2025, a yearly growth of 2,2% (Bauer *et al.*, 2014). However, the level of potential value that Industry 4.0 releases depends critically on how successfully a firm implements the concept.

This thesis differentiates between the technical and the organisational aspects of the implementation of Industry 4.0. Whereas the technical side examines the implementation of single technical Industry 4.0 components (mostly at the shop floor level), the organisational side examines the organisational and management aspects that occur more at the strategic firm level of the company, as Chapter 2 will show.

1.2 Problem definition

The review of the literature has identified a strong knowledge gap regarding the implementation of Industry 4.0 (Acatech, 2016b; Strozzi et al., 2017; Moeuf et al., 2018). The risk of failing the implementation is a threat to firms as this would potentially lead to a reduced return on investment and loss of competitive advantage (Tuptuk and Hailes, 2018; Sjödin et al., 2018). Existing research mostly focusses on the technical aspects of the implementation only (Liao et al., 2017; Strozzi et al., 2017; Galati and Bigliardi, 2019). Furthermore, the limited existing managerial literature is still strongly affected by the technical aspects (Piccarozzi et al., 2018), which leaves a great research gap in the organisational aspects of the implementation of Industry 4.0. Studies refer to strategic and operational turbulence, a lack of understanding of the complex nature, uncertainty about requirements, immense challenges, a lack of strategy and a lack of theory, as examples of the present research gap. In addition, most of the existing approaches are restricted to secondary research, which is performed by examining the implementation of Industry 4.0 through literature reviews or surveys (Hoyer et al., 2020). Therefore, there is a clear need for primary qualitative research in this area that generates meaningful empirical evidence.

Besides the calls for qualitative empirical evidence about the organisational aspects of real implementation cases, there is also evidence for the need for more comprehensive approaches on the implementation of Industry 4.0 (Piccarozzi et al., 2018; Staufen AG and Staufen Digital Neonex GmbH, 2019; Hoyer et al., 2020). Such a need for more comprehensive approaches derives from the high complexity that the implementation of Industry 4.0 incarnates (Hoyer et al., 2020). Several recent studies have highlighted and confirmed the complex nature of Industry 4.0 and the complexity of challenges of its implementation (DFKI, 2011; Kagermann *et al.*, 2013; Bauer *et al.*, 2014; Petrovic and Leksell, 2017; Tuptuk and Hailes, 2018; Lin *et al.*, 2018a; Moeuf *et al.*, 2018; Odważny *et al.*, 2018; Cordeiro *et al.*, 2019; Madsen, 2019; Veile *et al.*, 2020), which leads the approach of this thesis to define the implementation of Industry 4.0 as a complex system (Hoyer et al., 2020). Exploring the single factors in complex environments is necessary. However, exploring their relationships in a more comprehensive manner potentially leads to a better understanding of the complexity in focus. In summary, the reviewed literature for this thesis (provided in Chapter 2) indicates a clear research gap regarding qualitative empirical evidences on the organisational aspects of the implementation of Industry 4.0 in manufacturing firms.

1.3 Objective and research question

Addressing this research gap in an explorative and qualitative way contributes to the frequently stated demand to deliver empirical knowledge about the organisational aspects of the implementation of Industry 4.0. Therefore, the aim of this thesis is the examination of the organisational aspects of the implementation of Industry 4.0 in a high value German manufacturing company. Directed at closing this research gap, the research questions of this thesis are: 1.) How does a high value German manufacturing firm organise the implementation of Industry 4.0 at the firm level?, and 2.) Why does a high value German manufacturing firm organise the implementation of Industry 4.0 at the firm level as they do? The complex nature of the implementation as well as the benefits of a comprehensive perspective on the topic provide reasons to apply systems thinking (Hoyer et al., 2020) as a theoretical lens for this research. Complex Adaptive Systems (CAS) theory is one related opportunity that offers wider comprehensiveness in taking also the relationships between systems elements into account. CAS focusses on the systems' learning capabilities as well as on how new rules, structures and behaviours evolve (McCarthy et al., 2006). As such, the application of CAS offers significant potential to address the detected research gap of this thesis, not only by offering the required comprehensiveness on the complex topic but also by capturing adaptability i.e. "self-organisation", "emergence", and "nonlinearity" in the centre of the theory. Since the people and their behaviours (the actors and actions) in the firm must adapt to new circumstances due to the implementation of Industry 4.0, CAS enables the further structuring, exploring, and analysing of the influential mechanisms that interrelate with the implementation outcomes.

1.4 Research method

To address the research objective and support answering the "how" and "why" research questions of this thesis, a qualitative empirical research design was chosen that offers an explorative and in-depth understanding of the phenomenon. The use of a qualitative research strategy is particularly appropriate since research on the organisational aspects of the implementation of Industry 4.0 is at an early stage, and because comprehensive and systematic investigations are rare (Silverman, 2009). Qualitative approaches are recommended to be used in novel, complex and evolving real world environments (Yin, 2009), which is the case for the exploration of the implementation of Industry 4.0 (Veile et al., 2020). Furthermore, researching CAS behaviour in social systems requires qualitative perspectives (Brown and Eisenhardt, 1997; Bradach, 1997; Eisenhardt and Bhatia, 2002), making it an appropriate research framework for this thesis.

The research philosophy of this thesis is critical realism (Bhaskar, 1989) and represents the researcher's ontological and epistemological position. The relevance of an interpretivistic perspective in this study emerges from the explorative character and the collection of data through interviews. Critical realism understands reality as an "open system of emergent entities" (O'Mahoney and Vincent, 2014). If the structure, procedure or the process of social conditions change, reality may change too (Saunders et al., 2012). This thesis adopts an inductive research approach, which refers to understanding the nature of a problem by analysing collected data, making sense of it and finally formulating theory (Saunders et al., 2012). Central to theory building and to a theoretical contribution in this sense is the notion of understanding the "why" of a phenomenon in question (Whetten, 1989). The choice of strategy is based on a holistic single case study (Yin, 2014). The real world context and the embeddedness in rich empirical data enables case study research to produce not only interesting, but also accurate and testable theory (Eisenhardt and Graebner, 2007). Case studies with their iterative and descriptive nature, are well suited to capture the rich and qualitative structures of social CASs and to build new theory (Brown and Eisenhardt, 1997; Bradach, 1997; Eisenhardt and Bhatia, 2002).

In line with Eisenhardt and Graebner (2007), this thesis used inductively analysed semi structured in-depth expert interviews with managers and employees as the methodological technique of data collection. The semi-structured interviews enable collecting data in a structured way, yet maintaining an adequate and necessary level of openness to allow unexpected and novel knowledge to emerge (Yin, 2009). 35 interviews of about 45 minutes in length led to 303 pages of transcripts. Data collection of the cross-sectional study started in March 2019 and ended in July of the same year after it became increasingly apparent that saturation had been reached and additional data no longer led to greater theoretical insights (Charmaz, 2006). The interviews captured the empirical knowledge, behaviour and experiences about the successful implementation of Industry 4.0 in the firm (Denzin and Lincoln, 2003). A firm operating in the German economy was chosen due to its representative character for a developed and industrialised nation, its economic importance for the European Union, and particularly because of its advanced experience in the implementation of Industry 4.0 (Veile et al., 2020). The targeted German high value manufacturing firm of the single case study represents a leading organisation in its field and is considered as an early and advanced adopter of Industry 4.0.

Interview participants were selected on the basis of their relevance for the organisational implementation of Industry 4.0 and their potential contribution to a holistic exploration of the case. New data from interviews continuously developed the researcher's understanding of the complex system of intertwined relationships in the implementation of Industry 4.0. The processes of data management, i.e. coding and analysis, were guided by the research questions of this thesis and the key variables of Complex Adaptive Systems Theory. The theoretical sampling used for the interviews of this thesis ensured the continuous elaboration and refinement of the findings as well as the identified codes and themes in the data (Charmaz, 2006). The data display and analysis approach followed the three steps suggested by Miles and Huberman (1994), which consist of the data reduction, data display and drawing and verifying conclusions. The applied thematic analysis is a systematic method for determining themes in complex data sets by coding and categorising common phrases and themes expressed by the interviewees (Braun and Clarke, 2006). Reliability and validity is determined based on the collected data representing the same phenomena (Mason, 1996). Throughout the course of this thesis, developed material was repeatedly evaluated in the context of academic conferences.

1.5 Contribution of this dissertation

This thesis addresses the defined research gap with new empirical qualitative evidence on the organisational aspects of the implementation of Industry 4.0. The findings demonstrate how a high value German manufacturing company implemented Industry 4.0 at the firm level, as well as why this firm implemented it as it did. Nineteen system elements were derived from the thematic data analysis and developed into a new system model that demonstrates the complex and adaptive interconnected variables which are part of and influence the implementation of Industry 4.0. The system elements represent important new examples of how manufacturing firms can organise the implementation of Industry 4.0 in praxis. Covering the three areas of actions, influences and relationships, the implications of the analysed elements are discussed in relation to six theoretical themes, namely centralisation and hierarchy, diffusion of new ideas, working in teams, trust, open innovation and path dependence.

This study furthermore stresses the importance of the systems thinking perspective when researching the mechanisms and complexities of the implementation of Industry 4.0 in manufacturing firms. In this sense, this thesis represents the first existing study that approaches the organisational aspects of the implementation of Industry 4.0 as a Complex Adaptive System of interrelated system elements, which continuously evolve over time. The acknowledgement of important relationship characteristics in the new developed system model led to a “more comprehensive” understanding on the implementation of Industry 4.0. The application of CAS in combination with a holistic single case study enabled the detection of new relationship characteristics that could potentially not have been detected without the application of CAS as the theoretical lens. This thesis contributes to the research field as the first suggesting a “dual approach” encompassing important decentralised as well as centralised implementation patterns for a successful process. It furthermore demonstrates how workforce concerns regarding job security risk influence significantly the emergence of system elements regarding change management during the implementation of Industry 4.0. Such patterns of interconnectedness are the true examples of the original contribution that only the application of CAS as a theoretical lens enabled. No other study was found that either applied CAS as a lens in this subject area or that detected such relationship characteristics in their research. This thesis offers academic contributions to the Industry 4.0 implementation literature, as well as organisational elements recommended for practitioners when organising the implementation of Industry 4.0.

1.6 Thesis outline

Following this introduction, Chapter 2 explores the literature on the concept of Industry 4.0 as well as the management of its implementation. This chapter will identify the organisational aspects of the implementation of Industry 4.0 as a major research gap which leads to the formulation of this thesis's research objective and research questions. Complex Adaptive Systems Theory will be chosen as an appropriate theoretical lens to develop a more comprehensive system model for the implementation of Industry 4.0. Chapter 3 sets out the methodological choices of this thesis, articulating the researcher's philosophical position, the research approach and design, as well as the reliability and ethical considerations of this empirical study. Chapter 4 presents a critical analysis of the findings in the light of the developed research framework and the methodological choices articulated in Chapter 2 and 3 of this thesis. The data analysis in Chapter 4 leads to the formulation of nineteen systems elements and the development of a new system model for the implementation of Industry 4.0. Chapter 5 discusses these findings in relation to the earlier literature review leading to identifying the original contributions of this thesis in relation to the research questions highlighted before. Last but not least, Chapter 6 concludes this empirical study before discussing potential limitations and identifying areas for future research.

Chapter 2. Literature Review

2.1 Introduction

This chapter presents analysis of the current knowledge about Industry 4.0 (For brevity, the abbreviation I4.0 will often be used in this thesis) and its implementation. The main databases used for the literature review are “EBSCO – Business Source Complete” and “Google Scholar”. Publications were selected according to their relevance for the research topic and were supplemented with a backward / forward search. Backward / forward search is an acknowledged method for literature reviews (Webster and Watson, 2002). Next to the relevance of the topic, articles were chosen by journal ratings, citation count, and the year of publication. Industry 4.0 related articles have been published from 2011 onwards, as the term and the concept of Industry 4.0 was first introduced in 2011 (Tortorella and Fettermann, 2018). The latest publications at the time of the current research were published in 2020, which indicates that Industry 4.0 is still a developing research field. The literature review prepares an effective development of knowledge about new theories and uncovered areas where research may still be needed (Webster and Watson, 2002).

2.2 The concept of Industry 4.0

Industry 4.0 refers to intelligent self-managing production processes where machines, products, people, equipment and logistic systems directly communicate and cooperate with each other (Plattform Industrie 4.0, 2018). With the aim of optimising the efficiency of value creating processes, Industry 4.0 raises the overall customer value (Bauer *et al.*, 2014; Roth, 2016; Vachálek *et al.*, 2017). A central element of I4.0 is the integration of cyber physical systems (CPS) along the value chain (Bauernhansl et al., 2015; Burmeister et al., 2016; Wang et al., 2016a). The integration of CPS along the value chain brings great digitalisation to products and processes (Bauer *et al.*, 2014; Burmeister *et al.*, 2016). The digitalisation of the manufacturing industry in combination with the emergence of the internet of things are the main reasons why Industry 4.0 is also called the “Fourth Industrial Revolution” (Kagermann et al., 2011; Acatech, 2013). The internet of things offers the required infrastructure for CPS in an Industry 4.0 environment. Industry 4.0 may enable individualised customer orders to lead their way autonomously (Acatech, 2013) by telling machines and cellular transport systems what treatment they require and where they need to go. The product leads its way through the production towards the distribution directly to the customer (Vogel-Heuser et al., 2017).

To achieve such results, CPS constantly collect data. Analysing this data may lead to clarity, and background knowledge for optimisations.

I4.0 represents a new level of managing and controlling value chains over entire lifecycles. The lifecycles includes all phases from the idea, through the order, development, production, distribution, and recycling, as well as connected services (Bauer *et al.*, 2014). Ultimately, Industry 4.0 will optimise the efficiency of value creating processes, and in doing so the customer value (Bauer *et al.*, 2014; Roth, 2016). Production facilities, warehousing systems, logistics and even social requirements are meant to be integrated to establish a global value creation network (Acatech, 2013; Wang et al., 2016a). The following sections analyse the evolution, drivers, definition, key technologies, and the potential benefits of Industry 4.0 that are referred to in the existing literature.

2.2.1 The Evolution from Industry 1.0 to Industry 4.0

The first three industrial revolutions evolved from the introduction of mechanisation, electricity and IT, whereas the fourth industrial revolution builds on the implementation of information and communication technology (ICT) related solutions such as CPS and IoT (Acatech, 2013; BMBF, 2014; Westerlund et al., 2014). This section provides an overview of the evolution starting at Industry 1.0 and leading to Industry 4.0. The first industrial revolution started around 1784 with the introduction of mechanical manufacturing equipment (Acatech, 2013). The development of the steam engine by James Watt enabled a new method of how producing goods and provided a breeding ground for the development of better logistics and more trade through the use of steam ships and steam trains. Machines and engines transformed the present agricultural oriented society into an industrial oriented society and have led to what is known today as the era of industrialisation.

The second industrial revolution built upon the discovery of electricity (Acatech, 2013). The development of electric engines replaced the steam engines in most centralised applications. The development of the fuel engine on the other hand replaced the steam engine in most decentralised applications. Oil became an important raw material for the production of fuel, needed for machines like cars. The introduction of the conveyor belt and assembly line in 1870 fostered the division of labour and mass production. The third industrial revolution was based on the introduction of programmable logic controllers in manufacturing industry around 1969 (Acatech, 2013). The main enabler of the third revolution was the development of electronic components and information and communication technology (ICT). The automation of modern industrial productions increased. The third industrial revolution appeared together with the German "economic miracle" after the second world war. The wealth of the middle class rose and markets turned from seller to buyer markets. Manufacturing companies had to turn from mass production to varied serial production and mass customisation. The introduction of the internet brought worldwide access to knowledge and fostered the global competition between vendors. Companies at that time intended to decentralise their productions on a global scale to profit from better conditions in other parts of the world. The proportion of value added decreased and the majority of western countries believed that developed economies would turn into service oriented societies (Bauernhansl, 2017).

The financial crisis of 2008 showed that economies with a higher percentage of value added recovered more quickly and are more sustainable than service orientated economies. It proved that a certain minimum of "value added" stabilises economies. Hence, many of the western economies are trying to return and to re-establish regional production sites. This is the time where the fourth industrial revolution began. New methods and technologies are mainly responsible for the emergence of Industry 4.0 (Danjou et al., 2016). The term Industry 4.0 was introduced at the Hannover exhibition in 2011 (Kagermann et al., 2011; Drath and Horch, 2014; Tortorella and Fettermann, 2018) and served from 2013 onwards as part of the German high-tech-strategy to increase the competitiveness of the national manufacturing industry (BMBF, 2014; Buer et al., 2018). The main characteristics of Industry 4.0 are connected machines, smart products and systems and inter-related solutions (Tortorella and Fettermann, 2018). It promotes computerisation, cloud computing, IoT and CPS in manufacturing (Brad et al., 2018). It is expected that I4.0 will have a significant impact on the way people live and work, on technologies and on business models, just as industrialisation, mass production and automation did before (Acatech, 2016a). I4.0 is an approach for further improving production management. Keeping the lean production principals in mind, autonomy and additional automation should result in a better interaction of human, data and machines. The aim is to establish highly automated smart factories, which produce individualised products with close to the efficiency of mass production. Intelligent self-managing production processes where machines, products, people, equipment and logistic systems directly communicate and cooperate with each other enable this vision (Plattform Industrie 4.0, 2018). The idea is that individualised customer orders lead their way through the production autonomously by telling machines and cellular transport systems what they need and where they need to go. The product leads its way through the production including the distribution to the customer (Vogel-Heuser et al., 2017). The internet of things in combination with the implementation of cyber physical systems are the major pillars of smart factories and hence the fourth industrial revolution. It may be highlighted at this point that the complexity of each of the four industrial systems has increased, with the highest complexity at Industry 4.0 (DFKI, 2011). Figure 1 shows the four industrial revolutions and their complexities on a timeline.

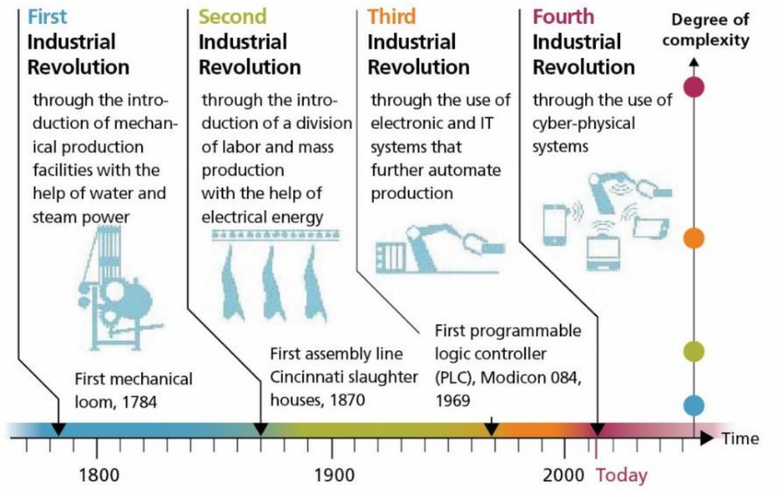


Figure 1: Illustration of the 4 industrial revolutions
Source: DFKI (2011)

2.2.2 Drivers of Industry 4.0

The main drivers of Industry 4.0 that have been identified in the literature review are emerging technologies, political support and changing market situations. Two technological drivers are highlighted most in Industry 4.0 related publications, i.e. the development of the IoT and the development of CPS, also defined as networked embedded systems and cloud computing. Therefore, the 4th Industrial revolution seems to be once again triggered from technological developments, just as the three industrial revolutions before (compare DFKI, 2011). However, Industry 4.0 emerged more from a synergistic effect between the ICT and the manufacturing industry. The ICT industry developed pioneering innovations and achievements the last two decades, and is merging in Industry 4.0 with traditional manufacturing industry. Therefore, it may be argued that the digital world is merging with the physical world and the borders between one and the other are becoming increasingly blurred.

The sophisticated political support in Germany fostered the development and acceptance of Industry 4.0 on the practitioners' side as well as in society. The manufacturing industry plays an immense role in the German system, since Germany is globally a strong manufacturing industry and traditionally among the largest exporters in the world. In 2016 the German surplus in goods trade and capital movements was about 297 billion USD. In comparison, the Chinese surplus was about 245 billion USD, whereas the US recorded a deficit of 478 billion USD. In fact, this means that Germany and China receive more capital for exports than they paid for imports, whereas the US consumes more than they produce (Spiegel-Online, 2017). Political encouragement of Industry 4.0 fosters the preservation to hold Germany in its position as one of the strongest manufacturing bases. One of the indicators for the support of I4.0 is its adoption in the German High-tech-strategy of 2013 (Bauernhansl et al., 2015).

Politics additionally play a key role in terms of establishing a stable IT infrastructure, legal frameworks, certain standards and norms, and training their society and future employees with the right education. IT security and the provision of a certain level of freedom for the commercial implementation of data-driven business models is required to gain the best success out of I4.0 (Acatech, 2016b). The German vision of developing a successful I4.0 economy in 2030 is based on a balance of humans, technology and the state (Acatech, 2016a). In detail, Germany aims to develop a nationwide information and communication infrastructure, support the compatibility of family, free time and professional life, and to reach a position as one of the leading centres for technology, services and platforms. Germany also aims to offer the economy and civil society choices of different I4.0 supply alternatives, and to be able to create significant business models to implement into global value networks (Acatech, 2016a).

Globalisation, the rise of the BRIC countries, shortened technology lifecycles and disruptive online competitors increased the pressure on companies in Germany. Individualisation, the diversity of variants and the increasing dynamic of innovations further challenge the industrial world (Ganiyusufoglu, 2013). Companies in the 21st century have to deal increasingly with volatile markets. Since the world is subject to constant change, the manufacturing industry is too. The strongest "predictable" triggers of change are categorised as global megatrends. Westkämper et al. (2013) define effects of mega trends that will eventually require changes in the manufacturing industry. Table 1 presents these megatrends and their effects for manufacturing. Some of these effects are subject to the evolution of Industry 4.0, such as individualisation, volatility or energy and recourse efficiency (Bartodziej, 2017). Some put pressure on the cost sensitive production sector and lays a certain threat on the German manufacturing industry to lose their competitive advantage, especially individualisation requirements, triggered from saturated markets, the constant advent of new competitors in a globalised industrial world and the change from hardware to software in the product portfolio (Acatech, 2016a).

Global megatrends	Effect on manufacturing
Aging sociaty	Future markets and production; Workflow and management of production
Individualisation	Individualised and customised products; Complexty of products and production; Synchronisation in between the networked global production
Knowledge	Knowledge based product development; Knowledge based production processes
Sustanability	Economic, ecologic, and social efficiency of production; Changing the availability and cost of materials and energy; Global competition for resources
Globalisation	Products and production technologies for global markets; Global process standards in OEMs; Local framework conditions in global competition (location factors)
Urbanisation	Local infrastructure; Emissions, mobility, traffic (around factories); Production / work in megacities
Finances	Economic cycles with high dynamics; Financing of investments in R&D and property, plant and equipment
Indebtedness of states	More added value, more employment; Economic policy, public changes; Competition of locations

Table 1: Global megatrends with an effect on manufacturing

Source: Own representation based on Westkämper et al. (2013)

2.2.3 Similar international approaches

Similar strategies and investigations emerged internationally soon after the concept Industry 4.0 was introduced in 2011 and was adopted in the German governmental High-Tech-strategy in 2013. Different European and international approaches are for example smart production;

smart manufacturing; integrated industry; or connected industry. All approaches describe mainly the same key features, i.e. interconnected industries and the creation of smart manufacturing systems. Germany focuses in particular on the integration of information, communication and manufacturing technologies in smart, self-organising factories (Acatech, 2016b). Thereby, Germany wants to maintain its traditionally strong position in manufacturing and mechanical engineering. The US and China associate Industry 4.0 more with smart products, internet platforms and new business models. However, all considered countries see a holistic conceptual base, and hence networking and digitalisation, as a key theme of Industry 4.0 (Acatech, 2016b). Relevant concepts and activities are tailored towards specific views and emphases of individual countries or areas (Acatech, 2016a).

For example, the Chinese government released a public driven initiative focussing on an industrial transformation towards innovation, smart technology, mobile Internet, cloud computing, big data and the internet of things. The initiative is called “Made in China 2025” and evolves in parallel with the so-called “Internet Plus”. China thereby aims to foster its globally strong position as an industrial heavyweight (Bartodziej, 2017). The “Industrial Internet Consortium” (IIC) from the US calls the phenomena of Industry 4.0 “Industrial Internet”. It describes an internet of things, machines, computers and people, enabling intelligent industrial operations, using advanced data analytics for transformational business outcomes. The IIC is a private non-profit organisation that attempts to catalyse and coordinate the priorities and enabling technologies of industry, academia and the government around the Industrial Internet (Bartodziej, 2017). The IIC furthermore defines the Industrial Internet as: “[…] the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes” (Industrial Internet Consortium, 2015). The US government is supporting research and development around the field of advanced manufacturing with a 2.2 billion dollar fund (President’s Council of Advisors on Science and Technology, 2014). Japan established an Industry 4.0 consortium in 2015. As one of the leading industrial countries in the world where robotic systems, automation and advanced production systems are developed and applied nationwide, Japan wanted to take its position in the international discussion about standards of the connected production technologies of tomorrow. The “Industrial Value Chain Initiative” (IVI) combines more than 120 companies and organisations to focus on linking all research and development around internet of things in Japan (Heilmann et al., 2016). Other international initiatives are, for instance, Nouvelle France Industrielle in France, Production 2030 in Sweden, Smart Industry in the Netherlands, Industria Conectada in Spain, Fabbrica Intelligente in Italy, and Průmysl 4.0 in Czech Republic (Acatech, 2016b).

2.2.4 Definition of Industry 4.0

There is a long and complex debate about the correct definition of Industry 4.0 in the literature. This section will introduce different perspectives on this matter and conclude with one definition of Industry 4.0 for the context of this thesis. Kagermann *et al.* (2013) describe I4.0 as real time, intelligent, horizontal and vertical interconnectedness of people, machinery, objects and ICT-systems for the dynamic management of complex systems. Industry 4.0 assists companies to vertically integrate smart machines, products and production resources into flexible manufacturing systems, and supports companies to horizontally integrate into cross-industry value networks to optimise cost, availability or resource consumption (Acatech, 2016b). Burmeister et al. (2016) additionally explain that a variety of practitioners and academics relate I4.0 to a disruptive change in the organisational structure of manufacturing and value creation in industrial manufacturing companies. Tortorella and Fettermann (2018) describe Industry 4.0 with three characteristics, namely 1.) comprehensible connected machines, 2.) smart products and systems, and 3.) inter-related solutions. The authors see the concept as intelligent production units equipped with integrated computers and ICT that monitor and control physical devices. Industry 4.0 represents the development of autonomous and dynamic production to enable mass customisation (Tortorella and Fettermann, 2018).

Ivanov et al. (2016) picture Industry 4.0 and smart manufacturing as the future form of industrial networks. CPS play the central role in Industry 4.0 by enabling machines and products to interact with each other without human control (Ivanov et al., 2016). The novel factories share characteristics which are known from smart networking (Davis et al., 2012; Chick et al., 2014). The evolution happens through adaptation and reconfiguration of structures, i.e. through structure dynamics (Ivanov and Sokolov, 2012). Moeuf et al. (2018) analysed different definitions of Industry 4.0 from scholars such as Schumacher et al. (2016), Danjou et al. (2016), and Trappey et al. (2017). Whereas Trappey et al. (2017) define the concept as manufacturing that includes elements of tactical intelligence using techniques and technologies such as the IoT, cloud computing and big data, Schumacher et al. (2016) define Industry 4.0 as technological advances which enable a new kind of intelligent, networked and agile value chain, integrating physical objects, human actors, intelligent machines, product lines and processes across organisational boundaries (Moeuf et al., 2018). Danjou et al. (2016), however, defined Industry 4.0 more loosely as a set of initiatives for improving processes, products and services to support decentralised decisions based on real-time data acquisition. The definition of Industry 4.0 is complex. However, most definitions have the emergence of new technologies such as CPS, IoT, cloud computing and big data in common, which should improve communication and the transport of data as well as optimisation of operations to adapt in real time to address frequently changing demands (Moeuf et al., 2018).

Kolberg et al. (2017) describes Industry 4.0 as the vision of a smart production in which smart components and machines are integrated into a digital network to meet the future market requirements. Industry 4.0 is a technology-driven approach. The utilisation of innovative ICT enables autonomous and dynamic production. Kolberg et al. (2017) see ICTs as the enablers of Industry 4.0. CPS, which are described as "flexible, powerful, affordable microcontrollers that are able to interact with their environments, are the key technology of the concept. CPS enable modularity and changeability, thereby enabling mass customisation (Lee, 2008; Broy, 2010; Kagermann et al., 2013), which is the expected future market requirement. Kolberg et al. (2017) also criticise existing architectures as they do not yet take the organisational aspects much into account. Hermann et al. (2015) approach the definition of Industry 4.0 as following: "Industry 4.0 is a collective term for technologies and concepts of value chain organisation. Within the modular structured smart factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralised decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time." (Hermann et al., 2015). At the 49th Hawaii International Conference on System Sciences, Hermann et al. (2016) continued the argument around I4.0 by presented research on design principles for Industry 4.0 scenarios. Through a quantitative text analysis and a qualitative literature review of 130 publication, from academic (49) as well as practical (81) journals, the researchers identified four distinct design principles of I4.0. These are a) interconnection b) information transparency, c) decentralised decisions, and d) technical assistance. Design principals offer a systematisation of knowledge and a description of the constituents of a phenomenon. They support practitioners in developing appropriate solutions and serve academics as a base for design theory. Hermann et al. (2016) highlighted the absence of a generally accepted understanding of the term Industry 4.0. However, they state that design principles will give guidance on “how to do” Industry 4.0: “By providing design principles of Industry 4.0, the paper creates a common understanding of the term, […].” (Hermann et al., 2016).

Strozzi et al. (2017) place their definition of Industry 4.0 around the integration of its key features CPS and the IoT, as well as the development of smart factories. In Industry 4.0 CPS link physical with virtual objects via information networks and connect digital, physical and biological systems (Strozzi et al., 2017). IoT applications drive innovations such as smart maintenance and cloud computing systems (Strozzi et al., 2017). The smart factories of Industry 4.0 are flexible and reconfigurable, which enables the production of customised small lot orders to the cost-efficiency level of mass production (Strozzi et al., 2017). smart factories are meant to be more efficient, safer and more environmentally sustainable than traditional factories, enabled through the introduction of new technologies, information and communication systems, as well as data and services in network infrastructures (Strozzi et al., 2017). Nevertheless, the authors state that a consistent accepted definition of Industry 4.0 and the smart factory does not yet exist (Strozzi et al., 2017). Buer et al. (2018) define Industry 4.0 operationalised as the usage of intelligent products and processes, which enables autonomous data collection and analysis as well as the interaction between products, processes, suppliers, and customers through the internet (Buer et al., 2018). However, at the same time the authors highly criticise the fact that even though Industry 4.0 has been the most frequently discussed phenomenon among practitioners and academics in the last few years, no clear and commonly accepted definition of it has yet been established (Buer et al., 2018). The term evolved into an overall label for describing future manufacturing, which makes it a poorly defined buzzword and difficult to understand (Buer et al., 2018). Different researchers support different opinions about the constituent technologies of Industry 4.0 and some even state that Industry 4.0 simply combines existing technologies into a new package (Drath and Horch, 2014). In fact, studies have detected more than 100 different definitions of Industry 4.0 (Moeuf et al., 2018). The result of this ambiguity is manifested in in communication difficulties and identification and implementation issues for companies (Hermann et al., 2016; Buer et al., 2018).

Chiarello et al. (2018) support the position that Industry 4.0 is not a new technology but a novel combination of technologies. They argue that the term Industry 4.0 captures considerable disagreement and misalignment with respect to constituent technologies (Chiarello et al., 2018). It is the aggregation point of more than 30 different fields of the technology without common ground in the definition and delineation of the field (Chiarello et al., 2018). I4.0 shares features of fast growth and technological uncertainty as well as market uncertainty, which together makes it an emerging phenomenon (Chiarello et al., 2018). They point out that the concept of Industry 4.0 builds on the digitalisation of factories, the internet, as well as innovative technologies that integrate intelligence in devices, machines and systems. The authors mention four interrelated problems that harm the clear definition of Industry 4.0; (a) the large number of technologies, (b) the definition of the constituent technologies depend critically on the specific application, (c) the stakeholders are located in different organisational positions, and (d) the constituent technologies are facing rapid changes in their nature and performance (Chiarello et al., 2018).

Hofmann and Ruesch (2017) researched the current status as well as future prospects of Industry 4.0. The authors define the term as a shift in the manufacturing logic towards an increasingly decentralised, self-regulating approach of value creation, enabled by concepts and technologies such as CPS, IoT, the internet of services (IoS), cloud computing or additive manufacturing and smart factories, so as to support firms in meeting future manufacturing requirements (Hofmann and Ruesch, 2017). However, Hofmann and Ruesch (2017) note that this description of the concept is quite vague and fails to outline the real characteristics and features of Industry 4.0. It is a result of that there is no commonly agreed-upon definition and understanding of Industry 4.0, and, furthermore, that there is simply not one single truth and reality behind this approach (Hofmann and Ruesch, 2017). Companies are required to individually define what Industry 4.0 means to them. Hofmann and Ruesch (2017) adopt this highly explorative approach because Industry 4.0 is still in its infancy. As Hofmann and Ruesch (2017) highlight, some of the questioned experts of the conducted interviews were convinced that the Industry 4.0 significantly changes industries, whereas others argue that Industry 4.0 is only a term for different technologies and concepts that actually have been known and applied for a long time (Hofmann and Ruesch, 2017).

Liao et al. (2017) conducted an extensive review of the literature and found that more than 40% of the publications on Industry 4.0 cited the final report of the Industry 4.0 working group (Kagermann et al., 2013) to define the concept. This makes the final report the most cited reference from a frequency perspective (Liao et al., 2017), and shows that its definition of Industry 4.0 have gained reasonable consensus. In addition, the authors detected that the most commonly recognised terms associated with Industry 4.0 are cyber physical systems, smart factories and the internet of things (Liao et al., 2017). However, although the most accepted definition of Industry 4.0 was found, the frequency of different definitions is still huge in academic papers (Liao et al., 2017). The literature does not deliver a common definition of the concept Industry 4.0 yet (Bauer *et al.*, 2014; Hermann *et al.*, 2015, 2016; Acatech, 2016b; Liao *et al.*, 2017; Hofmann and Ruesch, 2017; Strozzi *et al.*, 2017; Chiarello *et al.*, 2018; Buer *et al.*, 2018). Several literature reviews conclude with only a description of what Industry 4.0 enables or on what technologies it consists of. Furthermore, organisational aspects of Industry 4.0 have been omitted (Kolberg et al., 2017). The focus and understanding of Industry 4.0 seems to be constantly evolving due to persistent developments of new approaches, concepts and solutions (Acatech, 2016a). This leads to the result that many technology-related companies are engaged in their own sense-making of the concept (Bartodziej, 2017; Hofmann and Ruesch, 2017). Madsen (2019) provides a long list of the different interpretations and neologisms that have derived from Industry 4.0, which is provided in Appendix A of this thesis. The complex and elusive nature of the concept and the multitude of definitions leads to conceptual confusion, which may affect the successful implementation of Industry 4.0 in the corporate environment (Madsen, 2019).

Facing the difficulty to find a solid definition of Industry 4.0, a knowledge transfer event was attended by the researcher in Berlin on 4th December 2017. The event was organised by Labs Network Industrie 4.0 e.V. (2017) and attended by professor Henning Kagermann (president of acatech and one of the top pioneers of the fourth industrial revolution in Germany), who held a presentation and attended a round table discussion afterwards. His answer to the question regarding the loose definition of the term Industry 4.0 was as follows: “The rather open definition of Industry 4.0 has been placed on purpose. We expected a rejection of the complex technologies and a rejection in the belief of the power of the 4th industrial revolution. A tight definition would have been a breeding ground for negative feedback from industries and organisations with different needs. The idea was to leave room to own interpretation.

Tighter definitions are to be made on a micro-level.". This thesis defines Industry 4.0 in line with the final report of the Industry 4.0 working group (Kagermann et al., 2013) as real time, intelligent, horizontal and vertical interconnectedness of people, machinery, objects and ICT-systems for the dynamic management of complex systems.

2.2.5 Central components of Industry 4.0

Industry 4.0 consists of various interacting technologies, and various different combinations of these technologies can be used for implementing and enabling Industry 4.0. This section will introduce different perspectives from the literature regarding the central group of technologies which are particularly significant for Industry 4.0 in more detail. The selected technologies are referred to as the most important ones, but by no means meant cover all technologies. Xu et al. (2018) notes that Industry 4.0 technologies originate from different disciplines such as cyber physical systems, IoT, cloud computing, Industrial Integration, Enterprise Architecture, Business Process Management, and Industrial Information Integration (Xu et al., 2018). The central I4.0 technologies represent the latest automation technologies in manufacturing (Xu et al., 2018). Industry 4.0 integrates the virtual- in the physical world by applying embedded systems, semantic machine-to-machine communication, the IoT and CPS technologies (Germany Trade & Invest, 2014). In addition Liao et al. (2017) highlight the relevance of modelling technology and virtualisation and visualisation technology as important enabling technologies that support the realisation of Industry 4.0. In a keyword clusters analysis Liao et al. (2017) found that keywords related to data modelling represent 41.7% of all keywords, as well as that augmented reality and virtual reality are the two most frequently mentioned technologies related to I4.0. Furthermore, Ruessmann et al. (2015) developed nine groups of methods and technologies which mainly enable Industry 4.0. These groups are: big data and analytics, simulation, internet of things (IoT), cyber physical systems (CPS), cloud computing, virtual reality, cyber security, collaborative robots, and machine-to-machine communication (Ruessmann et al., 2015). By analysing these methods and technologies Moeuf et al. (2018) found a disparity in research effort regarding the realisation of I4.0. They highlight that there is a clear concentration on cloud computing platforms and a lack of publications related to the other technologies (Moeuf et al., 2018).

Hofmann and Ruesch (2017) found that presently CPS and the IoT are the core components of Industry 4.0. Furthermore, the authors state that since these "concepts" are much intertwined (CPS communicate over the IoT) and since the application of these intertwined technologies enables the development of the so called "smart factory", the concept of smart factory may be also considered as a key feature of Industry 4.0. The idea of smart factories builds on decentralisation and a close linkage between products, machinery, transport systems and humans. Just as in social networks, human beings, machines and resources naturally communicate with each other (Kagermann et al., 2013). Beyond these central enablers of I4.0 Hofmann and Ruesch (2017) refer to many more technologies and characteristics that may also be important to the development of Industry 4.0 applications, such as wearables, augmented reality, autonomous transport systems, blockchain technology, etc. (Hofmann and Ruesch, 2017). Chiarello et al. (2018) developed a rich overview of Industry 4.0 enabling technologies as well. The authors clustered the Industry 4.0 technologies into 11 main clusters. Each of the clusters captures the top 15 technologies in the cluster. The results of Chiarello et al.'s (2018) research, i.e. the technologies and the technology clusters, are provided in Appendix B of this thesis.

Taking the perspectives and insights from the literature, this thesis shares the perspective that CPS, the IoT and cloud computing may be seen as the three central components of Industry 4.0. Hence, these three technologies are reviewed further in detail. Cyber physical systems (CPS) are embedded systems of microcomputers, sensors and actuators which can be connected to a network, and which are able to communicate with other smart devices over the internet. CPS can be embedded in materials, devices or machines and lead through production-, logistic-, engineering-, coordination-, and management processes as well as internet services (Broy, 2010; Acatech, 2013; Burmeister et al., 2016; Negri et al., 2017). CPS operate at virtual and physical levels, sensing and acting on the real world (Negri et al., 2017). They collect and process data to make intelligent decisions mostly autonomously and without human interaction. Integrated algorithms permit CPS the controlling and monitoring function. It enables objects to communicate with each other and to reconfigure in real time in response to new needs. To provide a basis for intelligent connection, passive objects have been supplemented with microcontrollers, communication- and identification systems and sensors and actuators. The results are intelligent objects, i.e. CPS, which enable the connection of humans, machines and products (Bauernhansl et al., 2015). CPS appear in diverse dimensions in terms of structure and spatial volume. They can be placed on a single microchip or constructed as an entire machine. Even a whole factory or a consortium of factories could be constructed as a single CPS (Lucke et al., 2014). Therefore, CPS have to be designed and implemented according to the needs of the factory of context (Bartodziej, 2017).

The internet of things (IoT) enables CPS to go online and communicate with each other. It has become a new paradigm which enables access to information of physical things anywhere and anytime. IoT describes interconnectedness for various purposes such as communication and identification. Its dynamic digital environment provides a breeding ground for novel applications based on information and service orientation. The IoT distinguishes itself from the common internet in size and number of its nerve ends (Fleisch, 2010). The nerve ends of the common internet are “fully developed” computers, whereas the nerve ends of the IoT are very small, often invisible, with low end and low energy consumption computers (Fleisch, 2010). The number of network nodes differ from trillions in the IoT to only billions in the common internet (Fleisch, 2010). Another difference between the internet and the IoT is the machine centric nature of the IoT. Whereas the common internet focusses on service and support for people as users (user centric), the IoT most often excludes human interaction and is limited to the communication between smart things only (machine centric). For the case that humans need to be involved in a process (e.g. a decision making process) they can contribute via personal computers or mobile devices (Fleisch, 2010). The internet offered companies and individuals a virtual platform to reach out for customers on a global scale for comparable low costs. Amazon and ebay are two examples who mastered the potential of this technology. “Internet 2.0” triggered the next large wave of potential value generation. It enabled users to generate content by themselves. Hence, data was not only consumed but also generated by the user. Three examples which resulted from this innovation are Facebook, Youtube and Wikipedia. Today, the IoT begins to enable the physical world to also participate by sending and receiving data. This sensing of the physical world enables humans to build a nerve system with trillions of new nerve endings (Fleisch, 2010).

The term IoT became established at the beginning of the 21st century and can be considered as the initiator of the concept of Industry 4.0 (Kagermann et al., 2013). The literature provides several definitions for the IoT, differing from specific to more general ones (Hofmann and Ruesch, 2017). From its emergence the IoT has been described as uniquely identifiable interoperable connected objects using radio-frequency identification (RFID) technology (Ashton, 2009; Xu et al., 2014). RFID tags have been placed on objects, which enable an automatic unique identification by RFID readers. The RFID readers are connected to the internet and thereby the objects can be tracked in real time (Xu et al., 2018). As Xu et al. (2018) described, over time other technologies have been added to the IoT to further improve the construct e.g. technologies such as sensors, actuators, global positioning system (GPS) and mobile devices that are operated via Wi-Fi, Bluetooth, cellular networks or near field communication (NFC) (Xu et al., 2018). For this thesis the definition of van Kranenburg (2008) is utilised, which referrers to a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual “things” have identities, physical attributes and virtual personalities, and use intelligent interfaces, and are integrated into the information network (van Kranenburg, 2008). The IoT may be seen as the required infrastructure for CPS and data exchange.

Cloud computing is “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction”, as the U.S. department of commerce described it (Mell and Grance, 2011). With its key characteristics of agility, scalability and elasticity, on-demand computing and self-service provisioning, cloud computing has proven to be a disruptive technology in the IT field (Wu et al., 2014). Technologies such as utility computing, parallel computing or virtualisation are positively affected by cloud computing (Wu et al., 2014). A cloud based control system offers a functional base for the connection and provision of computing power for the operation of CPS in a manufacturing environment (Verl and Lechler, 2014). Cloud based manufacturing is a new manufacturing paradigm arising from cloud computing (Wu et al., 2014). It is described as decentralised and networked, building on a set of enabling technologies such as cloud computing, social media, the IoT, and service-oriented architecture (Wu et al., 2014). Cloud computing enables real time communication and data exchange across multiple systems and networks with a reaction time of milliseconds and large bandwidths to ensure data and application availability everywhere, anytime and from any terminal (Gupta et al., 2013).

2.2.6 The idea of smart factories

This section introduces and analyses different perspectives from the literature regarding the term smart factory in relation to Industry 4.0. There has been unclarity about the differences and meanings of both terms, however, it is shown that Industry 4.0 and smart factory consist of the same technologies and are closely intertwined in the same context. The end of this section will conclude by aligning the understanding of both terms.

The smart factory related literature can be divided into three large connected components, which refer to “manufacturing monitoring and scheduling”, “smart factory from a political and economic perspective”, and “demonstration and research test beds for smart factory technologies” (Strozzi et al., 2017). “Radio-Frequency Identification” (RFID) and “agent-based intelligent decision support system architecture” for manufacturing- monitoring and scheduling purposes are the most studied components in the smart factory literature. “Agents” in this definition are often called cyber physical systems (CPS) elsewhere. This path of the literature on smart factory describes objects as intelligent and able to communicate and to take autonomous decisions. This literature refers to agent-based service-oriented integration architectures, agent-based workflow management, event-driven shop floor work-in-process management platforms, and the implementation of RFID technologies. The second largest connected component analyses the smart factory landscape from a political and economic perspective. Key publications in this group come from Davis et al. (2012), who studied the efforts necessary to trigger the adoption of the smart factory concept in the US. Whereas the European Union defined plans to invest and accelerate changes in manufacturing on a governmental level from 2009 onwards, it took the US government until 2014 to support research and development activities in this area. Davis et al. also analysed why many companies were still uncertain about implementing the smart factory concept. These reasons are: 1.) the architecture of present distributed control systems exclude the use of smart factory technologies, 2.) the costs of implementation are too big for SMEs, 3.) the risk of wrong application of technologies and not having the right industrial infrastructure. Overall, Davis et al. define the smart factory as a networking and on information-based production and supply chain. Other publications of the second largest connected component refer to sustainability and the ability to adapt to fast changing requirements of production control (Lao et al., 2014;

Kumar et al., 2015) as well as to the capability to rapidly manage demand fluctuations and product quality (Kim et al., 2015; Jung et al., 2015).

Demonstration and research test beds for smart factory technologies are in the focus of the third largest connected component of the smart factory literature. The main test bed has been funded by a collection of industrial and academic organisations in Germany. A key author in this field is Zuehlke (2010), who published the paper "Smart Factory - Towards a factory of things". Zuehlke (2010) is the one who introduced the term smart factory" for the first time and hence many following publications name him in this context. Smart factory is one of the four most frequent stated terms alongside Industry 4.0 (Liao et al., 2017). This indicates the clear focus of Industry 4.0 literature on manufacturing firms. Some publications define the smart factory concept as a merger of different abilities, e.g. the ability to collect information about the company, referring to "context awareness"; the ability to predict the future; the use of information to make knowledge-based decisions; the ability to conform to collaborative networked organisations; the ability to work as one, referring to the integration capability of a firm; a high degree of flexibility in the kind of responses that have to be made due to environmental changes; the ability to compete and generate profit; the fulfilment of survival and purpose needs of the society; or environmental sustainability in terms of products, processes and regulations (Chavarría-Barrientos et al., 2018). Kiel et al. (2017) further utilise the term smart factory by referring to intelligent and self-controlling objects that enable control of complexity in manufacturing (Kiel et al., 2017). Products in a smart factory are constantly identifiable, locatable, and are aware of their latest condition and alternative paths to their destination (Kiel et al., 2017). The full idea covers the autonomous guidance of production orders through entire value chains including automatic machine set-ups and the rescheduling of production planning if required (Kiel et al., 2017).

Kusiak (2018) developed an understanding of smart factory by encapsulating it into six key components that differentiate it from previous manufacturing (Kusiak, 2018). The six components are 1.) manufacturing technologies and processes, 2.) materials, 3.) data, 4.) predictive engineering, 5.) sustainability and 6.) resource sharing and networking (Kusiak, 2018). Liao et al. (2017) highlight internet networks as a key technology of smart factories, including wireless-sensor-networks and industrial-wireless-networks. Additionally, several services, sensors, robot components and the human factor, belong to the important components a smart factory consists of (Liao et al., 2017). Additionally, Hofmann and Ruesch (2017) define smart factory as the idea of decentralisation, and a natural communication between humans, machines, resources, products and transport systems in the context of manufacturing firms (Hofmann and Ruesch, 2017). The enabling technologies of the smart factory are CPS, the IoT and the IoS, which are closely linked to each other (Hofmann and Ruesch, 2017). Since these technologies are the same as the key technologies of Industry 4.0, the authors state that smart factories can be considered as another key feature of Industry 4.0 (Hofmann and Ruesch, 2017).

Strozzi et al. (2017) specifically studied the concept of the smart factory and defined the term in their scope of the analysis as "a production plant where the pillars of Industry 4.0 are implemented, i.e. additive manufacturing, augmented reality, internet of things, big data analytics, autonomous robots, simulation, cyber-security, vertical and horizontal integration and cloud. Smart objects are able to make autonomous decisions and to control the global manufacturing process. RFID and sensor technologies are important components in this sense to enable autonomy. Cloud computing is an essential technology too, since smart factories operate in a closely linked network of suppliers, customers, and other companies. Smart factories are more efficient, safer, and more environmentally sustainable, enabled due to the introduction of new technologies, information and communication systems, as well as data and services in network infrastructures (Strozzi et al., 2017). The smart factory is flexible and reconfigurable, which enables the production of customised small lot orders to the cost-efficiency level as mass production (Strozzi et al., 2017). However, Strozzi et al. (2017) criticise that in the context of the fourth industrial revolution no commonly accepted definition of the term smart factory yet exist, even though it is being extensively used by both practitioners and scholars.

In addition, Xu et al. (2018) note that Industry 4.0 will results in the establishment of smart factories. The authors describe both terms as a connection of the physical and the virtual world, as well as a collaborative system involving various communicating agents including physical agents, software agents and human agents (Xu et al., 2018). The implementation of networks, things-to-things interactions, and the fusion of technical and business processes are present in smart factories (Xu et al., 2018). Xu et al. (2018) highlight the importance of CPS when referring to smart factories. The authors constantly position both terms, Industry 4.0 as well as smart factory, in the same wording, resulting in an equation of their meanings. CPS enable Industry 4.0 as well as smart factories (smart production) (Xu et al., 2018). CPS is the key technology for Industry 4.0 as well as for smart factories (Xu et al., 2018). Both, Industry 4.0 and smart factory are defined by the same technologies. This intertwines results in that Xu et al. (2018) determine both terms as the same thing, stating that “Industry 4.0 is also known as smart manufacturing” (Xu et al., 2018). Several other authors also combine the terms Industry 4.0 and smart factory in the same wording, equating their meanings. Indications for such combinations have been detected in the form of the following statements visualised in Table 2.

Authors	Statement
Ivanov et al. (2016)	“Industry 4.0 represents a smart manufacturing networking concept where machines and products interact with each other without human control.”
Hofmann and Ruesch (2017)	“[…] these “concepts” are closely linked to each other, since CPS communicate over the IoT and IoS, therefore enabling the so-called “smart factory” […].”
Strozzi et al. (2017)	“A Smart Factory is a production plant where the pillars of Industry 4.0 are implemented […].”
Xu et al. (2018)	"Industry 4.0 also known as smart manufacturing and cognitive manufacturing offers new opportunities for manufacturing firms […].”
Buer et al. (2018)	“[…] the new possibilities introduced by Industry 4.0, also referred to as smart manufacturing.”
Moeuf et al. (2018)	“However, the intent of this paper is to focus solely on the impact of Industry 4.0 on the production planning and control functions that is also referred by some researchers to the concept of Smart Factory or Digital Manufacturing.”
Kasapoğlu (2018)	“Industry 4.0 is the common name used to describe the current trend towards a fully connected and automated manufacturing system, or Smart Factory.”
Xu et al. (2018)	“The essence of Industry 4.0 is applying CPS to realise smart factories.”

Table 2: Equating meanings of Industry 4.0 and smart factory

Analysing the literature specifically on smart factory definitions showed that the concept most often refers to the same set of interacting technologies as Industry 4.0 does. The literature proves that besides the enumeration of interacting core technologies there is not yet one generally accepted definition of smart factory. Instead, the term Industry 4.0 and smart factory are often closely combined and intertwined with each other. As analysed in Section 2.2.4 and 2.2.5, Industry 4.0 is defined as real time, intelligent, horizontal and vertical interconnectedness of people, machinery, objects and ICT-systems for the dynamic management of complex systems, enabled by several different but three key technologies: CPS, the IoT and cloud computing. To conclude and to set the context for this thesis, it is defined that the smart factory is the strived-for result of deep and successful Industry 4.0 implementation. In other words, a smart factory is defined as one in which the key technologies of Industry 4.0 (CPS, IoT, and cloud computing) are implemented. Therefore, in this thesis smart factory refers to “real time, intelligent, horizontal and vertical interconnectedness of people, machinery, objects and ICT-systems, which all together raises efficiency in an organisation and enables the dynamic management of complex systems”, just as Industry 4.0 does. Hence, this thesis equates the meaning of Industry 4.0 and smart factory, calling it “Industry 4.0” only. Furthermore, it is highlighted at this point that Industry 4.0 refers not only to new technologies on the shop floor of firms, but also to the organisational aspects of the implementation and the firm level of organisational systems.

2.2.7 Benefits and economic potential of Industry 4.0

Galati and Bigliardi (2019) developed a literature review using a text mining approach and sorted the existing literature into four overarching themes: “Business”, “Operations”, “Technological solutions” and “Work and skills”. The literature of the “Business” theme considers publications that investigate the impacts of Industry 4.0 on the business perspectives of firms and the potential increase of firm performance (Galati and Bigliardi, 2019). Studies such as Glova et al. (2014), Porter and Heppelmann (2014) and Strange and Zucchella (2017) jointly assume that Industry 4.0 holds great potential to impact economies and societies (Galati and Bigliardi, 2019). The impact of Industry 4.0 on the nature of competition and corporate strategies is already present, even though the topic is still in its infancy (Galati and Bigliardi, 2019). Some authors highlight new business models as the greatest benefit of Industry 4.0 (Bauernhansl et al., 2015; Burmeister et al., 2016). Potential triggers of business model innovation are imminent new technologies, changing customer requirements and a need for operative improvement (Burmeister et al., 2016). Industry 4.0, the IoT and the idea of running smart factories function as such triggers and lead organisations to rethink their current business model in order to stay competitive and in order to raise the profitability of their business (Kagermann *et al.*, 2013; Porter and Heppelmann, 2014; Turber *et al.*, 2014; Lee *et al.*, 2014; Piller, 2015; Bauernhansl *et al.*, 2015; Kans and Ingwald, 2016; Arnold *et al.*, 2016; Acatech, 2016a; BITKOM, 2017; Zollenkop and Lässig, 2017; Chavarría-Barrientos *et al.*, 2018). Nevertheless, the most common position in the literature is that the highest beneficial outcome of Industry 4.0 implementation lies in production optimisations

(Acatech, 2016b). The benefits of production optimisation can, e.g. according to Wang et al. (2016a), be divided into the categories of flexibility, productivity, resource and energy efficiency, transparency, integration, profitability and user friendliness.

Companies that successfully implement Industry 4.0 potentially create value by lowering production costs, raising the quality by minimising waste, raising production flexibility and reducing the time to market, which together lead to the prospect of sales growth, increased market share and higher overall profitability (Sjödin et al., 2018). The increasing digitalisation of products and processes enables the fusion of production methods with information and communication technology. Academics state that the use of information technologies tends to have a positive impact on a broad set of organisational outcome variables and on the performance of a firm (Heim and Peng, 2010). Equipping the value chain with fully integrated CPS, using the internet of things in a unified network infrastructure, offers a disruptive potential to remodel the present industrial system (Acatech, 2013; Westerlund et al., 2014; Bauernhansl et al., 2015; Burmeister et al., 2016; Tuptuk and Hailes, 2018). Referring to research from BITKOM (Germany's digital association) and Fraunhofer IAO (Institute for Industrial Engineering), the economic potential of implementing Industry 4.0 in the German machinery and plant construction industry is very promising. It is estimated to lead to a rise from 76.8 to 99.8 billion Euro gross value added between 2013 and 2025, which equates to a yearly growth of 2,2% (Bauer *et al.*, 2014). Alongside this estimation of financial growth, there are five main themes of expected benefits of Industry 4.0, which emerged from 150 expert interviews in Germany, China, Japan, South Korea, the UK and the US (Acatech, 2016b). These themes are enhanced customer service, new business models, expansion of product and service portfolio, production optimisation and higher sales.

Manufacturing flexibility is linked to the megatrend “individualisation” (Westkämper et al., 2013) and was recently detected as the central objective of Industry 4.0 related academic publications (Moeuf et al., 2018). Manufacturing flexibility can again be divided into 15 different flexibility dimensions, e.g. machine flexibility, labour flexibility, routing flexibility, etc. (Vokurka and O'Leary-Kelly, 2000), and is widely acknowledged as a critical component to achieve competitive advantage (Hayes and Wheelwright, 1984; Vokurka and O'Leary-Kelly, 2000; Patel et al., 2012; Westkämper et al., 2013; Wei et al., 2017). Manufacturing flexibility eventually reduces resource constraints by developing efficient and robust processes in a firm

(Wei et al., 2017). This is especially important to companies in a highly competitive environment since competitive environments usually lead to external resource shortages where companies struggle to access and restructure resources. Firms working in such environments rely heavily on their internal resources (Wei et al., 2017). Customer orders increasingly become individualised, which in turn means that production facilities have to deal with decreasing lot sizes. Traditional production facilities often evaluate their benefits on the basis of scale effects. However, the trend shows that these benefits will shrink in future. Industry 4.0 potentially increases the flexibility of manufacturing enabled by a modular structure approach, solving the problem of decreasing scale effects by efficiently managing smaller orders (Wang et al., 2016a). New customised products that are introduced to the firm can instantly find their way through the production process and communicate their needs to different machines. This ability eventually lowers their unit costs immensely compared to the unit costs of customised products produced in traditional production facilities (Wang et al., 2016a). Furthermore, the modularity of machines provides a certain level of robustness to the firm. Modular machines follow standardisations and are able to be added in a running production system on a plug and play basis. When it comes to the production of small lot sizes and customised products, traditional production facilities struggle with overall productivity. Industry 4.0 is capable of keeping the setup time to a minimum even when switching between single product orders. Big data analysis thereby supports the coordination of orders so that the most efficient approach will automatically result. The big data analysis offers accurate knowledge about production processes, which eventually also leads to an optimisation of the resource and energy consumption of the firm. The determination of required raw materials and an intelligent operation of processes are two examples of resource optimisation (Wang et al., 2016a).

Industry 4.0 builds upon digitalisation, and one of the positive effects of digitalisation is transparency (Wang et al., 2016a). Transparency improvements are often supported by big data analysis that can provide real time information on many aspects of the firm. This information can be used to allocate key performance indicators and to accelerate the firm's responses to market inquiries (Wang et al., 2016a). Cloud computing, as an example of an Industry 4.0 technology, can support the integration of customers in design activities and suppliers in production activities (Wang et al., 2016a). The literature also argues that the user-friendliness of applications is supposed to raise with the implementation of Industry 4.0 (Wang et al., 2016a). As the authors state, user-friendliness can appear in 1.) co-working between people and machines (e.g. human-robot-collaboration), 2.) customers and companies co-creating products together, and 3.) processes partly running autonomously (Wang et al., 2016a). Similar beneficial impact categories of the implementation of Industry 4.0 are defined by (Lee et al., 2014). Accordingly, beneficial impacts of Industry 4.0 are to be expected in 1.) reduced machine downtime due to predictive maintenance, 2.) optimised manufacturing management due to prognostics information sent to the ERP system, 3.) transparency and organisational benefits due to optimised information flow on the shop floor-, 4.) the management of the supply chain level, 5.) advanced machine safety and a better working environment, 6.) less labour costs and 7.) reduced energy consumption (Lee et al., 2014).

Compared to other forms of manufacturing systems, the benefits of Industry 4.0 are based on new manufacturing technologies and processes, new materials evolving from the development of manufacturing technologies, data, predictive engineering, sustainability and resource sharing and networking advantages (Kusiak, 2018). The implementation of novel technologies such as additive manufacturing, low cost robotics and smart equipment lead, for example, to the development of new ways of manufacturing such as "net-shape manufacturing" (Kusiak, 2018). Smart materials such as shape-memory-alloys or organic-based materials are examples of what can be developed from new manufacturing technologies. As often mentioned in all sources of media, "data" plays an essential role in the development of Industry 4.0. Through the use of sensors, wireless technologies and data analytics, predictive models can be built to determine material properties, process parameters, customer behaviour and suppliers. Predictive engineering leads to a more anticipatory enterprise structure (Kusiak, 2018). The construction of digital representations of the phenomena of interest enables the prediction of supply chain behaviour and supports the decision-making process regarding future production and market conditions. Products that are sensitive to transportation cost, time-to-market or customisation could be manufactured at locations in close proximity to the customers (Kusiak, 2018). Sustainability in the context of manufacturing considers different materials, manufacturing processes, energy and pollutants. For an organisation this often means that it applies sustainable product design and sustainable manufacturing processes, and is involved in the development of sustainable materials, products and processes. Resource sharing and networking advantages often lie in the digital layer of the firm. Industry 4.0 offers a base for sharing resources by connecting to other businesses, for example in creative and decision-making processes, sharing manufacturing equipment, software or expertise (Kusiak, 2018).

2.2.8 Criticism of Industry 4.0

On the basis of quick rise to prominence and the constraints in its definability, the concept of Industry 4.0 risks fading into a so-called "management fashion" (Hofmann and Ruesch, 2017; Madsen, 2019). A management fashion refers to a management concept which on the one hand relatively quickly gain large shares in the public management discourses (Madsen and Stenheim, 2013), but which fail to gain consistent practical relevance due to the non-fulfilment of its promises (Alexandru, 2015) on the other hand. Management fashions usually evolve with highly topical issues accompanied by a great number of publications, workshops and conferences (Hofmann and Ruesch, 2017). However, a noticeable percentage of these publications do not meet the scientific standards (Abrahamson, 1996). The concept of Industry 4.0 indeed gained very fast prominence since it was announced at the Hannover exhibition in 2011 and was adopted in the German high-tech strategy in 2013. The field is also characterised by a fast growing number of publications, which, unfortunately, not only a few fall below scientific requirements (Hofmann and Ruesch, 2017). Some authors also argue that Industry 4.0 has partially fuelled excessive expectations (Hofmann and Ruesch, 2017). Taking these facts together, Industry 4.0 seems to meet many of the indicators that constitute a typical management fashion. Despite the described negative perspectives, the overwhelming majority in the field are positive towards Industry 4.0 and its development. In fact, the empirical investigation of this research, the careful evaluation of the scientific publications, and the analysis of data collected in the field suggest that Industry 4.0 constitutes a robust concept instead of being a management fashion only. It seems that several interesting research gaps around the topic are worth addressing in future scientific research projects.

2.3 The management of Industry 4.0 implementation

This section analyses the current knowledge about the implementation of Industry 4.0. The section first analysing the implementation in the light of technical aspects and then moves to implementation in the light of the organisational aspects. Detected barriers and enablers of the implementation are analysed at the end of this section.

2.3.1 Implementation in the light of technical aspects

Several publications focus on technical aspects of Industry 4.0 implementation. The reviewed papers have developed, for example, specific solutions for Industry 4.0 such as new manufacturing execution systems, indoor localisation systems, or monitoring systems. The largest number of papers focuses on new solutions in connectivity and information flow for Industry 4.0 environments. On this topic, Coronado et al. (2018) present a low-cost manufacturing execution system (MES) that consists of an app, cloud database, and a web application, and which is capable of integrating an additional database such as MTConnect. The authors use available manufacturing operation data to gain improvements in capability, adaptability and awareness of processes. Collected machine tool data can be provided using standard protocols such as MTConnect. The low-cost MES is powered by Android devices and cloud computing tools, which are easy to implement and especially suitable for SMEs. Coronado et al. (2018) present a way of implementing a complete digital model of the shop floor, which leads to production control and optimisation. Sun et al. (2018) introduce an indoor localisation system, built on bluetooth beacons in the shop floor, as part of an enterprise IoT platform. The indoor localisation system aims to track workers and working parts and connects wearables with machines in Industry 4.0 environments. The researchers investigated various algorithms to reach accuracy and stability of the sensor signals by the bluetooth sensor networks. The final algorithm improved the communication between different devices by utilising the location information from the beacon network and orientation information from the compass sensor. Sun et al. (2018) present an approach to enhance employee competencies through both an indoor localisation service as well as sound smart devices.

Lee et al. (2007) developed a real-time sensor based monitoring system for Industry 4.0 using wireless sensor network architecture. The architecture enables monitoring in a real-time environment which leads to an extension of machine lifetimes by checking figures such as vibration, white noise or temperature. Sensor devices of the system are designed to be mobile in-between the range of transmission of radio frequency. Lee et al. (2007) thereby offer an intelligent answer to a factory maintenance strategy and gained first validation of functionality by developing a prototype system.

Industry 4.0 requires a complex allocation of resources in manufacturing (Wan et al., 2018). Dynamic resource management provides support for this allocation and hence for the implementation of Industry 4.0. Wan et al. (2018) suggest an information interaction model for resource interconnection. The model is based on the integration of 1.) open-platform-communications (OPC-UA) for process control technology, 2.) software defined industrial network (SDIN), and 3.) device-to-device (D2D) communication technology. The authors developed a load balancing mechanism that is based on Jena reasoning (a Java framework for building semantic web and linked data applications) and Contract-Net Protocol technology, which manages overloaded intelligent equipment in Industry 4.0 environments. Wan et al. (2018) introduced a model to virtualise manufacturing resources.

Rosendahl et al. (2018) argue that the inter-connection and cooperation across the technologies of Industry 4.0 are not yet appropriately elaborated. Hence, the authors investigated into a multi-agent-system that intelligently supports such co-operation. The paper underlines the suitability of open industrial standards OPC UA for service-oriented communication, as well as the suitability of AutomationML for semantic data exchange in Industry 4.0 environments. The developed multi-agent-system enables the required connectivity and interoperability for intelligent co-operation that should realise the capabilities of Industry 4.0.

Pedone and Mezgár (2018) argue that the interoperability between Industry 4.0 ICT remains a barrier to realise the full potential value creation of Industry 4.0. The authors present the conceptual similarities of the industrial internet reference architecture (IIRA) and the reference architectural model industry (RAMI 4.0), two standardisation frameworks for industrial Internet architectures for modelling distributed industrial services. The framework RAMI 4.0 was analysed by the authors with respect to the open connectivity unified architecture (OPC UA), a service-oriented architecture for the standardisation of IoT platforms. The results show similarities in the interoperability and virtualisation layers of both architectures. In both architectures, services can be conceptualised and provided to customers via a cloud-based interface.

Wang et al. (2017) continue in presenting a cloud-centric framework to support the implementation of Industry 4.0. The framework is based on the protocols EtherCAT, DDS, and

OPC UA to satisfy the diverse communication requirements in Industry 4.0. EtherCAT supports high-speed real-time synchronous control, whereas DDS is flexible and suitable for machine-to-machine communication. OPC UA enables the semantic data interaction between machines and cloud. The authors argue that a solid network and communication are fundamental requirements for Industry 4.0 implementation. Accordingly, a network provides the interconnection for communication and data and a cloud provides the required computing and storage abilities (Wang et al., 2017). Furthermore, Theorin et al. (2017) present an event-driven line information system architecture (LISA), which features loose coupling, a prototype-oriented information model and formalised transformation services. The information system architecture supports the integration of smart devices and services on all levels and supports the visualisation and control of information. The authors argue that the system is applicable for asynchronously running processes and a nonlinear product flow. It offers required flexibility and scalability for the aggregation of information in Industry 4.0. Additionally, Akpolat et al. (2017) have developed a middleware that enables intercommunication between heterogeneous resource-constrained devices in Industry 4.0 manufacturing. The middleware is able to work with various protocols and builds up a runtime environment and scalable and dynamic communication layer that abstracts the connected devices. The authors introduce this communication layer to realise the potential of the IoT.

Yoon et al. (2016) developed a reference architecture for the information service bus or middleware for Industry 4.0. The architecture enables information acquisition and analysis, and is applicable at several levels such as machine, factory and enterprise resource planning. The authors build a strong real-world context by identifying and transforming real industrial problems into the information architecture. The architecture supports service exchanges at machine, factory and enterprise levels as a middleware to improve the total performance index in terms of productivity, environment and social impact (Yoon et al., 2016). Wang et al. (2016b) introduce a framework that combines industrial networks, cloud computing and supervisory control stations with smart shop-floor objects such as machines, conveyers and products. The Framework is based on independent decision making and intelligent negotiation mechanisms and supports the implementation of Industry 4.0. The authors furthermore provide a classification of smart objects and the allocation of the resulting agents to coordinators in the cloud. The research illustrates that through the improvement of agents' decision making as well as the coordinator's behaviour, potential deadlocks can be prevented.

Nayak et al. (2016) developed a resource sharing-based framework (RSBF) for cyber physical systems (CPS) for enabling the modulation of a wide range of CPS or CPS systems in Industry 4.0. The focus of the research lies on the resource sharing point of view. The propositions are based on a literature review and have been validated by case studies. The authors combine elements from graph theory and social welfare to describe the complex arrangements of overlapping task and resource communities in CPS. From case studies, for example on the scheduling in Industry 4.0 environments, it has been validated that the implementation of the framework functions successfully. The results show that the framework is able to represent both static and dynamic systems and is able to scale with changing network structures (Nayak et al., 2016). The research of Nayak et al. (2016) supports the overall implementation of Industry 4.0 since CPSs and their communication to each other are one of the major technologies associated with the concept. Additionally, Shariatzadeh et al. (2016) analyse the implementation of information technology and the IoT in an existing heterogeneous IT environment of firms. Approaches and principles are introduced that aim to guarantee data consistency and identify what, when and how information should be integrated in the environment. The authors state that it requires attention to three different layers to achieve interoperability between the real time data of a factory and the “digital factory”. These layers are “data transfer protocols”, “data representation and presentation” and “semantics and the understanding of data”. Furthermore, the paper suggests the application of semantic web technologies and open services for lifecycle collaboration (OSLC) to build the integration between IoT and PLM platforms and the interoperability of tools (Shariatzadeh et al., 2016).

Brad et al. (2018) analysed the economic feasibility of Industry 4.0 implementation. They provide an index to measure the changeability and reconfigurability capability of manufacturing resources and development of tools to design smart connected manufacturing resources offers a practical guideline for the implementation of Industry 4.0 and the development of convenient applications for total-cost-of-ownership business models. The research builds upon a literature review after which the theoretical contributions are explained in a case study. The results present the practicability of a time-efficient design of smart connected manufacturing resources and their implementation in the architecture of Industry 4.0. The implementation supports convertibility, integrability, modifiability, adaptability, serviceability, scalability, the integration of resources from various producers, service clustering and cloud-based services (Brad et al., 2018).

Pagnon (2017) presents a guideline for Industry 4.0 implementation by developing a methodology to achieve manufacturing automation. The method illustrates automation from customer orders to the distribution of the manufactured product, without human intervention. The research builds upon a literature review. This level of automation is, furthermore, reachable through already existing technologies. The smart technologies are mature and ready to put into practice. Pagnon (2017) highlights the feasibility of successful Industry 4.0 implementation and the strong beneficial results for the customers, factory owners and the workforce. However, at the same time the author states that future work is still required to determine the most efficient process for implementing Industry 4.0 in manufacturing firms. Another model was developed by Ivanov et al. (2016) and focusses on adjustments in supply chain scheduling, which becomes important in Industry 4.0 environments with small lot sizes and a market with frequently changing demands. The dynamic model and algorithm considers non-deterministic issues in flow-shop scheduling where scheduling is interconnected to the control function. Factors like temporal unavailability of machines and fluctuations of processing times and technological are components of this model.

Yao et al. (2015) describe manufacturing enterprises as socio-technical systems since enterprises usually consist of technical aspects such as smart devices on the shop floor, as well as social aspects such as human interactions and behaviour. On the basis of a literature review the authors analyse different manufacturing systems including the smart factory of Industry 4.0, cloud manufacturing and socialised enterprise and present a vision of manufacturing which combines complementary aspects of these models to function as a whole and to build strengths and mitigate weaknesses. A case study is used to illustrate the vision landscape. The resulting "Sociocyber-Physical System" enables the holistic integration of the physical, the cyber and the social system. In the perspective of Yao et al. (2015), having a systems engineering perspective in mind, manufacturing is a synthesis of different attributes such as organisational wisdom, collaborative learning, innovation, and creativity, where the whole is greater than the sum of its parts.

Chavarría-Barrientos et al. (2018) developed a methodology based on the principles of enterprise architecture to design a sensing, smart and sustainable manufacturing enterprise. The concept pragmatically describes how to include Industry 4.0 characteristics into an enterprise design and offers a holistic approach by taking different viewpoints, from the management to the shop floor level, into account. The core characteristics for the sensing, smart and sustainable manufacturing enterprise begin with Context Awareness, and continue with foresight, intelligence, collaboration, integration, adaptiveness, economic sustainability, social responsiveness and environmental sustainability (Chavarría-Barrientos et al., 2018). The research builds upon a literature review. Theoretical contributions are explained in a case study afterwards. The methodology identifies the role of the enterprise within its supply chain and defines the company's perspectives within specific strategies and the business model. The study of Chavarría-Barrientos et al. (2018) includes some organisational aspects, however, it is largely based on technical suggestions regarding Industry 4.0 implementation.

Moeuf et al. (2018) analyse Industry 4.0 in relation to SMEs, stating that so far firms find themselves ill-equipped in addressing the complex nature of the current industrial revolution. The research builds on a literature review and the classification of publications according to a developed framework. The framework identifies 1.) the performance objectives, 2.) the required managerial capacities, and 3.) the required base technologies. Moeuf et al. (2018) present various insights about Industry 4.0, such as that firms do not yet exploit all the available resources for the implementation and that implementation projects often remain cost-driven initiatives. Many firms limit themselves to cloud computing and the IoT, trying to gain benefits in monitoring processes and production flexibility only. The implementation framework of Moeuf et al. (2018) is provided in Appendix C of this thesis.

The framework of Moeuf et al. (2018) is comparable to the framework of Frank et al. (2019), who refer to a lack of understanding of how companies can implement Industry 4.0. The aim of the research is to understand the adoption patterns of manufacturing firms regarding Industry 4.0 technologies that provide digital solutions. The research builds upon a cross-sectional survey in 92 manufacturing companies in Brazil. Frank et al. (2019) divide Industry 4.0 technologies into two layers, i.e. front-end and base technologies, and developed a new implementation framework for them. Front-end technologies refer to smart manufacturing, smart products, smart working and smart supply-chains. Smart manufacturing has a central role in Industry 4.0 and is strongly interrelated to smart products. Base technologies refer to cloud computing, IoT, big data and analytics. The implementation framework presents how Industry 4.0 technologies can be implemented as well as how they interrelate to each other

(Frank et al., 2019). The results of the research show that implementations mainly focus on the front-end technologies, and especially on the smart manufacturing part. The implementation of the base technologies (big data & analytics) is less visible in industry and more challenging to firms (Frank et al., 2019).

Furthermore, an interesting finding of Frank et al. (2019) refers to the important potential benefit of Industry 4.0 implementation, i.e. manufacturing flexibility. The authors found that investigations into the maturity of "flexible production lines" have widely been neglected so far in the industrial sector (in the sample of firms of the research). The researchers brainstorm if this phenomenon has resulted from the required changes in layout and production methods that may interrupt present operations routines, from financial restrictions, or because manufacturing firms have simply adopted an implementation pattern from other business contexts that focus more on economies of scale and productivity improvements rather than flexibility improvements (Frank et al., 2019). The main difference between the framework of Frank et al. (2019) and the models of several other authors is that instead of proposing ideal stages of implementation Frank et al. (2019) present findings based on empirical evidence. Another differentiation is the broadness of the model, which includes many dimensions and technologies and does not limit itself to only the internal smart manufacturing technologies (Frank et al., 2019). The framework of Moeuf et al. (2018) and the framework of Frank et al. (2019) both consist of three closely related blocks, i.e. the targeted objectives (stage 1-3), the levels of managerial capacity sought (the front-end technologies), and the technical resources (the base technologies). The framework of Frank et al. (2019) is provided in Figure 2.

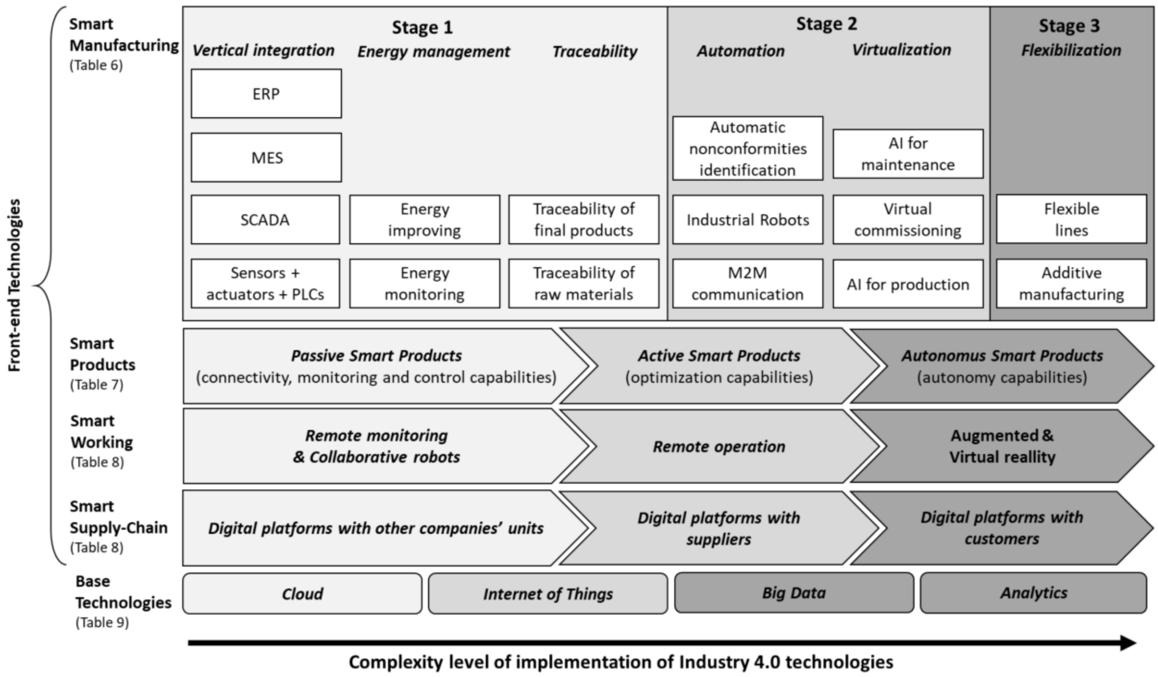


Figure 2: Implementation framework of Industry 4.0

Source: Frank et al. (2019)

2.3.2 Implementation in the light of organisational aspects

Liao et al. (2017) found in an extensive systematic literature review that the final report of the Industry 4.0 working group (Kagermann et al., 2013) is the most recognised Industry 4.0 reference today. The report points out three features and eight priority areas for action necessary for successful Industry 4.0 implementation. 20.5% of the papers included in Liao et al. (2017) research (46 papers) mention at least one of the three integration features. 45 papers thematised the feature vertical integration, 39 papers horizontal integration, and 23 papers thematised the feature end-to-end digital integration. Furthermore, 54.5% of the papers included in Liao et al.'s (2017) research (122 papers) present their contributions in one of the eight priority areas for action. The integration features and priority areas are of a quite general nature and include technical as well as organisational aspects. The research of Kagermann et al. (2013), however, enjoys great acknowledgement in the field (Liao et al., 2017). The three integration features of Kagermann et al. (2013) are 1.) Horizontal integration through value networks, 2.) Vertical integration and networked manufacturing systems, and 3.) End-to-end digital integration of engineering across the entire value chain. The priority areas for action, which refer to the organisational aspects of the implementation of Industry

4.0, thematise work organisation and design, as well as training and continuing professional development. According to Kagermann et al. (2013), increasingly real-time oriented control will transform work- content, processes and environment. Work organisation must hence be designed in a way that enables workers to take over responsibility and that enables personal development. Participative work design and lifelong learning measures may be effective tools. Furthermore, the implementation of Industry 4.0 requires appropriate trainings strategies to foster the continuous learning ability of the workers. Digital learning techniques can be effective tools to achieve the desired continuous professional development.

Cordeiro et al. (2019) have developed six stages for implementing Industry 4.0 considering management and operational aspects during the implementation flow. The research builds upon a qualitative literature review. The authors argue that the technological change that Industry 4.0 brings to the firms is accompanied by many organisational implications too. The six stages that could support firms by implementing Industry 4.0 are 1.) strategy mapping, 2.) pilot project development, 3.) definition of required resources, 4.) specialisation in data analysis through professional trainings in a continuous way, 5.) increasing company digitalisation, and 6.) including the entire value chain (Cordeiro et al., 2019). Furthermore, it is argued that Industry 4.0 implementation requires the effective involvement of the top management (Cordeiro et al., 2019). Companies experience strategic and operational turbulences due to the lack of understanding of the complex nature of Industry 4.0. Hence, Cordeiro et al. (2019) suggest how these companies can introduce the aspects of Industry 4.0 into their organisation in a structured way and thereby reach its promised benefits better. The authors argue that Industry 4.0 must be understood as a complex system that involves several different aspects. Cordeiro et al. (2019) implement other researchers work into their implementation stages, such as for the stage “strategy mapping” a maturity model developed by PWC (2016), for the stage “pilot projects development” the “architecture for manufacturing in the context of Industry 4.0” developed by Lee et al. (2015), and for the stage “definition of required resources” the “Digital Compass for Capacity Building” developed by McKinsey & Company (2015). The authors refer to an exploratory character of the research. However, not many explorative characteristics were found when reviewing the paper. It is not explained why the researchers have chosen these particular models instead of others to support their implementation stages. No evidence was presented why for example Lee et al. (2015) and their “architecture for manufacturing in the context of Industry 4.0” is more promising than other ways of developing pilot projects. The same can be seen regarding the "Digital Compass for capacity building", developed by McKinsey & Company. A limitation that the authors themselves refer to is the theoretical nature of the contribution and the missing validation in practice. The research has been investigated through a literature review and delivers a proposal only.

Research on Industry 4.0 typically discusses the technical aspects of the concept but leaves out managerial approaches or organisational culture perspectives (Mohelska and Sokolova, 2018). Mohelska and Sokolova (2018) took advantage of this gap to some extent and studied the managerial approaches to build an innovative organisational culture that supports the implementation of Industry 4.0. The level of corporate innovation and education required for realising Industry 4.0 depends on the people's abilities and also on the organisational culture of the firm (Mohelska and Sokolova, 2018). Innovative culture characteristics, according to Wallach (1983), are driving, enterprising, challenging, stimulating, pressurised, creative, result-oriented and risk taking. The research builds on a questionnaire survey that was distributed to multiple organisations of the private and public/government sectors located in the Czech Republic. The empirical data suggests that at present the organisations' culture tends to be rather bureaucratic and supportive rather than innovative, which would support Industry 4.0 implementation better (Mohelska and Sokolova, 2018). This leads to the conclusion that it is necessary to adjust existing managerial approaches to better support the development of organisational cultures that supports the environment for innovation to effectively implement and operate Industry 4.0 (Mohelska and Sokolova, 2018). The authors refer to a collaborative, explorative and entrepreneurial mind-set of the employees as well as the need for strong management commitment as two important enablers of successful implementation projects. Unclear benefits and the high costs of implementation often associated with Industry 4.0 act as barriers (Mohelska and Sokolova, 2018). Mohelska and Sokolova (2018) highlight the existing problem that many firms do not have an Industry 4.0 strategy yet and have no assigned responsible employees for the topic either. Changing the current managerial approaches to create a supportive and innovative environment would foster the potential of successful Industry 4.0 implementation (Mohelska and Sokolova, 2018). Since all data was collected in Czech organisations the authors limit their results to the current situation in Czech Republic only (Mohelska and Sokolova, 2018). Furthermore, data was only collected from employees with a certain education level. Employees with lower levels of education were underrepresented in the sample (Mohelska and Sokolova, 2018).

An important organisational aspect of Industry 4.0 implementation is furthermore the application of solid risk management (Tupa et al., 2017). Tupa et al. (2017) analyse these aspects on the basis of a literature review and focus on the implementation of risk management for Industry 4.0. Management in general requires performance measurement. Performance measurement identifies the delta between the targeted and the actual performance of a firm. It identifies performance gaps and provides an indication of progress towards closing the gaps (Tupa et al., 2017). The implementation of Key Performance Indicators (KPI) is an effective tool of risk management for Industry 4.0 implementation (Tupa et al., 2017). Carefully selected KPIs can identify precisely where to act in the firm to improve and return to the targeted performance level. Furthermore, Tupa et al. (2017) recommend the development of a tool to connect KPIs and KRIs (Key Risk Indicators) in order to increase their applicability in relation to the performance measurement of Industry 4.0 implementation (Tupa et al., 2017).

On the basis of a literature review Odważny et al. (2018) identified a lack of clarity amongst businesses concerning the operational implementation of Industry 4.0, and hence developed a guideline in the form of an evaluation sheet to fill this gap. The evaluation sheet distinguishes three different implementation phases within the firm. These are 1.) the aspiration phase, 2.) the maturity phase, and 3.) the smart factory phase. Furthermore, each of the three phases has three evaluation areas. These are 1.) human factors, 2.) technical and organisational aspects, and 3.) management related point. According to the authors these features should be considered as undisputed requirements to successful implementation projects (Odważny et al., 2018). Additionally, and also highlighted as an important variable, is that motivation should not only be recognised within the management of the firm, but also on the shop-floor level in operating teams (Odważny et al., 2018). The implementation of Industry 4.0 is fraught with various obstacles of which the organisational obstacles are an important part. The authors underline the evolutionary nature of an implementation process and the complexity challenges that come with it. The fact that Odważny et al. (2018) take HR, management, and a selection of further organisational aspects into account puts it to the category of organisational Industry 4.0 implementation studies for this research. The evaluation sheet is provided in Appendix D of this thesis.

The research of Odważny et al. (2018) offers interesting insights into some of the aspects of Industry 4.0 implementation, although it fails to provide the required information regarding its methodology. Odważny et al. (2018) state that the evaluation sheet was formulated on the basis of a systematic literature review and a detailed case study. However, no more indication regarding the methodology appears in the paper. It is unclear in what way the systematic literature review was structured, as well as in what context, width and depth the "detailed case study" has been conducted. This lack of methodological context awareness makes it hardly usable for future consideration. Furthermore, the research is titled to be in the context of FMCG (Fast Moving Consumer Goods), even though no indication of this specification is provided anywhere else in the research. It is stated that the results of the paper will present advantages and disadvantages of modern management strategies, but this information wasn't findable. Last but not least, Odważny et al. (2018) mention that the results of the research may differ depending on prevailing conditions in different countries, but they fail to provide information on where the data was collected, i.e. from which context the "results may differ".

Industry 4.0 maturity models prepare firms to evaluate and organise their Implementation strategy building and execution. The maturity model of Schumacher et al. (2016), for example, builds on nine different dimensions that firms could consider. Each dimension is described with examples of maturity items. The research is structured according to Becker et al.'s (2009) step-by-step process for the development of maturity models, including a systematic literature review, expert interviews, questionnaires and a case-study. The major contribution of this maturity model, compared to most other models focussing dominantly on the technological aspects of Industry 4.0 implementation only, is the inclusion of a set of organisational aspects of Industry 4.0 implementation. The maturity model even acknowledges organisational structure changes by also evaluating the existence of a central coordination for implementation projects. With the inclusion of the organisational aspects the maturity model of Schumacher et al. (2016) attempts to offer a more comprehensive picture of the reality. The nine dimensions refer to "strategy", which includes e.g. the presence of an implementation roadmap, "leadership", which includes e.g. the willingness of leaders, as well as management competences and the existence of a central coordination for I4.0, “customers”, which includes the utilisation of customer data, “products”, which includes e.g. product integration into other systems, “operations”, which includes e.g. decentralisation of processes and interdisciplinary and interdepartmental collaboration, “culture”, which includes e.g. open-innovation and cross company collaboration, “people”, which includes e.g. openness of employees to new technology as well as autonomy of employees, “governance”, which includes e.g. labour regulations for I4.0, and last but not least, “technology”, which includes e.g. the existence of modern ICT. An example of an Industry 4.0 maturity analysis according to Schumacher et al. (2016) is captured in a radar chart and provided in Appendix E of this thesis.

Another maturity model to support manufacturing firms in implementing Industry 4.0 has been developed by Petrovic and Leksell (2017). The authors developed a framework that focuses on the success factors, challenges and outcomes of an implementation project. The research builds on six exploratory in-depth case studies with a total number of 31 interviews in five factories and one central department of two leading automotive companies. The central department was responsible for supporting all other departments of its firm regarding their individual implementation projects. The research results in a framework for defining different maturity levels of Industry 4.0 implementation. With the new framework manufacturing firms are guided before they start a production transformation. The framework informs about necessities and the complexity of a successful transformation process. The authors were surprised by the complexity of Industry 4.0 implementation. Petrovic and Leksell (2017) also suggest the use of an agile stage-gate model, as well as a top management defined business case of Industry 4.0 to mitigate potential barriers. The larger research of Petrovic and Leksell (2017) has been compressed, refined, and published as a journal contribution under Sjödin et al. (2018). The argument of the research stayed the same, i.e. the implementation of Industry 4.0 challenges firms, hence the challenges must be identified and solutions must be developed to overcome them (Sjödin et al., 2018). The maturity model builds upon three guiding principles that should support firms in designing their manufacturing 1.) cultivating digital people, 2.) introducing agile processes, and 3.) configuring modular technologies. It provides guidance to support the implementation of Industry 4.0 and to successfully transform production processes. The maturity model of Sjödin et al. (2018) is provided in Appendix F of this thesis.

A framework consolidating different recommendations for the implementation of Industry 4.0 was developed by Veile et al. (2020). On the basis of 13 interviews the researchers analysed the "Lessons learned from Industry 4.0 implementation in the German manufacturing industry". In a multiple case-study approach, the study focuses on technical, organisational and human aspects, as well as their intersections. The empirical results concluded with six lessons, stating that 1.) employees' competencies should be conveyed via education programs, 2.) knowledge should be developed by utilising research results, 3.) organisational structures should be of flat hierarchy and decentralised decision making, which may also include the foundation of spin-offs and interdisciplinary project teams, 4.) communication is to be opened up so that employees are able to freely communicate across hierarchical levels, 5.) cooperation networks and data exchange may be adequate, and 6.) integrations of Industry 4.0 solutions may be systematic, but also based on trial-and-error methods following an incremental bottom-up approach. The research furthermore mentions a potential risk of internal resistance from the employees of the firm to cultural changes and recommends an "incremental" implementation strategy rather than a radical one to reduce this risk. In addition, it was detected that one of the 13 interview participants of Veile et al. (2020) referred to the foundation of a new division in their organisation to implement Industry 4.0 separated from the daily business. The research concludes with the development of an implementation framework that consolidates and summarises the results of the study. The framework is illustrated in Figure 3 and demonstrates the interactions inside the organisational structure as well as exchange with the environment of the organisation.

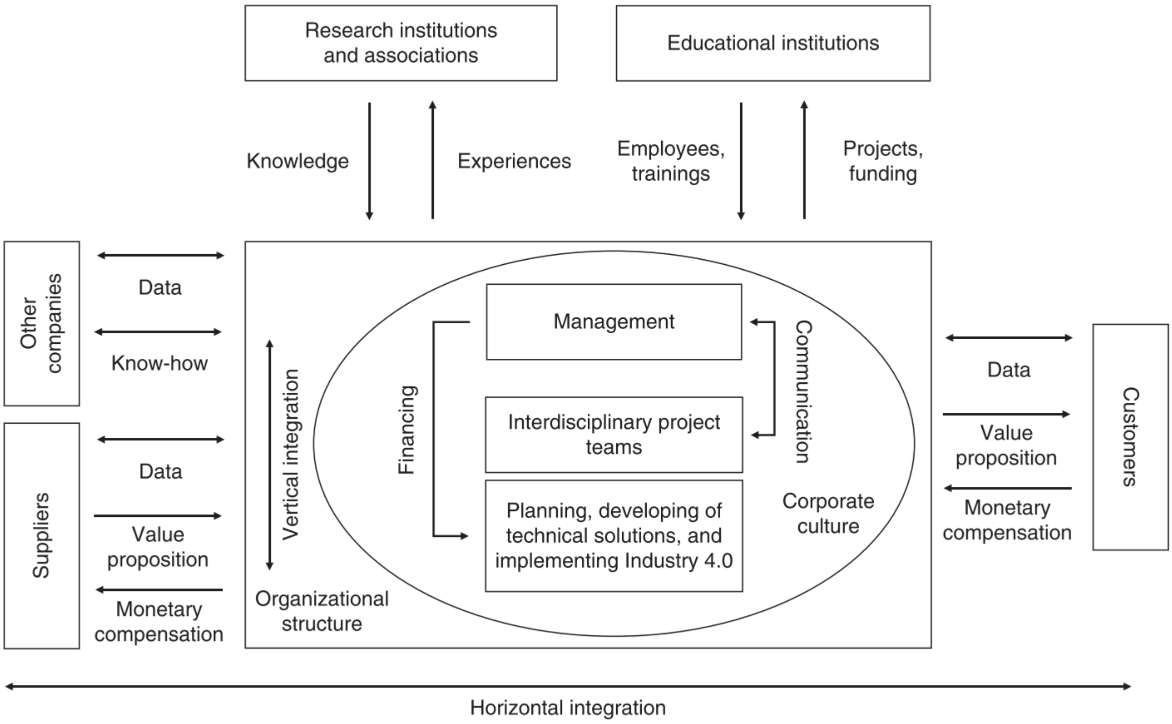


Figure 3: Framework of Industry 4.0 implementation

Source: Veile et al. (2020)

Sousa Jabbour et al. (2018) published a study about the synergies of Industry 4.0 and environmentally-sustainable manufacturing. Eleven components are identified as critical success factors which enable the successful implementation of Industry 4.0 and environmentally sustainable manufacturing. The first component is management leadership followed by organisational change readiness, top management commitment, strategic alignment, training and capacity building, empowerment, teamwork, organisational culture, communication, project management, as well as national culture and regional differences. Regarding "management leadership", the very first stated component of the eleven, the authors suggest that a transformational leadership style may be required for a smoother adoption of the Industry 4.0 principals (Sousa Jabbour et al., 2018). Overall, the eleven success factors of Sousa Jabbour et al. (2018) present well the very high priority of the organisational and management perspective that successful Industry 4.0 implementation projects require. The developed integrative framework that includes the critical success factors of implementing Industry 4.0 is provided as Appendix G of this thesis.

Human Resource (HR) management is also an essential component of the organisational aspects of successful Industry 4.0 implementation. According to Jerman and Dominici (2018), who screened the business, management and accounting literature, there is, however, a significant knowledge gap regarding Industry 4.0 and HR management. Therefore, the following provides an overview of some of the existing perspectives on HR management in relation to Industry 4.0 implementation. Rana and Sharma (2019) investigate best management practices to encourage innovation and learning, and thereby the adoption of Industry 4.0 in firms. The authors place the human resource (HR) management of firms in the centre of successful transformation and organisational survival in the disruptive time of change. The management is responsible for recognising the new transformed role of the HR by enabling the implementation of innovative HR practices (Rana and Sharma, 2019). The developed framework of Rana and Sharma (2019) illustrates the required proactive steps of the transforming role of HR management and offers a platform to employees to find solutions to data-centric issues. HR management includes the investigation of digital and immersive tools that facilitate talent acquisition, remote workforces and employee engagement, as well as the provision of trainings in data skills and the creation of an overall data-driven work culture (Rana and Sharma, 2019).

Whysall et al. (2019) analysed the transformational changes to business environments that appear with the introduction of Industry 4.0. The focus of the research lies on the strategic human resource management and its implications for talent management theory and practice. For that, Whysall et al. (2019) conducted in-depth interviews with HR directors and senior leaders of organisations. The speed of technological change created a significant gap between the capabilities of employees and the requirements of their roles (Whysall et al., 2019). The authors criticise firms especially for underestimating the middle managers as critical talent for a successful change management towards Industry 4.0. Lateral hiring, a common talent management practice, is detected as an ineffective strategy in the case of Industry 4.0 due to the rare existence of these talents (Whysall et al., 2019). Whysall et al. (2019) provide empirical insights into the impact of change brought about by Industry 4.0 on talent management and suggest a need for evolution towards the development of dynamic, systems-thinking oriented and interrelated talent management activities. The qualitative and inductive research builds on in-depth interviews. Data was collected from UK manufacturing firms from multiple industries, such as construction and engineering, defence, aerospace and energy and utilities sectors. The data analysis, following Miles and Huberman's (1994) framework for qualitative data analysis, presents four main themes, i.e. 1.) talent attraction challenge, 2.) new core competencies, 3.) pivotal talent positions: the neglected middle, and 4.) transforming talent management (Whysall et al., 2019). This interesting research, however, fails to provide any further insights about the reliability and validity of the findings and the analysis. More information could have been provided regarding statements as "several interviewees highlighted […]", or "a strong theme across all interviews […]".

Chulanova (2019) analyses professional standards of corporate education to prepare human resources to the adaptation of Industry 4.0. The fast-changing technological advancements and the adoption to new conditions are major challenges for employees. A rejection of such changes will harm the successful implementations and the generation of the potential benefits from Industry 4.0. However, human resources may also act as a central driver for change, presenting ingenuity and creativity for new opportunities and personal development. The employees of a firm can act independently as an active shaper of the transformation towards Industry 4.0 (Chulanova, 2019). The qualitative modernisation of the vocational education system of Chulanova (2019) requires digital skills of employees to use the new smart systems and adapt them to future technologies. Vocational education must include the basic digital literacy as well as a deep understanding of how to implement technologies to enable organisations to profit from Industry 4.0 (Chulanova, 2019). Additionally, Kazancoglu and Ozkan-Ozen (2018) analyse the human resource requirements in Industry 4.0 from an operations management perspective. The research is based on a literature review. The authors developed a structural competency model and set new criteria for the recruitment process of HR in an Industry 4.0 environment. The important criteria are the ability of dealing with complexity and problem solving, thinking in overlapping processes, and the flexibility to adapt new roles and work environments (Kazancoglu and Ozkan-Ozen, 2018). Further criteria are IT skills including IT security and data protection, knowledge production technologies, the ability of fault and error recovery, organisational and processual understanding, and the ability to interact with I4.0 interfaces (Kazancoglu and Ozkan-Ozen, 2018). Analytical thinking and a system approach supports building the "workforce 4.0" and the overall organisational transformation to Industry 4.0 (Kazancoglu and Ozkan-Ozen, 2018). Interesting as well is the fact that the high-tech firm, in which the research was conducted, founded a separate department to centralise the responsibility to modify the firms' processes and to transform its organisation according to Industry 4.0. Partly, the data was collected from experts of this department. Furthermore, Kazancoglu and Ozkan-Ozen (2018) refer to smart manufacturing, the IoT, and also "self-organisation" as the core concepts of Industry 4.0.

2.3.3 Implementation barriers and enablers

Researchers agree that Industry 4.0 presents disruptive positive potential to firms utilising the concept in a suitable way Acatech (2016a). However, the successful implementation of Industry 4.0 faces several barriers, risks and challenges before, during and after the implementation. Acatech (2016a) categorised five global challenges of Industry 4.0 as data security, standards, migration and interoperability, business models and the fulfilment of expectations tied to "the brand" Industry 4.0. The so far detected barriers, risks and challenges are, however, weakened by the enablers of Industry 4.0 that work constructively in supporting good implementation. The enablers often mirror the barriers, hence both barriers and enablers are thematised in the same section of this thesis. Standardisation itself is not a barrier, however, the time it takes to develop them may be crucial to the success of technologies that are to be standardised Acatech (2016a). Governments, pioneering companies and academia often collaborate closely to set regulations before working in alignment with them and exporting them. Norming institutions such as the DIN in Germany are coordinating the collaborations to ensure a dialogue-based consensus. Standards are especially important to Industry 4.0 as the whole idea builds upon connectivity. Manufacturing firms must be able to integrate machines and systems on a plug and play basis so that they can communicate directly with other items along the value chains. Ideally, this philosophy functions for machines and equipment from any supplier, nationally as well as internationally.

Specific areas in the field of Industry 4.0 that require norms and standards are 1.) interoperability, 2.) reference models, 3.) APIs, 4.) semantics, 5.) standard Industry 4.0 glossary, and 6.) data formats (Acatech, 2016b). Since innovation cycles become shorter and entrepreneurial environments increasingly dynamic, time-consuming standardisation processes become a critical factor and hence a barrier to Industry 4.0 implementation. Companies and institutions need to speed up in agreeing on beta standards as a first step to foster a pragmatic approach for future actions. Furthermore, they are recommended to run a dual strategy, meaning to continue building reference architectures, norms and standards on the one hand, but developing pragmatic solutions that show real benefits to users on the other hand (Acatech, 2016b). Missing standards and success-stories of previous implementation projects support the appearance of a “wait and observe” mentality towards Industry 4.0 (Choi, 1997; Acatech, 2016b). In the discipline of network-theory this effect is called the “penguin effect”. The penguin effect states that early adopters of a network often cannot generate the estimated success as there is not yet the critical mass of other users in the network. Potential users create a “wait and observe” attitude from which the network could even collapse in the worst-case. The term penguin-effect arose based on research of hungry penguin groups waiting at the shore due to their inability to estimate whether there are predators waiting in the water or not. The penguins wait until the first one of the groups cannot wait anymore and jumps in the potentially dangerous water to fish. All others can now observe if something happens to that penguin. The observation is the trigger of the penguin effect. Based on the observation the rest of the group decides to follow or not (Choi, 1997; Acatech, 2016b).

The “time to market” is crucial to some features of Industry 4.0. Coming from the internet industry, service orientated business models such as “platform businesses” immigrate with the ongoing development of the fourth industrial revolution into the manufacturing industry. This brings new logics and phenomena into the manufacturing industry to which established manufacturers have to adopt quickly. A well-known phenomenon of the internet industry is the “the winner takes it all” phenomenon. This logic and its prestigious example corporations e.g. Google, Amazon, ebay, Uber, Airbnb, etc. have lasting success in the internet industry. Platform businesses, as an example, build ecosystems and enable both reaching end-customers directly as well as generating all sorts of data from it. The generated and original data will eventually enable organisations to analyse patterns and to derive predictions of future actions from it. However, an important specification about platform businesses is that usually only one supplier can survive the race to be the leading platform. In other words, “the winner takes it all”. This puts pressure on manufacturers since the effect of not being the “winner” potentially means becoming unimportant (Schumann, 2018). In order to not lose their strength, SMEs are especially recommended to accelerate their development of industry specific software platforms to create important network effects before large internet companies do so. Generally, companies with the goal of actively shaping the future of Industry 4.0 should begin to deeply engage in ecosystems around Industry 4.0 platforms (Acatech, 2016b).

Additionally, data security is rated as one of the highest risks of Industry 4.0 implementation in German manufacturing firms (Acatech, 2016b). The challenge of "securing smart manufacturing systems" has been explored by Tuptuk and Hailes (2018). With the implementation of complex Industry 4.0 technologies the possibility for attack in form of industrial espionage or sabotage has massively increased (Tuptuk and Hailes, 2018). The authors argue that it is relatively easy to gain access to the present systems and that there is little to stop attackers from modifying process parameters once they have access to critical systems or data. Two reasons for an often missing effective security of manufacturing systems are the high complexity of systems and dependencies on the technology of suppliers (Tuptuk and Hailes, 2018). Tuptuk and Hailes (2018) have not developed solutions to solve security problems. Instead, the paper describes what can happen, e.g. injuries, death, and damage to physical infrastructure, equipment and environment, as well as suggest in a wishful way what should be done against it, e.g. research and industry communities need to work together and focus on efficient, robust, reliable, low-cost security solutions. Lin et al. (2018a) suggest a hierarchical framework that allows a secure and efficient implementation of Industry 4.0 technologies. The authors focus especially on security and argue that the complexity of Industry 4.0 systems requires robust security solution. Existing security solutions are insufficient to address the present concerns according to the authors. Hence, a blockchain-based framework leverages the security level with its underpinning characteristics of blockchain as well as several cryptographic materials to realise decentralisation, anonymous authentication, confidentiality and auditability (Lin et al., 2018a).

The risk of losing core competences may appear as a risk when cooperating and opening up to external suppliers. The implementation of certain technologies or solutions, such as the "digital twin", potentially requires the provision and sharing of a wide range of sensitive process data (Moeuf et al., 2018). This process data may represent the core competences of the firm. Especially SMEs fear becoming "interchangeable suppliers" when losing their core competences. The risk of entering a supplier lock-in may also appear when implementations are built heavily on external partners instead of internal self-development, or when standards are not yet available. Industry 4.0 is a complex interaction of several high-technologies and a new management system as well. It is challenging for firms to understand each aspect of the concept in detail before the decision must be made to buy or to make the desired I4.0 solution. The risk of investing into a solution that is not standardised, and which can only be operated and maintained by the suppliers is present. Furthermore, the conventional belief about the result of the implementation of Industry 4.0 and automation in general is that these innovations will lead to less human interaction or even complete workerless production facilities. This belief may foster the fear in employees of losing their jobs and may sometimes lead to a rejection of supporting implementation projects. However, hardly any reliable research supports this fear (Hofmann and Ruesch, 2017). Instead, researchers state that Industry 4.0 will not lead to less human interaction or workerless production facilities, but that the roles of employees and their competence requirements will change (Dworschak and Zaiser, 2014; Weyer et al., 2015) in a way that skill requirements and specialisation increase (Tortorella and Fettermann, 2018), as well as that responsibility, decision making and supervising tasks are included (Spath et al., 2013).

The information and communication technology (ICT) applied within Industry 4.0 requires a stable, fast and wide-ranging infrastructure to function. Just as streets and railways need to be built to enable on land logistics, Industry 4.0 requires infrastructure to enable data transfer and connectivity. Out of the technological advanced countries, Germany, as an example, lags behind in providing such an infrastructure (Acatech, 2016a). Germany also lacks competences in innovating Business Models with the intelligence of internet technologies. These abilities are necessary when it comes to the point to understand the full potential of Industry 4.0 (Acatech, 2016b, 2016a). There is the further risk of not fulfilling the expectations that firms "individually" have tied to Industry 4.0 (Madsen, 2019). This may appear due to the mass of different interpretations and neologisms of Industry 4.0, as analysed above in this chapter. The complex and elusive nature of Industry 4.0 leads to conceptual confusion in corporate practice and may hinder successful adoption and implementation (Madsen, 2019). Furthermore, managerial and organisational challenges (with reference to Agostini and Filippini, 2019), inertia forces (with reference to Kovacs, 2019) and attitudinal and decision-making issues (with reference to Hamada, 2019) are named as potential barriers against successful adoption, diffusion and implementation of the concept Industry 4.0 in organisational practice (Madsen, 2019). Madsen (2019) presents many interesting aspects of Industry 4.0, but does not mention any recommendations regarding how to implement Industry 4.0. Cordeiro et al. (2019) on the other hand developed a comprehensive overview of potential barriers and challenges that potentially affect the implementation of Industry 4.0. The overview captures barriers such as "employee engagement", including potential resistance to change and the fear of exchanging people for smart equipment, “organisational and process changes”, including the requirement of developing new work organisation and collaborations with partners, and “technology”, including the challenge of different maturity levels of solutions in the firm at the same time (Cordeiro et al., 2019). The full scope of individual issues that may affect a firm in its implementation of Industry 4.0., i.e. the overview of challenges developed by Cordeiro et al. (2019) is provided as Appendix H at the end of this thesis.

Lean management is often perceived as a general enabler for successful Industry 4.0 implementation. Buer et al. (2018), for example, link established lean manufacturing methods with overall efficiency as well as Industry 4.0 with extended automation. They further argue that automation on top of efficient structures will lead to improvements, whereas automation on top of inefficient structures will lead to even higher inefficiency. Hence, the presence of established lean manufacturing practices will positively influence the result of Industry 4.0. In general, Industry 4.0 implementation often happens on the top of established lean manufacturing structures in companies. This makes sense since lean manufacturing is the most applied manufacturing paradigm of recent times (Buer et al., 2018). Some researchers even emphasises that lean manufacturing must be seen as a prerequisite for a successful Industry 4.0 implementation (Kaspar and Schneider, 2015; Staufen AG, 2016). The research of Buer et al. (2018) builds upon a systematic review of the literature.

The interplay of Industry 4.0 technologies and lean manufacturing can furthermore lead to additional operational performance improvement (Tortorella and Fettermann, 2018). Even though lean manufacturing is a rather socio-technical and low-tech continuous improvement approach, digital technologies can enhance its potential if properly integrated. Empirical evidence shows that companies which have implemented lean manufacturing are more likely to also adopt Industry 4.0 technologies (Tortorella and Fettermann, 2018). Companies who are currently implementing lean manufacturing may be advised to simultaneously implement Industry 4.0 to reach the benefits of the combination right from the beginning. The research of Tortorella and Fettermann (2018) builds upon surveys carried out with 110 companies of different sizes and sectors. Industry 4.0 technologies are significantly associated with lean practices, which make a company’s experience on lean manufacturing an important variable also for the success of implementing Industry 4.0. Tortorella and Fettermann (2018) identified how the implementation of Industry 4.0 technologies into present manufacturing practices (lean manufacturing) corroborates operational performance improvement. In doing so they analyse a “how” question regarding the value creation that Industry 4.0 implementation can bring to a firm. However, the study showed that operational performance improvements are not always the resulting effect of Lean and/or Industry 4.0 implementation. This result leads the authors to conclude that any improvement approach, irrespective of its methods, when misunderstood or misemployed may have its benefits reduced, or even cause negative effects. Hence, an implementation approach of Industry 4.0 must carefully be verified if aligned with the company’s strategy (Tortorella and Fettermann, 2018).

2.4 Problematisation

Section 2.4 identifies the gaps and weaknesses of the reviewed literature on the implementation of Industry 4.0. The section will close with the formulation of the research questions that address the detected research gaps.

2.4.1 Composition of the literature

The literature overwhelmingly agrees that Industry 4.0 implementation can lead to the creation of value (Acatech, 2013; Westerlund *et al.*, 2014; Bauer *et al.*, 2014; Bauernhansl *et al.*, 2015; Burmeister *et al.*, 2016; Kiel *et al.*, 2017; Kusiak, 2018; Moeuf *et al.*, 2018; Buer *et al.*, 2018; Tuptuk and Hailes, 2018; Sjödin *et al.*, 2018). The highest beneficial outcome is seen in production optimisations (Acatech, 2016b). However, the level of potential value that Industry 4.0 releases depends critically on how successfully a firm implements the concept. The integration of single Industry 4.0 components and the systematic transformation of the whole corporation challenges firms (Tuptuk and Hailes, 2018; Sjödin et al., 2018). The risk of failing an implementation attempt e.g. due to resistance to change from the employees of a firm, and consequently the burden of a worse return on investment places pressure on the management. The challenges of correctly evaluating the potential benefits of investments restricts companies to a limited portfolio of Industry 4.0 components and consequently hinders the full potential of Industry 4.0 (Wang et al., 2016a; Moeuf et al., 2018).

The literature review led in the current research to the differentiation between two perspectives of the implementation of Industry 4.0, namely the "technical" and the "organisational" side. So far, most existing studies focus on the technical side of Industry 4.0 only (Liao et al., 2017; Strozzi et al., 2017; Galati and Bigliardi, 2019). Even the limited existing managerial literature on Industry 4.0 is still strongly affected by the technical aspects of the topic (Piccarozzi et al., 2018). Furthermore, and in line with Buer et al. (2018) and Tortorella and Fettermann (2018), it seems to be reasonable to place solid lean management structures in the centre of the implementation of Industry 4.0 solutions. The organisational aspects can be understood as surrounding the technical and lean management aspects and thematise important management requirements. This three-dimension logic is illustrated in Figure 4.

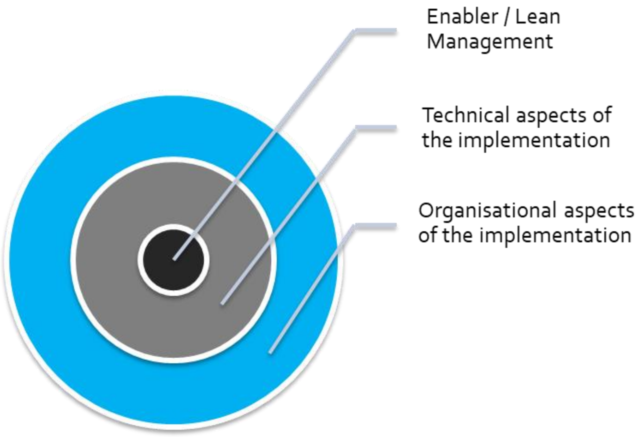


Figure 4: Composition of the literature

The reviewed literature of the first dimension thematises the enablers, i.e. lean management as a pre-requisite of successful Industry 4.0 implementation for manufacturing firms (Buer et al., 2018; Tortorella and Fettermann, 2018). The reviewed literature of the second dimension, which thematises the technical aspects of Industry 4.0 implementation, has developed and described e.g. knowledge about indoor localisation systems (Sun et al., 2018), monitoring systems (Lee et al., 2007), indexes to measure the capabilities of manufacturing resources (Brad et al., 2018), methodologies for new manufacturing systems (Yao et al., 2015; Chavarría-Barrientos et al., 2018), for manufacturing automation (Pagnon, 2017), and for adjustments in supply chain scheduling (Ivanov et al., 2016). Furthermore, the technical aspects capture Industry 4.0 implementation frameworks (Moeuf et al., 2018; Frank et al., 2019), as well as solutions regarding the connectivity and information flow for Industry 4.0 environments

(Shariatzadeh et al., 2016; Nayak et al., 2016; Wang et al., 2016a; Yoon et al., 2016; Akpolat et al., 2017; Theorin et al., 2017; Wang et al., 2017; Pedone and Mezgár, 2018; Rosendahl et al., 2018; Wan et al., 2018; Coronado et al., 2018). Last but not least, the reviewed literature of the third dimension, which thematises the organisational aspects of Industry 4.0 implementation, has developed and described e.g. priority areas for action (Kagermann et al., 2013), different stages for implementation (Cordeiro et al., 2019), a supportive organisational culture (Mohelska and Sokolova, 2018), required risk management (Tupa et al., 2017), implementation guidelines (Odważny et al., 2018), maturity models (Schumacher et al., 2016; Sjödin et al., 2018), implementation frameworks (Veile et al., 2020) and synergies of Industry 4.0 and environmentally-sustainable manufacturing (Sousa Jabbour et al., 2018). The organisational aspects of Industry 4.0 implementation also cover the HR field in forms such as educational topics (Chulanova, 2019), talent management (Whysall et al., 2019), transformational steps (Rana and Sharma, 2019) and new recruitment processes of employees (Kazancoglu and Ozkan-Ozen, 2018). From all reviewed studies, the following, in Table 3 provided, have been identified as of central relevance for the research field of this thesis.

Category	Author	Title	Journal
LR	Liao et al. (2017)	Past, present and future of Industry 4.0 - A systematic literature review and research agenda proposal.	International Journal of Production Research
LR	Piccarozzi et al. (2018)	Industry 4.0 in Management Studies. A Systematic Literature Review.	Sustainability
LR	Hoyer et al. (2020)	The Implementation of Industry 4.0 - A Systematic Literature Review of the Key Factors	Systems Research and Behavioural Science
Technical	Moeuf et al. (2018)	The industrial management of SMEs in the era of Industry 4.0.	International Journal of Production Research
Technical	Frank et al. (2019)	Industry 4.0 technologies. Implementation patterns in manufacturing companies.	International Journal of Production Economics
Orga	Veile et al. (2020)	Lessons learned from Industry 4.0 implementation in the German manufacturing industry	Journal of Manufacturing Technology Management
Orga	Sjödin et al. (2018)	Smart Factory Implementation and Process Innovation.	Research-Technology Management
Orga	Schumacher et al. (2016)	A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises.	Conference Proceedings; Changeable, [...] Conference
Enabler	Buer et al. (2018)	The link between Industry 4.0 and lean manufacturing. Mapping current research and establishing a research agenda.	International Journal of Production Research
Enabler	Tortorella et al. (2018)	Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies.	International Journal of Production Research

Table 3: Overview of key literature

2.4.2 Lean management as the first dimension

Buer et al. (2018) and Tortorella and Fettermann (2018) both analyse the relationship between Industry 4.0 implementation and lean management and identify that existing lean management practices function as an important enabler for the successful implementation of Industry 4.0. On the basis of a systematic literature review, Buer et al. (2018) identify four main research streams regarding the relationship of Industry 4.0 and lean management. These are, 1.) Industry 4.0 supports lean manufacturing, 2.) Lean manufacturing supports Industry 4.0, 3.) Performance implications of an Industry 4.0 and lean manufacturing integration, and 4.) The effect of environmental factors on an Industry 4.0 and lean manufacturing integration. Buer et al. (2018) further argue that lean methods may be most associated with overall efficiency (the performance benefits are proven in numerous cases), whereas Industry 4.0 may be most associated with extended automation. Automation on top of efficient structures will lead to improvements. However, automation on top of inefficient structures will lead to even higher inefficiency (Buer et al., 2018). Hence, the presence of established lean manufacturing practices will positively influence the result of Industry 4.0 implementation. Lean manufacturing practices are perceived as a general enabler for successful Industry 4.0 implementation and some researcher even emphasises that it must be seen as a prerequisite (Kaspar and Schneider, 2015; Staufen AG, 2016).

Tortorella and Fettermann (2018) foster the arguments of Buer et al. (2018) by stating that the interplay of Industry 4.0 and lean manufacturing can lead to additional operational performance improvements (Tortorella and Fettermann, 2018). Even though lean manufacturing is a rather socio-technical and low-tech continuous improvement approach, digital technologies can enhance its potential if properly integrated (Tortorella and Fettermann, 2018). The research of Tortorella and Fettermann (2018) builds on questionnaires and surveys carried out in 110 companies of different sizes and sectors. The empirical evidence shows that companies which have implemented lean manufacturing are more likely to also adopt Industry 4.0 successful (Tortorella and Fettermann, 2018). A company's experience with lean manufacturing is an important variable for the success of Industry 4.0 implementation and hence the expected operational performance improvements (Tortorella and Fettermann, 2018). However, the authors strongly highlight that the management level must first verify if such implementation approaches of Industry 4.0 and/or lean manufacturing can contribute directly to the company's strategy to avoid reduced benefits or even contrary effects to the expected ones (Tortorella and Fettermann, 2018). Furthermore, Tortorella and Fettermann (2018) found that only firms which have implemented lean manufacturing for at least two years will likely benefit from this experience when implementing Industry 4.0. The adoption of Industry 4.0 has been deemed as to increase the firms' performance. However, since the data collection was conducted in Brazilian manufacturing companies, and hence in the context of an "emerging country", the results of the research may be influenced by local issues.

2.4.3 Technical aspects as the second dimension

The analytical framework of Moeuf et al. (2018) was developed to classify relevant studies identified in a systematic literature review and functions as a guideline to support firms in structuring an Industry 4.0 implementation project. The framework of Moeuf et al. (2018) is comparable to the framework of Frank et al. (2019). Both frameworks consist of three closely related blocks, i.e. the targeted objectives (stage one to three), the levels of managerial capacity sought (front-end technologies), and the technical resources (base technologies). The research of Moeuf et al. (2018) addresses particular SMEs, is of a rather technical nature and fails to provide insights into the organisational aspects that an implementation project contains. The implementation framework that Frank et al. (2019) have developed also presents the technical side of Industry 4.0 implementation. As analysed in Section 2.3, the research shows how Industry 4.0 technologies may be implemented in the firm as well as how they relate to each other. The authors obtained a sample of 92 cross-sectional surveys of manufacturing companies from the southern regional office of the Brazilian Machinery and Equipment Builders´ Association. Frank et al. (2019) state that they aimed to understand the adoption patterns of manufacturing firms regarding Industry 4.0 technologies that provide digital solutions.

The framework of Frank et al. (2019) can be well understood and provides a good structure for the technical implementation of Industry 4.0. However, since the data collection was conducted in the Brazilian industrial sector only, the reality in other regions of the world may look different. Brazilian firms and firms of "emerging countries" in general may have specific characteristics which may differ from the characteristics of, for example, German manufacturing firms. One example of a specific characteristic from firms in emerging countries is the focus on "productivity" as the main industrial concern, instead of "flexibility" (Frank et al., 2019). Furthermore, almost half of the data sample (48%) of the cross-sectional study was collected from the agriculture sector. Differences in other industrial sectors are to be expected. The authors themselves state that future researcher should be cautious about generalising the findings of this research as a standard pattern for Industry 4.0 implementation (Frank et al., 2019). Last but not least, Frank et al. (2019) also miss to provide insights about the organisational perspectives and the strategic implications of Industry 4.0 implementation.

Recent literature reviews on Industry 4.0 offer interesting overviews of the current debates in the field. Liao et al. (2017), Strozzi et al. (2017), Piccarozzi et al. (2018), Galati and Bigliardi (2019) and Hoyer et al. (2020) all contribute to a simplification and better understanding of the complex nature of Industry 4.0. In this sense, Liao et al. (2017) found that the final report of the Industry 4.0 working group (Kagermann et al., 2013) is the most recognised Industry 4.0 reference today. The report defines eight priority areas for action necessary for successful Industry 4.0 implementation, as described in Section 2.3. Strozzi et al. (2017) divide the Industry 4.0 literature into three large connected components, and Galati and Bigliardi (2019) define the existing literature in four overarching themes. These three literature reviews are of rather technical nature, even though one of the themes of Galati and Bigliardi (2019) refers to the "business" perspective. The reviews of Piccarozzi et al. (2018) as well as Hoyer et al. (2020) are of a rather organisational and management nature and are hence analysed in the next section of this chapter. Table 4 visualises the main findings of the above-named literature reviews. All reviews jointly refer to the strong need to gain deeper understanding about the nature of Industry 4.0 implementation.

2.4.4 Organisational aspects as the third dimension

Schumacher et al. (2016) and Sjödin et al. (2018) both developed "maturity models" that can be utilised either for pre-implementation evaluations to check the readiness of a firm, or as an evaluation model to check the progress of implementation projects. The maturity model of Schumacher et al. (2016) builds on nine different dimensions, covering 62 items. The main contribution of the research is that the model includes organisational aspects of implementation projects, such as strategy, leadership, governance, culture, and people aspects (Schumacher et al., 2016). The research builds upon a multi-methodological approach including a systematic literature review, conceptual modelling and qualitative and quantitative methods for empirical validation (Schumacher et al., 2016). The research is structured according to the step-by-step process for the development of maturity models designed by Becker et al. (2009). The maturity model found its roots in the official recommendations for Industry 4.0 implementing from the German government and has been refined by including different scientific works, studies and reports (Schumacher et al., 2016). Data was collected in an Austrian company in the aerospace sector, which is considered an early adopter of Industry 4.0 in several journals in Austria (Schumacher et al., 2016). The maturity model is utilisable in manufacturing companies independently of their industries (Schumacher et al., 2016). Schumacher et al. (2016) add an important aspect to the knowledge about and guidance of Industry 4.0 implementation projects by including five organisational aspects of Industry 4.0 implementation in their maturity model. However, besides a short statement about the evaluation of the "existence of a central coordination for I4.0" the paper does not mention any further insights about changes in the organisational structure of the firm, such as the requirements of building new communication channels for the successful diffusion of Industry 4.0.

Soon after Schumacher et al. (2016) a second maturity model for Industry 4.0 implementation was developed by Sjödin et al. (2018). The model is structured in three guiding principles, i.e. 1.) cultivating digital people, 2.) introducing agile processes, and 3.) configuring modular technologies, as well as four levels of maturity, i.e. 1.) smart, predictable manufacturing, 2.) real-time process analytics and optimisation, 3.) structured data gathering and sharing, and 4.) connected technologies. Furthermore, the research suggests the use of an agile stage-gate model, as well as top-management commitment to mitigate potential barriers. Sjödin et al.'s (2018) research builds on six exploratory in-depth case studies with a total number of 31 interviews, conducted in five factories and one central department of two leading automotive companies. The maturity model offers an interesting perspective on the implementation of Industry 4.0, including some of the organisational aspects. However, since the data was collected in the automotive industry only, it is questionable whether the results are transferrable to other industries. The automotive industry in Germany is known as a very advanced industry, most often at the forefront of research and development. People, processes and the high-tech products of this industry might differ essentially from other industries. The research furthermore suffers from ambiguity regarding its unit of analysis. At one time it is stated that the “central technology development unit” was included in the data collection to provide broader insights and validate the “factory-level” findings of the remaining data. However, it is unclear if the research at the end is based on the factory level, the firm level, or even the industry level.

The research of Veile et al. (2020) offers new perspectives into “lessons learned” from Industry 4.0 implementation cases in German manufacturing companies. With the objective of providing managers with purposeful guidelines, the authors developed a new implementation framework. The framework refers to technical, organisational and human aspects, as well as their intersections in the implementation of Industry 4.0. The empirical data and the results of the data analysis offer interesting real-world insights into the practicalities of implementing Industry 4.0. However, the research seems to lack depth for the novel field of Industry 4.0 related research. Veile et al. (2020) highlight the use of an inductive research design that aims to answer how and why questions, however, they undertake their research rather shallowly by conducting 13 interviews in the context of a multiple case study with only one interview per firm. The complexity and richness of this new research field, however, potentially requires a deeper exploration such as done in single case studies to filter out the real mechanisms of the successful implementation of Industry 4.0 solutions. Furthermore, Veile et al. (2020) collected their data in spring 2016, which is, compared to the year of publication in 2020, a rather long time ago for this fast evolving research topic.

Different to the three before mentioned literature reviews of Liao et al. (2017), Strozzi et al. (2017), and Galati and Bigliardi (2019), the literature reviews of Hoyer et al. (2020) and Piccarozzi et al. (2018) focus more on the management perspective of the implementation of Industry 4.0. Piccarozzi et al. (2018) systematically review the existing Industry 4.0 literature in management studies to analyse and classify the main contributions that have been published so far in the management literature. The managerial literature on Industry 4.0 is still strongly affected by the technical aspects of the topic (Piccarozzi et al., 2018). The authors state, however, that this phenomenon appears quite predictable since Industry 4.0 is at an early stage and all previous industrial revolutions have also had their starting point within the engineering side of the firm (Piccarozzi et al., 2018). Overall, the implementation of Industry

4.0 from a strategic management and organisational perspective has so far been much under-researched and hence deserves attention in future under different profiles in management studies (Piccarozzi et al., 2018). The developed list of the 10 main principal issues in the research of Piccarozzi et al. (2018) (compare Table 4) shows how essential the organisational perspective is for the successful implementation of Industry 4.0. The few existing publications in the management field focus on specific topics around Industry 4.0, such as the impacts and changes in HR, sustainability, or social innovation (Piccarozzi et al., 2018). Nevertheless, none of the publications developed comprehensive approaches to Industry 4.0, which is very necessary for management studies according to Piccarozzi et al. (2018). The issue on strategy formulation is particularly important and at the same time heavily under-researched (Piccarozzi et al., 2018). The strategy literature on Industry 4.0 is at an early stage and existing papers in this field typically examine the presence and suitability of strategies for the successful development and application of Industry 4.0 in the firm only (Piccarozzi et al., 2018). Three examples of strategy literature on Industry 4.0 that Piccarozzi et al. (2018) provide are Wahl (2015), Basl (2017) and Lin et al. (2018b). However, so far present studies have not investigated if new approaches, skills, or capabilities, etc., may support the formulation of such strategies for successful Industry 4.0 implementation (Piccarozzi et al., 2018). In addition to the need of strategy formulation is the issue about HR management, which is of crucial importance for the success of Industry 4.0 implementation projects and hence the accomplishment of the expected performance improvements of the firm (Piccarozzi et al., 2018). Publications that focus on HR management in relation to Industry 4.0 all support the opinion that a closer observation of the expected role changes of employees is required (Piccarozzi et al., 2018).

Hoyer et al. (2020) developed a systematic literature review analysing the key factors of the implementation of Industry 4.0. The authors identified and discussed fourteen factors that potentially influence the implementation. These factors refer to political support, IT standardisation and security, corporate and institutional cooperation, cost assessment and available funding options, available knowledge and education, pressure to adapt, perceived implementation benefits, strategic consideration, IT infrastructure maturity, internal knowledge and skills development, lean manufacturing experience, occupational health and safety, variations on the industry sector, and company size. The findings of the study offer a perspective into the large list of different publications thematising each of the mentioned factors. Hoyer et al. (2020) explain their choice of using systems thinking for the identification of the key factors to form the research as comprehensively as possible. The authors continue by highlighting the complex nature of Industry 4.0, further justifying the need to apply systems thinking. The literature review of Hoyer et al. (2020) demonstrates that most of the research approaches of other studies about the implementation of Industry 4.0 can be classified as literature reviews, and secondly as surveys. Only a few articles applied a qualitative research approach, and again less were based on explorative case studies. This result supports the understanding regarding a gap in the literature on explorative qualitative research that produces in-depth insights about real implementation cases. The authors themselves highlight the need for further research to develop better frameworks for the implementation of Industry 4.0. The three mentioned literature reviews from the "technical" side, as well as the two literature reviews from the "organisational" side, are illustrated with their main findings in Table 4.

<table>
<tr><th>Liao et al. (2017)</th><th>Strozzi et al. (2017)</th><th>Piccarozzi et al. (2018)</th><th>Galati et al. (2019)</th><th>Hoyer et al. (2020)</th></tr>
<tr><td rowspan="2">Standardisation and reference architecture</td><td rowspan="3">Manufacturing- monitoring and scheduling</td><td>Production Method</td><td rowspan="3">Business</td><td>Political Support</td></tr>
<tr><td>Business model</td><td>IT standardization and security</td></tr>
<tr><td>Managing complex systems</td><td>Strategy</td><td>Corporate and institutional cooperation</td></tr>
<tr><td rowspan="2">A comprehensive broadband infrastructure for industry</td><td rowspan="3">Smart Factory from a political and economic perspective</td><td>Impacts and consequences</td><td rowspan="3">Operations</td><td>Cost assessment and available funding options</td></tr>
<tr><td>Human resources</td><td>Available knowledge and education</td></tr>
<tr><td>Safety and security</td><td>SMEs</td><td>Pressure to adapt</td></tr>
<tr><td rowspan="2">Work organisation and design</td><td rowspan="3">Demonstration and research test beds for Smart Factory technologies</td><td>Supply chain</td><td rowspan="3">Technological solutions</td><td>Perceived implementation benefits</td></tr>
<tr><td>Sustainability</td><td>Strategic consideration</td></tr>
<tr><td rowspan="2">Training and continuing professional development</td><td>Information system</td><td>IT infrastructure maturity</td></tr>
<tr><td></td><td>Social innovation</td><td rowspan="3">Work and Skills</td><td>Internal knowledge and skills development</td></tr>
<tr><td>Regulatory framework</td><td></td><td></td><td>Lean manufacturing experience</td></tr>
<tr><td>Resource efficiency</td><td></td><td></td><td>Occupational health and safety</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Industry sector</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Company size</td></tr>
</table>

Table 4: Thematic comparison of recent literature reviews

2.4.5 Gaps in the literature

The key literature of this thesis points to a clear research gap in the implementation of Industry 4.0. Buer et al. (2018), for example, suggest further research in developing a new implementation framework that acknowledges both Industry 4.0 and lean manufacturing integration. The impacts of Industry 4.0 on the "soft side" of lean management practices need further investigation. Furthermore, empirical studies are required to analyse the actual performance benefits of an Industry 4.0 and lean manufacturing implementation framework (Buer et al., 2018). Also, Tortorella and Fettermann (2018) argue that further research is required on developing solutions regarding the integration of Industry 4.0 into existing production systems such as lean management. Moeuf et al. (2018) argue that the implementation of Industry 4.0 as well as its impact on the internal processes need to further be studied. Current research on Industry 4.0 mainly focuses on the development and the validation of technologies only. Hence, there is a clear need for investigations into the exploration of paths and methods for the implementation on Industry 4.0 (Moeuf et al., 2018). Furthermore, the few existing implementation processes of Industry 4.0 technologies are not clearly described, at least in the context of SMEs (Moeuf et al., 2018). The authors suggest taking a careful look at real implementation cases as well as their success. In this sense qualitative research is required to clarify the real advantages that firms receive as well as if Industry 4.0 can result in benefits other than flexibility only (Moeuf et al., 2018).

Frank et al. (2019) further highlight the lack of understanding of how companies can successfully implement Industry 4.0. For further research the authors suggest comparing their implementation framework, which presents empirical evidence from the industrial sector, with the work of other authors that mostly build on theoretical assumptions only. Furthermore, there is extensive uncertainty about technology requirements for the implementation, as well as about the benefits that Industry 4.0 generates (Frank et al., 2019). The whole field about the relationship between Industry 4.0 and firm performance at the firm level, in terms of real evidence, may be a very interesting avenue for future research (Frank et al., 2019). Frank et al. (2019) also mention the possibility to extend their findings to other industries and to collect more empirical evidence to validate such an extension. Also, Schumacher et al. (2016) highlight the need to better prepare manufacturing firms in their evaluation and organisation of Industry 4.0 Implementation projects. Based on the findings and the developed maturity model, Schumacher et al. (2016) suggest further research in more domain specific assessments of Industry 4.0 maturity. The authors themselves plan more investigations into implementation projects in the automotive industry (Schumacher et al., 2016). Sjödin et al. (2018) join the line of academic research that highlights the point of view that companies face immense challenges in implementing Industry 4.0. The large-scale and systemic transformation that Industry 4.0 implementation requires, as well as how firms can possibly handle this task, needs to be further researched deeply (Sjödin et al., 2018).

Piccarozzi et al. (2018) suggest that Industry 4.0 implementation does not necessarily need to follow a top-down path only. Instead, leaving space for bottom-up innovation may result in the vital emergence of new organisational relationships and the redesign of organisational structures. Furthermore, it is suggested to investigate the topic as in-depth studies based on empirical methods enabling the discovery of the real relationships and interplays between the different issues that may influence the firm management in its decision-making, as well as the comprehensive impact of the issues on the firm performances. Additionally, the weaknesses and threats of Industry 4.0 implementation need to be identified and analysed, and potential solutions to overcome them need to be suggested (Piccarozzi et al., 2018). As mentioned in the previous section, the literature review of Hoyer et al. (2020) demonstrates that most of the research approaches of exiting articles about the implementation of Industry 4.0 can be classified as literature reviews or surveys. Only a few articles apply a qualitative research approach, which leaves a great gap in the literature on explorative qualitative research that produces in-depth insights about real implementation cases. The authors themselves further highlight the need to develop better frameworks for the implementation of Industry 4.0. The major research gap that Veile et al. (2020) open up is the lack of depth and exploration in answering their inductive how and why questions regarding the implementation of Industry 4.0. Although the results offer interesting insights into many aspects of the implementation, the research raises questions in regard of the implementation of Industry 4.0 (such as about the adaptability of the organisation), which was mentioned at the beginning of the study. Veile et al. (2020) also highlight that existing research so far lacks comprehensiveness as well as systematic approaches to build knowledge on the implementation of Industry 4.0. There is a general lack of knowledge in management research as well as in corporate practice about a purposeful and successful implementation of Industry 4.0 (Veile et al., 2020).

Additional perspectives from scholars other than the ones of the key literature refer to similar research needs. Cordeiro et al. (2019), for example, highlight the strategic and operational turbulence that companies experience in implementation project, due to the lack of understanding of the complex nature of Industry 4.0. The authors suggest the promotion of more detailed empirical studies on each stage of Industry 4.0 implementation as well as the development of a tool to measure the maturity of manufacturing firms. There is the need for further knowledge about the required steps for successful Industry 4.0 implementation (Cordeiro et al., 2019). Furthermore, it is suggested to test the six implementation steps developed in the research in real projects (Cordeiro et al., 2019). Mohelska and Sokolova (2018) point out that the Industry 4.0 literature most often discusses the technical aspects of the concept only, leaving a research gap about the managerial approaches or organisational culture perspectives that effect an implementation project. Manufacturing firms still lack their own Industry 4.0 strategy and they have not assigned responsible personnel to take care of changing this status (Mohelska and Sokolova, 2018). Further research is required in the field of managerial approaches to support the innovative environments to effectively implement and operate the Industry 4.0 concept (Mohelska and Sokolova, 2018). In addition, Whysall et al. (2019) highlight the lack of existing research or theory addressing the talent management challenges of Industry 4.0 implementation. The speed of technological change created a significant gap between the capabilities of employees and the requirements of their roles (Whysall et al., 2019). Hence, this issue needs to be a subject of further investigation leading to practicable results.

Since Industry 4.0 is a fragmented ground it needs to be explored how firms can implement Industry 4.0 in a way that leads to actual value creation (Acatech, 2016b). The chain of academics highlighting the research gap about Industry 4.0 implementation does not seems to decrease. Examples are further provided by Pagnon (2017), who calls for investigations to determine the most efficient process for transforming incumbent firms into the Industry 4.0 concept, or Petrovic and Leksell (2017), who request research about Industry 4.0 implementation in other industries than the automotive one. Xu et al. (2018) also highlight the growing demand for research regarding Industry 4.0 and its implementation and management. Odważny et al. (2018) state that firms are challenged by the evolutionary nature of Industry 4.0 implementation and its complexity, and Kolberg et al. (2017) refer to existing architectures for implementing Industry 4.0, but criticise the mostly high-level approach these architectures present. In the perspective of Kolberg et al. (2017) current research focuses too much on a technology point of view, neglecting the importance of the organisational aspects and HR point of view. Strozzi et al. (2017) specifically highlight that the organisational aspects of the implementation have been rather neglected so far. Papers have begun to focus on managerial aspects and response to changing requirements, however, at a conceptual level only (Strozzi et al., 2017). The authors suggest deepening the study of the organisational impacts, change management and research about the integration of HR management in the context of Industry 4.0 (Strozzi et al., 2017). Actual testbeds and lessons learned are rarely described and discussed in the literature. Hence, Strozzi et al. (2017) suggest case studies as beneficial contributions to shed some light on the ways in which Industry 4.0 is and can be implemented in reality.

Also, Yin et al. (2018) suggest rigorous, deep, and insightful case studies to explain how to create, manage, operate and maintain Industry 4.0. Madsen (2019) continues the identification of research gaps by arguing that presently only little systematic research is available on the effects and merits of Industry 4.0 implementation as well as about what impact the concept has on the firm. Researchers could collect primary data, using, for example, interviews, to map the diffusion of the concept (Madsen, 2019). Mapping out the diffusion process that unfolds over time is necessary since the field of Industry 4.0 is relatively new and is currently rapidly expanding (Madsen, 2019). Madsen (2019) highlights that especially interviews with key actors involved in the field may lead to a better understanding of the evolution of the concept.

2.4.6 Summary

The reviewed literature for this thesis points to a strong research gap in the implementation of Industry 4.0. Existing research mostly focusses on the technical aspects of implementation only. It is challenging to find qualitative empirical evidence which provides real insights about implementation cases. The literature highlights subjects such as strategic and operational turbulences, a lack of understanding of the complex nature, uncertainty about requirements, immense challenges, a lack of strategy, and a lack of theory, as this chapter demonstrated. There is evidence for a need for more comprehensive approaches on the implementation of Industry 4.0. Particularly the organisational aspects of the implementation have not been considered in depth yet. The existing literature highlights the need for detailed scientific studies and empirical evidence about the organisation of implementation projects, managerial approaches, the organisational culture perspective and the correct HR management of Industry 4.0 related implementation projects. Besides the mentioned differentiation between the technical and organisational aspects of the implementation of Industry 4.0, this thesis further argues to have stable lean management structures as the required enabler at the centre of Industry 4.0 implementation projects. The literature review developed an understanding that the technical implementation aspects as well as organisational implementation aspects of Industry 4.0 could surround a foundation of present lean management structures to enable better implementation results. The organisational aspects of the implementation thematise e.g. the management and organisational structure changes in the organisational system. The present literature calls for interviews and case studies to answer the open questions in the emerging environment of Industry 4.0.

2.4.7 Research questions

Existing literature strongly highlights the need of further research about the organisational aspects of the implementation of Industry 4.0. So far, most of the reviewed studies in the field focus on specific topics within Industry 4.0 only, or are of conceptual and/or technical basis only. Research providing a holistic overview of the organisational aspects of the implementation of Industry 4.0 could not be found. Exploring this research gap in an explorative and qualitative way contributes to the frequently stated demand to deliver empirical knowledge about the implementation of Industry 4.0. Therefore, with the objective of closing this research gap, the research questions of this thesis are as following:

RQ1: How does a high value German manufacturing firm organise the implementation of Industry 4.0 at the firm level?

RQ2: Why does a high value German manufacturing firm organise the implementation of Industry 4.0 at the firm level as they do?

2.5 Theoretical lens

The aim of this thesis is to examine how the implementation of Industry 4.0 is organised by discussing the case of a high value German manufacturing company. The research questions hence refer to how a firm implemented Industry 4.0, as well as why this firm implemented Industry 4.0 in this particular way. This section examines the chosen theoretical lens for this thesis. In search for the right lens several different theories have been analysed, such as Transaction Cost Economics (TCE), Structuration Theory, Loose Coupling, and Complex Adaptive Systems. Transaction Cost Economics are the costs of running the economic system and making economic trades. Firms that facilitate low transaction costs increase economic growth and gain competitive advantage in terms of efficiency. TCE as a lens for this thesis would have supported the understanding of buying and selling transactions, i.e. the analysis of a potential make-or-buy decision in the pre-implementation phase of Industry 4.0. Structuration Theory on the other hand was evaluated as a potential lens for this thesis in order to analyse the influences of present structures on the implementation of Industry 4.0 and vice versa. As Giddens proposed, social structure is not independent of agency, nor is agency independent of structure. Therefore, existing structures and new subjects influence each other. Loose Coupling Theory describes systems which have limited or fragile variables in common. The idea of applying Loose Coupling as a lens for this thesis emerged from the believe that through the implementation of Industry 4.0 an interesting duality of loose and tight couplings could emerge and be analysed.

However, a more comprehensive approach seemed to be most appropriate to understand the complex relationships and underlying mechanisms of the implementation of Industry 4.0 in the organisational context. Several recent studies have referred to and confirmed the complex nature of Industry 4.0, as well as the complex challenges of its implementation (DFKI, 2011; Kagermann *et al.*, 2013; Bauer *et al.*, 2014; Petrovic and Leksell, 2017; Tuptuk and Hailes, 2018; Lin *et al.*, 2018a; Moeuf *et al.*, 2018; Odważny *et al.*, 2018; Cordeiro *et al.*, 2019; Madsen, 2019; Veile *et al.*, 2020). Hoyer et al. (2020) furthermore compared the specific characteristics of complexity with the concept of Industry 4.0 and concluded in defining the implementation of Industry 4.0 as a complex system. Exploring the single factors in complex environments is necessary, however, exploring their relationships in a comprehensive manner potentially leads to a better understanding of the complexity in focus. Hoyer et al. (2020) highlight this need for change of perspective and refer to a study of Staufen AG and Staufen Digital Neonex GmbH (2019) that identified that only very few practitioners undertake a holistic approach towards the implementation of Industry 4.0, which in turn leaves a great additional research gap for this thesis. Systems Theory represents one related opportunity that can offer such comprehensive exploration of the relevant implementation factors and their inter-relationships. A systems perspective consequently seems to yield great potential to arrive at significant contributions for this thesis. Thus, Complex Adaptive Systems Theory (CAS) was chosen as the theoretical lens for this thesis. CAS is expected to hold significant potential to address the detected research gap in a comprehensive manner and to add important insights to the limited existing knowledge about the organisational aspects of real implementation cases of Industry 4.0. Therefore, the reminder of this section will examine the key aspects of CAS, including some aspects of general systems theory at the beginning.

2.5.1 An overview of systems theory

The origin of the explicit scientific discussion on systems theory can be traced back to Bertalanffy (1951) and his article on general systems theory. However, the problems which are today analysed as "systems" have potentially already been recognised for centuries, but only discussed with the language available at that time (Bertalanffy, 1972). Systems theory has as well a wide range of roots in different disciplines such as philosophy, natural sciences, engineering, psychology and sociology (Kleve, 2010). From the philosophical perspective it is argued that systems theory and systems thinking originated from the Greek philosopher Aristoteles and his assumption that "the whole is greater than the sum of its parts" (Bertalanffy, 1972; Kleve, 2010). The biological perspective made plausible that the understanding of living organisms requires more than the analysis of its single components. Identically to general systems theory, the biological perspective argues that for understanding living organisms (systems) it requires the analysis of the relationships between the single components (organs), their individual function for the organism, and the exchange of the organism and its components with the environment (Kleve, 2010). The roots of systems theory in engineering emerged from cybernetics (Kleve, 2010), which describes scientific research on control and communication (Wiener, 1948). The psychological roots of systems theory can be found in the analysis of correlations between individual behaviour and social relationships (Kleve, 2010). Systems theory in sociology analyses the interactions of human beings and the framework where this interaction happens (Kleve, 2010). The sociological perspective does not analyse the individual human being itself (Kleve, 2010).

Early ideas of systems thinking applied specifically in the field of innovation research have been published in Jantsch (1947) and Jones (1962) in the context of education, as well as in Morton (1967) and Gray (1981) in the context of business. Different studies that utilised systems theory explicitly to understand organisations have been detected by Dekkers (2015). Examples are Beer (1959) and Beer (1966) who analysed the viable system model, Forrester (1961) who analysed system dynamics, Checkland (1981) who analysed soft systems methodology, Nelson and Winter (1982) who analysed evolutionary approaches, Ulrich (1983) who analysed critical systems thinking, Schwanninger (2001) who analysed management cybernetics, and Dekkers (2005) who analysed the allopoietic systems view on organisations. Systems theory in the social sciences has been formed e.g. by Parsons (1970) and Luhmann (1984). They developed a theoretical focus on the difference between a system and its environment, replacing the focus on the relationship between the whole and its parts. Accordingly, providing clear context awareness, in terms of the differentiation of a system and its environment, is essential for the definition of a system (Vester, 2000). Systems theory developed by researchers from the social sciences may best suit research on organisational phenomena and innovation. Organisational phenomena and innovation focus on the analysis of peoples' interaction in organisational processes, the awareness of present structures and the influencing factors surrounding the phenomena. Some of the present perspectives of systems theory in social sciences with a particular focus on innovation research are, for example, Galanakis (2006), who analyses innovation processes, Hekkert et al. (2007), who analyses innovation systems and technological change, as well as Akgün et al. (2014), who analyse product innovation using Complex Adaptive Systems Theory. Industry 4.0 implementation is defined as a management innovation in the context of this thesis. Systems theory in this context can support the understanding of organisational innovation as innovation research naturally strives for comprehensive approaches (Colapinto and Porlezza, 2013). Hence, it seems surprising that Colapinto and Porlezza (2013) detect the actual application of systems theory in this field as rare. This further underlines the potential of a systems perspective to unveil novel insights related to the implementation of Industry 4.0 as a management innovation.

2.5.2 Complex adaptive systems

Referring to McCarthy et al. (2006) the concept and study of Complex Adaptive Systems (CAS) originates in the life and physical sciences (Prigogine and Stengers, 1984; Kauffman, 1993; Gell-Mann, 1994; Kauffman, 1995), has been developed and used by the engineering sciences (Holland, 1995; Krothapalli and Deshmukh, 1999; Frizelle and Suhov, 2001), and has been discussed significantly by the social sciences in areas such as strategic organisational design (Brown and Eisenhardt, 1998; Anderson, 1999; Dooley and van de Ven, 1999; McKelvey, 1999; Eisenhardt and Bhatia, 2002), supply chain management (Choi et al., 2001), and innovation management (Buijs, 2003; Cunha and Comes, 2003; Chiva-Gomez, 2004). Research on CAS is less interested in examining the complicatedness or complexity of systems (Anderson, 1999; Morel and Ramanujam, 1999; McCarthy, 2004), but focusses more on the systems' learning capabilities as well as how they create new rules, structures and behaviours (McCarthy et al., 2006). Especially for systems with a higher nature of exploration and innovation are these characteristics of importance.

A system in general consists of two or more components which together produce, from one or more inputs, one or more results that could not be produced from the components individually (Grieves and Vickers, 2017). A system can be seen as a set of elements with attributes that are connected by relationships to each other and to their environment to form a whole (Schoderbek et al., 1985). Systems can be categorised into simple systems, complicated systems, chaotic systems and complex systems. Simple systems are transparent and predictable. The actions performed on the inputs of the system are obvious, just as the outputs of the system. Complicated systems are predictable too. Just as in simple systems, the inputs and the resulting outputs of the system are well known. The only difference from simple systems is the component count. An example of a complicated system could be a mechanical watch or many other complicated mechanical machines. The connection between components in complicated systems is linear. Linear interactions are those in expected and familiar sequence, which are visible even if unplanned (Perrow, 1984). It is possible to reduce a complicated system to its constituent elements to understand, to model and to reproduce these systems. Chaotic systems on the other hand are not linear, but rather unstructured and loosely coupled, which leads to outcomes that appear random and disorganised (McCarthy et al., 2006). Complex systems are usually larger networks of components with many-to-many communication channels. They host a considerable level of uncertainty (Hazy, 2017) due to interactions of unfamiliar, unplanned and unexpected sequences, which are not visible or not immediately comprehensible (Perrow, 1984). These systems are difficult to predict due to their sophisticated information processing (Mitchell, 2009) and the potential of surprise, which often lead to unwanted outcomes (Grieves and Vickers, 2017). As several recent studies have highlighted (Kagermann *et al.*, 2013; Moeuf *et al.*, 2018; Veile *et al.*, 2020) Industry 4.0 and the challenges of its implementation are considered to be highly complex and can thus be regarded as a complex system (Hoyer *et al.*, 2020).

Complex Adaptive Systems (CAS) are an advanced form of complex systems. CAS are recognised due to their core attributes of “nonlinearity”, “self-organisation”, and “emergence”. In other words, the important difference that distinguishes CAS from the above mentioned forms of systems is the ability to adapt (McCarthy et al., 2006). CAS are systems in which elements (agents) have the ability to change their individual attributes and interactions to develop new system configurations, behaviours and corresponding levels of order or disorder (Schoderbek et al., 1985; Gell-Mann, 1994; Holland, 1995; Dooley, 1997). The relationships and types of interactions between the agents of CAS differ from those of linear or non-linear chaotic systems (McCarthy et al., 2006). In linear systems relationships are structured and tightly coupled, which results in higher predictability and efficiency but lower adaptability (Eisenhardt and Bhatia, 2002). In non-linear chaotic systems relationships are unstructured and loosely coupled, which gives an impression of unplanned and disorganised results which cannot be adapted by the system (McCarthy et al., 2006). The nature of the relationships and interactions of the elements in CAS are a mixture of both the linear and the chaotic system relationship types (McCarthy et al., 2006). Their elements are only to some extent connected and hence produce “semi structured” (Brown and Eisenhardt, 1997) behaviours and outcomes that are neither fully controlled nor fully random, which may be a suitable way to describe complex implementation processes in organisations in general and the implementation of Industry 4.0 in particular. Nevertheless, complex systems would typically consist of non-linear ($1+1 \neq 2$) interactions and more loosely coupled connections (Perrow, 1984). As McCarthy et al. (2006) stated by referring to Kauffman (1993), CAS produce system behaviours that lie between order and chaos, which in turn leads to system adaptability (the edge of chaos).

Nonlinearity can occur at multiple levels between single agents or groups of agents. It triggers self-organisation and emergence in systems which together lead to changing system behaviours from linear and chaotic states (McCarthy et al., 2006). Self-organisation is an increase of order and regularity in a process (Foerster, 1960), not directed from an external or central power, but arising from the autonomous behaviours of the individual agents in a process (Maturana and Varela, 1980). The concept of autopoiesis in this sense influenced the development of CAS. Autopoiesis describes the ability of self-creation and reproduction of a system, such as known from explaining the nature of cells and organisms in living systems (Dekkers, 2015). An autopoietic system is an autonomous and self-maintaining system with the ability to let system structures emerge in order to fulfil a specific function or purpose (Dekkers, 2015). Self-organisation in CAS is not affected by the absence or presence of formal control rules, however, it arises when a process independently adapts and develops new configurations and behaviours. Self-organisation requires the systems' agents to be "partially connected". A tight or too loose connection would harm the emergency of self-organisation. Tight couplings lead to rather inflexible processes, whereas fully unstructured and hence too loose couplings lead to instabilities and issues in building new process configurations and behaviours.

Emergence is the product of self-organisation. It arises when a process is able to generate new behaviours, triggered for example through tolerating experimentation, rule breaking and exploratory actions. As McCarthy et al. (2006) describes, emergence is the appearance of new process characteristics due to the collective behaviour of the agents constituting the process. It is not the result of a single agent with changing behaviour (McCarthy et al., 2006). Nonlinearity, self-organisation and emergence hence form the basis of adaptability in Complex Adaptive Systems (Stacey, 1995; Morel and Ramanujam, 1999; Dooley and van de Ven, 1999; Anderson, 1999; Choi et al., 2001; McCarthy, 2004). They are the causes as well as the characteristics of adaptability in systems (McCarthy et al., 2006). The quantity, identity and the interactions of the agents in a system regulate the potential appearance of nonlinearity, self-organisation and emergence. As the behaviour of a CAS as a whole is different from the sum of the behaviours of its individual agents ($1+1\neq2$), the difference between CAS and linear complicated systems is that its resulting behaviours resist reductionism (analysing and describing phenomena in their single elements) and hence reproducibility (McCarthy et al., 2006). Controlling and strategically influencing a CAS is challenging as the system as a whole sometimes produces behaviours and results inconsistent with the rules imposed on the system beforehand. The process of sensemaking of the complexities of Industry 4.0 and its implementation in a German manufacturing firm is considered as nonlinear, especially for early adopters of this change.

The agents in the CAS as well as the CAS itself are furthermore affected by different internal and external influence factors, i.e. their environment. The environment of the CAS refers to neighbouring systems or elements whose changes in attributes have an effect on the system in focus (McCarthy et al., 2006). Influence factors can e.g. be existing organisational structures, actions of other agents and self-directed decision making. A resulting behaviour of the agents is to begin to experiment with these influence factors by selecting and rejecting both structures and option space and thereby consequently produce again by their collective dynamic nonlinearity, self-organisation, and emergence in the system. Andrus (2005) developed a framework that visualises an example of a CAS which may clarifies such system structures. The framework is presented in Figure 5.

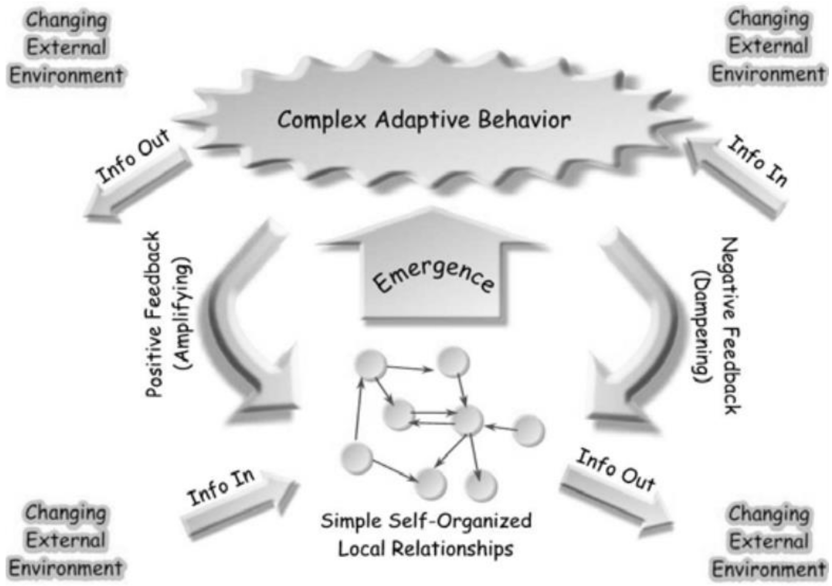


Figure 5: Example of a Complex Adaptive System
Source: Andrus (2005)

2.6 Conclusion

The literature overwhelmingly agrees that the implementation of Industry 4.0 leads to the creation of value (Acatech, 2013; Westerlund *et al.*, 2014; Bauer *et al.*, 2014; Bauernhansl, 2015; Burmeister *et al.*, 2016; Kiel *et al.*, 2017; Moeuf *et al.*, 2018; Buer *et al.*, 2018; Kusiak, 2018). However, the potential value creation depends on how successfully firms are able to implement these new technologies. As demonstrated in this chapter, academics and practitioners continuously refer to a clear knowledge gap regarding the implementation of Industry 4.0 (Acatech, 2016b; Strozzi et al., 2017; Moeuf et al., 2018). A particular research gap exists in the organisational aspects of the implementation of Industry 4.0. The risk of failing the implementation challenges firms as this would potentially lead to a worse return on investment and loss of competitive advantage. Therefore, the aim of this thesis is to examine the corporate organisation of the implementation of Industry 4.0 in a high value German manufacturing company. The research questions hence refer to how a high value manufacturing firm implements Industry 4.0, as well as why they implemented it as they did, beyond the factory level. The unit of analysis is therefore the firm level. The exploration of complex environments such as Industry 4.0 may require comprehensive approaches to research (Piccarozzi et al., 2018; Staufen AG and Staufen Digital Neonex GmbH, 2019; Hoyer et al., 2020). The higher complexity that the implementation of Industry 4.0 incarnates has been confirmed by several recent studies (DFKI, 2011; Kagermann *et al.*, 2013; Bauer *et al.*, 2014; Petrovic and Leksell, 2017; Tuptuk and Hailes, 2018; Lin *et al.*, 2018a; Moeuf *et al.*, 2018; Odważny *et al.*, 2018; Cordeiro *et al.*, 2019; Madsen, 2019; Veile *et al.*, 2020). Systems theory is one related opportunity that may offer the required comprehensiveness by including the relationships between systems elements, which potentially leads to a beneficial scientific exploration of the organisational aspects of the implementation of Industry 4.0. Therefore, a theoretical lens of Complex Adaptive Systems is chosen for this thesis.

The combination of the systems thought with the notion of complexity theory makes CAS especially suitable to describe real-world problems (Dekkers, 2015), i.e. to address the research objectives of this thesis. The implementation of Industry 4.0 is furthermore considered and cited various times as a disruptive change for manufacturing firms. This disruption requires organisational systems to adapt, which means that actors and the organisational structure may need to change. This change may be analysed through a more comprehensive approach to understand the connections and dependencies of the actions and behaviours that result from the system. Complex Adaptive System Theory captures significant potential to address the detected research gap of this thesis, not only by offering the required comprehensiveness but also by capturing adaptability i.e. “self-organisation”, “emergence” and “nonlinearity” in the centre of the theory. Overall, it is expected that CAS as a theoretical lens for this research project can add significant value to the present knowledge about the implementation of Industry 4.0. Research on CAS focusses on a systems’ learning capabilities as well as how they create new rules, structures and behaviours (McCarthy et al., 2006). These characteristics are especially import for systems with a higher nature of exploration and innovation, as is the case for the implementation of Industry 4.0.

The developed perspective on the corporate implementation of Industry 4.0 as a CAS captures actors, actions, characteristics, relationships, and internal- as well as external influences. Actors and their characteristics are structured in so called “self-organising local relationships”. A system may host more than one self-organising local relationship (n > 1). The actors of the system are the employees and managers of the firm. Each actor owns certain characteristics, such as “skills and competences”, “resistance”, “motivation” and “commitment”. The relationships are the interactions that connect the actors of a system. Actors are partially connected and have the capacity for autonomous decision making and social action in the “self-organising local relationship”. They furthermore are able to receive and to process information, as well as to respond according to their personal rules and connections to other agents. Responses may be self-directed, meaning that actors can respond in an independent way from sensing changes in circumstances. The actors’ characteristics originate from past experiences and continuously develop through new experiences.

From the self-organising local relationships actions emerge, or in other words “complex adaptive behaviour”. These complex adaptive behaviours can e.g. be “initiation of organisational structure changes”, “initiation of personnel changes”, or “cultural changes”. All actions have feedback loops to the “self-organising local relationship” from which the action originated. The feedback loops influence future emergence from the “self-organising local relationship” and thereby close the cycle of the CAS. Last but not least, the CAS is affected by its environment, i.e. internal and external influences. The environment is defined as neighbouring systems or actors whose changes in characteristics have an effect on the system in focus. Internal influences may, for example, be present in organisational structures such as the presence of lean manufacturing, present corporate culture, and available resources such as time and money. Taking the characteristics and relationships of all actors as a whole is what governs the behaviour of the system and hence the performance of the implementation of Industry 4.0 in the firm. It is assumed that organisations implementing Industry 4.0 show a complex behaviour that emerges and self-organises throughout the implementation process.

The choice of CAS as the theoretical lens for this thesis provides the required flexibility and space for the exploration and sense making of the implementation of Industry 4.0 in the complex corporate environment. It is assumed that CAS theory supports the understanding of the implementation as a living system that co-evolves in its dynamic corporate environment. The patterns of behaviour and action that emerge throughout an implementation process are brought into relation with the characteristics of actors and the dynamics of the systems environment. A challenge in researching the complex implementation patterns may appear through the decision of studying narrow subjects in-depth or acknowledging influential relationships between these subjects. The application of CAS may lead to insights into influential mechanisms that interrelate with the implementation outcomes. Overall, applying CAS as a lens in this thesis provides a comprehensive base for further structuring the exploration and analysis of the organisational aspects of the implementation of Industry 4.0 in organisational systems. The research framework of this thesis is illustrated in Figure 6. Figure 6 captures the so far generated understanding of the implementation as a Complex Adaptive System and will in the remainder of this thesis be filled with the generated knowledge from the data collection and data analysis.

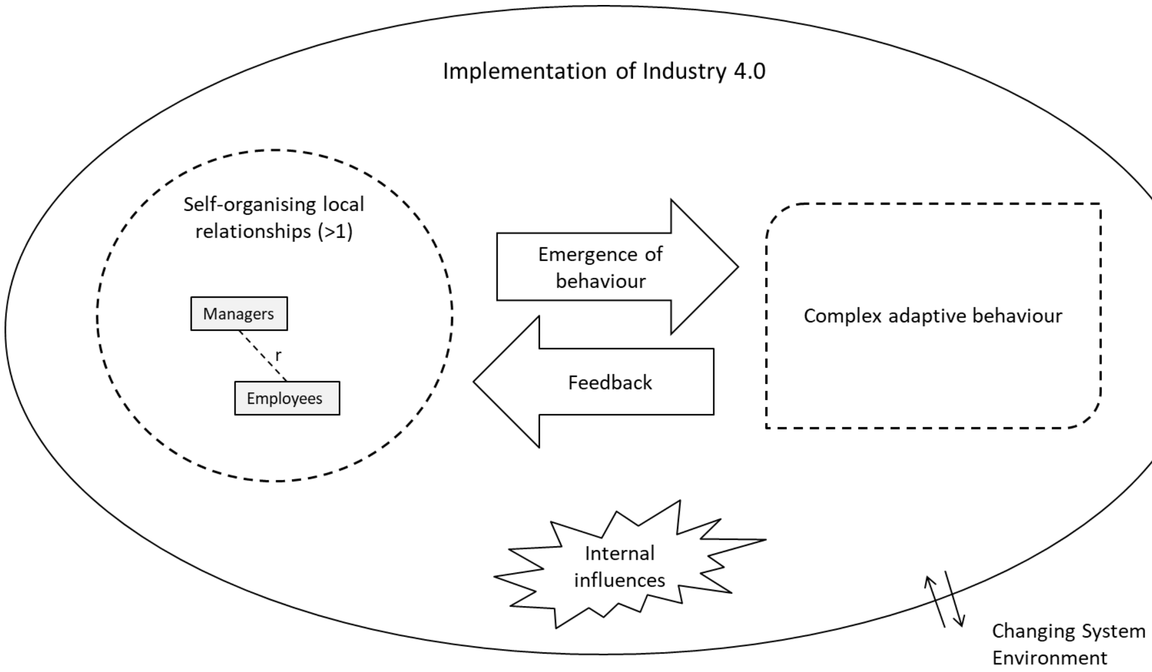


Figure 6: Research framework

Chapter 3. Methodology

3.1 Introduction

The review of the literature in Chapter 2 of this thesis indicates a clear research gap regarding the organisational aspects of the implementation of Industry 4.0 in manufacturing firms. The academic debate suggests therefore further research in the field to clarify this missing component. In this respect, methodological decisions are required that address the research objective and support to answers the research questions of this thesis. To achieve this goal and to answer the "how" and "why" research questions of this thesis, a qualitative empirical research design was chosen that offers an explorative and in-depth understanding of the phenomenon rather than a quantitative approach intended more at statistical generalisability (Patton, 1990). The use of a qualitative research strategy is particularly appropriate since research on the organisational aspects of the implementation of Industry 4.0 is at an early stage and comprehensive and systematic investigations are rare (Silverman, 2009). Qualitative approaches are recommended to be used in novel, complex, and evolving real world environments (Yin, 2009), which is the case for the exploration of the implementation of Industry 4.0 in an organisational system (Veile et al., 2020). This chapter introduces and explains the methodological choices made to answer the research questions of this thesis. It describes the researcher's philosophical position, the research approach and design as well as the process of data collection and data analysis, which are illustrated in Table 5.

Research Philosophy	Research Approach	Methodological Choice	Strategy	Time-Horizon	Technique / Procedure
Ontology / Epistemolo. Critical Realism	**Inductive Approach**	**Mono-Method**	**Case Study**	**Cross-Sectional**	**Data Collection** Interviews **Data Analysis** Thematic Analysis

Table 5: Methodological structure and choices

3.2 Research philosophy

The research philosophy of this thesis represents the researcher's ontological and epistemological position. In this sense, the ontological position represents the researcher's assumption on the nature of reality, whereas the epistemological position represents the researcher's assumption on how knowledge is created. An interpretive position is furthermore based on the assumption that knowledge of reality is a social construction by human actors (Walsham, 1993). This perspective defines, in contrast with positivistic positions, that an objective reality which can be discovered and replicated by researchers does not exist. Interpretive studies see humans' perspectives as individual subjective meanings influenced and expressed in relation to their environment. Researchers with an interpretive position try to understand phenomena by measuring the related meanings of participating individuals (Orlikowski and Baroudi, 1991). The relevance of an interpretive perspective in this study emerges from the explorative character and the collection of data through interviews. Instead of using scientific measurements and numbers only, the author must delve deep into the phenomenon.

A philosophical position of critical realism (Bhaskar, 1989) is adopted in this thesis. Critical realism understands reality as an "open system of emergent entities" (O'Mahoney and Vincent, 2014). The interaction of different entities causes the events one can observe. The social world is influenced by continuously changing entities. Therefore, events cannot be understood in isolation from their surrounding entities. Critical realism has been developed as a philosophy of science mainly since Bhaskar published a series of books in the 1980s challenging interpretivism and positivism (Bhaskar, 1989). As a philosophy of science, critical realism is a meta-theory and not a testable body of ideas (O'Mahoney and Vincent, 2014). According to critical realists, reality is a result of social conditioning. If the structure, procedure or the process of social conditions change, reality may change too (Saunders et al., 2012). Researching social phenomena therefore requires considering the social structures that caused a phenomenon. Critical realism argues that real structures and phenomena exist in the world, even if humans were not present. However, social and political structures are created by humans and these structures need to be continually maintained. They only exist because of their constant reproduction. Studying the social world should generally not differ from studying the natural world. Both are real. Critical realism considers human consciousness as a natural phenomenon that emerges from matter over historical evolution. In other words, human consciousness is historically produced. When studying the social world in a critical way the researcher must only recognise the historical nature of their own consciousness. This so-called critical objectivity is what forms the critical realism perspective. Furthermore, critical realism makes a distinction between the "real" (social and/or natural facts that generate the actual world), the "empirical" (what we observe) and the "actual" (events that occur) level of reality (Sayer, 2004). Different from positivism and its deductive approaches, critical realism analyses the embedded mechanisms on which the reality depends (Saunders et al., 2012). It supports the position that there is a mind independent world that can be studied. However, critical realism sees the context of events as unstable.

Analysing the research gap utilising a critical realism perspective and its understanding of the reality as an open system of emergent entities offers the necessary space for the exploration of the organisational aspects of the implementation of Industry 4.0. As mentioned, this thesis divides the implementation of Industry 4.0 into the technical and the organisational aspects. The organisational aspects of the implementation of Industry 4.0 consist of the management of people and processes (the entities) that in the end cause the success of an implementation project (the event we can observe). Hence, also the benefits of the implementation of Industry 4.0 cannot be understood in isolation from its surrounding entities and the organisational aspects that critically affect the success of an implementation project. Successful implementation of Industry 4.0 requires taking the organisational aspects and hence the social structures into account that surround the implementation. The philosophical position of critical realism understands the interactive society as a shaper of the people's behaviour, it underlines that multiple entities may lead to new phenomena (emergence concept), and understands the cause behind social interactions. Critical realism analyses the embedded mechanisms on which the reality depends and thereby delivers the required foundation to address the research objective of this thesis, i.e. the exploration of the organisational aspects of the implementation of Industry 4.0.

3.3 Research approach

The most widespread distinction for research approaches lies between the deductive approach, which involves testing theory or hypothesis, and the inductive approach, which involves building theory or hypothesis (Saunders et al., 2012). Deductive approaches refer to developing a wanted theory from a more general source theory, i.e. the specific adaption of a theory. Inductive approaches refer to understanding the nature of a problem by analysing collected data, making sense of it and finally formulating a theory (Saunders et al., 2012). This thesis adopts an inductive research approach to explore the problem of how a manufacturing firm may implement Industry 4.0 focussing on the organisational aspects. In line with Eisenhardt and Graebner (2007), this thesis uses inductively analysed in-depth expert interviews. The theory of Complex Adaptive Systems is applied to support this exploration and to further structure the research process. Theory in general helps explaining patterns found in the real world. In natural as well as in social phenomena theory building supports the understanding of how things come to be as they are and how they function (Osterwalder, 2004). Central to theory building and to a theoretical contribution is the notion of understanding the "why" of a phenomenon in question (Whetten, 1989).

3.4 Research design

The research design clarifies the process of how the research project is conducted (Robson, 2002). The following will explain the chosen research strategy, methodological choices, the process of data collection and data analysis and the time horizon of the research project. The research design sets the structure of how to answer the research questions (Saunders et al., 2012).

3.4.1 Research strategy

The research strategy defines the process that enable addressing the research objective and answering the research questions (Saunders et al., 2012). It must be coherent with the philosophical position of the research and may be conducted in form of e.g. experiments, surveys or case-studies (Saunders et al., 2012). The choice of strategy for the course of this thesis is based on a case study, following Yin (2014). Case studies can be distinguished between single or multiple case studies and holistic or embedded case studies (Yin, 2014). For this thesis, a holistic single case study was chosen as the most promising research strategy. Case study approaches are a widespread strategy in qualitative research. Rather than testing theory, referring to deductive research, case study approaches are a strategy for inductive research with the aim of building theory. Case studies explore social phenomena within a specific context. However, a clear border between the subject to be studied and its context or environment is not necessarily present (Yin, 2014). Its real world context and the embeddedness in rich empirical data enables case study research to produce not only interesting, but also accurate and testable theory (Eisenhardt and Graebner, 2007). Case study research focusses on particular details and instances rather than on generalities. They are utilised, for example, for comparison, evaluation or process analysis reasons. The explorative nature of case studies enables the researcher to analyse unique single cases in an effective way (Simons, 2009). Case study research focusses on a comparable small number of cases but commits to conduct in-depth observation, reconstruction and analysis to understand a case fully. The approach is about action and not controlling the collection of qualitative data too tightly.

Research based on case studies is evaluated as one of the most interesting kinds of research to readers (Bartunek et al., 2006). Some of the papers are within the most cited ones in, for example, the Academy of Management Journal (e.g., Eisenhardt, 1989, Building Theories from Case Study Research, cited 57,030 times by 29th April 2020, 10:15 AM, according to google scholar). The advantage of case study research lies in the depth of the research. The full engagement with a subject matter leads most likely to a stronger appreciation for details and boundaries of the research conducted. The iterative development of research questions leads to truly original data and rich results. Case studies also require strictness. Careful and nuanced description of the cases is fundamentally important and part of the pre-investigations of research.

3.4.2 Methodological choice

According to Saunders et al. (2012), the methodological choice of research can be distinguished between qualitative, quantitative and multi methods designs. Research that basis on a philosophical position of critical realism most often aims to “understand” social phenomena rather than “describing” them (Vincent and O’Mahoney, 2017). Furthermore, research on the basis of critical realism often builds on case studies using techniques such as interviews for the data collection (Vincent and O’Mahoney, 2017). This thesis adopts a qualitative mono-method since the objective of the research refers to the exploration and understanding of the organisational aspects of the successful implementation of Industry 4.0.

3.4.3 Data collection

The methodological technique of data collection for this thesis is semi-structured expert interviews with managers and employees of one high value German machine manufacturing company. The interviews capture the empirical knowledge, behaviour and experiences about the successful implementation of Industry 4.0 in the firm (Denzin and Lincoln, 2003). Semi-structured interviews enable collecting data in a structured way, yet maintain an adequate and necessary level of openness to allow unexpected and novel knowledge to emerge (Yin, 2009). The German economy has been chosen due to its representative character for a developed and industrialised nation, its economic importance for the European Union, and particularly because of its advanced experience in the implementation of Industry 4.0 (Veile et al., 2020). The German machinery and plant industry is particularly suitable due to the large number of innovative organisations it contains, which places a strong impact on the world market that in turn makes Germany be a well-recognised export champion in technological solutions. Furthermore, the German machinery and plant industry invented the term Industry 4.0 (Industrie 4.0), which led to its adoption by the national high-tech strategy of the German government in 2013, as discussed in the review of the literature in Chapter 2 of this thesis. Many of the organisations that this industry contains in Germany are still family owned and rather medium sized compared to the really large all-rounders such as SIEMENS with about 393,000 employees and about 58.5 billion Euro turnover (Siemens AG, 2020).

Notwithstanding the sizes, many of the firms in the German machinery and plant industry lead the global innovation development in their specific field and are referred to as “hidden champions”. The targeted high value manufacturing firm of this thesis represents such an organisation of the German machinery and plant industry. BERTLEI is fully family-owned and considered as one of the leading organisations in their field. The firm employs about fifteen thousand people in more than 70 different operating subsidiaries around the world. BERTLEI was founded in the first quarter of the 20th century and generates a turnover of about 4 billion Euros (in 2019). The firm is present in many important markets and represents one of the largest machine suppliers worldwide. Production sites are located in Germany, China, Great

Britain, France, Italy, Japan, Mexico, Switzerland, Austria, Poland, Czech Republic and the USA. BERTLEI is considered as an early and advanced adopter of Industry 4.0 in statements of several articles in Germany, as well as a consensus agreement of experts from the field met at related trade fairs. In-depth discussions with academics from German universities located in the geographic location of the firm confirmed the very positive reputation of the firm in terms of the implementation of Industry 4.0. The firm was furthermore selected based on significant investments to support all Industry 4.0 related investigations, as well as due to its interest and commitment in securing access to appropriate interview participants. BERTLEI applies digital technologies throughout the whole value stream, which has positively impacted and strengthened the operational performance and socio-economic relevance of the firm (as the data will demonstrate in Chapter 4 of this thesis). As such, according to Lasi et al. (2014), BERTLEI is evaluated as an authentic "Industry 4.0" company, i.e. a firm that managed the implementation of Industry 4.0 successfully.

Access to data was prepared through several actions between 2018 and 2019. The first contact was conducted by attending a conference in Great Britain in February 2018 where the general manager of one British subsidiary of BERTLEI held a key speech about the implementation of Industry 4.0. After a longer conversation and lunch together, the manager agreed to build connections to colleagues from the headquarters in Germany who could potentially participate in the data collection and provide a central perspective on the topic. A few weeks after the conference, in April 2018, the attendance of the "Hannover Messe", one of the most important exhibitions on industrial production, provided the second platform to contact different actors at BERTLEI and exchange ideas as well as contact details. The Hannover Messe hosts about 5'000 exhibitors and welcomes about 220,000 visitors every year and hence represents an unusual grouping of expertise on industrial production and therefore the implementation of Industry 4.0. Attending the Hannover Messe had the positive side effect of comparing BERTLEI with other firms in the industry, leading to the further development of the belief that BERTLEI can be evaluated as an authentic "Industry 4.0" company in its industry. The third and most effective entry point to data collection at BERTLEI emerged from the attendance of a three-day conference on technology management and innovation in Germany in June 2018. BERTLEI functioned as one of the main sponsors of the conference and sent the head of the corporate research department to speak to the academic audience of the conference about BERTLEI's way of implementing Industry 4.0. A personal conversation with the head of the research department resulted in interest in the Ph.D. research topic and the exchange of contact details. A meeting was arranged a few months later in January 2019 at BERTLEI's headquarters in Germany to discuss the research topic more in detail, to get to know each other, and to speak about possible data collection. The participants of this meeting were the head of the research department, one additional R&D manager, one employee from the R&D department and the Ph.D. student. On the basis of consent about data collection, the managers connected to the first interview partner, who then connected to further interview partners to create a sort of snowball effect. The attendance of an in-house exhibition in Mach 2019 enabled the first physical interviews as well as the connection to additional future interview partners. Also, the participation of the following Hannover Messe in April 2019 led to a stronger connection and to more valuable interviews. The snowball effect of interest in participating in the data collection process for this thesis worked well, probably due to an overall open corporate communication culture and previous research experiences that was recognised during the interactions with the actors in the firm. The main actions of building the access to interview participants in the firm is visualised in Table 6.

Step No.	Action	Date
1	Industry 4.0 conference in Great Britain	2018 February
2	Hannover Messe in Germany	2018 April
3	Technology conference in Germany	2018 June
4	Meeting at head-quarter of BERTLEI in Germany	2019 January
5	In-house exhibition at BERTLEI in Germany	2019 Mach
6	Hannover Messe in Germany	2019 April

Table 6: Main steps of access to data

The theoretical sampling used for the interviews of this thesis ensured the continuous elaboration and refinement of the findings as well as the identified codes and themes in the data (Charmaz, 2006). Interview participants were selected on the basis of their relevance for the corporate implementation of Industry 4.0 and their potential contribution to a holistic exploration of the case. As this thesis explores the organisation of the implementation of Industry 4.0 in the corporate environment, all interview participants were involved in the organisation or execution of the implementation. Interviews were conducted either with managers or employees of the firm. Employees are defined as the people who are commissioned with value-adding activities. Value-adding activities are those for which a customer would be willing to pay. Employees could be shop floor workers as well as office staff or consultants, e.g. machine operators as well as software programmers. Managers refer to the group of people who are commissioned with organisational and management task. They do not directly perform value-adding activities but are responsible for the success of the corporate implementation of Industry 4.0. Managers, by the definition in this thesis, do not necessarily have authority over employees and must neither necessarily be part of the CEO board. An overview of background information about the interview participants is set out in Table 7.

New data from interviews continuously developed the researcher's understanding about the complex system of intertwined relationships regarding the implementation of Industry 4.0 at BERTLEI. Therefore, the interview questions continuously developed throughout the course of data collection to work through the defined topic of the research questions. An earlier and a later version of the conversation guide including the basic interview questions addressing the respective topic is attached as Appendix I and Appendix J of this thesis. The order of the interview questions may have varied depending on the course of each interview and allowed additional questions arising from the contexts of interviews if particularly interesting statements appeared (Saunders et al., 2012). In total, 35 semi-structured interviews of about 45 minutes on average were conducted either in person or via telephone. The interviews together led to 303 pages of transcripts. The 35th and last interview was conducted in July 2019 after it became increasingly apparent that saturation had been reached and additional data no longer led to greater theoretical insights (Charmaz, 2006). The resulting qualitative sample of interviews builds a deep exploration of the successful implementation of Industry 4.0 in the targeted high value German manufacturing firm. Full transcripts of all 35 interviews are provided in Annex 1 of this thesis.

No.	Participant	Professional position of the interview participant	Actor group	Gender
1	IP-02	Smart Factory Consultant	Employee	Male
2	IP-03	LEAN Management Expert and Project Coordinator	Manager	Male
3	IP-05	Business Development	Manager	Male
4	IP-06	Corporate Inhouse Consulting	Manager	Male
5	IP-07	Central Department for Digital Transformation	Manager	Female
6	IP-08	Engineering Industry 4.0	Employee	Male
7	IP-09	Consultant Digital Solutions	Employee	Male
8	IP-10	Smart Factory Consultant	Employee	Male
9	IP-11	Software Engineer	Employee	Male
10	IP-14	Product Manager	Manager	Male
11	IP-15	Customer Management and Sales	Manager	Female
12	IP-16	Smart Factory Consultant	Employee	Male
13	IP-17	Head of Smart Factory Consulting	Manager	Male
14	IP-18	Smart Factory Consultant	Employee	Male
15	IP-19	Project Manager	Manager	Male
16	IP-20	Smart Factory Consultant	Employee	Male
17	IP-22	Smart Factory Consultant	Employee	Male
18	IP-24	Investment Manager in the Corporate Venture Capital Firm	Manager	Male
19	IP-25	Product Owner Software Development	Manager	Female
20	IP-26	Smart Factory Consultant	Employee	Male
21	IP-27	Department for New Digital Business / After-Sales Services	Employee	Female
22	IP-28	Produkt Manager	Manager	Male
23	IP-29	Smart Factory Consultant	Employee	Male
24	IP-30	LEAN Management Expert	Manager	Male
25	IP-31	Product Owner in the Connectivity Department	Manager	Male
26	IP-32	Team Leader and Project Leader of Predictive Services	Manager	Female
27	IP-33	Product Owner	Manager	Male
28	IP-34	Business Development Manager	Manager	Male
29	IP-35	Development Department for Services	Manager	Male
30	IP-36	Product Manager for Software and Service Products	Manager	Female
31	IP-37	Product Manager in the Connectivity Department	Manager	Male
32	IP-38	Smart Factory Consultant	Employee	Male
33	IP-39	Program Manager for Digital Solutions	Manager	Male
34	IP-40	Central Department for Digital Transformation	Manager	Male
35	IP-41	Rollout Manager in the Central Dep. for D. Transform.	Manager	Female

Table 7: Background information on interview participants

3.4.4 Coding and analysis

The processes of data management, i.e. coding and analysis, were guided by the research questions of this thesis and the key variables of Complex Adaptive Systems Theory. The identified codes and themes in the data were continuously elaborated and refined while conducting the interviews (Charmaz, 2006). Furthermore, the process of interpreting, coding, linking and reflecting continued throughout the whole writing phases of this thesis. The data display and analysis approach followed the three steps suggested by Miles and Huberman (1994), which consist of the data reduction, data display and drawing and verifying conclusions. Data reduction refers to the preparation and aggregation of findings from the collected interview data through summaries, coding and thematic clustering. Data display refers to visualising the data through matrices or networks, e.g. tables with clearly defined rows and columns where the respective cells include the data. Drawing and verifying conclusions finally refers to the knowledge that can be built from the structured visualisation of relationships between elements from the data (Miles and Huberman, 1994).

In analysing the interview data, the focus lay on identifying the main activities and relationships of and between the actors in the organisational system throughout the implementation of Industry 4.0. Each interview was audio-analysed shortly after it was concluded to develop a better understanding of the available insights and to learn for the next interview. Some of the interviews were additionally transcribed to better facilitate the incremental coding and analysis process. The remaining audio files of the interviews were transcribed after all data was collected. A set of ten interviews were then thematically analysed to produce a final version of codes and themes to start the analysis of the whole set of 35 interviews accordingly. The applied thematic analysis is a systematic method for determining themes in complex data sets by coding and categorising common phrases and themes expressed by the interviewees (Braun and Clarke, 2006). All codes were informed by the research questions concerned with exploring and understanding the implementation of Industry 4.0 in the chosen corporate environment. The final number of 38 codes led to 744 nodes and the detection of 4 main themes in the data. The final themes of the data analysis refer to the emergence of complex behaviour and action that form the implementation of Industry 4.0, the effects of actors and their relationships' characteristics, the internal influences such as lean management, continuous improvement, and trial-and-error, as well as the presence of emergence and feedback that leads to the acknowledgement of adaptability in the organisational system. The processes of data management, i.e. coding and analysis, were supported furthermore by NVivo. NVivo is a qualitative software package and data management tool with the capacity to store and analyse data from interviews in one place (Bazeley and Richards, 2005; Bazeley, 2007). NVivo primarily facilitated a good overview on the data and enabled an evaluation of the different emergent themes and therefore the development of knowledge about the implementation of Industry 4.0. The identified themes of the analysis are utilised as the basis for the discussion and contribution of this thesis.

3.4.5 Time horizon

All data was collected between March and July 2019. Hence, the time horizon of this thesis is cross-sectional. The collected data represent a snapshot of the perceptions the interviewees shared in the moment of the interview.

3.5 Reliability and validity

Conducting the larger set of 35 expert interviews in the frame of a single-case study allowed the development of a deep and holistic perspective on the implementation of Industry 4.0 at BERTLEI. The development of codes, nodes and themes using NVivo supported the magnitude to which the data could be representative. Reflecting on the reliability and validity, the collected data represent the same phenomena and the developed system model as well as yielding comparable data (Mason, 1996). The iterative analysis of the results with previous ones and the literature supported the validity of the detected system elements and the system model as a whole (Yin, 2014). Replication logic is present when the results can be identified in a variety of material such as interview data and the literature (Eisenhardt, 1989; Yin, 2014). Throughout the course of this thesis, developed material was repeatedly evaluated in the context of academic conferences, such as the IEEE annual International Conference on Engineering, Technology and Innovation (see the list of publications deriving from this thesis in Appendix K).

3.6 Ethical considerations

According to Sieber (1992), the core principles of ethics in qualitative studies are based on beneficence, respect and justice. Beneficence stands for the maximisation of good outcomes for science, humanity and the individual research participants. Unnecessary harm, risk or wrong are meant to be avoided or at least minimised. Respect highlights the protection of the autonomy of autonomous persons, courtesy and respect for individuals as persons, including those who are not autonomous. Justice stands for ensuring reasonable, non-exploitative and carefully considered procedures and their fair administration as well as fair distribution of cost and benefits among persons and groups. In other words, those who bear the risk of the research should also be those who benefit from it. This research received full ethical approval from the ethics council of Newcastle University Business School. It ensured that no harm, risk or wrong was committed to the participants of the research project. The study respected individuals as autonomous persons and did not conduct research on non-autonomous individuals. All data was collected on a voluntary basis. Detailed information about the course and content of the interviews was provided verbally. An information sheet and confidentiality agreement was provided in written form prior to performing each interview. An example of the information sheet and confidentiality agreement is provided as Appendix L and Appendix M of this thesis. Anonymity and privacy were ensured by either blacking out or renaming all content containing identifying, personal or company information in transcripts and the thesis. In addition, the company in focus of the case study has been renamed to “BERTLEI”.

3.7 Limitations and conclusion

This research project captures a number of limitations. First of all, the use of scientific literature and in-depth qualitative data could always be extended by the consideration of other literature and other data. The restricted number of resources in terms of time and money available for the interviews and the thesis as a whole is an influencing factor for the results. Furthermore, the data collection of this thesis which was conducted in the form of a single case study in a German manufacturing firm may include regional and company specificities and hence imply some limitations in terms of generalisability. However, generalisability of this thesis contribution was demonstrated by the thematic analysis of the qualitative empirical data that referred to the same content and same subjects. Given the characteristic properties of the chosen company for this case study related to the challenges of Industry 4.0 implementation in Germany, it is likely to identify same or similar patterns of the implementation of Industry 4.0 in other regions and companies. Also the data collection technique of conducting interviews may be subject to limitations, as interviews potentially capture problems of bias, poor recall, and poor or inaccurate articulation (Yin, 2003). However, by using an in-depth single-case study with a total number of 35 interviews as the methodological strategy for this thesis, and in combination with the pre-existing knowledge and experience about manufacturing, the risk of problems with bias and lower validity in the data generation process were minimised. Another limitation is represented in the fact that interviews were conducted with managers and employees who are responsible for the organisation and execution of the implementation of Industry 4.0, however, with employees in terms of office staff only, leaving a gap regarding the employees in terms of the shop floor workers. Interviews at the shop floor level could offer an additional perspective about the implementation of Industry 4.0, which however is not part of this thesis and its firm level perspective and leaves room for future research and publications. A similar limitation is represented in the fact that interviews were not conducted with the very top management of the firm group, which potentially could have provided a closer perspective into strategic decisions regarding the implementation at BERTLEI.

Quantitatively oriented researchers often criticise qualitative research based on case studies as being suitable for exploratory purposes only, making surveys necessary for the descriptive phase and experiments for explanatory inquiries (Yin, 2009). Five common criticisms (misunderstandings) about case study approaches furthermore refer to 1.) theoretical knowledge (context-independent) is more valuable than practical knowledge (context-dependent), 2.) one cannot generalise from a single case, therefore the single case study cannot contribute to scientific development, 3.) the case study is most useful for generating hypotheses, while other methods are more suitable for hypotheses testing and theory building, 4.) the case study contains a bias toward verification, and 5.) it is likely to be difficult to summarise and develop general propositions on the basis of specific case studies (Flyvbjerg, 2006). However, countering these criticisms, quantitative research and statistics also rely on humans who (often subjectively) select the concepts the statistics are based on, whereas case studies are narratives in their entirety, which present ambiguity and problems of the real world, thereby providing opportunities for a better understanding (Flyvbjerg, 2006). The thick descriptions and rich data of case studies are the advantages of qualitative research, whereas summarising potentially destroys the richness of research (Flyvbjerg, 2006).

The limitations and criticisms of the applied theoretical lens of Complex Adaptive Systems Theory in this thesis evolved around the uncertainty about the best use of a research method (Morel and Ramanujam, 1999), the confusion of the terms complex and complexity (Eisenhardt and Bhatia, 2002), and the false impression that system outcomes are always random and not predictable (Baumol and Benhabib, 1989; Radzicki, 1990). There has been a general belief in the past that CAS research creates universal models and metatheories applicable to all types of systems (McCarthy et al., 2006). However, the sources of adaptability in physical, life, and social systems are very different from each other, which means that it is not at all likely for CAS to produce such universal models and metatheories (Levy, 1994). Researching CAS behaviour in social systems requires qualitative perspectives to complement the methods developed by the physical sciences (Brown and Eisenhardt, 1997; Bradach, 1997; Eisenhardt and Bhatia, 2002). Case studies with their iterative and descriptive nature are thereby well suited to capturing the rich and qualitative structures of social CASs and to build new theory (Brown and Eisenhardt, 1997; Bradach, 1997; Eisenhardt and Bhatia, 2002). A general critique on system theory may furthermore lie in the nature of systems to continuously evolve and that a studied system therefore may not be the same system after a period of time (Luhmann, 2017). However, as Luhmann (2017) replies, basically everything is subject to continuous evolution, which makes every study a snapshot of a certain moment only.

Last but not least, the application of NVivo as a software package to support the process of data management, coding and analysis in this thesis also brings limitations. It is important to understand that NVivo is also subject to "human factors", which may lead to "poor workmanship". NVivo is able to provide a good data management warehouse (Bazeley, 2007), however, it relies on the researcher to actually conducts the necessary data analysis. This chapter provided a detailed explanation of the research process, its method and how this research was approached. The iterative process of self-reflection, coding and analysis was defined and discussed in order to answer the research questions. Notwithstanding its limitations, the methodology of this thesis is considered to lead to reliable and valid results and new knowledge (theory) relevant for the implementation of Industry 4.0. Chapter 4 presents the analysis of the findings of this thesis before Chapter 5 discusses the findings in the light of the literature. Chapter 5 also examines and answers the research questions of this thesis.

Chapter 4. Findings

4.1 Introduction

The findings of the case study identify the roles of important system elements and their means for the overall system in focus. The boundary of the system is the boundary of the firm, as the system represents the firm in which the implementation of Industry 4.0 emerges. The findings are based on the analysis of the data collected in the course of the interviews to address the two research questions of this thesis referring to how a high value German manufacturing firm organises the implementation of Industry 4.0 at the firm level, as well as why such a firm organises the implementation as they do. The collected data is presented and analysed in the light of systems theory and structured in the following themes.

First, the behaviours and actions that have emerged at BERTLEI due to the implementation of Industry 4.0 are identified and analysed. These themes refer to the foundation of a new connectivity department, the foundation of a new central department for digital transformation, the foundation of a new cloud platform, the foundation of a new smart factory consulting team, the foundation of a new corporate venture capital firm, and the foundation of a new demonstration smart factory. The themes referring to the emergent behaviours and actions furthermore include the appointment of a new chief digital officer and new change managers, as well as a detected corporate opening up towards more partnerships with external suppliers as a form of cultural and mindset change. Second, the main internal influences of the system are presented and analysed. The detected influences refer to existing lean management structures, a continuous improvement approach, as well as a trial-and-error approach. Third, the actors, their characteristics, and their relationship characteristics are presented and analysed. These themes mainly highlight the fear of the management to meet resistance to change from the employees of the firm. And fourth, the feedback loops and learning of the emergent behaviours and actions are identified and analysed, and therewith demonstrate the adaptability of the complex system.

This chapter will close with the development of a comprehensive system model that supports the understanding of the interconnected variables influencing the implementation of Industry 4.0 in the organisational system.

4.2 Emergent adaptive behaviour

Three themes are very outstanding in the data analysis and refer to the initiation of organisational structure changes, the initiation of personnel changes, and cultural as well as mind-set changes. Organisational structure changes emerged e.g. in form of the foundation of a central department for digital transformation which aligns all Industry 4.0 related projects in the different parts of the company group. A personnel change was detected in the form of one shareholder of BERTLEI being appointed as the chief digital officer (CDO) for the firm. The CDO is the head of the central department for digital transformation and has overall responsibility for the successful implementation of Industry 4.0. A cultural and mind-set change was furthermore identified in the form of a corporate opening up towards building a strong and wide partnering ecosystem instead of remaining all in-house.

4.2.1 Initiation of organisational structure changes

The implementation of Industry 4.0 triggered a set of different organisational structure changes at BERTLEI, as this section demonstrates. Table 8 presents in advance a list of the organisational structure changes that were captured in the case study of this thesis in a chronological order before exploring and analysing these in textual form.

2015	Foundation of the connectivity department with about 80 people (by 2019) responsible for bringing digital products into the market (divided into hardware, software and service areas)
2015	Foundation of a spinoff to build a cloud system for data transfer between the firm and its customers with a size of about 90 people (by 2019)
2016	Foundation of a team of smart factory consultants with the aim to consult BERTLEI's customers in Industry 4.0
2016	Foundation of a corporate venture capital firm with a fund of € 40 Mio to invest minority shareholdings in Industry 4.0 related start-ups
2017	Foundation of the central department for digital transformation with about 25 people (by 2019)
2018	Foundation and opening of a fully automated smart factory as a corporate light house project to test new solutions and to demonstrate the benefits of Industry 4.0

Table 8: Organisational structure changes in a chronological order

The earliest organisational structure change that could be detected throughout the data analysis is the foundation of a new department in 2015 responsible for connectivity solutions.

This new department emerged with the idea of transforming the firm from a plain machine builder to a more solution-oriented provider, as an interviewed program manager of this department (IP-39) stated in the following way: “[the connectivity department] is our world for connectivity products, so [BERTLEI] is now in a state that we want to change our strategy from a product producer, manufacturer up to a solution provider.”. The first step into the implementation of Industry 4.0, after appropriate research and development efforts, was the foundation of this connectivity department to build a more holistic view of Industry 4.0 including the customer as a team leader and project leader of predictive services (IP-32) further explained: “[…] they started to create a new department which is called [the connectivity department] and they want to be a solution offering department for customers and don't think in like only certain products but thinking in bigger or surrounding solutions and this is the smart factory. So actually, they founded a totally new department for it.”. At the time of the data collection in 2019 the connectivity department hosted about 80 people working on the development and management of Industry 4.0 solutions. One example of the solutions the connectivity department manages is a new “track and trace system” that identifies current locations of products and parts at the shop floor level of the firm as the above quoted team leader and project leader of predictive services (IP-32) also mentioned. The above evidence from the data indicate that the connectivity department was founded to develop Industry 4.0 products and solutions for BERTLEI itself and also for its customers. The references in the data regarding “thinking in a holistic smart factory way” and to “transform into a solution provider” furthermore indicate the complexity on the implementation of Industry 4.0 in the organisational system.

The second detected organisational structure change also emerged in 2015 when BERTLEI founded a new spinoff to build a cloud platform for connectivity and data transfer between machines. This spinoff connects BERTLEI’s as well as customers’ machines, including the older pre-Industry 4.0 machines that do not yet have any connectivity solutions integrated, as an interviewed product owner of this cloud spinoff (IP-33) described: “So [the cloud spinoffs’] USP is our strong connectivity solutions. We take pride in connecting our diverse machines, very fast, into the cloud and this is the biggest challenge the industry is facing because most of them are really good at building apps but the solution is not about building apps, the biggest challenge is how do you connect these damp, very old, legacy machines and how are you able to extract data from running machines.”. At the time of the data collection in 2019 the cloud spinoff employed about 90 people according to IP-26, a smart factory consultant. A program manager for digital solutions (IP-39) further explained that the cloud spinoff is in parallel to the connection of machines as well responsible for storing and analysing collected machine data to enable knowledge generation from the past data: "[the cloud spinoff] is more in the data collection and analysing part, so that you have the possibility to monitor your production and to see more in the history of what your production does.". Whereas the connectivity department was founded to develop new Industry 4.0 products and solutions, the cloud spinoff enables the connection of machines to a corporate cloud system to then extract, store and analyse the collected data. Both organisational structure changes integrate the customers of BERTLEI, which indicates the relevance of the customers for the implementation of Industry 4.0.

The third organisational structure change due to the implementation of Industry 4.0 was detected in the form of the emergence of a new team named "smart factory consulting". The smart factory consultant team was founded in 2016 to provide specific consultancy regarding the implementation of Industry 4.0 to the customers of BERTLEI. An interviewed smart factory consultant (IP-38) described the role of his team: "So we go out and analyse the customer towards Industry 4.0 digitalisation potentials, but also guiding them to the smart factory of the future. The interesting thing here is that for the customers the journey always looks completely different and this is something were [BERTLEI] wants to become a part for the customers and this is where our consulting comes into play, together with the customer to find a clear road map, optimised processes, optimise material flow, information flow, as well as design these smart factories for the customer.". As explained by IP-38, the smart factory team aims to improve the corporate processes, material flows, information flows, and last but not least to build a smart factory that suits the present demand of the customer. The organisation of the implementation of Industry 4.0 solutions furthermore starts with a potential analysis, continues with the development of a potential list, and ends with the development and execution of different projects arising from the potential list, as explained by a second interviewed smart factory consultant (IP-02) in the following way: "Yes. So, like I have said the first step would be a potential analysis, to identify like the biggest potentials we have at the customer. And then, yes, we create, out of this potential analysis we create like a potential list, and out of this potential list we create like several projects which we think have the biggest return on investment. So, we try to think for each potential, we try to think like how we can reduce costs, and therefore we were able to identify like the priorities the most important projects for us, which are the projects with the highest return on investment, or the shortest return on investment.”.

As explained by IP-02, the priorities of different projects are ordered according to which project captures the highest value for the firm. The implementation of Industry 4.0 solutions at the customer site and with the support of BERTLEI’s smart factory consultants is organised by defined milestones, i.e. a defined beginning, a defined end, and an expected result. IP-02 described a present consultancy project in Asia coming up the week after the interview was conducted: “[…] next week I am at a project in China and at that project we have like fixed milestones, yes. And we also need to. Like in [our industry] we have to present our solutions and the benefits our project created to the company. So, but, yea, we try to work with fixed milestones. So, after the potential analysis at the beginning, we think about like, ah, a way to implement those solutions, those digital solutions, and then we try to create like something.”. The foundation of the smart factory consulting team indicates that BERTLEI further extends the implementation of Industry 4.0 at their customers’ site similar to how it is executed also from the connectivity department and the cloud spinoff as described earlier. This leads to the assumption that the consultancy business functions as an additional bridge to customers that supports the distribution of BERTLEI’s machines and solutions.

The fourth detected organisational structure change emerged in 2016 with the foundation of a corporate venture capital firm. The venture capital firm manages a fund of 40 million euros to invest in minority shareholdings in Industry 4.0 related start-ups relevant to BERTLEI, as the responsible and interviewed investment manager from the corporate venture capital firm (IP-24) explained: “[BERTLEI]-venture is a corporate venture capital arm. We have a 40 million euro fund out of which we do minority shareholdings in start-ups that are of relevance to [BERTLEI].”. According to IP-24, the investments into the start-ups enable BERTLEI to explore and offer Industry 4.0 solutions which the firm could not offer by themselves without the start-ups: “So I do invest in start-ups that might have a [BERTLEI] offering, something that we couldn't offer just by ourselves and therefore say leveraging deliberately an open innovation approach of collaborations especially with start-ups.”. Examples of technologies and solutions the venture capital firm aims to invest in were defined from IP-24 as in the proximity of robotics, sensors, I.T., connectivity, computing infrastructure, artificial intelligence-based models, blockchain based models, data-based business models such as platform businesses, and industrial enterprise software solutions: “We usually invest in companies that are in proximity to the [BERTLEI] business. It's not exactly always in the core but also in adjacent fields. That also includes everything necessary to implement what you call smart factory.”.

The corporate venture capital firm functions as a tool for BERTLEI to scan the market for new developments and to establish a wider partnership network as IP-24 explained in the following way: “[…] there's different goals that we actually follow or aim to implement by having such a venture capital unit, that goes from monitoring disruptive movements, some technology or business models, to actually establishing a very broad and strong partnership network […].”. The above cited evidence from the data indicate that the foundation of the corporate venture capital firm represents one example of how BERTLEI opens up for interactions with external partners. This may lead to the conclusion and assumption that the complexity of the implementation of Industry 4.0 exceeds the capacity of BERTLEI, i.e. “one firm” to implement Industry 4.0 with only internal resources. As the emergent behaviour of opening up has been a distinct pattern in the overall data analysis, this theme is further explored in the following sections of this chapter.

The fifth organisational structure change was detected in form of the foundation of a central department for digital transformation (CDDT) in 2017 that connects and consolidates Industry 4.0 solutions companywide. An interviewed rollout manager from the CDDT (IP-41) explained the objective of this department as to overview, consolidate and consult the individual Industry 4.0 initiatives from the independent subsidiaries and departments of the company group: “[…] they said we need a department that consolidates all that projects that are working towards that ambition and so they founded this department and we are working on several projects all over the company and so we try to consolidate all the initiatives for the digitalisation and on the other hand we support all the departments in projects so they really can transform every department digitally. So, it’s a combination of consultancies for the internal departments and also to consolidate all the initiatives; so we have one overview over the whole organisation in terms of digitalisation.”. At the time of the data collection in 2019 the CDDT consisted of about 25 people according to IP-41. As a second interviewed manager from the same department (IP-40) further explained, the main goal of the CDDT is to connect and to build bridges between ideas and solutions in the company group to minimise the risk of isolated solutions but to make them function from end to end: "[…] the challenge within digitalisation is that you don't think in functions like sales, production, development, research and so on, but you have to bring them all together, and this is kind of where we are the networker we are the glue between all these, to bring them together, to think holistically and also to optimise holistically, not only for a certain function.". Two examples where the CDDT is involved in at BERTLEI is the product development of the connectivity department and the start-up potential evaluation at the corporate venture capital firm as explained in the following by IP-40: "[…] if we talk about [the connectivity department] products, that's where also we are involved in, so our core part for example. [BERTLEI-] ventures we, sometimes we work with them to see for example digital expertise or if they have a new start up identified, which need to be evaluated, so we work together, so that works pretty well […].".

The aspired holistic perspective that is highlighted by IP-40 as well as the consolidating role of the CDDT that highlighted by IP-41 indicate that Industry 4.0 initiatives emerge individually at BERTLEI from independent subsidiaries and departments of the company group. This in turn indicates that subsidiaries and departments are granted a certain level of autonomy regarding their organisation of the implementation of Industry 4.0. Further evidence underlying the presence of autonomy for self-organisation are provided in Section 4.5.1. A third interviewed manager from the CDDT (IP-07) confirms this autonomy by explaining that her department especially cares about not taking away the granted autonomy of the subsidiaries and departments when consolidating Industry 4.0 solution: "[…] [we look for potentials to consolidate solutions, however, always with the aim not to take autonomy off the single departments]". The references and claims of the three interviewed managers from the CDDT therefore lead to the assumption that the implementation of Industry 4.0 emerged in a decentralised organisation at each department and subsidiary of BERTLEI. The described objective of the CDDT provided by IP-41 to "overview the whole organisation in terms of digitalisation" indicates moreover the complexity of the implementation of Industry 4.0 and the need of such CDDT.

The sixth organisational structure change was detected in form of the foundation of a new and fully automated corporate test and demonstration smart factory in 2018 in the United States. This smart factory functions as a corporate lighthouse project to test new solutions in a safe environment and to demonstrate the benefits of Industry 4.0 as a program manager for digital solutions (IP-39) highlighted: “[…] we can try new kinds of processes and new technologies and we have a productions similar field, but not the pressure which the customer has with his customers. Where you don't have the time to experiment with those things and I think there we can show many benefits out of it”. As the program manager (IP-39) continued to explain, it is very difficult to transfer the vision of Industry 4.0 to all the people inside the company, but also outside the company and to make them understand the potential and why firms need it: “I think it's very difficult to transfer the vision to all the people in the company or outside the company and to make clear what's the benefit out of it and why you need it. And therefore, as I said before, are these lighthouse projects […] where you try to demonstrate what the potential is behind it and that's possible for other people to grasp and to realise it.”. One product which is currently being tested in this demonstration smart factory is a new type of intra logistic system, which improves the material flow and data availability. The program manager (IP-39) further explains: “We want to show how it's possible to integrate more intra logistics processes, so that you have the whole data available, holistic view of the whole process, that you don't have this break of data information in the process and there is still ongoing in [the demonstration smart factory], there is a proof of concept.”.

In a telephone interview with a smart factory consultant (IP-29) from this new founded test smart factory in the United States, it was explained that the specific benefits that are demonstrated capture an increase of productivity, decreasing required manpower due to automation, and a controlling system of data that makes paper redundant in the production area: “Higher productivity, less manpower needed being able to run lights out. Controlling system of data, essentially a paperless production, those are the main benefits.”. The references above indicate that the demonstration smart factory functions not only to test new solutions but also as a new communication channel to reach the internal as well as external stakeholders of BERTLEI to get them on board to participate in the implementation of Industry 4.0. IP-39 in this sense reported that he realised that lighthouse projects such as the demonstration smart factory are extraordinarily accelerated in the firm, assuming that the positive communication and demonstration of benefits pushed the overall implementation of Industry 4.0: “[…] I realised that it's the way that we have some lighthouse projects, in different parts of the company and these lighthouse projects push the whole process, because they do very fast and very quick, you show the whole company what you can gain. What's the benefit out of it. So, I think that's the enablers […].”. As IP-39 stated at the end of the last quote, this may lead to the assumption that the demonstration smart factory is utilised as an enabler in the implementation of Industry 4.0 at BERTLEI.

As the data above in this section demonstrated, the six discovered organisational structure changes have emerged at BERTLEI due to the implementation of Industry 4.0 in the organisational system. Their detection supports the understanding of how BERTLEI implemented Industry 4.0, which addresses the first research question of this thesis. The analysis of these structure changes furthermore supports the understanding of why BERTLEI implemented Industry 4.0 as they did, which in turn addresses the second research question of this thesis. An illustrative summary is provided in Figure 7. Figure 7 captures the organisational structure changes as well as their underlying mechanisms, which were explored and analysed in textual form earlier in this section. From the analysed evidence of the data it can be summarised that the different organisational structure changes at BERTLEI jointly demonstrate the complexity and disruptive nature of the implementation of Industry 4.0 in the organisational system in focus.

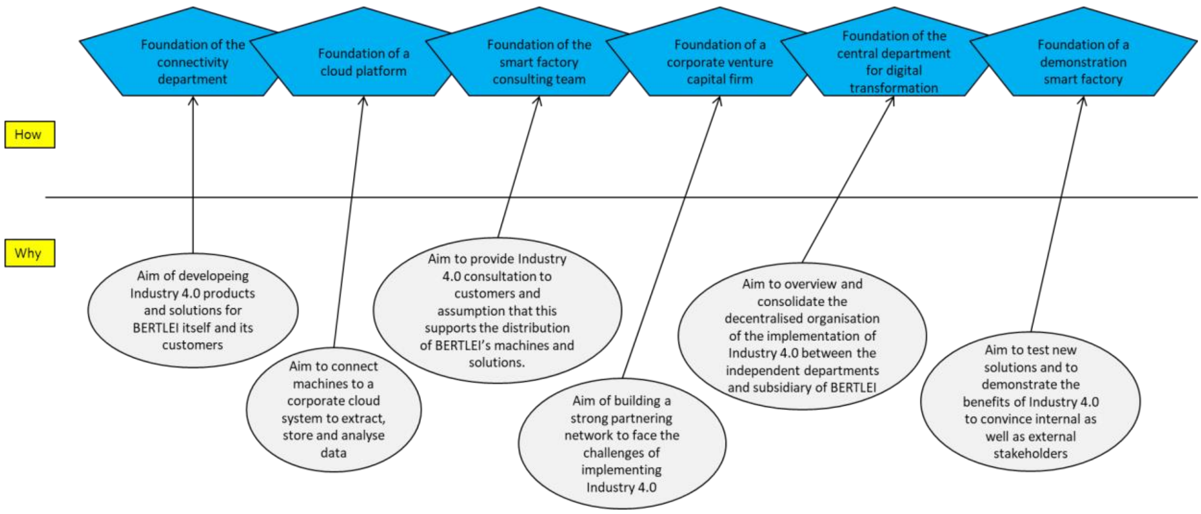


Figure 7: Analysis of organisational structure changes

4.2.2 Initiation of personnel changes

In parallel to the organisational structure changes analysed in the section above two personnel changes were also detected at BERTLEI, i.e. the appointment of a chief digital officer (CDO) and the appointment of rollout managers, which emerged due to the implementation of Industry 4.0. The CDO was appointed in 2017 and represents the head of the CDDT, which was founded just after the CDO was appointed, as an interviewed manager from the CDDT (IP-41) explained: "[…] the chief digital officer was announced in July 2017, […] and a few months later I would say, I don't know the exact months but, after July 2017 they founded the central department for digital transformation […].". BERTLEI decided to position one of the shareholders of the company group, i.e. a member of the owner family, as the CDO. A manager from the development department (IP-35) further explains: "So, what [BERTLEI] did was, they said, okay, this is so important so we must give the topic to one of the family members. We will make it in a new central area that will coordinate all new efforts, in the direction of smart factory, of all the other areas.". As IP-35 highlighted in the quote above, the fact that BERTLEI appointed one owner family member as the highest responsible management position indicates the importance the firm grants the implementation of Industry 4.0.

IP-41 confirms the perspective that the implementation of Industry 4.0 must be of importance to BERTLEI due to the appointed CDO being a family member of the organisation: "[…] we have the chief digital officer and also to mention is, that it's one family member that is actually having that position and let's say for us it's very important to transform digitally […].". IP-41, i.e. the interviewed manager from the CDDT was asked about his interpretation of the role of the CDO as the head of the CDDT, especially alongside the aim of the firm to actually let the implementation of Industry 4.0 emerge from bottom-up, i.e. from the independent subsidiaries and departments. The manager responded by interpreting that the appointment of the CDO may have to be seen more as a sign of commitment that BERTLEI wants to communicate to the organisation: "So I would say it's more about a sign into the firm that this topic is really important for us and that we really want to go into this digital future.". The manager continued explaining that now all stakeholders of the firm know the specific face responsible for the change: "It is a very important sign that one family member is taking, so Mr. [confidential] is taking this position of the chief digital officer. And, so also everybody knows who is working on that in the organisation, so who is the face of the digital transformation […]".

The evidence from the above cited references from the data indicate that BERTLEI strategically appointed one family member as the CDO to demonstrate the highest management commitment for the implementation of Industry 4.0 to the internal stakeholder of the organisation. This demonstration of management commitment may lead to the conclusion that BERTLEI aims to place a force against a potential behaviour of demotivation and resistance to support the implementation of Industry 4.0 in the firm. Such behaviour may emerge due to various reasons, including behavioural inertia as well as the fear of people losing their jobs due to Industry 4.0 as highlighted by an interviewed corporate in-house consultant (IP-06): "[…] a huge fear is going outside in the market and there, the fear is that they will lose their job […].". IP-35, the mentioned manager from the development department for services, supports the perspective of IP-06 and highlighted further that good communication is therefore required: "[…] if you do not explain it, they fear that they will just lose their jobs towards smart factory.". The employees' characteristic of resistance to change due to the fear of losing their jobs will be analysed more in detail in a later section in this chapter. However, at this position it may provide evidence supporting a better understanding why BERTLEI appointed the CDO as the head of the CDDT.

The second detected personnel change due to the implementation of Industry 4.0 was the appointment of rollout managers. The rollout managers belong to the CDDT and take care of the diffusion of Industry 4.0 solutions in the company group after they have been developed and implemented in one department or subsidiary of BERTLEI. A project coordinator (IP-03) explained: "[…] how digital solutions are implemented first in the department and then how could a rollout be in other departments, there is a really good process which is coordinated by our central department […].". The rollout managers are responsible to reach and convince the internal stakeholders about the advantages of the change to eventually manage and minimise a potential resistance of the employees to support the implementation of Industry 4.0. An interviewed rollout manager from the CDDT (IP-41) explained her role: "[…] we really try to reach every employee and to convince every employee of that initiative, because I think the most important factor in digital transformation is the employee and the mind-set of the employees. Because if you're, if the employees don't want to work on digitalisation they don't, they are not aware of the advantages of digitalisation, you can't get better if, because then they don't want to do anything and then they… how do you call that… [they block], such initiative or any topic because they are not committed.". This statement indicates that BERTLEI evaluates the potential of resistance and blockage to support the implementation of Industry 4.0 as a risk to the successful transformation. The initiation of the position of the rollout managers may therefore lead to the conclusion that this action seeks to mitigate against the risk of resistance to change. The rollout managers are involved in nearly every Industry 4.0 related project at BERTLEI. According to the interviewed rollout manager (IP-41): “So, we have rollout managers nearly in every project. So, yes there are. […] We can enable that communication to all the employees and all the internal customers of the projects.”.

A demonstrative example of the tasks of a rollout manager was provided by IP-41, who described a current project and her responsibility for assuring that the affected employees of a product change are picked up and understand how to handle the change: “[…] I am working on the rollout of our digital tools to the internal customer. So we are working on digital tools for the service department and this, yes, for example, a browser application for the service technician and I am responsible that the service technician can use that tool and is working with the tool […].”. IP-41 further describes her role in the current rollout project as a close communicator with personal contact if possible: “[…] for example if in my project and then I also talk to the different people that are, that are connected to that solution, I try to also, if it’s not too many, I try to contact them also personally, I say they can always contact me and so we try to really talk to them in person or maybe also if it’s more than just a few to have the option to have a call with us.”. A second example of how the rollout managers manage communication is by sharing internal articles about the implementation of Industry 4.0 that the employees can comment and discuss with the rollout managers. As explained by IP-41: “[…] we try to make it as transparent as we can, so, as I said we try to have articles in the intranet that every employee can read and they are free to make comments.”. Both examples indicate the willingness of BERTLEI to involve and convince the employees about the implementation of Industry 4.0 and hence to manage potential resistance to change.

The references from the data now may lead to the conclusion that the rollout managers were initiated so as to enable direct communication to the internal stakeholders. The references may also lead to the conclusion that the rollout managers function as a tool to manage motivation and commitment of the internal stakeholder and therefore to reduce the risk of potential resistance to the change from the employee side. The fear about a potential resistance to the change, i.e. lacking motivation and commitment, was detected in the data, such as from IP-41, who intertwined this with the overall success of the implementation of Industry 4.0 at BERTLEI: “So from the employees in every subsidiary and every department almost towards the management the commitment must be there to digital transform. Just this mind-set and also motivated employees are there and work on it, a digital transformation can be successful.”. As the data above in this section demonstrated, the appointment of the CDO as well as the rollout managers have emerged at BERTLEI due to the implementation of Industry 4.0. This information supports the understanding of how BERTLEI implemented Industry 4.0, which addresses the first research question of this thesis. The analysis of these personnel changes furthermore supports the understanding of why BERTLEI implemented Industry 4.0 as they did, which in turn addresses the second research question of this thesis. An illustrative summary is provided in Figure 8. Figure 8 captures the two personnel changes as well as their underlying mechanisms that have been explored and analysed in textual form before in this section. From the analysed evidence of the data it can now be assumed that the appointment of the CDO as well as the rollout managers represent new communication channels to manage potential resistance to the implementation of Industry 4.0.

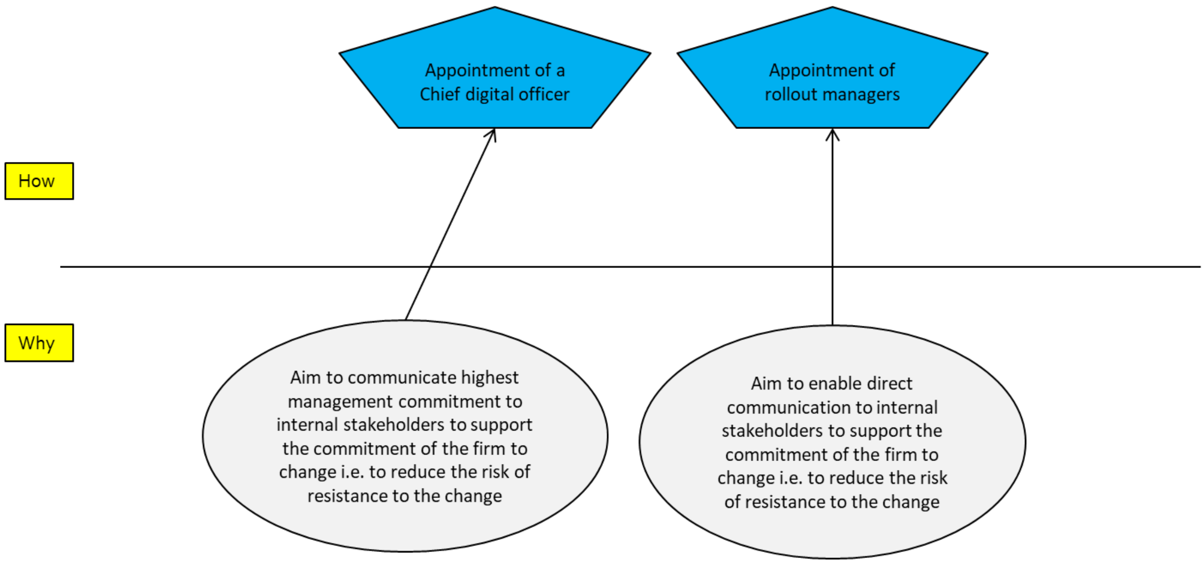


Figure 8: Analysis of personnel changes

4.2.3 Cultural & mind-set change

The cultural and mind-set change that was detected throughout the data analysis emerged in the form of a corporate opening up towards partnerships with external actors. The evidence from the data refer to different reasons why developing Industry 4.0 solutions in-house only is not reasonable and therefore why the firm is opening up to external partners. As an interviewed smart factory consultant (IP-02) explained with the example of missing IT-competences: “[…] smart factory solutions are also, are always, also software solutions and for, for many software products [BERTLEI] is offering, I think there is no other way than using external suppliers because they are quite specialised for different fields, so I think if you consider software as smart factory solutions then there is no way that [BERTLEI] is doing all there smart factory projects and products by itself.”. Based on this statement it can be argued that IP-02 interprets Industry 4.0 to be strongly related to software capabilities which BERTLEI currently does not hold. The fact of missing competences was as well explained by a second smart factory consultant (IP-26) who highlighted the required manpower and hence workload that the implementation of Industry 4.0 captures: “No this is also a way of transformation where [BERTLEI] is going through. […] our own IT-infrastructure, for example, can almost no longer achieve this, in terms of manpower. […] So, this is also just a change where just [BERTLEI] goes. Because they realise that if I program everything myself, then I slow down so much from the project business, then I can no longer get around.”. IP-26 captured in his statement above the missing competences in terms of manpower as well as the time constraint of developing all solutions in-house without external support.

These two factors, i.e. missing competences and time, forced BERTLEI to make a decision on each Industry 4.0 project whether it is wisest to buy a solution than to make it in-house, as an interviewed program manager for digital solutions (IP-39) explained upon the question about important evaluation in the pre-implementation phase: “So, this is crucial. So that we, because our capacities are very rare, we are big company, but we have so much projects running so that it's the first evaluation to think are we doing this. Is it worth it or and the question, do we make it or do we buy it?”. The importance of the make or buy decision in the pre-implementation phase of Industry 4.0 was further underlined by an interviewed manager for customer management and sales (IP-15) who highlighted the fast-moving market, i.e. the time, as the important factor for BERTLEI to open-up: “No, it's definitely not a good idea to try to do everything ourselves. The market is so big and there are so many solutions out there. It's more about, and, it's so fast moving so you have to use parts of other technology, of other ideas. Yeah. It doesn't make any sense to. If you think about make or buy, it usually should be a buy decision. That's not what everybody in the company would say, but we're on the way to learn that.”. As explained by the manager for customer management and sales, the opinion of the firm about developing all solutions in-house or to cooperate and to buy solutions from the market may be contradictory. This indicates that BERTLEI finds itself in a transition mode, moving from a making it in-house approach to opening up towards more cooperation with external suppliers to meet the challenges of missing competences and overcome time constraints.

Some statements, however, were detected in the data that show some of BERTLEI's staff still support the development of Industry 4.0 solutions from the traditional internal perspective, as it is demonstrated by a statement of an interviewed smart factory consultant (IP-26) in the following way: "Yes, that's the special thing about [BERTLEI], except of course the logistics, of course [BERTLEI] does everything completely by itself. Because they simply say that we don't want to pass on this know-how to the outside world.". This perspective of developing all competences regarding the implementation of Industry 4.0 in-house was underlined by the opinion of a manager from the development department for services (IP-35) who justified a making it in-house approach by the potential risk of missing Industry 4.0 competences if they have not been developed internally: "[…] I think you have to distinguish between core and context. So, what you do by yourself because you believe this is very important for your future business. So, the core, in which direction you have to change, and on the other side, what is just context that actually others can do because it does not touch the core of your business. So, if we now say that [BERTLEI] is becoming a solution provider for smart factory, then we have to build up those skills by ourselves to provide and to build solutions. We cannot give this to somebody else […] we have to be very careful where to engage and especially where we rely on external consultants […].". The data analysis of the interviews with the participants IP-26, IP-35, IP-37, and IP-38 further indicates that an intention of making it in-house may even be typical for the region where BERTLEI is located. These contradictory perspectives, however, represent a small minority of the interviewees in the case study. Most of the interviewed experts, such as all the ones cited further above in this section and the ones who are more senior, refer to the very clear need of cooperating with external suppliers to be able to face the challenges in terms of missing competences and time to implement Industry 4.0.

The current transition between the indicated pre-Industry 4.0 pattern, i.e. a making it in-house approach, and the current/post Industry 4.0 pattern, i.e. the emergent behaviour of opening up towards cooperation with external partners, may be demonstrated further in detail by an interviewed program manager for digital solutions (IP-39) who was specifically asked about when the openness to external partners emerged at BERTLEI: “It came just recently because of the need. [BERTLEI] is a company which is doing all by themselves. Because we are proud, we are developers. We want to have the full control about the technology, this is our old mindset but with this digitalisation products and the change the digitalisation, it's not possible anymore. We can't, well it's possible but not in this kind of speed. We are not as fast as we are needed to be so therefore, we have no other reason than to, there are no other possible ways to realise this, when we're doing it by our own, we need 10 years to build up these people and this know how these technologies and therefore we're going the other way and say OK we have to be open minded. We have to open ourselves, […].”. The reference of IP-39 demonstrates the emergence of opening up as well as indicating that time constraints may be the reason for this change.

An interviewed corporate in-house consultant (IP-06) further supports the perspective of IP-39 and explains in even more detail how the transition between the old and the new emerged at BERTLEI. In this sense the firm chose to internally develop connectivity and data management solutions before opening up to external partners to develop most of the remaining implementation of Industry 4.0: “[…] you can choose different kinds of strategies, build your own, or build it with other partners, and [BERTLEI] has chosen a way to just do it, yea, by ourselves, this is like, in my opinion a huge, huge important thing and this, maybe the core all of this by handling data and how can you connect things. That's why it was the first step. A couple of years ago the planet is quite old and it's around, well we are also open minded and we are open for other partners and solutions. So, this is now like more like a floating thing, and we are challenging that, yea, connecting us with other partners. It's not like we want everything by our own, this was in the past, quite often done, why, well, we are technology, a huge technology based company and, we are focused on, yea, are really good engineers and we can develop the future in the [BERTLEI] world, but now we're facing, yea, new challenges, for example in the software world which is, really, really fast what's going on outside, so new companies are appearing new products, and they can push us even, even further. So that's why now we switched totally […]. We know how to build good machines, but everything else, we, it’s really necessary to work with good partners outside.”.

The foundation of the corporate venture capital firm in 2016 that was analysed in Section 4.2.1 may demonstrate one example of how BERTLEI opened up in the previous years to build a stronger partnering network. As explained by the interviewed investment manager from the corporate venture capital firm (IP-24), the investments into start-ups in the field of Industry 4.0 enable BERTLEI to explore and offer new solutions which the firm could otherwise not offer due to missing competences: “So I do invest in start-ups that might have a [BERTLEI] offering something that we couldn't offer just by ourselves and therefore say leveraging deliberately an open innovation approach collaborations especially with start-ups.”. This organisational structure change that emerged due to the implementation of Industry 4.0 functions as a tool for BERTLEI to scan the market and to establish a wider partnership network. IP-24 further explained the goals of this firm: “[…] there's different goals that we actually follow or aim to implement by having such a venture capital unit, that goes from monitoring disruptive movements, some technology or business models, to actually establishing a very broad and strong partnership network […].”. The foundation of the corporate venture capital firm in 2016 hence represents one example of how BERTLEI opened up for interactions with external partners. The analysed interview with IP-24 furthermore indicates that the reason for opening up emerged on the basis of the aim to extend the corporate competencies and capacities to address the complexity of the implementation of Industry 4.0.

The evidence above in this section demonstrates a transformation in the perspective of the organisation from supporting a making it in-house approach towards opening up for more cooperation with external partners. This process can be understood as an emergent behaviour that evolved due to the implementation of Industry 4.0. The detection of the transformation towards opening up supports the understanding of how BERTLEI implements Industry 4.0, which addresses the first research question of this thesis. The analysis of this phenomenon furthermore supports the understanding of why BERTLEI changed its perspective towards opening opened up, which in turn addresses the second research question of this thesis. The data analysis may lead to the conclusion that the complexity and speed of Industry 4.0 stretched the capacities of BERTLEI, which again leads to the identified behaviour of opening up for external support and the establishment of a stronger partnering network. An illustrative summary is provided in Figure 9. Figure 9 captures the behaviour of opening up as well as its underlying mechanisms explored and analysed in textual form earlier in this section. From the analysed evidence of the data it can be summarised that the emergent behaviour of opening up demonstrates another part of the complexity of the implementation of Industry 4.0 in the organisational system in focus.

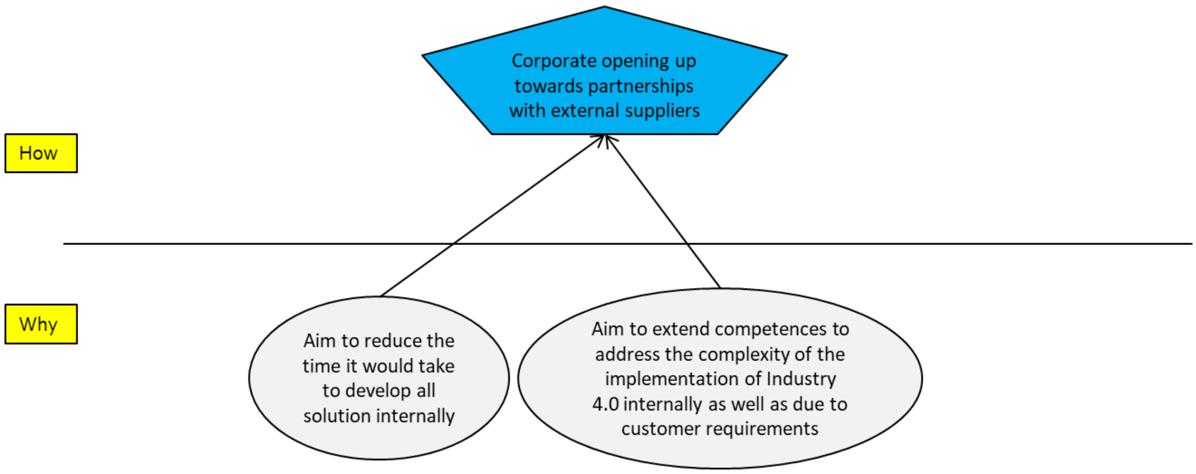


Figure 9: Analysis of the emergent behaviour of opening up

4.3 Internal influences

The organisation of the implementation of Industry 4.0 at BERTLEI is influenced and characterised by three logics detected throughout the data analysis. These logics are patterns of lean management structures, a continuous improvement approach, and trial-and-error behaviour. They represent organisational patterns which the employees and managers of the firm utilise to organise the implementation of Industry 4.0, as the following section will demonstrate.

4.3.1 Lean management

The organisation of the implementation of Industry 4.0 at BERTLEI is influenced by lean management structures developed from 2002 onwards after one of the CEO board members returned from a visit in China where he was introduced to this method. As a product manager from the connectivity department (IP-37) explained: “[BERTLEI] really started optimising his productions, his internal productions after our CEO came back, he lived a time in China and he really got a lot of the production theory and paradigms of Toyota lean production and we [BERTLEI] adopted the lean production paradigm from Toyota to [BERTLEI] and we called it [xyz] and this was the first way we started to optimise our production without any digitalisation at the beginning.”. IP-37 also indicates the importance of the adoption of lean management for the optimisation of manufacturing processes at BERTLEI. Lean management is furthermore highlighted by a large set of the interview participants as the first steps of the organisation to implement Industry 4.0 due to lean management creating structured processes in the firm which can then afterwards be digitised. An interviewed business development manager (IP-34) framed this e.g. in the following way: “I think the first stage is introducing processes because without processes you cannot digitalise anything; you can just digitalise processes. And I think that's something that we did very good with our [xyz] principle which is basically a lean principle.”. A second example was provided by an interviewed smart factory consultant (IP-38) who supported the perspective of IP-34 that lean management generated structured processes at BERTLEI and that it therefore belongs to the organisation of the implementation of Industry 4.0 in the firm: “[…] really the first step was to build up a lean production. So that it wasn't really technology was just the philosophy that was brought in to [BERTLEI] […].”. “[…] the lean philosophy and also that is part of the smart factory, having clear structured workflow as well as transparency within the, within the production lines, so that I would say is part of the smart factory, […].”. The statements of IP-34 and IP-38 lead so far to the understanding that lean management structures have paved the way for the implementation of Industry 4.0 solutions at BERTLEI due to the generation of structured processes.

Lean management, however, is not only an important subject in the pre-implementation phase of Industry 4.0 because it generates and structures processes as IP-34 and IP-38 highlighted before. It is also appreciated because it further optimises and standardises existing processes. A rollout manager from the central department for digital transformation (IP-41) underlined it in the following way: “So [BERTLEI] is working in [Lean], […] and that is also one step towards digitalisation because you cannot digitalise processes that are not standardised or are not very good. So, yes, that is one big step towards it; and I know that they did this […].”. A second manager, also from the central department for digital transformation (IP-07), supported the perspective of her colleague IP-41 and further indicates that lean management is still today an important tool that is executed before each implementation of an Industry 4.0

solution: “Before you go for a smart factory, it’s important [first of all to analyse the processes and to make them lean. Digitalisation upon bad running processes is waste. Hence, it is important to us to first improve the processes according to lean and afterwards to implement Industry 4.0 upon it].”. The perspectives of IP-34, IP-38, IP-41, and IP-07 all highlight the importance of lean management structures prior the implementation of Industry 4.0, which leads to the assumption that lean management competences must also be included in the organisation of the teams that implement Industry 4.0 solutions at BERTLEI.

According to the majority of the interviewees Industry 4.0 related project teams consist of different competences depending on the specific requirements for developing the solution in focus. However, one stable competence in these teams that is always included are lean management experts who evaluate the suitability of Industry 4.0 solutions with existing lean management standards at BERTLEI. A smart factory consultant (IP-38) explains it the following way: “[…] who is always involved is the lean philosophy team also they're always part of these projects because if we are bringing in new technology, we also always have to make sure that this technology fits the philosophy and doesn't ruin a lean way of producing.”. A business development manager (IP-34) further supports the opinion of IP-38 and additionally states that also smart factory consultants of BERTLEI should capture a certain level of lean management competences for their smart factory consultant projects: “I think all Industry 4.0 smart factory consultants or experts, they need at least a basic knowledge of optimising processes in a lean perspective. I think that's something that they have to bring as a competence. […] I think there are a lot of examples at [BERTLEI] from [lean-] specialists improving or changing to smart factory specialists.”. One lean management expert who is in parallel also a project coordinator at BERTLEI (IP-03) was interviewed throughout the data collection for this thesis and confirmed the requirement of stable processes and hence lean management prior to the implementation of Industry 4.0: “I think before you implement an Industry 4.0 solution, the process should run stable. And there should be a need to digitalise the process.”.

A practical example of how BERTLEI organises the implementation of Industry 4.0 for their customers was provided in an interview with a smart factory consultant (IP-26), who describes the importance to first make the customer understand that lean management is necessary to then implement Industry 4.0 on top of it: “[…] you first have to accompany him and say, well, let's create the basics, define processes and do classic lean management. If these processes are there as a foundation, then build on it with the software, because of course, if you have a bad process to digitise it, you have a bad digitised process afterwards. That's why we say the foundation must first of all be the natural processes of classic lean management, then software is placed on it, then you can automate, […].”. A second smart factory consultant, working for the cloud spinoff of BERTLEI (IP-10) supports the statement of his colleague IP-26 by referring to lean management structures at the customer site as a prerequisite for the execution of consultancy in the direction of the implementation of Industry 4.0 solutions: “In terms of smart factory, I would say that you don't digitise processes that are not really well adjusted and adopted, so we always take a look if lean management or lean production make sense. […] smart factory only makes sense in my opinion, if your processes are not full of waste.”.

The evidence above in this section demonstrate that the organisation of the implementation of Industry 4.0 incarnates the execution of lean management up-front to build, optimise and standardise relevant processes that can be digitised. From the analysed data it can therefore be concluded that lean management structures existed prior the implementation of Industry 4.0 at BERTLEI. It can further be concluded that the existing lean management structures influenced the implementation of Industry 4.0 at BERTLEI in a positive way. This leads to the understanding that lean management structures pave the way for a successful implementation of Industry 4.0 at BERTLEI, which again addresses the first research question of this thesis. The analysis of this phenomenon furthermore supports the understanding of why lean management supports BERTLEI in the implementation process, which in turn addresses the second research question of this thesis.

4.3.2 Continuous improvement

The organisation of the implementation of Industry 4.0 at BERTLEI is influenced in parallel to the lean management patterns by an understanding of the implementation as a continuous improvement process. This means that BERTLEI pictures the implementation of Industry 4.0 as a continuous implementation of new technologies and solutions around production optimisation, connectivity and automation, instead of an ending change project with a defined beginning and a defined end. A product owner from the software development department

(IP-25) explains the phenomenon in the following way: “Okay, it’s a complicated question because you cannot start to implement a smart factory and you cannot finish it because it's a process that cannot be finished. I think, and to my mind the start of the project was before the idea of the smart factory came. It's, you cannot say now we implement smart factory, it’s a process to understand what a smart factory is and understanding of smart factory changing while the process.”. It seems that IP-25 sees the implementation of Industry 4.0 as one step of a continuous process of production optimisation which began long before the term Industry 4.0 emerged.

This matches the statement of IP-37 from Section 4.3.1, who stated that BERTLEI started optimising its production after one CEO experienced lean management methods in Asia, which was years before Industry 4.0. IP-25 furthermore demonstrates the “emergence” of the implementation of Industry 4.0 by underlining that it equals a process of understanding that changes over time. A manager from the development department for services (IP-35) explains additionally why following a masterplan would not suit the needs of the implementation of Industry 4.0: “So, you planned something, you did it and when you have reached this, you plan the next step. So, there was no masterplan behind this, I think. So, that’s also meaningful from my perspective because if you execute one step and that takes a couple of months and when you have reached your milestone, you have all the experience you’ve collected through this journey and, in the meantime, you have new technical capabilities that you have to consider for your future journey. So, I think it makes sense to do this step by step and not to have a masterplan and then follow this masterplan.”. IP-35 therewith refers to the importance of enabling the use of learnings from previous experiences for future tasks regarding the implementation of Industry 4.0. These learnings also represent feedback loops in the organisational system.

A corporate in-house consultant (IP-06) explains the continuity of the implementation of Industry 4.0 and the optimisation of the corporate processes that come with it in the light of the targeted profit: “Well, you'll never be finished in my opinion. It is more like, when is it enough. Is 20 percent margin enough? 30 percent, 40 percent, I don't know. […] it will never end because you will never stop optimising the process.”. IP-06 seems to equate the continuous implementation of Industry 4.0 related technologies with the generation of efficiency and hence profit at BERTLEI. The corporate in-house consultant furthermore indicates implementation as an emergent behaviour of the firm by linking it to an explanation about “growing together of the old and the new world” in the following way: “So just like, yea, there is not a clear cut between the old and the new world. It's more like, yea, growing together.”. Supportive to how IP-06 framed the continuity of the implementation was the highlighting of a smart factory consultant (IP-38) about the standardised aim to integrate continuously new developments in the running organisational system of BERTLEI: “That's not something we'll then just sit on and say Ok now this is this smart factory we're done. So, whenever there's new developments and new technologies coming in, this is always something we'll then put into the running system and always optimise the process. So, I would say it never finishes for [BERTLEI] to have the smart factory.”. The perspectives of the large majority of interviewees all refer to the execution of the internal implementation of Industry 4.0 at BERTLEI as a continuous improvement process without a defined end. In parallel to the above cited references this phenomenon was further detected and explained by a business development manager (IP-05) who referred to a “step-by-step implementation”, a program manager for digital solutions (IP-39) who referred to a “permanent transformation”, as well as two smart factory consultants who referred to an “evolution” (IP-26) and to a “further development with an open end” (IP-22).

One example of the continuous implementation of Industry 4.0 at BERTLEI was provided by a corporate in-house consultant (IP-06) who explained the implementation of Industry 4.0 in one advanced subsidiary of BERTLEI in the following way: “Honestly, when we started in [city xyz], you never know what’s going to be in the future, and then step by step it was like building a puzzle, and then it was like, after 7 years the picture was clear, now we have an app you can just order your [product], just scan the code on the [product] and then you can just order it. So, this was just like the final step and now it’s done. So, the customers’ smartphone is really linked to our production.”. IP-06 highlights until this point that BERTLEI managed to transform one subsidiary into a fully automated factory where customers are able to order personalised products via an app. Throughout the data collection for this thesis this fully automated subsidiary was visited by the researcher, which left an impressive impression of how the implementation of Industry 4.0 can look like at an advanced level. In line with the previously cited interview participants in this section, IP-06 continued to explain that even though the subsidiary is at an advanced level of implementation of Industry 4.0 it is still subject of continuous improvement of the current processes, especially due to the fast changing technological achievements available on the market: “Five years ago or like 8 years ago there was not even a smartphone like the level of today in the market, we never thought about doing something like this. That’s what I have mentioned before, technology is changing now so fast, and that’s why you have to be opened minded and challenging your process more and more […].”. The requirement of a continuity of improvements to enable the successful implementation of Industry 4.0 at BERTLEI was last but not least also explained by a manager from the central department for digital transformation (IP-40), who spoke about the required duration of his own department to support the implementation of Industry 4.0 in the company group: “[…] it’s not seen as a project, we see it as an ongoing transformation, we have not defined an end.”. IP-40 seems to picture his central department as an ongoing requirement to support the implementation of Industry 4.0. The manager continues to explain that even the strategy of the central department for digital transformation will have to emerge over the time of the implementation: “We will adapt the strategy as we see a need for change. But we don’t say there’s a deadline for that.”, “[…] you don’t know how fast the market will change, it changes is pretty fast and so we have to do it on a year-to-year perspective.”.

The evidence above in this section demonstrates that the implementation of Industry 4.0 is understood and organised at BERTLEI as a continuous improvement of existing production and management processes. From the analysed data it can be concluded that the continuous improvement approach applied to the implementation of Industry 4.0 influences BERTLEI because it provides an understanding of the bigger whole as a living system that emerges over time. As it has been analysed in this section, the applied continuity in the implementation of Industry 4.0 builds upon feedback loops and learnings (which is further analysed in Section 4.6.1) and describes the implementation as an emerging growing together of the old and the new world, which addresses the first research question of this thesis that questions how the firm organises the implementation. The analysis of this phenomenon furthermore supports the understanding of why the continuous improvement approach influences the implementation of Industry 4.0 at BERTLEI, which in turn addresses the second research question of this thesis.

4.3.3 Trial and error

The organisation of the implementation of Industry 4.0 at BERTLEI is furthermore influenced by a trial-and-error behaviour of the organisation. The insights from the data analysis demonstrate that the planning ability of the implementation is rather low and that a trial-and-error / learning by doing approach is therefore executed in praxis, as e.g. a manager from the central department for digital transformation (IP-40) indicates it in the following: "So we, to be honest we didn't know what was happening there, […]. I think we started in 2012 and now we have 2019 and it's still in a let's say experimentation phase […] but I think what interesting is that [BERTLEI] was aware of this, […].". IP-40 indicates the uncertainty of BERTLEI in terms of the organisation of the implementation of Industry 4.0 at the beginning of its emergence and even mentions that this uncertainty and the resulting experimentations, i.e. the conscious trial-and-error behaviour, is still executed at BERTLEI. While IP-40 interprets the trial-and-error behaviour as a result of uncertainty, a manager from the development department for services (IP-35) even understands the willingness to execute the trial-and-error behaviour as a critical success factor for the implementation of Industry 4.0 due to important time savings: "The willingness to try out and fail and try again. So, we are entering from a world where we could plan everything to detail and even calculate a return on investments to a world where we don't know. […] for me, it is the actual organisational groundwork; doing things, making quick decisions, fail and gain experience and do it better the next time. That's the critical thinking. If we discuss too much about what could be, then we stand still so we have to do things even if we're not sure whether this is the right thing or not.". IP-35 seems to also believe that the overall ability to plan and organise the implementation is limited, which leads to result that only a trial-and-error approach may suit this "world where we don't know". The indication regarding gaining experiences and to do it better the next time might furthermore suggest a systemic perspective with feedback loops, learning and emerging behaviour.

A demonstrating example of the trial-and-error approach was provided by a product owner from the software development department (IP-25) who explained one of her cases from a previous project in the following way: "So I took over from my colleague, what happened before as I heard it was first idea was to make machine data transparent […]. So, this is a new field of products, and the company has to try something out and the first idea was failed. So, we had to start again and it's like in all new areas that you have to try something out and maybe it will fail maybe it will be successful. But from the first idea from the first option, I think we learned a lot of and now we can implement new products with the learning we had before […].”. IP-25 seems to evaluate the executed trial-and-error approach as normal and required for the establishment of new learning for her project and for the new areas in the firm in general. The development of solutions that failed in praxis belong to this implementation approach. An interviewed lean management expert (IP-30) from the same advanced subsidiary of BERTLEI that was referred to in Section 4.3.2 provides another example of the trial-and-error execution during the organisation of the implementation of Industry 4.0 and hence confirmed the perspective of IP-25: “So, here in [city xyz] it was always doing by trial-and-error. We had as I said before, we had to do something about automatisation and standardisation […] we made a configuration for let's say three or four tools, we tried it with the e-shop, we try to design tools only via parameters that works as simple tools like the [ABC] tools or the [DEF] tools that worked and then after being successful with that, we made the next step we took like another shade we said, okay the [GHI] tools, let’s try this with a parameter design. That also worked and then, so it was always one step after the other and it was the same with the manufacturing process.”.

The foundation of the cloud spinoff that has been analysed in Section 4.2.1 is a physical example and further demonstration of the trial-and-error approach that BERTLEI utilises to organise the implementation of Industry 4.0. The decision to invest in this spinoff was made on the basis of experimentation as a manager from the central department for digital transformation (IP-40) explains: “[…] So I think we knew that something was coming and in 2015 we also tried with experiments establishing a start-up like [cloud spinoff] and trying out what it means the platform business to us, we are still for us in the evaluation period, how we can play a role in the future and what does it mean for us, for our customers […].”. A second physical examples of the corporate trial-and-error approach, also analysed in Section 4.2.1, is the foundation of the demonstration smart factory that was founded as a lighthouse project in 2018. This demonstration smart factory was founded to try out and test new solutions in a showroom environment in the United States, as a program manager for digital solutions (IP-39) explains it in the following: “Another thing is, like what we are doing at the smart factory in [the United States], there we can try new kinds of processes and new technologies and we have a productions similar field, but not the pressure which has the customer with his customers. Where you don't have the time to experiment with those things and I think there we can show many benefits out of it.”. IP-39 therewith indicates that the foundation of the demonstration smart factory may be understood as a strategic action to build a safe environment for testing.

The data analysis above in this section leads to the conclusion that BERTLEI performs a trial-and-error approach to the organisation of the implementation of Industry 4.0. On the basis of the evidence from the data one could argue that the trial-and-error approach emerged due to uncertainty and a limited ability to plan the implementation of Industry 4.0. The execution of the trial-and-error approach may lead to simplifications and time savings in the implementation process. The detection of the utilised trial-and-error approach supported the understanding of how BERTLEI organises the implementation of Industry 4.0, which addresses the first research question of this thesis. The further analysis of this phenomenon supported the understanding of why this approach is executed in the organisational system, which in turn addresses the second research question of this thesis. Since the applied trial-and-error approach builds upon failing, learning and adaptation, it may therefore suggest an understanding of the implementation of Industry 4.0 as a sum of emergent behaviours of a living system.

Sections 4.3.1, 4.3.2, and 4.3.3 demonstrated the presence of lean management structures, continuous improvement approaches and a trial-and-error approach in the organisation of the implementation of Industry 4.0 at BERTLEI. Whereas the data analysis led to the conclusion that lean management structures build, optimise and standardise relevant processes, the continuous improvement approach as well as the trial-and-error behaviour have been found to be present due to uncertainty in the market, a limited ability to plan the implementation, and due to simplifications and time savings in the implementation process of Industry 4.0. The continuous improvement approach as well as the trial-and-error behaviour furthermore lead to the understanding of the implementation of Industry 4.0 as an emerging phenomenon. An illustrative summary is provided in Figure 10. Figure 10 captures the three discussed influences as well as their underlying mechanisms that have been explored and analysed in textual form before in this section. From the analysed evidence of the data it can be summarised that lean management structure, a continuous improvement approach, as well as the trial-and-error behaviour are part of how BERTLEI organises its implementation of Industry 4.0 in the organisational system.

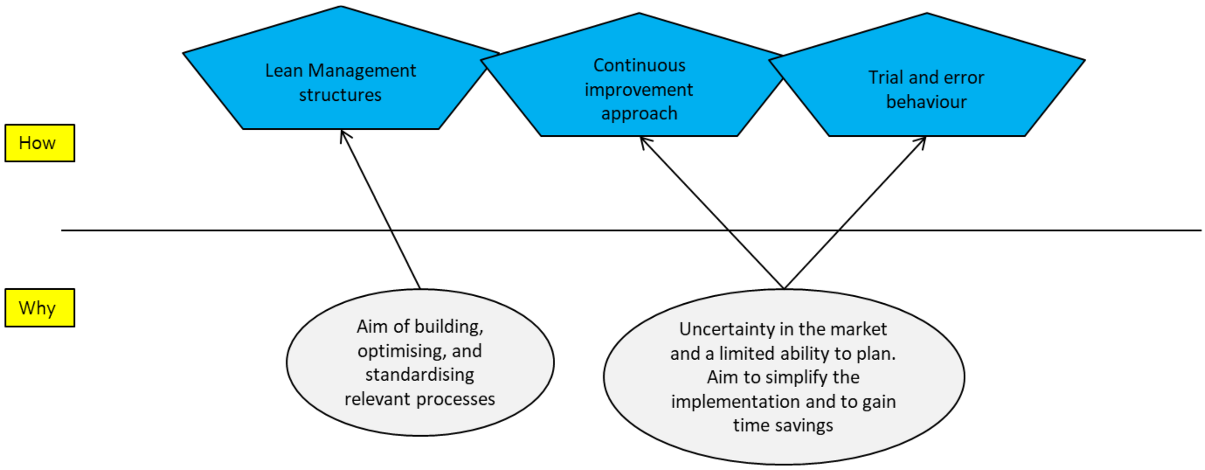


Figure 10: Internal influences on the implementation of Industry 4.0

4.4 Actors and their characteristics

The implementation of Industry 4.0 is organised and executed by actors in the system. The analysis of the characteristics of these actors may therefore lead to a better understanding about how BERTLEI implemented Industry 4.0 as well as why this implementation emerged as it did. The new developed system model at the end of this chapter will demonstrate the interdependencies and hence the relevance of the actors and their characteristics for the overall system and the implementation of Industry 4.0. The actors in the system are divided into managers and employees. For this thesis employees are defined as the people who are commissioned with value-adding activities. Value-adding activities are those for what a customer would be willing to pay. Employees can be shop floor workers as well as office staff, e.g. machine operators as well as software programmers. Managers refer to the group of people who are commissioned with organisational and management task. They usually do not directly perform value-adding activities but are responsible for the successful organisation of the implementation of Industry 4.0 at BERTLEI. Managers may be present at various levels in the organisational structure. They do not necessarily have authority over employees. The characteristics of the managers are the focus of this section, since these actors provide perspectives about the organisation and management of the implementation of Industry 4.0 at BERTLEI, which this thesis aims to explore in.

4.4.1 Management fear of resistance to change

The main characteristic of the actors, which was detected throughout the data analysis to be relevant to the understanding of the organisation of the implementation of Industry 4.0, is the fear of the management of meeting resistance to change from the employees of the firm. This fear was expressed in various ways throughout the interviews, such as by a business development manager (IP-05), who highlighted the risk of employees not accepting the implementation of new technologies: “What’s very important is the support of our shop floor workers and they really have to be convinced that these new technologies will help them in their daily tasks. Otherwise, they will not accept these new technologies […].”. The statement indicates an awareness by IP-05 about the requirement of employees’ support in the implementation of Industry 4.0 as well as that there is a risk that this support may not be present. A lean management expert (IP-30) supports the perspective of IP-05 by referring to projects of BERTLEI that have failed in the past due to miscommunication and non-acceptance: “I guess there are a lot of examples with good products, with good solutions where people did not think, who would work later with those systems and they were not asked how to work with it and then it was not successful. So, I guess soft success factors, the biggest one is to make sure everybody who has contact with the new implementation also accepts it and works with it or has a benefit out of it.”. The provision of this example also indicates that IP-30 acknowledges a certain level of fear for the potential resistance to change from the employee’s side.

A smart factory consultant (IP-38) provides another example of the present management fear against employee resistance by highlighting again the importance of communication and involvement of the employees into a project to make them understand their personal benefits of the change: “So that is always very important that one makes sure that the people involved also understand why one does it. And what the benefits are for them, because what we see is, I have done it ten years like this, it works for me and now this new option, I have to click two more buttons. It’s worse. So that’s one very critical part that’s always making the people working with the system understand what is their benefit as well.”.

4.4.2 Employee fear of unemployment

So far, the data leads to the understanding that the management fears a potential resistance to change from the employees of the firm, which could lead to failures in the overall implementation of Industry 4.0. It could furthermore be identified that the management interprets the potential resistance to change as a result of fear of the employees of losing their jobs due to the implementation of Industry 4.0, as e.g. an interviewed corporate in-house consultant (IP-06) indicates in the following: "Although, it's people's fear that you have to consider because it's an efficiency programme, in the end, smart factory and if you do not explain to the employees that it is not about replacing them but making sure that a lot that is done is repeatable work. […] but if you do not explain it, they fear that they will just lose their jobs towards smart factory.". IP-06 highlights an expected fear of the employees which may stand in relation to the previously mentioned potential resistance to change of the employees.

A product manager from the connectivity department (IP-37) confirms the reasonableness of this expectation by adding the following about the elimination of jobs due to the implementation of Industry 4.0 at BERTLEI: "People will lose their jobs because of digitalisation, but that's one of the biggest challenges we have. Also, within [BERTLEI]. At one point we will reduce the number of machines.". The product manager continues to indicate that this fear of the employees may be followed by a resistance to support the implementation, as explained in the following: "We are still working with people and that's often forgotten. […] everybody is telling about digitalisation and so on, but you read every time in the news, you read about losing jobs because of digitalisation. And if people do not want to supply, they will not do it.".

On the basis of the above cited statements, one could argue that the management interprets the potential resistance to change as a result of fear of the employees of losing their jobs due to the implementation of Industry 4.0. IP-06 (the corporate in-house consultant), furthermore added a demonstrative example of the executed people reduction of one of his previous projects in one of the subsidiaries of BERTLEI: "So that's the result of what we saw in [city xyz]. And you can connect everything, that's correct, we started with 14 employees, at the end three and a half. So that's the result out of it, and we had, yea, this is like the way you can earn at the end money. […] the fear is that they will lose their job. Honestly, I think for a lot of people it will happen, the connectivity will destroy a lot of easy jobs, that's my opinion, I saw it in [city xyz]. We did it.". The example of IP-06 demonstrates that the implementation of Industry 4.0 reduces the quantity of employees required in the factories of BERTLEI. The example also demonstrates why the management expects the employees to fear that their own job will be redundant after the implementation, which in turn may lead to a potential resistance to the change.

4.4.3 Management competences and commitment

The evidence from the data further indicates that the management evaluates change management competences and commitment as important management characteristics to minimise the analysed risk of the employees' resistance to change, as e.g. a rollout manager from the central department for digital transformation (IP-41) indicated in the following: "[…] we really try to reach every employee and to convince every employee of that initiative, because I think the most important factor in digital transformation is the employee and the mindset of the employees. Because if you're, if the employees don't want to work on digitalisation they don't, […] how do you call that [they block], such initiative or any topic because they are not committed. So, and [BERTLEI] is really working on that mind set and on that commitment of all employees. It seems that IP-41 evaluates the importance of a sensitive change management and handling of the employees as high and the real risk of resistance to the implementation of Industry 4.0 as present. It furthermore seems that the management of BERTLEI tries to get the employees "on board" to believe in the benefits of the implementation.

A product manager from the connectivity department (IP-37) indicates a similar picture by explaining the importance of involving the employees in the implementation process in the following way: "You have to explain to them, you have to teach them, you have to just involve them in the process. And that they can bring on their, bring in their own ideas. So, if you will be really successful with the smart factory, it will not work if you have a boss that stands in front of his crew and say, you have to do this, I decided this.". One could argue that the statement of IP-37 provides room for an understanding of the implementation of Industry 4.0 as partially a bottom-up approach, which was also supported by IP-41, who referred to such approach as a success factor against potential resistance to change: "[…] we try, really try to do that bottom-up and not just top down. That is one main reason that we are successful in what we do.”. So far, the data leads to an understanding of the organisation of the implementation as integrative and cooperative to eventually minimise the risk of resistance.

IP-41 (the rollout manager from the central department for digital transformation) provided an example of how she executes the communication and involvement of the employees in her projects: “I try to also, if it’s not too many, I try to contact them also personally, I say they can always contact me and so we try to really talk to them in person or maybe also if it’s more than just a few to have the option to have a call with us. So, we try to do it as transparent as we can […].”. She continues to explain: “[…] we try to have articles in the intranet, which every employee can read. And they are free to make comments.”. IP-41 thereby indicates two communication channels of the management that BERTLEI utilises to reach its employees and to manage the change. As analysed in Section 4.2.2, the references from the data lead to the understanding that the appointment of rollout managers, who are listening to the people, to their fears, and to their concerns, are part of the change management actions of BERTLEI. They enable direct communication to the internal stakeholders of the firm and therefore reduce potential conflicts and resistance to the implementation of Industry 4.0.

A second detected action of change management is a guarantee that BERTLEI granted its employees to not being released due to the implementation of Industry 4.0, as e.g. a product manager from the connectivity department (IP-37) explains: “They got the real assurance that they will not lose their job, that they will stay in the company, they will get other qualifications and so on. Training, they can also do other jobs, work on other machines, because work is still there, but on another point in the production.”. As IP-37 indicates, BERTLEI reduces the fear of its employees of losing their jobs due to Industry 4.0 by offering training and other positions in the firm. A corporate in-house consultant (IP-06) furthermore supports this point by referring to the following: “[…] there is a clear statement of the management that [BERTLEI] is growing and growing and no one, there, no one has to be, yea, there is no reason to, to have fear inside, because on Industry 4.0.”. In this sense the data may now lead to the conclusion that change management competence is an important characteristic of management positions at BERTLEI to support the organisation of the successful implementation of Industry 4.0 and ultimately to reduce the fear of the management about the potential risk of employees’ resistance to change. The evidence from the data lead to the conclusion that the granted guarantee of the management, that no employee will be released due to the implementation of Industry 4.0, supports the integration and motivation of the employees to participate in the change.

The long-term investments and organisational structure changes, as well as the appointment of one family-member owner for the position of the Chief Digital Officer (both analysed in Sections 4.2.1 and 4.2.2 at the beginning of this chapter) demonstrated the commitment of the senior management to Industry 4.0. As analysed in Section 4.2.2, the fact that BERTLEI appointed one family-member owner as the highest responsible management position indicates the importance the firm places on the implementation of Industry 4.0, as e.g. a rollout manager from the CDDT (IP-41) indicates in the following: "[…] we have the chief digital officer and also to mention is, that it's one family member that is actually having that position and let's say for us it's very important to transform digitally […].". It seems that IP-41 interprets the role of the CDO as the head of the CDDT as an important sign to the stakeholders in the firm. IP-41 continued explaining this importance and that now all employees know the specific face responsible for the change: "It is a very important sign that one family member is taking, so Mr. [confidential] is taking this position of the chief digital officer. And, so also everybody knows who is working on that in the organisation, so who is the face of the digital transformation […].". The references indicate that BERTLEI appointed one family member as the CDO to demonstrate highest management commitment to the employees of the firm, which leads to the assumption that this action was undertaken to eventually manage the risk of potential resistance to change.

The communicated commitment of the management was further underlined by a smart factory consultant (IP-02), who referred to statements of the top management regarding the requirement to meet a certain return of investment (ROI) of Industry 4.0 related departments in the following way: "[…] management is not as strict with the return on investment of the [connectivity department] or the Industry 4.0 department from [BERTLEI] than with other departments, because they really think, that's what they always say in meetings, and they really believe that, they really believe that, that its necessary to go to this step and develop and invest into Industry 4.0 even though it does not give you the return on investment you wish to have, but it's necessary to survive in the future as a company.". The statement of IP-

02 indicates that BERTLEI committed to the implementation of Industry 4.0 even though the ROI may not be calculable yet.

The implementation of Industry 4.0 is organised and executed by actors in the system. These actors have characteristics that the data above in this section demonstrated as being influential for the emergence of the implementation of Industry 4.0 at BERTLEI. The main characteristic was analysed to be the fear of the management to meet resistance to change from the employees of the firm. This fear in turn was analysed to be a result of the expected fear of the employees to lose their jobs due to the implementation of Industry 4.0. The references in this section furthermore indicated that the management evaluates change management competences and commitment as important management characteristics to minimise the fear of the employees and hence potential resistance to change.

The appointment of the CDO and the granted guarantee that no employee will be released due to the implementation of Industry 4.0 have been demonstrated to be two influential actions of change management that supported the implementation at BERTLEI. It can be summarised that the detection of the actors' characteristics support the understanding of how BERTLEI organised the implementation of Industry 4.0 in the organisational system, which thereby addresses the first research question of this thesis. It can furthermore be summarised that the analysis of these characteristics supports the understanding of why BERTLEI organised the implementation of Industry 4.0 as they did, which in turn addresses the second research question of this thesis. The analysed evidence of the data jointly demonstrate the complexity of the relationships between the actors, their characteristics, and their actions. An illustrative summary of the insights of this section is provided in Figure 11. Figure 11 captures the actors' characteristics as well as their underlying mechanisms that have been explored and analysed in textual form in this section.

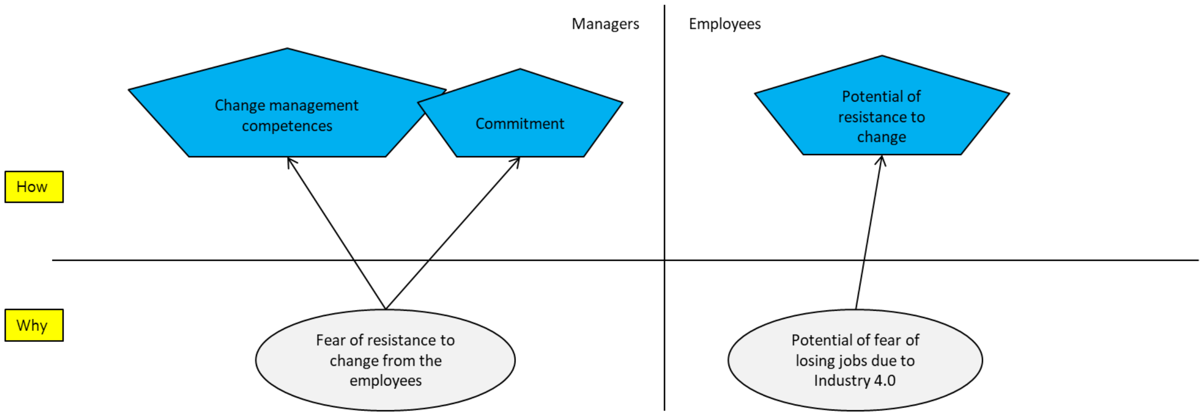


Figure 11: Actors and their characteristics

4.5 Characteristics of relationships and interactions

The analysis of the actors' characteristics in Section 4.4 extended the understanding of how BERTLEI organises the implementation of Industry 4.0, as well as why this organisation emerged as it did. Throughout the data analysis it could furthermore been identified that the exploration of the relationships between actors and groups of actors may also support the understanding of BERTLEI's organisation of the implementation. Groups of actors such as teams, departments and subsidiaries are defined in the context of this thesis as "self-organising local relationships" (SLR) of which more than one exists in the organisational system, and which have the ability to change. Further guidance about the location of the SLRs in the overall organisational system is provided in Figure 14 and Appendix O. Autonomy for self-organisation, a bottom-up approach and partial connectedness are the three relationship characteristics that were detected in the data analysis to be relevant to the understanding of the implementation of Industry 4.0 at BERTLEI, as the following section will demonstrate.

4.5.1 Autonomy for self-organisation

In the process of collecting and analysing the data for this thesis, it was identified that the implementation of Industry 4.0 at BERTLEI is organised in a decentralised manner in the single teams, departments and subsidiaries of the firm. A business development manager (IP-34) indicated this with the following two statements: "[…] basically most departments would say that they are trying to, or they are working on that digitalisation in their departments, in their processes.", "So all the different departments are also setting up their own digitalisation solutions or units or that's really coming through the entire company […]". IP-34 seems to know that the single departments of BERTLEI self-organise the development of Industry 4.0 solutions to enhance their individual processes. A product manager from the connectivity department (IP-37) extended this perspective from the mentioned departments to the relationships between the subsidiaries and the headquarter of BERTLEI by stating the following: "Because every production area do this on themselves. So, here everybody's responsible for it. […] every production area has to do on his own, because they are independent companies on the whole structure.". IP-37 describes the independence in the company group and hence the responsibility of each subsidiary to organise the implementation of Industry 4.0 by themselves. The product manager continues to elaborate on this point in the following way: "We have every production location for example Austria, Switzerland and so on, is responsible for his own. So, they are not basically controlled by the central department, because every production location is producing a different machine, so they are not comparable to each other.". Therewith IP-37 indicates furthermore that the implementation of Industry 4.0 is not organised through top-down management by the analysed CDDT in Section 4.2.1 and underpins this point by referring to the individuality of the single subsidiaries that produce different products which are not comparable to each other.

In line to the perspectives of IP-34 and IP-37, lean management expert (IP-30) adds a similar perception but based on the responsibility of the actors in teams on the shop-floor to self-organise and execute the implementation: "So we have that main goal. But how we manage the project was not really defined. That's more like here on the shop floor.". IP-30 seems to acknowledge that a greater goal regarding the implementation of Industry 4.0 exists, but the responsibility to reach that goal is based on self-organisation of the actors in the teams on the shop-floor level of the firm. So far, the evidence from the data leads to an understanding that the organisational structure of BERTLEI grants the local relationships, i.e. groups of actors such as teams, departments and subsidiaries, autonomy for self-organisation in the implementation of Industry 4.0 in their respective environment. The evidences further indicate that the implementation is organised in a decentralised manner, which was underlined by an employee from the department for new digital business and after sales services (IP-27), who denied that a central responsibility for the implementation exists at

BERTLEI: “So I would say, it’s not really that somebody at the moment is really responsible for all projects.”.

An example of the appearance of self-organisation in relation to cooperation between start-ups that BERTLEI invested in and the established departments and subsidiaries of BERTLEI was provided by an interviewed investment manager from the corporate venture capital firm (IP-24), who explained the following: “Investing in start-ups is an activity that we do only out of the [BERTLEI] venture unit, if it comes to collaboration projects, integration projects and development projects and other and let’s say partnering projects, then it's the responsibility of the business units that actually implement, develop, to sell products or services at the end.”. IP-24 indicates the responsibility of the departments to self-organise and build cooperation with the Industry 4.0 related start-ups that BERTLEI centrally invests in through its venture capital firm that has been analysed in Section 4.2.1 above in this section. The example of IP-24 demonstrates not only the freedom but also the requirement to self-organise the implementation of Industry 4.0 in the organisational system. This requirement was confirmed by a manager from the central department for digital transformation (IP-07), who provides a perspective about interplay between the decentralised self-organisation and the existence of the CDDT at BERTLEI: “So, we have the central department digital transformation for the strategy. But we set the departments themselves so maybe, for example, the sales department have to improve their process themselves. So, the central department can help them and can help them to set up a strategy, but they have to improve their own process.”. IP-07 therewith confirms the responsibility of the departments to self-organise the implementation but further indicates that his own department, the CDDT, develops the wider strategies for the corporate implementation of Industry 4.0.

A second interviewed manager from the CDDT (IP-41) supported the standpoint about the expected independence of the actors in the system in her response by highlighting the “freedom” to self-organise, towards the “expectation” to self-organise in the following way: “[…] they are free to evolve ideas and so I would say that they are, that they can do a lot on their own and they are also allowed to do a lot on their own. They are, so [BERTLEI] wants them to have ideas and work on their own digital solutions.”. The statement of IP-41 may also indicate a form of change management action to involve the employees, which in turn may further indicate an action against potential resistance to change as analysed in Section 4.4.3, but also an action to empower innovation from bottom-up, which will be further analysed in the following Section 4.5.2. The evidence from the data above, however, leads to the conclusion that BERTLEI not only grants autonomy to its teams, departments and subsidiaries but also expects this autonomy in regard to self-organise the implementation of Industry 4.0 successfully in their respective environments.

A consequence of the self-organising nature of relationships is that different subsidiaries and departments are at the same time at different implementation stages of Industry 4.0 in the company group. It was detected that this decentralised organisation of the implementation and the resulting different implementation stages made it difficult for the interviewees to respond to questions about the implementation progress at BERTLEI. For example, a product manager (IP-14) explains in the following: “This is, this is not easy to tell, because [BERTLEI] consists of a lot of different organisations and organisational units, with a variety of products. So, I would say that [BERTLEI] has different products in different parts of the firm in different stages.”. It seems that the product manager explains the phenomenon of different implementation stages due to the large variety of different products in the firm. Most other respondents connected the different implementation stages to the large size of the organisation, however, not due to the large variety of different products but due to the different capabilities of the actors in the respective subsidiaries, departments and teams. A smart factory consultant (IP-22) explained in the following: “[…] we are continuously adding more and more features. And we are also use of course the feedback. But, that’s why it is hard to tell, for the entire company. It really depends on area to area, but the people have a real, clear picture, but I have the feeling that some still are not so much into the topic yet.”.

It seems that in the perspective of IP-22 some actors in the firm are more into the topic than others, which was as well highlighted by an in-house corporate consultant (IP-06) as the reason for the different implementation stages in the following: “This is also, it depends on the department, some cases well, the head of the department is smart enough to do everything by his own, sometimes it is like this, so he knows and it is already linked to all the partners, it is just doing it. In other cases, we need some support, […] so, yea, there is a huge difference between them.”. The phenomenon of different implementation stages due to different capabilities of the local actors and as a result of granting the freedom to self-organise was demonstrated furthermore by a product manager for software and service products (IP-

36), who highlighted how and why her department is more advanced in the implementation of Industry 4.0 than other departments in the firm: “[…] within the service department, the mindset it's much more open and they very much understand that we should collect data from the machines and the field and like build algorithms for predictive maintenance or stuff like that. And then in other departments they're just like you have to convince them, you have to really get them started. So, there are definitely different stages for smart factory projects within our company.”. IP-36 thereby confirms the dependence of the successful implementation of Industry 4.0 at BERTLEI on the actors’ capabilities and motivation to involve themselves in the change process. One could now argue that this also provides evidence for the requirement of the change management competences analysed in Section 4.4.3, as this competence may support the effective adjustment towards the required employees’ motivation and capabilities.

The above cited references from the data lead to the conclusion that BERTLEI grants but also expects autonomy in its teams, departments and subsidiaries in regard to self-organise the implementation of Industry 4.0. The references also demonstrated a fragmented result of implementation stages due the different capabilities and motivation of the actors to self-organise. The CDDT may set a wider goal as IP-07 mentioned above and may also consolidate and standardise Industry 4.0 solutions as it was analysed in Section 4.2.1. However, the references from data demonstrate that the local relationships, such as teams, departments and subsidiaries, are meant to manage the implementation of Industry 4.0 on the basis of self-organisation. Hence, these local relationships are defined in the context of this thesis as “self-organising local relationships” (SLR). On the basis of this conclusion, one could now argue that BERTLEI organises the implementation of Industry 4.0 in a decentralised manner due to an aim of reducing the management effort that it would take to organise the implementation from one centralised position.

4.5.2 Bottom-up approach

The previous section analysed the detected phenomenon that BERTLEI grants and expects self-organisation to and from its SLRs, as well as that the successful implementation of Industry 4.0 may depend on the capabilities of the actors inside the SLRs. Further evidence from the data analysis underlines this point and demonstrate the aim of BERTLEI to utilise the employees’ capabilities and innovation potential from bottom-up to support the implementation of Industry 4.0, as e.g. a rollout manager from the central department for digital transformation (IP-41) confirmed in the following: “[…] it’s very important that it, that the idea comes out of the department, because they know the processes and they know where the actual problems are. So, they should have the idea of what they can do and what could be improved.”. IP-41 indicates that the relevant knowledge may be located at the bottom of the firm, which leads to her conclusion that this must be the origin from where Industry 4.0 solutions are developed and implemented. The advantages of utilising the employees’ knowledge was also supported by a product manager from the connectivity department (IP-37), who referred to the close intertwining between the employees and the actual implementation of Industry 4.0: “So you have to use the knowledge of your people to improve the system every day and if they know about how it works and if they understood it, they will help you […].”. IP-37 indicates the value for BERTLEI of utilising the employee’s knowledge and hence to implement Industry 4.0 from bottom-up in a continuous manner.

One action to involve the employees and to build knowledge about the topic was analysed in Section 4.4.3 when the interviewed rollout manager from the CDDT (IP-41) highlighted that BERTLEI shares publications about the implementation of Industry 4.0 in the company-intranet, which the employees can read and comment on. Such evidence may now lead to an understanding of why IP-41 indicates a strong relationship between the utilisation of the employee’s knowledge, i.e. bottom-up innovation, and the overall successful organisation of the implementation of Industry 4.0, as highlighted again in the following: “[…] we try, really try to do that bottom-up and not just top down. That is one main reason that we are successful in what we do.”. One could argue, on the basis of the data analysed so far, that the autonomy to self-organise and the aim to innovate from bottom-up support and are part of “change management”, which at the same time reduces the effort to organise the implementation from one centralised position. The data at least might suggest that these characteristics and phenomenon are closely intertwined to each other.

An indication for the aim of the reduction of centralised management effort was provided by a product manager for software and service products (IP-36) in the following way: “So we give a lot of responsibility to the teams and to the individual employee. So, it's really just to have a general overview what they are doing and is it worth investing the money. But it's not like micromanaging because our management very much trusts in the capability of the team. So, the teams are very independent when they're where, when they have started a project and can make a lot of decisions very independent.”. It seems that IP-36 referred to the intention to grant independence to the SLRs and thereby to shift the responsibility of the implementation and to avoid centralised management effort, which he calls “micromanagement”. The product manager continues to elaborate on the role of the CDDT in the relation to the autonomy of the SLRs in the following way: “[…] the individual department within the different business unit they have some authority about what they want to do or not. So, if it’s not completely against the strategy overall of [BERTLEI], then they can decide to do something even though the central department recommends doing something different.”. Thereby, IP-36 underlines again the autonomy of the SLRs as well as the low level of centralised management structures in the organisational system.

A detected counterpoint to the perspective of self-organisation and bottom-up innovation at BERTLEI appeared from a program manager for digital solutions (IP-39), who refers to a change in the management approach from bottom-up to top-down in the following way: “I think in the beginning it was a bottom-up decision and experience from different parts of the company and up to now, we have a very clear vision and a clear strategy which [the CDO] is driving and improving. And so, I think it changed over the years.”. IP-39 seems to evaluate the presence of a top-down corporate implementation as a substitute to the bottom-up approach in the organisational system. However, through the analysis of the data set it was demonstrated in this section that the presence of the CDDT, the presence of the CDO, and nor the presence of a greater corporate implementation goal changes the conclusion that BERTLEI organises the implementation of Industry 4.0 through the self-organisation of local relationships from bottom-up. It may further be concluded that BERTLEI aims to utilise the employees’ knowledge as well as integrate the employees as an action of change management. The data analysis indicated a relationship between the executed bottom-up approach and the overall successful organisation of the implementation of Industry 4.0. It may furthermore be concluded that BERTLEI aims to reduce the management effort that it would take to organise the implementation of Industry 4.0 from one centralised position in the complex organisational structure of the firm.

4.5.3 Partial connectedness

The data analysis identified that relationships between actors involved in the implementation of Industry 4.0 at BERTLEI are rather situational and loosely coupled rather than tight and rigid. Several implementation projects are executed at the same time and each project is managed by a separate project team, as an interviewed business development manager (IP-05) explained in the following: “Yes, so for each of these small projects within the transformation from the factory to a smart factory, we have like a team who takes care of these small project and we have maybe 10 or 15 ongoing of these small projects, and for each of these projects we have a project team.”. IP-05 thereby not only indicates that projects are executed parallel to each other, but also that all implementation projects are managed by a separate project team. This point was supported by a product owner from the connectivity department (IP-31), who referred to the implementation teams in his area that currently work in parallel to each other: “You normally don't have one team who takes care of these, of all the smart factory issues. Currently there are five, six teams involved in this in this area, and they have to share the knowledge and talk with each other. So, I think communication is one of the key soft skills factors.”. IP-31 seems to confirm the existence of more than one implementation team at the same time and evaluates the communication and exchange of information between these teams as important for the success of the implementation in the bigger picture. One could argue that this parallelism of implementing different Industry 4.0 solutions, as well as its management by separate project teams, may have emerged due to the self-organising nature of relationships at BERTLEI, which was analysed at the beginning of this chapter.

Projects used to be organised in functional silos, meaning that project tasks moved from one department to the next, such as from the development department to the IT department, to the automation department, and finally to the service department during the implementation process of one solution. The competences required for the implementation were hence comprised and isolated in their respective departments. A software engineer (IP-11) speaks to this point in the coming quotation, and BERTLEI realised that this type of organisation is not effective for the implementation of Industry 4.0 and therefore changed its approach to build cross-functional teams, where all required competences come together situationally in a team to develop and implement a specific solution over a period of time: “So, in the beginning of [BERTLEI], we were structured differently. We had like functional silos so to speak in details.

So, this turned out not to be beneficial for us. So, we made a move towards cross-functional teams. There you say to provide the customer solution, everyone that's necessary or everyone that's involved in contributing to the solution is required to be in the same team, so to speak, so you would have a team of product owners, project managers, software developers, software engineers, quality assurance for software operations, and service as well. Whatever is necessary to deploy the solution is a member of the same team and this turned out to be a better way of organising things.". It seems that IP-11 has experienced the organisation in functional silos as not as suitable compared to the organisation in cross-functional teams. The software engineer furthermore indicated that this change in the organisation of the actors emerged due to and in-between the implementation of Industry 4.0.

The emergence of the cross-functional implementation teams was also recognised by a team and project leader from the department for predictive services (IP-32), who referred to new dependencies between the SLRs and different competences especially in the development phase of new solutions: "It is pretty new that the development and the IT have to work so closely together because in the past development could develop their own products that are machines and that was fine. And now are they depending on like the right database and enough capacity of data […], so I think it will be what it is right now pretty close interdisciplinary team, with the IT, the development and the product management. And this is new. And not so easy.". IP-32 seems to not only evaluate the emergence of the cross-functional teams as a result of the implementation of Industry 4.0, but also indicates the challenge to situationally depend on each other.

The challenge and importance of building such relationships between cross-functional actors and SLRs was also underlined by a program manager for digital solutions (IP-39) in the following way: "[…] it's really necessary that you enable a company to connect their people in between the departments and that they make their focus on this point, because that's really something which slows you down. So, it's very difficult to build up the communication and that we work together on these goals. And I think this was something which we underestimated a little bit.". IP-39 seems to evaluate cross-functional teams and hence relationships and communication between actors and departments as an essential mechanism for an efficient implementation with regard to time requirements. Furthermore, IP-39 indicates that the acknowledgement of the importance of cross-functional team structures is a newly learned and hence emergent behaviour due to the implementation of Industry 4.0. The data may lead at this point back to the role of the previously analysed CDDT, whose aim it is to function as a networker and "glue" between the different actors and SLRs in the company group, as a manager from the respective department (IP-40) reported in the following: "[…] the challenge within digitalisation is that you don't think in functions like sales, production, development, research and so on, but you have to bring them all together, and this is kind of where we are the networker we are the glue between all these, to bring them together, to think holistically and also to optimise holistically, not only for a certain function. […].". The reference of IP-40 leads in this respect to an understanding of the CDDT as an active enabler for the formation of effective cross-functional implementation teams.

It may be concluded at this point that the evidence from the data leads to the understanding that BERTLEI executes different implementation projects at the same time managed by separate project teams. It may further be concluded that the different implementation teams consist of different competences that work cross-functionally and situationally together depending on the specific requirements of an implementation project. The references lead also to the conclusion that this organisation of the relationships between actors emerged due to the implementation of Industry 4.0.

One example of the different actors that may be involved in implementation projects was provided by a manager from the CDDT (IP-07), who referred to a set of different competences that she evaluates as important: "It depends on the project. Important part is, I would say is I.T. department you need. Then when it's a project in a production area, you need the production area with the departments maybe. Maybe also the sales department, if you want to improve the whole value stream, you also need the sales department. Also, the development department if you want to look at the whole value stream, you also need a development department. Yeah. And also, the service department for the after sales for example. So, it depends on the on the project.". IP-07 underlines again the fact that the cross-functional implementation teams consist of situationally connected actors with different competences. The same point was explained by many other interviewees, such as by a smart factory consultant (IP-26), a lean management expert (IP-30), a business development manager (IP-05) and a product manager for software and service products (IP-36), who all highlighted the dependence between the individual projects and the required competences in the individual implementation teams, as e.g. IP-36 did in the following short statement: “So really cross-functional teams. And it really depends on what this certain project is about.”.

The quantity and variation of the involved actors in an implementation team depends, however, not only on the required competences to address the needs of the project, but also on the question how many stakeholders will be potentially affected by the change. This means e.g. that implementation projects which affect processes in one department only may be of a smaller project team, whereas implementation projects that potentially affect several subsidiaries or even the whole company group may include several more decision-makers from all potentially affected entities in the firm, as an employee from the department for new digital services and after sales services (IP-27) explained in the following: “So all the digital solutions, so it always depends how many people work with the system you want to implement or the tool you implement and then if the size is like, okay it’s company-wide, then you really have to include the most departments, and if it’s only something for a small department, then it’s normally only the department, the IT, I would say the controlling and the [evaluation-committees].”. IP-27 thereby indicates that the quantity of members of an Industry 4.0 related implementation team varies depending on how many people would have to work with the system afterwards. This point was supported by a smart factory consultant (IP-38), who determined as well that the quantity and variation of actors in a project team depends on the “scale” of the new solution: “[…] depending on how deep you want to scale it, you involve more and more people so I would say it's not a typical standard of one team that goes from one production facility to then to another to implement the solution.”. IP-38 thereby confirms the statement of IP-27 and hence leads to an understanding that the participants in an Industry 4.0 implementation project team do not only depend on the required competences but also on the outspread of the project.

This section analysed the characteristics of relationships and interactions between actors and groups of actors organising and executing the implementation of Industry 4.0 at BERTLEI. Autonomy for self-organisation, bottom-up approach and partial connectedness are the relationship characteristics which the data above in this section demonstrated as being influential to the implementation of Industry 4.0. The data analysis leads to the conclusion that BERTLEI organises the implementation of Industry 4.0 through the self-organisation of local relationships in their respective environments to involve stakeholders and increase bottom-up innovation. Different implementation projects are managed by separate project teams at the same time, whereas the separate implementation teams consist of different competences that work cross-functionally and situationally together depending on the specific requirements of an implementation project. It can be concluded that BERTLEI aims to utilise the employees' knowledge and that it is expected that such situational and loosely coupled relationships lead to greater effectiveness of the peoples' capabilities and motivation than if they were tight and rigid. This organisation of the relationships between the SLRs enables BERTLEI to flexibly loosen or tighten the interactions between actors according to the situational need. Last but not least it can be concluded that BERTLEI aims to reduce the management effort that it would take to organise the implementation from one centralised position in the complex organisational structure of the firm. It can be summarised that the identification of the relationship characteristics analysed above in this section supports the understanding of how BERTLEI organised the implementation of Industry 4.0 in the organisational system, which addresses the first research question of this thesis. It can furthermore be summarised that the analysis of the relationship characteristics supports the understanding of why BERTLEI organised the implementation of Industry 4.0 as they did, which in turn addresses the second research question of this thesis. The analysed evidence of the data jointly demonstrates the complexity of the relationships between the actors in the organisational system. An illustrative summary of the insights of this section is provided in Figure 12. Figure 12 captures the relationship characteristics as well as their underlying mechanisms that have been explored and analysed in textual form in this section.

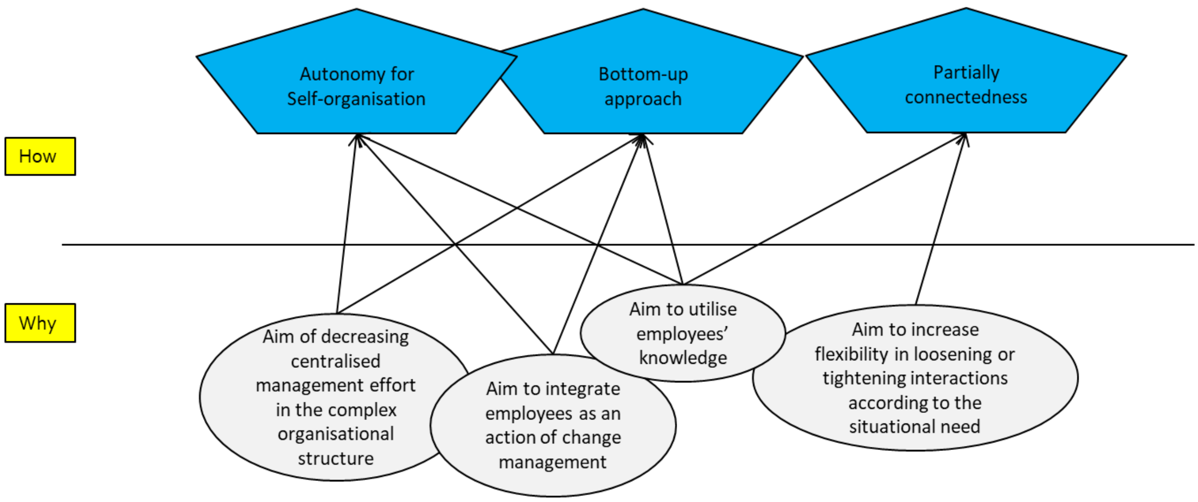


Figure 12: Characteristics of relationships and interactions

4.6 The implementation of Industry 4.0 in the organisational system

The previous sections in this chapter have identified, analysed and demonstrated the emergent behaviours, the internal influences, the actor's characteristics and the relationship characteristics that emerged due to, and influenced the implementation of Industry 4.0 in the organisational system, i.e. the firm BERTLEI. The categories and themes are illustrated again in Table 9. These themes represent furthermore the conclusions of the data analysis so far and answer the first research question of this thesis. This section will further frame the identified themes under the perspective of systems theory and conclude by developing a comprehensive system model that represents the knowledge generated from the data analysis in this chapter. However, before developing the system model of the implementation of Industry 4.0, one last identified theme of the data analysis will be examined in the following. The existence of emergence due to feedback and learning represents an important entity for the development and the understanding of the implementation of Industry 4.0 as a Complex Adaptive System that evolves over time, as the following will demonstrate.

Themes	Category groups	Categories
Complex adaptive behaviour / implementation actions	Organisational structure changes	Foundation of the connectivity department
		Foundation of the central department for digital transf.
		Foundation of a cloud platform
		Foundation of a smart factory consulting team
		Foundation of a corporate venture capital firm
		Foundation of a demonstration smart factory
	Personnel changes	Appointment of a chief digital officer
		Appointment of rollout managers
	Cultural changes	Corporate opening up towards more partnerships
Internal influences	Internal influences	Lean management
		Continuous improvement
		Trial and error
Characteristics of actors and relationships	Actors	Management commitment
		Change management competences of the management
		Employee potential resistance to change
	Relationships	Autonomy for self-organisation
		Bottom-up approach
		Partially connectness

Table 9: Sum of themes from the data analysis

4.6.1 Emergence and feedback loops

Throughout the data analysis it was identified that the implementation of Industry 4.0 is the basis of the emergence of actions that are adaptable by the feedback their own appearance provides to their origin, i.e. the actors in the system. In other words, the actors of the firm produce actions which consequently return to the actors as feedback of these actions, form which in turn adjustments and new actions are formed. A demonstration of the presence of emergence and feedback in the system was shown in Section 4.3.2 “continuous improvement” and Section 4.3.3 “trial-and-error”. These sections incarnate and represent types of learning and hence the adaptability of the resulting actions. Section 4.3.2 analysed Industry 4.0 as a continuous implementation of new technologies and solutions without a defined beginning and a defined end. This led to the conclusion that the implementation of Industry 4.0 implicates a process of learning through the use of feedback loops, as IP-25, a product owner from the software development department, as well as IP-35, a manager from the development department for services, explained above in Section 4.3.2 as following: IP-25: “[…] it’s a process to understand what a smart factory is and understanding of smart factory changing while the process.”, IP-35: “[…] you have all the experience you’ve collected through this journey […].”. Such evidence from the data analysis were equally identified from other interview participants, such as from IP-05, IP-06, IP-22, IP-26, IP-38, and IP-39, as was cited in the respective section above. The identified and analysed continuity in the implementation of Industry 4.0 was concluded to be building upon feedback loops and learning, which in turn describe the implementation as an emerging behaviour.

Section 4.3.3 identified and analysed a pattern of trial-and-error behaviour in the implementation of Industry 4.0. The references in this section jointly led to the understanding that the implementation is based on “learning by doing”, which was e.g. indicated in the respective section by IP-35, a manager from the development department, and IP-40, a manager from the CDDT, as in the following: IP-35: “[…] it was always one step after the other and it was the same with the manufacturing process.”, IP-40: “[…] we have 2019 and it’s still in a let’s say experimentation phase […].”. Further references in the same direction were provided by a product owner from the software development department (IP-25), and a lean management expert (IP-30). Section 4.3.3 concluded like Section 4.3.2 with the analysis that the applied trial-and-error approach builds upon trying, failing, and the development of learning, which therefore represents adaptability in the execution of the implementation of Industry 4.0 in the organisational system. A demonstration of how the organisational aspects of the implementation of Industry 4.0 emerged over the time due to feedback and learning was also provided in Section 4.5.3 when analysing the "partial connectedness" between actors and SLRs in the system. In this sense, it was found that Industry 4.0 related projects changed structure from "functional silos" to "cross-functional teams" due to the implementation of Industry 4.0. As IP-11, a software engineer, indicated, BERTLEI learned that a project organisation through functional silos is not effective for the implementation of Industry 4.0 solutions and hence adjusted it to cross-functional teams, as cited again in the following: "We had like functional silos so to speak in details. So, this turned out not to be beneficial for us. So, we made a move towards cross-functional teams. […] and this turned out to be a better way of organising things.". As indicated by this statement as well as in Section 4.5.3, IP-11 thereby demonstrates the adaptability of the organisation within the implementation of Industry 4.0 at BERTLEI.

The analysed cultural and mind-set change of "corporate opening up" in Section 4.2.3 demonstrates another example of emergent behaviour due to feedback, and therefore adaptability of the system. As it was examined in the respective section above, it seems that BERTLEI developed the understanding that implementing Industry 4.0 solutions with in-house capacities only is not reasonable and therefore opened up to cooperation with external partners. The cited references from the data, such as from IP-39, a program manager for digital solutions, and IP-15, a manager for customer management and sales, jointly provided evidence for the adaptation that happened at BERTLEI, as shown again in the following: IP-39: "We want to have the full control about the technology, this is our old mindset but with this digitalisation products and the change the digitalisation, it's not possible anymore.", IP-15: "If you think about make or buy, it usually should be a buy decision. That's not what everybody in the company would say, but we're on the way to learn that.".

Both interview participants indicate the transformational phase of moving from a making it in-house approach to opening up towards more cooperation with external suppliers. This indication was further underlined in Section 4.2.3 by IP-06, a corporate in-house consultant, as well as IP-26, a smart factory consultant, who elaborated on the corporate opening up in the following way: IP-06: "So that's why now we switched totally […]. We know how to build good machines, but everything else, we, it's really necessary to work with good partners outside.", IP-26: "No this is also a way of transformation where [BERTLEI] is going through. […] they realise that if I program everything myself, then I slow down so much from the project business, then I can no longer get around.". The adjustment in the organisation of the implementation, moving from a making it in-house approach to opening up towards more cooperation with external suppliers represents an action which emerged due to the feedback that the firm experienced from their older attempts to implement solutions based on internal resources only. On the basis of these references, Section 4.2.3 concluded that the "corporate opening up" demonstrates an emergent behaviour that evolved due to the implementation of Industry 4.0. This detection of emergence and feedback may lead to an understanding of the implementation of Industry 4.0 as a living system with the ability to adapt.

The above analysed examples about continuity, learning by doing, partial connectedness, and the corporate opening up all demonstrated the presence of emergence and feedback in the organisation of the implementation of Industry 4.0 at BERTLEI. The analysed data set captures further examples which underline this point, such as provided by IP-37, a product manager from the connectivity department, who indicated an adjustment in the corporate understanding how the result of the implementation of Industry 4.0 may look in future: "At the first beginning I think yes, we thought about those, so for the complete automated company for, you order your part online and you will be delivered it in 24 hours and then you, and no human being touches it in between. That's the, I think, that's the complete story of the smart factory, but we learned a lot. There might be some productions that can do this. But with increasing complexity of the parts you are producing, it's getting more and more unrealistic to have a complete autonomous production.". It seems that IP-37 adjusted his understanding while exploring and experiencing the implementation of Industry 4.0 over the time in the complex organisational system of BERTLEI and thereby presents another example of emergence and feedback in the system.

The above cited evidence in this section may now lead to the conclusion that the implementation of Industry 4.0 at BERTLEI is based on feedback loops and learning ability from which actions and behaviours emerge. This conclusion furthermore leads to the understanding of the implementation as a Complex Adaptive System that evolves over time, which addresses the first research question of this thesis. The feedback loops and the learning ability demonstrate BERTLEI and the organisation of the implementation of Industry 4.0 as a living system which continuously develops and improves. The so far analysed data is captured in an illustrative summary provided in Figure 13 and in a larger size in Appendix N. Figure 13 suggests a conjecture on the basis of the study result and illustrates the presence of emergence and feedback between the analysed emergent behaviours, the actors and their characteristics, the relationship characteristics, the internal influences, as well as the underlying mechanisms that have been explored and analysed in this chapter. The summary in Figure 13 furthermore captures all entities in an illustrated organisational system.

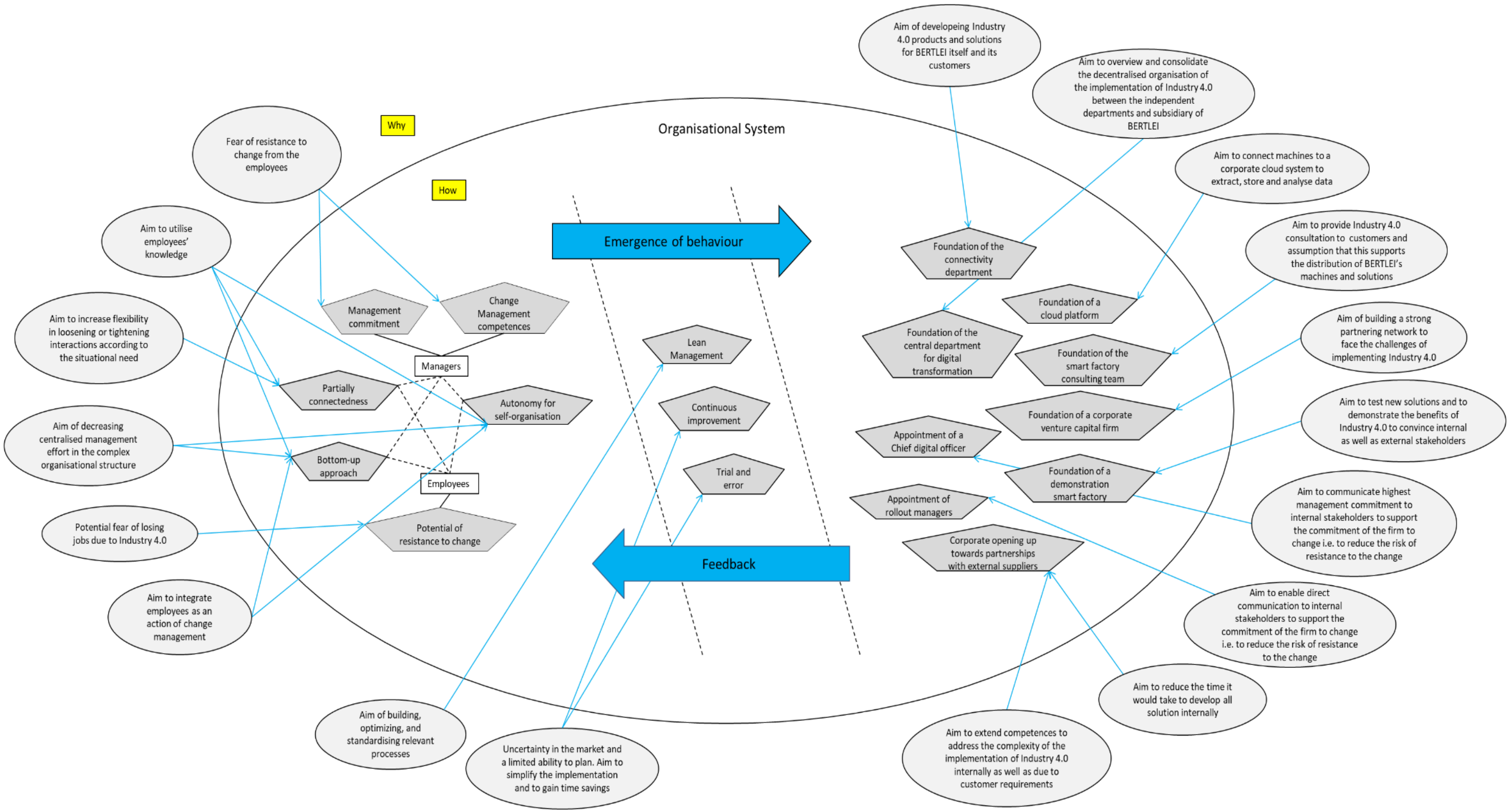


Figure 13: Emergence and feedback in the organisational system (larger size in Appendix N)

4.6.2 The system model

The previous sections in this chapter have identified, analysed and demonstrated the emergent behaviours, the internal influences, the actor's characteristics, and the relationship characteristics that emerged due to, or influenced the implementation of Industry 4.0 at BERTLEI. Furthermore, it has been demonstrated that the implementation of Industry 4.0 is based on feedback loops and learning ability from which the actions and behaviours emerged. This demonstration led to the conclusion to frame the findings and the implementation of Industry 4.0 as a Complex Adaptive System. Figure 13 illustrated the detected categories and themes of this chapter, including their analysed underlying mechanisms. This section will further summarise the findings and generated knowledge of this chapter in order to develop a comprehensive and clear system model for the implementation of Industry 4.0.

It has been detected that the implementation of Industry 4.0 led to organisational structure changes at BERTLEI. These structure changes are represented by the foundation of the connectivity department, the foundation of the central department for digital transformation, the foundation of the cloud platform, the foundation of the smart factory consulting team, the foundation of the corporate venture capital firm, and the foundation of the demonstration smart factory, which have all been analysed in the respective sections above in this chapter. The evidence from the data indicate that the connectivity department was founded due to the aim of developing Industry 4.0 products and solutions. The cloud platform in this sense was identified to be founded due to the aim to connect machines to a corporate cloud system to extract, store and analyse data. The analysis of the smart factory consulting team led to the conclusion that it was founded due to the aim to provide Industry 4.0 consultation to customers as well as to support the distribution of Industry 4.0 related products and solutions. The evidence from the data furthermore demonstrated that the corporate venture capital firm was founded due to the aim of building a strong partnering network to face the challenges of implementing Industry 4.0. The demonstration smart factory was concluded to be founded due to the aim to test new solutions and to demonstrate the benefits of Industry 4.0 to convince internal as well as external stakeholders.

Next to the organisational structure changes personnel changes and cultural changes were also identified throughout the data analysis as changes that emerged due to the implementation of Industry 4.0. The identified and analysed personnel changes are the appointment of a chief digital officer and the appointment of rollout managers. The data analysis led to the understanding that the appointment of the chief digital officer emerged due to the aim to communicate management commitment to internal stakeholders of the firm to support their commitment to the change, i.e. to reduce the risk of resistance to the change. The appointment of rollout managers has been analysed to be a result of the same aim, i.e. to enable direct communication to internal stakeholders to support the commitment of the firm to the change in order to reduce the risk of resistance. The cultural change was identified in the form of a corporate opening up towards partnerships with external suppliers. The phenomenon of opening up was in turn analysed to be a result of the aim to extend the corporate competences to address the complexity of Industry 4.0 and its implementation, as well as to reduce the time it would take to develop all solution internally. The organisational structure changes, the personnel changes, and the cultural changes may be concluded as the main identified actions that emerged due to the implementation of Industry 4.0 in the organisational system. For the development of the comprehensive system model these actions are all placed on the right side of the model as complex and adaptive behaviours.

The data analysis continued with the analysis of three identified internal influences, i.e. lean management structure, a continues improvement approach, and trial-and-error behaviour, which influence the implementation of Industry 4.0. Lean management was analysed in the respective section above and was found to be present in the firm long before the start of Industry 4.0. Lean management structures are utilised for the implementation of Industry 4.0 due to the aim of building, optimising, and standardising relevant processes, as concluded above. The understanding of continuity in the implementation was found to be a result of uncertainty in the market, a limited ability to plan, as well as due to the aim to simplify the implementation and to gain time savings. The detected trial-and-error approach that is executed for the organisation of the implementation was last but not least analysed to be a result of the same reason and aim as the continuity approach. These three entities were analysed throughout the data collection and were found to be part of and influence the execution of the implementation at BERTLEI. For the development of the comprehensive system model these internal influences might therefore to be placed in the middle of the model to demonstrate that the emergent behaviours pass this sort of “filter” in their emergence.

The data analysis furthermore identified and analysed two different actor groups performing in the system, their characteristics and their relationship characteristics between each other. The actors were separated into managers and employees. The detected manager's characteristics refer to management commitment and change management competences, as the respective section in this chapter demonstrated. Both managers' characteristics were found to be centrally relevant to the implementation of Industry 4.0, mainly due to the detected management fear of potential resistance to change from the employees of the firm. The management fear may also lead to the understanding that the previously mentioned appointment of the chief digital officer and the rollout managers, at least partly, resulted from it. The identified relevant employees' characteristic refers to a potential of resistance to change, i.e. a resistance to support the implementation of Industry 4.0, from which the data indicated the success is dependent. The potential of resistance to change, as the main relevant detected employees' characteristic, was found to be a result of fear of losing jobs due to Industry 4.0. The data may now lead to an understanding of the complexity and interconnection of the entities in the system. It seems that the main management characteristics, i.e. the change management competences and the management commitment, are related to the fear to meet potential resistance to change from the employees of the firm. For the development of the comprehensive system model the actors and their characteristics are placed on the left side of the implementation model to demonstrate that this is the origin from which the behaviours and actions in the system emerge.

It was furthermore identified that the actors in the system maintain relationships between each other. The analysis of these relationships in the respective sections demonstrated their essential contribution to the understanding of the organisation of the implementation of Industry 4.0 at BERTLEI. The identified relationship characteristics highlight the presence of autonomy for self-organisation, a bottom-up approach, and partial connectedness. The references of the data analysed in the respective section indicated that autonomy for self-organisation may be a result of the aim to utilise the employees' knowledge, to integrate the employees as an action of change management, as well as the aim of decreasing centralised management effort in the complex organisational structure. The detected pattern of the bottom-up approach was found to be a result of the same aims as highlighted for the relationship characteristic "autonomy for self-organisation" mentioned before. The third relationship characteristic analysed was the partial connectedness of the actors in the system. The partial connectedness was furthermore identified as a result of the aim to utilise the employees' knowledge, as well as to increase the flexibility in loosening or tightening the interactions according to the situational need in the implementation of Industry 4.0 in the organisational system. For the development of the comprehensive system model the relationship characteristics are connected to the actors and also placed on the left side of the model. The actors, their characteristics and their relationship characteristics are illustrated inside an SLR to demonstrate that these entities exist at various points in the larger and complex organisational system.

The last theme that was identified and analysed throughout the data analysis is the presence of emergence and feedback, which concludes the understanding of the organisational aspects of the implementation of Industry 4.0 as Complex Adaptive System that continuously develops further. The analysis of emergence and feedback as the infrastructure of continuity and adaptability develops an understanding of the organisation of the implementation of Industry 4.0 as a living system that evolves over time. For the development of the comprehensive system model two arrows are positioned around the SLR on the left side and the emergent behaviours on the right side, which illustrate a loop and the continuity inside the system model. Accordingly, the arrow departing the behaviour side (right side) transports feedback, whereas the arrow on the SLR side (left side) transports the emergence in the system. Two smaller arrows on the bottom of the system model furthermore illustrate information exchange with the system environment. Such information exchange was analysed e.g. though the corporate opening up for partnerships with external suppliers. The developed comprehensive system model of the implementation of Industry 4.0 is illustrated in Figure 14 and in a larger size in Appendix O. Figure 14 suggests a conjecture on the basis of the study result and represents the organisational system of the implementation of Industry 4.0, based on the generated knowledge from the case study and data analysis of this thesis.

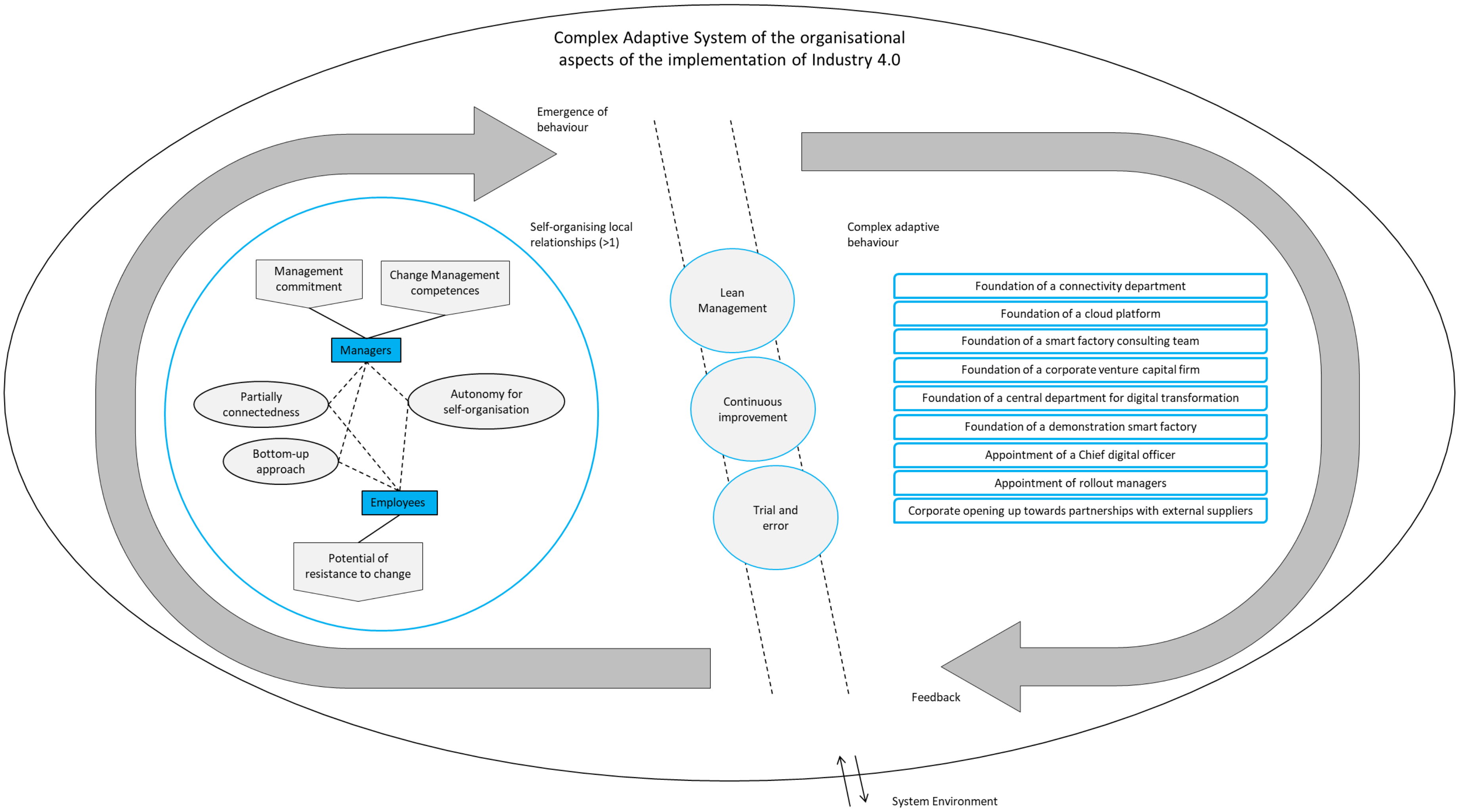


Figure 14: Organisational system of the implementation of Industry 4.0 (larger size in Appendix O)

4.7 Conclusion

The findings of the case study identified the roles of important system elements and their meanings for the overall system in focus. The boundary of the system is the boundary of the firm BERTLEI, as the system represents the firm in which the implementation of Industry 4.0 emerged. The main themes of the thematic data analysis were used to develop the system model illustrated in Figure 14 as the end result of this chapter. The comprehensive system model demonstrates the complex and adaptive interconnected variables which are part of and influence the implementation of Industry 4.0 in the organisational system of BERTLEI. The system model and hence the systemic perspective offers a more holistic understanding of the organisational aspects of the implementation of Industry 4.0 taking important relationship characteristics into account. Such a holistic perspective was not only required by the literature reviewed in Chapter 2 of this thesis, but also by several interviewees, such as a manager from the CDDT (IP-40) in the following way: "[…] the challenge within digitalisation is that you don't think in functions […] bring them together, to think holistically and also to optimise holistically, not only for a certain function.".

The research objective of this thesis is the exploration of the organisational aspects of the implementation of Industry 4.0. Therefore, the research questions of this thesis ask how BERTLEI organises the implementation as well as why they do so. The elements in the system model have been identified as the key mechanisms that enable the successful implementation of Industry 4.0 at BERTLEI, and thereby answer the first research question of this thesis. The analysis of these elements throughout this chapter furthermore developed an understanding of why they have emerged, which in turn answers the second research question of this thesis. On the basis of the exploration of a real implementation case at the firm BERTLEI, this chapter concluded with an understanding of the implementation of Industry 4.0 as a Complex Adaptive System that co-evolves in its corporate environment over time.

Chapter 5. Discussion

5.1 Introduction

Chapter 4 identified and analysed the roles of important system elements and their meanings for the implementation of Industry 4.0. Chapter 5 will discuss these system elements and the developed system model as a whole in the light of previous contributions of other researchers that were examined in the literature review. The developed system model and the analysed influential system elements are brought into the context of the current academic debate and its added value is elaborated. This chapter is structured around the two research questions of this thesis to demonstrate its contribution in the light of Complex Adaptive System Theory. Connections are drawn to different theoretical themes illustrated in Table 10 to further discuss the system elements of the developed adaptive system model of Industry 4.0 implementation. In this sense this chapter answers the research questions “How did a high value German manufacturing firm organise the implementation of Industry 4.0 at the firm level?” and discusses “Why did they implement as they did?”. Research on CAS focusses on a systems’ learning capabilities as well as how they create new rules, structures, and behaviours (McCarthy et al., 2006). The developed system model of this thesis captures these elements and thereby demonstrates the organisational aspects of the implementation of Industry 4.0 as a Complex Adaptive System.

System model area	System elements
Area 1 - Complex adaptive behaviour / implementation actions	Foundation of the connectivity department
	Foundation of the central department for digital transf.
	Foundation of a cloud platform
	Foundation of a smart factory consulting team
	Foundation of a corporate venture capital firm
	Foundation of a demonstration smart factory
	Appointment of a chief digital officer
	Appointment of rollout managers
	Corporate opening up towards more partnerships
Area 2 - Internal influences	Lean management
	Continuous improvement
	Trial and error
Area 3 - Characteristics of actors and relationships, i.e. the self-organising local relationships	Management commitment
	Change management competences of the management
	Employee potential resistance to change
	Autonomy for self-organisation
	Bottom-up approach
	Partially connectness

Theoretical themes
Centralisation vs.. decentralisation
Diffusion of new ideas
Working in teams / cross-functional
Security and trust
Open innovation
Path dependence

Table 10: Connection of system elements and theoretical themes

The developed system model (that was illustrated in Figure 14) was structured in three areas, i.e. 1.) the complex emergent behaviours of the implementation, 2.) the internal influences of the implementation, and 3.) the characteristics of the self-organising local relationships. These three areas, i.e. the respective system elements, are connected to theoretical themes (table 10) to discuss their meaning for the implementation. The theoretical themes represent a closer analysis of the "whys" from chapter 4. Table 11 illustrates which "whys" underlie each theoretical theme. The "whys" have furthermore been analysed in textual form in chapter 4 as well as visualised in detail in Figure 7 to 12. A summary of all analysed "whys" was provided in Figure 13. Therefore, it can be defined that the theoretical themes derived from the data, i.e. the analysis of the "whys" from chapter 4. In this sense the following of this chapter is structured according to the theoretical themes that refer to 1.) centralisation vs. decentralisation, 2.) the diffusion of new ideas, 3.) working in teams, 4.) security and trust, 5.) open innovation, and 6.) path dependence. This chapter will close by highlighting the contributions of the developed system model of Industry 4.0 implementation, and therefore the contribution of this thesis.

Theoretical themes
Centralisation vs.. decentralisation
Diffusion of new ideas
Working in teams / cross-functional
Security and trust
Open innovation
Path dependence

Related "Whys"
Aim of developeing Industry 4.0 products and solutions for BERTLEI and its customers internally
Aim to overview and consolidate the decentralised organisation of the implementation of Industry 4.0
Aim to connect machines to a corporate cloud system to extract, store and analyse data
Aim to provide Industry 4.0 consultation to customers
Aim of building a strong partnering network to face the challenges of implementing Industry 4.0
Aim to test new solutions and to demonstrate the benefits of Industry 4.0
Aim to communicate highest management commitment to stakeholders
Aim to enable direct communication to stakeholders
Aim to reduce the time it would take to develop all solution internally
Aim to extend competences to address the complexity of the implementation of Industry 4.0
Uncertainty in the market and a limited ability to plan (Aim to simplify and to safe time)
Aim of building, optimising, and standardising relevant processes
Aim to integrate employees as an action of change management
Potential fear of losing jobs due to Industry 4.0
Aim of decreasing centralised management effort in the complex organisational structure
Aim to increase flexibility in loosening or tightening interactions according to the situational need
Aim to utilise employees' knowledge
Fear of resistance to change from the employees

Table 11: Connection of theoretical themes and analysed "whys"

5.2 Centralisation and hierarchy

Table 10 illustrates the possible connections between the system elements and different theoretical themes. Five of the detected system elements refer particularly to the notion of centralisation, decentralisation and hierarchy. This section therefore discusses the connection of the foundation of a central department for digital transformation, the foundation of the connectivity department, the appointment of the CDO, the detected decision-making authority for self-organisation, and the bottom-up approach in the light of previously published Industry 4.0 studies, as well as a source that effects the level of centralisation and hierarchy in the firm.

In the sense of centralisation and hierarchy the five detected system elements seem to demonstrate on the one hand a higher preference for centralisation and hierarchy, however, on the other hand a higher preference for decentralisation, autonomy and self-organisation. Whereas the foundation of a central department for digital transformation, the foundation of a connectivity department and the appointment of the CDO refer more to an understanding of a higher level of centralisation and hierarchy, the detected bottom-up preference and autonomy in the decentralised organisational structure highlight more a flatter hierarchy and less centralisation in the firm. Such a "dual approach" of independent decentralised implementation and centralised support and a recognisable figurehead taking responsibility for it, was not yet detected in previously published studies in the context of this thesis. So far, literature in the organisation science either argues that "innovation" (such as the organisation of the implementation of Industry 4.0 solutions) requires a powerful centralised R&D department, or that "innovation" requires a good decentralised spread around the whole structure of the firm (Yakhlef, 2005). The level of centralisation and the degree of hierarchy may be seen as increasing and decreasing in parallel, as a hierarchical structure usually favours a central concentration of control at higher management levels (Büschgens *et al.*, 2013). Earlier literature furthermore tends to argue that stronger hierarchical orders and centralised management power support "radical innovation" and the successful implementation of changes (Dewar and Dutton, 1986; Ettlie *et al.*, 1984). However, later literature seems to shift this perspective towards less hierarchy, more decentralisation and a more open approach to innovation (Yakhlef, 2005; Chesbrough, 2003). The findings of the case study at BERTLEI demonstrated a dual approach of independent decentralised implementation, but with centralised support departments and a centralised face of responsibility for it, which is new to the research field around the implementation of Industry 4.0.

The Industry 4.0 implementation framework of Veile et al. (2020) indicates in regard to the new foundation of the central department for digital transformation (CDDT) that it may be reasonable to consolidate know-how and capacity about Industry 4.0 in one centralised organisational institution that captures the authority to make decisions. Such a centralised institution may then increase the ease and speed of the implementation of Industry 4.0 in a complex organisational system according to the authors. The study of Veile et al. (2020) indicates the potential benefits of a structure change towards the foundation of a new central department for digital transformation, however in an abstract and a very shallow way. In a similar way Schumacher et al. (2016) included the “existence of central coordination for Industry 4.0” to rate the Industry 4.0 maturity of firms in their developed Industry 4.0 maturity model. The inclusion of this item in the model again indicates that the authors grant relevance to such a central coordination department for the successful implementation of Industry 4.0. Nevertheless, no more information is provided about such structure change in the study. It continues with the studies of Petrovic and Leksell (2017), Sjödin et al. (2018), and Kazancoglu and Ozkan-Ozen (2018), who all included a central coordination departments in their respective data collection for their research. All three studies again indicate a certain relevance of an organisational structure change towards the foundation of a central department for digital transformation. However, no study is actually bringing this point to the centre of the discussion.

The evidence for a central organisation for the implementation of Industry 4.0 at BERTLEI continues with the identified new appointment of a CDO as well as the foundation of the connectivity department. The appointment of a CDO as the head of the CDDT demonstrates the present hierarchy in the implementation of Industry 4.0 in the firm. Even though the implementation is organised in a decentralised manner in the independent subsidiaries and departments, the CDO represents not only management commitment, but also a “central face of responsibility” and hence an additional layer of hierarchy for the implementation. Further evidence for the central concentration of the organisation of the implementation of Industry 4.0 is the new foundation of the connectivity department that centrally develops new Industry 4.0 solutions for the firm. The Industry 4.0 literature in this regard does not offer any comparable insights about the foundation of a centralised connectivity department that internally develops new Industry 4.0 solutions for the company group, especially not of the size of 80 people as is that case at BERTLEI. Neighbouring literature may discuss topics such as the possibility of a general need to separate new business units from established ones to mitigate potential risks of cannibalising behaviour between the old and the new ones (Kim and Min, 2015). However, such discussions do not specifically demonstrate the organisation of the implementation of Industry 4.0 in manufacturing firms. Either way, the foundation of the new connectivity department, the appointment of the CDO and the foundation of the CDDT all demonstrate a rather centralised side of the implementation of Industry 4.0 at BERTLEI.

The second side of the "dual approach" indicates a decentralised implementation based on self-organisation and decision-making authority, flatter hierarchical structures and a rather bottom-up approach to the implementation of Industry 4.0. As analysed in the findings of this thesis, the local relationships, such as teams, departments and subsidiaries are meant to manage the implementation of Industry 4.0 independently on the basis of self-organisation. These local relationships are therefore defined as "self-organising local relationships" (SLR) in the developed system model that was illustrated in Figure 14. Examples of the self-organising relationship structure at BERTLEI have been analysed in the findings through examples, such as provided by a product manager from the connectivity department (IP-37) who highlighted that: "[…] every production area has to do on his own, because they are independent companies on the whole structure. […] So, they are not basically controlled by the central department, because every production location is producing a different machine, so they are not comparable to each other.". Statements as this led to the understanding that each subsidiary of the company group is responsible to organise the implementation of Industry 4.0 by themselves.

An innovation approach based on self-organisation associates with various research streams that all support a higher degree of decentralisation and autonomy, especially for explorative activities (Foss *et al.*, 2014). A bottom-up approach to innovation furthermore widens the possibility of positive outcomes as innovation can emerge from all types of employees in an organisation (Foss *et al.*, 2013). Especially the idea generation, which appears important to the implementation of "something new" such as Industry 4.0 solutions, would possibly be harmed by a tendency of centralisation in an organisation according to Foss *et al.* (2013). Self-organising networks are furthermore connected to the theory of organisational learning as such networks are required to develop, accumulate and transfer knowledge, to then modify its behaviour and structure accordingly (Rycroft and Kash, 2002). Therefore, self-organisation may be understood as "learning in practice" (Rycroft and Kash, 2002), which makes the analysed organisation of the implementation of Industry 4.0 at BERTLEI a "complex organisational learning process" too.

The Industry 4.0 related literature in this sense shows commonalities in the way that some studies claim a need of more autonomy and responsibility for the employees in an Industry 4.0 environment. The early report of Kagermann et al. (2013), which was noted by Liao et al. (2017) as the by far most cited Industry 4.0 reference, mentioned that work organisation in an Industry 4.0 environment potentially requires offering employees the opportunity to enjoy greater responsibility. An applied bottom-up approach offers greater responsibility and the enhancement of personal development according to the authors. In line with the findings of this thesis, Kagermann et al. (2013) seem to have indicated in 2013 that autonomy for self-organisation and a bottom-up approach may be intertwined with each other as both relationship characteristics complement each other. The data demonstrated the presence of autonomy for self-organisation and bottom-up approach in several interviews. The cooperation between start-ups that BERTLEI invested in and the established departments and subsidiaries of BERTLEI represents one of these examples. As mentioned in the previous chapter, an interviewed investment manager from the corporate venture capital firm (IP-24), explained the phenomenon in the following way: "Investing in start-ups is an activity that we do only out of the [BERTLEI] venture unit, if it comes to collaboration projects, integration projects and development projects and other and let's say partnering projects, then it's the responsibility of the business units that actually implement, develop, to sell products or services at the end.".

Subsequent Industry 4.0 studies, such as the maturity model of Schumacher et al. (2016), the maturity model of Sjödin et al. (2018) and the evaluation sheet of Odważny et al. (2018) all claim in a similar sense positive effects of granting autonomy to the employees in order to reach a successful implementation of Industry 4.0. Schumacher et al. (2016) e.g. covers the item "autonomy of employees" for the evaluation of the maturity of the implementation of Industry 4.0 in a firm, whereas Sjödin et al. (2018) claims a positive effect of agile processes which provide autonomy and flexibility in teams which again create a continuous evaluation of production processes in the implementation phase. Odważny et al. (2018) then underlines such “human factors” and the relevance of a high level of autonomy in an organisational system. IP-24 indicated above the responsibility of the single departments to self-organise and build cooperation with the Industry 4.0 related start-ups that BERTLEI centrally invests in through its venture capital firm. The example of IP-24 demonstrates not only the freedom but also the requirement to self-organise the implementation of Industry 4.0 in the organisational system.

The detected second side of the dual approach in the findings of this thesis relates furthermore to indications which the structural competency model of Kazancoglu and Ozkan-Ozen (2018), the implementation framework of Veile et al. (2020), as well as the literature review of Piccarozzi et al. (2018) and the empirical data of Tortorella and Fettermann (2018) provided. Kazancoglu and Ozkan-Ozen (2018) highlighted that “self-organisation-ability” is becoming more and more a core requirement for human resources in the field of Industry 4.0. Granting autonomy for decision making is especially recommended for developing and utilising the employee’s creative and problem-solving ability as Veile et al. (2020) argued. The authors furthermore claim a requirement of an incremental bottom-up approach when it comes to the vertical interconnection of Industry 4.0 related solutions. A bottom-up approach furthermore can lead to the emergence of new organisational relationships as well as adjustments in the organisational structure according to Piccarozzi et al. (2018). Last but not least, also Tortorella and Fettermann (2018) claim that involving and empowering the employees makes them become active change agents in their decentralised structured environments for a better management of the implementation of Industry 4.0 in complex systems. The findings of this thesis demonstrate same patterns as the literature regarding a decentralised structured environment for a better management of the implementation of Industry 4.0, such as provided by an interviewed manager from the CDDT (IP-41) who stated: “[…] they are free to evolve ideas and so I would say that they are, that they can do a lot on their own and they are also allowed to do a lot on their own. They are, so [BERTLEI] wants them to have ideas and work on their own digital solutions.”. The data, such as the statement of IP-41, continuously demonstrate actions to empower innovation from bottom-up and last but not least to maintain the decentralised organisational structure.

Overall, it can be summarised that the related Industry 4.0 literature claims a link between decentralisation and autonomy for self-organisation and a successful implementation of

Industry 4.0. Some other studies furthermore indicate or claim in one way or other the possible relevance of a central coordination department for the implementation of Industry 4.0 in the organisational system. The findings of this thesis, however, add specific evidence that neither one of the approaches but both in parallel support the successful organisation of the implementation of Industry 4.0. Evidences were provided e.g. by a manager from the central department for digital transformation (IP-07), who confirms the responsibility of the decentralised departments to self-organise the implementation but further indicates that his own department, the CDDT, may develops the wider strategies for the corporate implementation of Industry 4.0: "[…] the central department can help them and can help them to set up a strategy, but they have to improve their own process.".

Despite the relevance of more guidance for the implementation of Industry 4.0, such a "dual approach" of independent decentralised implementation but with centralised support and a recognisable figurehead taking responsibility for it, was not yet mentioned in previously published studies. As stated above, most studies either argue that "innovation" requires a powerful centralised R&D department, or that "innovation" requires a good decentralised spread around the whole structure of the firm (Yakhlef, 2005). This thesis, however, argues that for the implementation of Industry 4.0 both approaches in parallel support a successful result. Even though Büschgens *et al.* (2013) argue that a central concentration of control at higher management levels usually derives from rather hierarchical structures, the findings of this thesis demonstrate that a central concentration of information and control can also be performed in parallel to a decentralised organisational structure based on self-organisation. The results thereby extend the current research through the analysis of empirical qualitative data which conclude by suggesting a dual approach between decentralisation and autonomy for self-organisation, as well as centralised support agencies and one recognisable figurehead taking responsibility for it. This can be achieved in praxis by the foundation of a central department for digital transformation, the foundation of a connectivity department and the appointment of a CDO, in combination with a culture of autonomy for decision making and bottom-up approaches in a self-organising decentralised organisational structure. The findings therefore contribute to the understanding of how firms may organise the implementation of Industry 4.0, as well as why structuring the implementation in a dual way may lead to successful implementation results. The acknowledgement of both, the decentralised and also the centralised characteristics in the developed system model of this thesis, makes the model the first in the literature that includes such a dual approach.

5.3 Diffusion of new ideas

As illustrated in Table 10 the appointment of rollout managers, the foundation of a demonstration smart factory, the foundation of a smart factory consulting team and the foundation of a cloud spinoff at BERTLEI are related to the notion of the "diffusion of new ideas", i.e. the diffusion of the concept of Industry 4.0. This in particular means that these four detected system elements aim to communicate the new Industry 4.0 solutions and their beneficial implementation to the internal and external stakeholders of the firm to potentially minimise a resistance to the change and to foster the support for the implementation. This section therefore discusses the connection of the four detected system elements in the light of previously published Industry 4.0 studies, as well as a source that effects the "diffusion of new ideas" in the firm.

The appointment of different rollout managers as part of the Central Department for Digital Transformation were found in this thesis as being responsible for involving all effected stakeholders of a change and improving the diffusion of new Industry 4.0 solutions in the company group. The rollout managers participate in most of the decentralised implementation projects and are responsible for convincing the internal stakeholders about the advantages of the implementation. The rollout managers eventually manage and minimise the potential resistance to change by involving the internal stakeholders in the implementation of new solutions. Active internal relationships between managers and/or employees from different departments and subsidiaries of a firm were evaluated as important, especially for the encouragement of information sharing and the diffusion of new ideas (Boukis, 2013). The appointment of rollout managers at BERTLEI addresses such "activation" of the internal relationships, as Boukis (2013) named it, and therefore supports the diffusion of new ideas, i.e. the implementation of Industry 4.0 solutions in the wider sense.

The foundation of the corporate demonstration smart factory, the foundation of the smart factory consulting team and the foundation of the cloud spinoff demonstrated similar aims in regard to the diffusion of new ideas. The foundation of the new and fully automated corporate smart factory for demonstration and test purposes was found in this thesis to be an important lighthouse project to communicate the abilities of the firm to its internal and external stakeholders. In this sense the demonstration smart factory diffuses the new implementation ideas, solutions and abilities around the company group to get as many stakeholders on board as possible to support the change. The foundation of the smart factory consulting team was furthermore found to support the aim to build an additional bridge for BERTLEI to reach its customers and to horizontally extend the implementation of Industry 4.0 by the application and connection of their own machines and services. The foundation of the smart factory consulting team therefore demonstrates another action of practice about how BERTLEI has built new communication channels to diffuse their Industry 4.0 ideas and solutions around their stakeholders. Finally, the newly founded cloud spinoff was identified as a new platform for connectivity and data transfer between internal machines and machines of customers. The foundation of the cloud platform was hence found to strengthen the relationship between BERTLEI and its customers, i.e. its external stakeholders, by delivering the required infrastructure for data transfer, storage and data analysis. The newly founded daughter company that legally represents the cloud spinoff represents an organisational structure change that demonstrates how to diffuse the idea and to execute the implementation of Industry 4.0 horizontally between BERTLEI and its external stakeholders.

The Industry 4.0 literature refers e.g. to the importance of also horizontally integrating Industry 4.0 solutions (Kagermann et al., 2013; Frank et al., 2019; Veile et al., 2020), which represents a diffusion of the idea to external partners. Veile et al. (2020) e.g. included “horizontal integration” in their implementation framework and claim that digital interconnection of supply chains and customers may lead to beneficial outcomes such as better data exchange and data analysis. In the same regard, Moeuf et al. (2018) refer to the application of cloud computing in relation to the development of networks to external partners. In this sense the authors mention that cloud computing platforms would improve the information and knowledge exchange between different organisations with a positive effect on the implementation of Industry 4.0, which can be associated with the statements of Boukis (2013) and the diffusion of new ideas in the firm. The developed Industry 4.0 implementation framework of Frank et al. (2019) divides Industry 4.0 technologies into front-end and base technologies, from which one of the base technologies refers to cloud computing. Cloud computing in this sense is categorised as a base technology as it potentially offers an infrastructure for connectivity to stakeholders (Frank *et al.*, 2019).

It can be summarised that the Industry 4.0 literature indicates the relevance of diffusing the idea about the implementation of Industry 4.0 internally and also to external partners. The respective literature furthermore claims in some studies that different connectivity solutions would improve the information and knowledge exchange in an organisational system. However, whereas the literature so far discusses the need to diffuse the idea of the implementation of Industry 4.0 internally and externally rather generally, this thesis and the detected appointment of rollout managers, the foundation of a demonstration smart factory, the foundation of a smart factory consulting team, and the foundation of a cloud spinoff at BERTLEI demonstrate more specific real-world examples based on qualitative data of how a firm can organise the diffusion of new ideas, i.e. the implementation of Industry 4.0 around the company group. The activation of such internal relationships from different departments and subsidiaries of a firm associates with the importance of encouraging information sharing and the diffusion of new ideas (Boukis, 2013), which is especially important in a decentralised and self-organised system such as at BERTLEI. The four detected system elements therefore not only demonstrate practical examples about how firms can organise the implementation of Industry 4.0, they also address the importance of diffusing new ideas around the stakeholders inside and outside the company group, which in turn minimise the risk of potential resistance to change. Such demonstration of the diffusion of new ideas in an organisational system was not yet addressed in the Industry 4.0 literature. As such, it is assumed that these findings fill an important knowledge gap in the existing literature.

5.4 Working in teams

Table 10 further illustrates that the detected system element and relationship characteristic “partial connectedness” is assumed to be related to the theoretical themes of “working in teams and cross-functional teams”. The findings chapter revealed that several implementation projects are executed at the same time, although each project is managed by a separate project team in which the involved actors are situationally and loosely coupled rather than tight and rigid. As the data revealed, the firm transformed its project organisation from functional silos to cross-functional project teams with different competences situationally connected over a period of time, depending on the specific requirements of an implementation project and in order to better address the higher complexity of the implementation of Industry 4.0. This change in the organisation of relationships is a newly learned and hence emergent behaviour that enables the firm to flexibly loosen or tighten the interactions between actors according to the situational need and therefore enables a better utilisation of the peoples' capabilities for the implementation of Industry 4.0. This section therefore discusses in the following the connection of the detected system element and relationship characteristic "partial connectedness" in the light of previously published Industry 4.0 studies, as well as in the light of the notion "working in teams and cross-functional teams".

As the previous section already highlighted, active internal relationships between managers and/or employees from different departments and subsidiaries are important for the encouragement of information sharing and the diffusion of new ideas (Boukis, 2013). Organising communication channels in general and cross-functional communication in particular can be considered as important for firms to innovate effectively (Lievens *et al.*, 1999). Thereby, especially in projects of higher complexity (as it is the case for the implementation of Industry 4.0) a team's effectiveness is directly influenced by its internal climate (Acikgöz *et al.*, 2014). The findings of this thesis highlighted the transformation of the project organisation from functional silos to cross-functional project teams, which seems to associate well with the perspectives of Acikgöz *et al.* (2014), Boukis (2013) and Lievens *et al.* (1999).

The Industry 4.0 literature in this respect offers a set of different perspectives too. The maturity model of Schumacher et al. (2016) e.g. includes the dimension "operations", which refers to the need for "interdisciplinary and interdepartmental collaboration" in Industry 4.0 environments. The inclusion of this item in the maturity model indicates the relevance that Schumacher et al. (2016) grant interdisciplinarity for the successful implementation and maturity of Industry 4.0. However, besides the inclusion of this item in the maturity model the study does not further examine why interdisciplinarity, i.e. cross-functional teams, and hence partial connectedness, is relevant as a relationship characteristic for the implementation of Industry 4.0. Sjödin et al. (2018) also refer to the need to develop methods for setting up cross-functional teams. In this sense the authors refer to cross-functional digitalisation networks to enable potential knowledge exchange and information gathering across the different departments working on the implementation.

Similarly to the studies of Schumacher et al. (2016) and Sjödin et al. (2018), Odważny et al. (2018) refer to partial connectedness and knowledge exchange between actors. In this respect, the developed evaluation sheet of the authors captures the evaluation area "management", which evaluates the readiness to cooperate with other departments within the enterprise. The inclusion of this characteristic in the evaluation sheet indicates the acknowledgement that Odważny et al. (2018) grant to cooperation between different competences in the company, which demonstrates in turn the need of partially connected actors and SLRs in the organisational system. In agreement with this argument and the findings of this thesis, also Veile et al. (2020) refer in their implementation framework to the requirement of changing participation in different interdisciplinary teams for a distinct period of time and for a certain purpose, due to continuously changing tasks, i.e. the complexity of the implementation of Industry 4.0. The authors continue to argue that combining the knowledge and expertise from different disciplines is mandatory due to the unique characteristics of the implementation of different Industry 4.0 related solutions.

The findings revealed the positive effect of partially connected actors and cross-functional project teams for the implementation of Industry 4.0. As Chapter 4 showed, BERTLEI transformed its project organisation from functional silos to cross-functional project teams with different competences situationally connected over a period of time, depending on the specific requirements of an implementation project and in order to address the higher complexity of the implementation of Industry 4.0 better. This associates with the claims of the Industry 4.0 literature as well as with the literature dealing with effective communication in teams and cross-functional teams. The findings of this thesis, however, offer a more specific demonstration based on empirical and qualitative evidence on how and why Industry 4.0 has led a transformation to a partial connected team structure at BERTLEI to support and enable the successful implementation of Industry 4.0 in the firm. Such a demonstration addresses the detected research gap on empirical data and real word examples about the implementation of Industry 4.0 in firms.

5.5 Security and trust

The four system elements “appointment of a chief digital officer”, “management commitment”, “change management competences” and “potential of resistance to change” were identified as being connected to the notion of “security and trust”, as illustrated in Table 10. All four system elements were shown to aim to build a secure environment at BERTLEI in which the employees trust and are able to support the implementation without risking negative results. This section therefore discusses the connection of the four elements in the light of previously published Industry 4.0 studies, as well as a source that effects a “secure and trustful environment” in the firm.

The findings identified a fear of potential resistance to change that could appear from the employees of the firm. The data in Chapter 4 highlighted the need of the employees to support the implementation of Industry 4.0 solutions as well as that there is a risk that this support may not be present. As analysed in the findings, previous implementation projects have already failed at BERTLEI in the past due to miscommunication and non-acceptance. The fear of the management of meeting resistance to change from the employee side was furthermore identified to be rooted in the fear of the employees of losing their jobs due to the implementation of Industry 4.0. This employee fear may be reasonable under the perspective that current research highlights the fact that the implementation of Industry 4.0 changes at least present job descriptions (Kazancoglu and Ozkan-Ozen, 2018; Rana and Sharma, 2019; Whysall et al., 2019; Chulanova, 2019). The findings furthermore demonstrated that the implementation of Industry 4.0 reduces the quantity of employees required in the factories of BERTLEI. The current Industry 4.0 literature acknowledges the influential characteristic of potential resistance to change due to the fear of employees of losing their jobs in some studies. One of the categories of the maturity model of Sjödin et al. (2018) e.g. refers to “people” and indicates complexities in the implementation of Industry 4.0 through potentially perceived threats of employees to their established competencies, i.e. their current jobs, which in turn may lead to resistance to support the implementation. Sjödin et al. (2018) furthermore highlight the transformation of current job descriptions due to the implementation of Industry 4.0, which indicates that previous job descriptions will be redundant after the implementation. Failing to achieve employee engagement, fear of exchanging people for smart equipment and resistance to change are relevant barriers to the successful implementation of Industry 4.0, also according to study of Cordeiro et al. (2019). The authors developed an overview presenting the scope of individual barriers and challenges that can affect a firm in its implementation of Industry 4.0, and the ones named above are part of it.

The discussion about establishing a secure and trustful environment in the firm to support the implementation of Industry 4.0 was further addressed by Veile et al. (2020). The authors argued that the implementation of Industry 4.0 potentially requires adjustments in the corporate culture of the firm, but those adjustments may cause internal resistances. Veile et al. (2020) recommend considering incremental adjustments rather than radical ones to decrease the risk of internal resistances when implementing Industry 4.0. It is indicated that the management fears the potential resistance to change from the employees' side of the firm, which associates well with data collected at BERTLEI. The findings of this thesis highlighted in this sense how workforce concerns regarding job security risk also significantly influence the emergence of system elements regarding change management during the implementation of Industry 4.0. Veile et al. (2020) state that some employees' personality traits may influence the implementation of Industry 4.0, and that such personality traits, however, have not been addressed in the Industry 4.0 literature so far. The detection and analysis of the job security risk that influences the emergence of system elements regarding change management during the implementation of Industry 4.0 therefore contribute to this research gap. Even though the conventional belief about the implementation of Industry 4.0, and automation in general, is that these innovations will lead to less human interaction or workerless production facilities, which in turn fosters the fear of employees of losing their jobs and hence leads to a rejection of supporting the implementation, hardly any reliable research supports that fear (Hofmann and Ruesch, 2017). Instead, researchers state that Industry 4.0 will not lead to less human interaction or workerless production facilities, but that the roles of employees and their competence requirements will change (Dworschak and Zaiser, 2014; Weyer et al., 2015) in a way that skill requirements and specialisation increase (Tortorella and Fettermann, 2018), as well as that responsibility, decision making and supervising tasks are included (Spath et al., 2013).

The recent study from Hoyer et al. (2020) highlighted the risk of psychological pressure due to the anxiety of losing one's job in return for supporting the implementation of Industry 4.0.

One of the 14 influential key factors that the authors discovered in regard to the implementation of Industry 4.0 refers to “occupational health and safety”. The lack of trust of the employees may occur due to previously negative experiences of implementing solutions that caused such job decreases (Hoyer et al., 2020). The appointment of the chief digital officer, the presentation of strong management commitment, as well as different other change management competences at BERTLEI, however, were shown in the findings to aim to decrease such potential lack of trust and to incorporate a more secure environment in the firm. The role of chief digital officer (CDO) as the head of the central department for digital transformation (CDDT) e.g. was taken by one of the company owner family members, which communicated strong management commitment as well as financial support. This action at BERTLEI provided a clear statement to the stakeholders of the firm about the high priority of the implementation of Industry 4.0 in the firm. This sign of commitment, that the appointment of a family member as the CDO has sent into the firm, was seen as an action against potential resistance to support the implementation of Industry 4.0.

Associating with the highlighted findings, the existing Industry 4.0 literature underlines the importance of management commitment and the need of effective involvement of the top management for a successful implementation of Industry 4.0 (Piccarozzi et al., 2018; Odważny et al., 2018; Sjödin et al., 2018; Mohelska and Sokolova, 2018; Cordeiro et al., 2019). Mohelska and Sokolova (2018) refer specifically to the requirement of a collaborative, explorative and entrepreneurial mind-set of the employees as well as the need for strong management commitment as two important enablers of successful implementation projects. According to the authors it is often necessary to adjust existing managerial approaches to better support the development of organisational culture that supports the environment for innovation and hence the implementation of Industry 4.0 in the firm. This findings in this thesis associate with these perspectives as strong management commitment was identified to be a major factor to motivate the decentralised stakeholders at BERTLEI. Imposing fear of unemployment or communicating in any other way no commitment of the management about Industry 4.0 would potentially decrease the chance of achieving a successful implementation, risking the implementation to fail.

Besides the appointment of a chief digital officer and the demonstration of management commitment, general change management competences were found to be an important management characteristic for the implementation of Industry 4.0. Change management competences in this sense were similar to the appointment of the CDO and the demonstration of management commitment found as important for getting the employees "on board" and to decrease any potential of resistance to change. Examples of change management actions at BERTLEI occurred in the form of the involvement of stakeholders in an integrative and cooperative implementation process. The appointment of rollout managers, who listen to the people, to their fears, and to their concerns, enables direct communication with the internal stakeholders of the firm and are part of such change management actions. The granted guarantee of the management, that no employee will be released due to the implementation of Industry 4.0, also represents an action of change management that supports the integration and motivation of the employees to participate the change.

The Industry 4.0 literature claims similar points. The literature review of Piccarozzi et al. (2018), the maturity model of Sjödin et al. (2018) and also the implementation framework of Veile et al. (2020) e.g. all highlight the need of an implementation approach that involves the employees of the firm and that acknowledges important HR topics. The literature states that the implementation of Industry 4.0 is transforming the requirements of the management of HR to successfully encourage innovation and learning in the firm (Rana and Sharma, 2019). Vocational education is potentially required to achieve a successful implementation of Industry 4.0, as the employees of a firm either act as a barrier or central driver for the change (Chulanova, 2019). Odważny et al. (2018) furthermore highlights that involving the employees and actively managing the change will increase the employees' awareness and support in the implementation of Industry 4.0.

Such indications of the literature for active change management actions correspond to the findings highlighted above in this section. Hoyer et al. (2020) add to these perspectives that a potential fear of employees of losing their jobs due to the implementation of Industry 4.0 is present and that this fear needs to be actively addressed by management actions. In this sense developing the ability of dealing with higher complexity, thinking in overlapping processes, and the ability to flexible adapt to new roles and work environments needs to be acknowledged and actively managed by firms (Kazancoglu and Ozkan-Ozen, 2018).

The findings of this thesis agree with the literature that it is necessary to place HR management (the people in the firm) as a central important mechanism for the successful implementation of Industry 4.0. However, instead of focussing on the encouragement of corporate education and learning (Rana and Sharma, 2019; Chulanova, 2019), or the misfit between employees' capabilities and the requirements in an Industry 4.0 environment (Kazancoglu and Ozkan-Ozen, 2018; Whysall et al., 2019), the developed system model of this thesis identifies the potential employee resistance to change as an essential mechanism that needs to be addressed by change management competences while implementing Industry 4.0. The findings of this thesis highlighted in this sense how workforce concerns regarding job security risk also significantly influence the emergence of system elements regarding change management during the implementation of Industry 4.0.

The detection of the interrelations between the potential fear of employees to lose their jobs and the emergence of new system elements regarding change management unexpectedly opened up original and valuable contributions regarding fear resistance management. Such interrelations could potentially not have been detected with a focus on a limited set of system elements only, i.e. without the application of CAS as the theoretical lens of this thesis, since CAS naturally takes important relationship characteristics between system elements into account. Due to the application of CAS, this study could detect and analyse that personnel changes such as the appointment of a chief digital officer and the appointment of rollout managers, as well as actors characteristics such as management commitment and change management competences, are interrelated to fear resistance management, i.e. the fear of the employees to lose their jobs due to the implementation of Industry 4.0. As mentioned before, existing literature emphasised corporate education and learning (Rana and Sharma, 2019; Chulanova, 2019), or the misfit between employees' capabilities and the requirements in an Industry 4.0 environment (Kazancoglu and Ozkan-Ozen, 2018; Whysall et al., 2019), however looked at a rather limited set of variables only. The application of CAS in combination with a holistic single case study enabled looking at a more comprehensive set of variables, leading to the identification of the before mentioned interrelationships that have not been spotted elsewhere in related academic work yet. Such interrelations represent new examples and an original contribution to knowledge deriving from the application of CAS in this subject area.

The four system elements “appointment of a chief digital officer”, “management commitment”, “change management competences” and “fear of resistance to change” refer to the notion of “security and trust” in the firm. It can be concluded that the fear of losing jobs, and hence the fear of potential resistance to change, influences the emergence of behaviour within the implementation of Industry 4.0. The appointment of a chief digital officer, management commitment, the granted job guarantee and other change management actions represent such resulting behaviours. This understanding extends the current research by addressing the questions that Hoyer et al. (2020) identified as to be unanswered yet, i.e. if the risk of occupational health and safety play a significant role in the decision making of enterprises during the implementation of Industry 4.0. In this sense, the developed system model represents system elements that are intertwined with the notion of “security and trust”, which offer new insights based on empirical qualitative data regarding effective “fear resistance management” in the implementation of Industry 4.0.

5.6 Open innovation

Table 10 illustrates that the corporate opening up towards partnerships with external suppliers, as well as the foundation of a venture capital firm, are related to the theoretical theme of “open innovation”. This section therefore discusses in the following the connection of the system elements “corporate opening up” and the “foundation of a venture capital firm” in the light of previously published Industry 4.0 studies, as well as in the light of “open innovation”.

The data analysis of this thesis identified an ongoing transition at BERTLEI from a making it in-house approach to opening up towards more cooperation with external suppliers. This transition was found to be based on the challenges of missing competences as well as the time constraints involved in developing all Industry 4.0 solutions in-house without external support. The complexity and speed of the implementation of Industry 4.0 stretched the capacities of the firm, which led to the identified behaviour of opening up for external support and the establishment of a stronger partnering network. The foundation of the corporate venture capital firm is one example of how a firm can organise an effective structure to strategically open up to manage a potential lack of internal competences and time constraints. In regard to open innovation, it is well acknowledged that innovations and ideas can derive and be implemented from external sources (Chesbrough and Crowther, 2006). Therefore, organisational structures are recommended to support the internal, but especially also the external “detection”, “absorption” and “learning” of and from new solutions to support the success of innovations in the firm (Minkes and Foxall, 2000).

The Industry 4.0 literature in this respect argues that there is a significant gap between the capabilities of employees and the requirements of their roles due to the speed of technological change as e.g. Whysall et al. (2019) mentioned. Therefore, firms find themselves forced in the pre-implementation phase to decide whether to make or buy a solution (Rüb and Bahemia, 2019). The speed of technological change in this sense acts as a trigger for firms to buy solutions rather than to make them, i.e. to increasingly open up for cooperation with external suppliers. Such phenomenon can also be analysed under a theoretical perspective of transaction cost economics (TCE), as highlighted in a previous publication deriving from this thesis (Rüb and Bahemia, 2019). In respect of the Industry 4.0 literature, studies such as the one of Sjödin et al. (2018), Moeuf et al. (2018), Piccarozzi et al. (2018), Odważny et al. (2018), Cordeiro et al. (2019), Rüb and Bahemia (2019), Hoyer et al. (2020) and Veile et al. (2020) all support the point of view that cross-organisational cooperation with external partners supports the implementation of Industry 4.0.

Zooming into more detail, e.g. Hoyer et al. (2020) refer to “corporate and institutional cooperation” in one of their 14 discovered key influencing factors. In this sense the authors highlight the need for more cooperation between one firm and its potential external partners to meet the challenges for the successful implementation of Industry 4.0. Especially the “skill gap” that appears during the implementation of Industry 4.0 may be one of the key factors that require such cooperation. However, Hoyer et al. (2020) discovered that lack of financial and human resources may also be one influencing factor that leads to cooperation with external partners. In this senses cooperation with partners may enable issues to be faced that one company may not be able to address by itself, and therefore reduce potential risk in developing, testing and producing new technologies and products (Hoyer et al., 2020). The development of corporate competences to be able to interact “across organisational boundaries and in complex systems” was underlined by Hoyer et al. (2020). It can be said that the foundation of the corporate venture capital firm, which was discussed in the findings of this thesis, demonstrates one of the examples on how firms could organise the development of corporate competences to be able to interact across organisational boundaries in praxis.

The foundation of a corporate venture capital firm enabled a systematic exploration and investment in start-ups offering Industry 4.0 solutions that could not have been developed internally without external inputs. Therefore, this venture capital firm was found to function as a tool to organise the establishment of a wider partnership network to accelerate the implementation of Industry 4.0. The fact that the venture capital firm manages a fund of € 40 million to invest in minority shareholdings in Industry 4.0 related start-ups demonstrates the relevance of establishing such partnership networks to meet the requirements of a successful implementation. As the findings of this thesis showed, the venture capital firm aimed for technologies and solutions to invest in, in the proximity of robotics, sensors, I.T., connectivity, computing infrastructure, artificial intelligence-based models, block-chain based models, data-based business models such as platform businesses, and industrial enterprise software solutions. The Industry 4.0 literature analysed these technologies as important for the implementation of Industry 4.0 as it was highlighted in Section 2.2.5 by the studies of Liao et al. (2017), Hofmann and Ruesch (2017), Bartodziej (2017), Xu et al. (2018), Moeuf et al. (2018), and Chiarello et al. (2018). Frank et al. (2019) also demonstrated the relevance of such technologies by including some of them in their implementation framework as base and front-end technologies.

Firms are increasingly confronted with the requirement of outsourcing tasks and the need to open up for cooperation with external partners to manage the complexity of the implementation of Industry 4.0 (Veile *et al.*, 2020). In this sense Veile et al. (2020) indicate by referring to Block et al. (2015) and Müller et al. (2018) that cooperation in general fosters R&D activities and bundles resources. Such resource and time issues (to bundle resources) corelate with the analysed reason why BERTLEI opened up for cooperation with external suppliers, as highlighted in Section 4.2.3. Cooperation furthermore offers the opportunity for knowledge adaptation from best practice examples of partners (Veile et al., 2020), which BERTLEI executed and achieved through the foundation of the venture capital firm in 2016. The maturity model of Schumacher et al. (2016), the evaluation sheet of Odważny et al. (2018), as well as many more Industry 4.0 studies such as the one of Sjödin et al. (2018), Moeuf et al. (2018), or Cordeiro et al. (2019) all indicate in one or the other way that opening up to cross company collaboration potentially leads to beneficial results for the implementation of Industry 4.0. Even if such indications are sometimes of rather technical nature, such as the one of Moeuf et al. (2018) who argue that cloud computing platforms would improve information and knowledge exchange and the development of networks to external partners, the claimed positive effects of opening up are common to most studies in the Industry 4.0 implementation literature. However, it is interesting that the literature review of Piccarozzi et al. (2018) especially underlined that related literature published before 2018 completely neglected the topic of “open innovation” in association with the implementation of Industry 4.0. As the literature review of this thesis showed, however, some studies in and after 2018 have at least indicated the importance for firms to open up for cooperation with external partners.

The detection and analysis of the interrelation between the two system elements a.) “corporate opening up towards partnerships with external suppliers” and b.) “foundation of a venture capital firm”, and the theoretical theme of “open innovation”, leads to the acknowledgement that this organisational change, i.e. the foundation of the new venture capital firm, represents an important step towards enabling the corporate opening up towards more partnerships with external suppliers. This interrelation was visible due to the application of Complex Adaptive Systems as a lens which offered the required understanding to acknowledge relationship characteristics in between a system. The detection represents a new and valuable example on how to open up, as well as original contribution to knowledge deriving from the application of CAS in the field of organising the implementation of Industry 4.0.

Overall, it can be concluded that the recent Industry 4.0 literature deals with the topic of opening up for more cooperation with external partners, but it is rather lacking in support by evidence and examples from praxis. The findings of this thesis extend the current research therefore by the provision of new knowledge about a real implementation case demonstrating how and why a leading manufacturing firm established new infrastructure to open up during the implementation of Industry 4.0. The findings and the developed system model relate in part to the theoretical theme of open innovation, such as discussed by Minkes and Foxall (2000) and Chesbrough and Crowther (2006). The findings place a contribution to the detected research gap of Piccarozzi et al. (2018) by demonstrating new examples and knowledge about the transition towards opening up for cooperation with external partners. The foundation of the new venture capital firm at BERTLEI is one of the examples that demonstrates "how" firms may organise the aggregation of new Industry 4.0 solutions, and that shows the aim of the firm to open up and partner to mitigate the risk of missing competences and overcome time constraints for the management of the high complexity of the implementation of Industry 4.0. No previous study in the Industry 4.0 related literature has so far been detected that highlighted such a foundation of a corporate venture capital firm as a practical form of organisation to establish a wider partnering network for the successful implementation of Industry 4.0.

5.7 Path dependence

As illustrated in Table 10, the three system elements "lean management", "continuous improvement" and "trial-and-error" refer particularly to the theoretical theme of path dependence. This section therefore discusses in the following the connection of these three system elements in the light of previously published Industry 4.0 studies, as well as an effect that was influenced by path dependence in the firm.

The theory of path dependence refers to influences by previous events upon new events (David, 1985). It is referred to as a powerful influence on the innovation of complex technologies (Rycroft and Kash, 2002). Basically, all organisational learning may be categorised as path dependent, at least to the degree that this learning is cumulative (Rycroft and Kash, 2002). Path dependence is present as soon as learnings builds on existing knowledge, which means in turn "the more learning builds on existing knowledge, the higher the level of path dependency" (Rycroft and Kash, 2002).

The organisation of the implementation of Industry 4.0 at BERTLEI was in this sense identified to be influenced by existing lean management structures, as well as a continuous improvement, and a trial-and-error approach. Such structures were adopted at BERTLEI long before Industry 4.0, as the data analysis in Chapter 4 revealed. Lean management creates and structures efficient processes without "waste", which can afterwards be digitised in the means of Industry 4.0. The data analysis showed in this sense that the influences of lean management paved the way for the implementation of the Industry 4.0 solutions. The Industry 4.0 literature supports these findings from the case study and also claims positive effects of applying lean management prior to the implementation of Industry 4.0. Buer et al. (2018) identified that existing lean management structures can be used as a foundation to implement Industry 4.0 upon. Whereas lean management can be understood as a way to gain efficiency, Industry 4.0 may be understood as extended automation (Buer et al., 2018). Automation on top of efficient structures will lead to improvements. However, automation on top of inefficient structures will lead to even higher inefficiency according to the authors. The empirical data of Tortorella and Fettermann (2018) furthermore underlines that lean management experiences raise the possibility of implementing Industry 4.0 solutions successfully. The authors identified that existing lean structures can be evaluated as an essential enabler for the implementation of Industry 4.0.

Some researchers even claim lean management as a prerequisite for a successful implementation of Industry 4.0 (Kaspar and Schneider, 2015). Some others indicate that lean management may be an existing concept in which Industry 4.0 solutions can be embedded (Veile *et al.*, 2020). Altogether, however, it can be said that there is a consensus among researchers regarding the compatibility of Industry 4.0 and lean manufacturing (Hoyer *et al.*, 2020). Both philosophies suggest decentralised structures over large and complex systems (Hoyer et al., 2020), which very well suits the analysed organisation of the implementation of Industry 4.0 at BERTLEI. It is furthermore claimed that Industry 4.0 can be implemented best by utilising an iterative and continuous improvement approach such as lean management (Moeuf *et al.*, 2018). This iterative approach that lean management captures incarnates a notion of path dependence as Rycroft and Kash (2002) would potentially argue.

The system element and implementation pattern “continuous improvement” matches both the lean management philosophy as well as the systems thinking perspective of this thesis. The continuous improvement approach may be seen as an important element of the lean management philosophy, making its relationship to path dependence for the implementation of Industry 4.0 clear too. The findings of this thesis showed that the implementation of Industry 4.0 can be understood as a continuous implementation of new technologies and solutions around production optimisation, connectivity, automation and management processes, instead of an ending change project with a defined beginning and a defined end. Following a masterplan straight from the beginning in this sense would not suit the needs, as the implementation requires actions, feedback loops and learning in the system, i.e. emergence and adaptation. The need to organise the implementation of Industry 4.0 as a continuous improvement of existing production and management processes may be due to the novelty of the phenomenon and the resulting lack of experiences with it, in combination with the ongoing fast-changing technological achievements available on the market, as the findings of this thesis have shown. The concept of "continuous improvement" aims to enhance performance in organisational processes (Bond, 1999) with a particular focus on the rise of the adoption rate (Hyland et al., 2007). Thereby, the strategic involvement of the actors in an organisational system, and hence the utilisation of their knowledge, are essential for the continuous incremental change process to better performance (Singh and Singh, 2013). The concept of "continuous improvement" furthermore predicts that it builds dynamic capabilities in organisations to face challenging and changing market situations (Gutierrez-Gutierrez and Antony, 2020).

The Industry 4.0 literature such as Moeuf et al. (2018), Sjödin et al. (2018), Odważny et al. (2018), Frank et al. (2019) and Veile et al. (2020) supports the perspective of a positive influence of "continuity" for the implementation of Industry 4.0, such as was identified at BERTLEI. In this respect Frank et al. (2019) compare Industry 4.0 maturity with the progressive adding of technologies and solutions as "Lego". The implementation framework of the authors represents the implementation of Industry 4.0 as a "growing" complexity over stages. It continues with Odważny et al. (2018), who speak about the evolutionary nature of the implementation as well as the complexity challenges that come with it. Sjödin et al. (2018) also evaluate continuity in the implementation of Industry 4.0 as relevant, instead of picturing the implementation as a "quick" transformation. The maturity model of Sjödin et al. (2018) refers to the aim of creating a corporate culture of "continuous smart factory innovation". Finally, Veile et al. (2020) claims a need to implement corporate cultural changes in an incremental way in order to reduce potential internal resistances for the change (Veile et al., 2020).

Taken together, it can be concluded that the Industry 4.0 literature acknowledged or at least claimed the relevance of a continuous implementation of Industry 4.0 solutions rather than picturing the implementation as a fixed project with a defined beginning and a defined end. The data analysis and the case study at BERTLEI demonstrated that the firm adopted such a “continuity perspective”. As part of lean management and in the form of a “path dependence”, this continuity perspective was found to be very supportive for the successful implementation of Industry 4.0 in the organisational system. The emerged acknowledgement at BERTLEI about the implementation as a system itself associates in this sense to the indications of the Industry 4.0 literature mentioned above. Such emergence furthermore seems to associate as well with organisational learning and can therefore be classified as path dependent (Rycroft and Kash, 2002).

In parallel to the positive path dependent influences of lean management and the continuity perspective, the data analysis also showed a trial-and-error behaviour during the implementation of Industry 4.0 at BERTLEI. This trial-and-error behaviour emerged mainly due to limited knowledge about Industry 4.0 and the uncertainty of its implementation at the very beginning. Defining the level of path dependence upon the level of organisational learning that is based on existing knowledge in the same field (Rycroft and Kash, 2002) potentially leads to the statement that there was not much chance for path dependence for the “overall” implementation of Industry 4.0 at the beginning at BERTLEI. This in particular can be analysed in the case of BERTLEI as this firm represents a leading high value manufacturing firm in its field which is considered an early adopter of Industry 4.0, as analysed in Section 3.4.3. However, due to such a low level of existing knowledge about the implementation of Industry 4.0, a known pattern of managing “the unknown” appeared. The “trial-and-error behaviour” is assumed to be a sort of practical standard choice for the “time effective” management of “new things” at BERTLEI. This “standard choice” in turn puts the execution of the trial-and-error behaviour itself into the perspective of path dependence.

The trial-and-error behaviour resulted in experimentation in the new field of Industry 4.0 and generated learning and new knowledge, as well as an understanding of the implementation as a Complex Adaptive System, which means that the system builds on feedback, learning and adjustments. The analysis of the data collected at BERTLEI demonstrated the execution of the trial-and-error approach for the reasons of simplification and time saving. As mentioned in the findings of this thesis, the foundation of the cloud spinoff and the foundation of the demonstration smart factory represent two examples of the executed trial-and-error approach at BERTLEI. The respective Industry 4.0 literature did not yet examine such a trial-and-error approach for the implementation of Industry 4.0. The only reference that was found was hidden in the implementation framework of Veile et al. (2020) and mentions "learning by doing" as one training type to build required employees' competences to support the implementation. This training type, however, is listed among many others, which does not indicate the same relevance of the approach as this thesis does for the overall implementation of Industry 4.0. In a second dimension of the implementation model, referring to "preparing the implementation of Industry 4.0 solutions", Veile et al. (2020) report the detection of a trial-and-error approach more clearly. In this sense the authors highlight that planning is limited due to the high complexity of the implementation of Industry 4.0, and therefore recommend a flexible trial-and-error approach. The authors continue to explain that such a trial-and-error approach captures testing new solutions and the ability to learn from mistakes quickly.

In conclusion it can be said that the respective Industry 4.0 literature acknowledges the relevance of lean management and continuity more than a trial-and-error approach for a potential successful implementation of Industry 4.0. Nevertheless, all three system elements are assumed to associate with path dependence and hence influence from previous events (David, 1985). The system elements have furthermore been evaluated as very supportive for the organisation of the implementation of Industry 4.0 in the complex and adaptive organisational system of BERTLEI. Therefore, "lean management", "continuous improvement", and "trial-and-error" are suggested in the developed system model illustrated in Figure 14 to be acknowledged as essential mechanisms that provide a positive understanding of the implementation as a living system that emerges over the time. The findings of this thesis thereby extend the current literature on the implementation of Industry 4.0 through the suggestion of acknowledging these three mechanisms in the developed system model, as well as by indicating that the implementation of Industry 4.0 can positively be affected by path dependence from previous events. The continuity perspective and the trial-and-error approach overall underline again the understanding of the implementation of Industry 4.0 as a Complex Adaptive System that emerges through failure and learning, which also represents an essential contribution to knowledge that derived from the empirical qualitative data of the findings.

5.8 Systems perspective

The new developed implementation model of this thesis framed the implementation of Industry 4.0 under a systemic perspective as a Complex and Adaptive System of intertwined system elements. Figure 14 illustrated that area one, area two and area three of the system model are connected, in the sense that actors, actions, characteristics, relationships and internal influences closely interrelate with each other. This section therefore discusses in the following the applied systems perspective in the light of previously published Industry 4.0 studies, as well as a source that inspired the understanding of the implementation of Industry 4.0.

The findings demonstrated that changes in attributes of e.g. existing and new organisational structures, actions of actors in the system or self-directed decision making have effects on the implementation of Industry 4.0 at BERTLEI. As McCarthy et al. (2006) state, these effects (the resulting behaviour of the actors) lead to experimentation with the new influence factors and thereby consequently produce by their collective dynamic nonlinearity, self-organisation, and emergence in the system (McCarthy *et al.*, 2006). The ability to learn and to adapt, which is represented through the presence of “feedback and emergence” in the developed system model of this thesis supports the understanding of the implementation of Industry 4.0 as a living system that co-evolves in its dynamic corporate environment. Nonlinearity, self-organisation and emergence thereby form the basis of adaptability in such Complex Adaptive Systems (Stacey, 1995; Morel and Ramanujam, 1999; Dooley and van de Ven, 1999; Anderson, 1999; Choi et al., 2001; McCarthy, 2004). Examples of the system’s ability to learn and to adapt were analysed in the findings of this thesis such as in Section 4.2.3 “corporate opening up”, Section 4.3.2 “continuous improvement”, Section 4.3.3 “trial-and-error”, and Section 4.5.3 “partial connectedness”.

The Industry 4.0 literature indicates in some studies a correspondence with systems perspective that is based on feedback and adaptability to receive more comprehensive insights on the complex organisation of the implementation of Industry 4.0. In this respect, Sjödin et al. (2018) refer to the implementation of Industry 4.0 as a process-innovation that captures a “systemic nature”. The maturity model of the authors referred to such a systemic nature by stating that changes in one system element will have effects on other subsystems too. The authors thereby indicate the relevance of the relationships between system elements, as well as the relevance of understanding the implementation as a system itself. Not only Sjödin et al. (2018) but also Moeuf et al. (2018) claimed in a similar way an association with more comprehensive systems thinking perspectives on the implementation of Industry 4.0. Moeuf et al. (2018) describe mainly technical subjects, however, they also identified managerial capacities referring to “systems capable of learning autonomously from their own behaviour and adapting themselves as a function of the results obtained”. Such interpretations underline the association between the findings at BERTLEI and a systems perspective that acknowledges learning and adaptability for the better understanding of the implementation of Industry 4.0.

Already at the very beginning of the emergence of the term “Industry 4.0” Kagermann et al. (2013) highlighted in one of their priority areas for action the need to understand the implementation of Industry 4.0 as the “management of complex systems”. The study of Kagermann et al. (2013) was pioneering and inspiring for many following studies in the field of Industry 4.0, as Liao et al. (2017) later analysed. Kagermann et al. (2013) furthermore refer to the need to develop appropriate models to provide a basis for managing such “systems” in relation to the high complexity of Industry 4.0 environments. The indication of the potential importance of relationships between different elements for the implementation of Industry 4.0 resonates with the systems perspective that takes such important relationship characteristics into account. Last but not least, the literature review of Piccarozzi et al. (2018) hints for more systems perspectives too, as the study identified that the Implementation of Industry 4.0 contains several different entities which all influence each other. The authors elaborate that it is expected that new relationship characteristics and organisational structures emerge due to the implementation of Industry 4.0, which all need to be explored on the basis of empirical data in order to understand their comprehensive interplay.

The relevance of a systems perspective capturing adaptability in its centre became particularly clear when collecting and analysing the data at BERTLEI that referred to the “corporate opening up”, the “continuous improvement and trial-and-error approach”, and the “partial connectedness” of relationship characteristics. These findings all demonstrated the adaptability of the systems and that changes in attributes have an effect on the overall implementation of Industry 4.0 in the firm. Indications in the Industry 4.0 related literature about an association between the implementation of Industry 4.0 and a systems perspective were further provided by Hoyer et al. (2020) who utilised a systems thinking approach for the identification of key factors that influence the implementation of Industry 4.0. The authors refer to a strong nonlinearity of the implementation of Industry 4.0 as it captures more than just the sum of the technologies associated with it. Furthermore, Hoyer et al. (2020) supported their choice for utilising a systems thinking perspective due to the aim of forming the research as comprehensively as possible, as well as due to the complexity challenges that the implementation of Industry 4.0 contains. Also Veile et al. (2020) argued according to a systems perspective by stating that the implementation of Industry 4.0 covers technical, organisational and social concerns that are closely inter-related to each other. The systems perspectives of interrelated dimensions that both Hoyer et al. (2020) and Veile et al. (2020) acknowledged in their studies underline the reasonableness of this thesis to examine the implementation of Industry 4.0 as a Complex Adaptive System.

The systems perspective and the application of CAS as a lens provided this thesis with a more comprehensive outcome by taking important relationship characteristics and interconnections of system elements into account. Several authors such as Sjödin et al. (2018), Moeuf et al. (2018), Piccarozzi et al. (2018), Kagermann et al. (2013), Hoyer et al. (2020) and Veile et al. (2020) referred to a need for more comprehensive systems thinking approaches. In this sense utilising CAS led to a broader understanding of the complexity of the implementation, which addresses an important research gap in the literature about the organisational aspects of the implementation. Similar to Ivanov and Sokolov (2012), this thesis argues that the evolution of the implementation of Industry 4.0 happens through adaptation and reconfiguration of structures, which led to the developed system model of this thesis illustrated in Figure 14. Understanding the implementation of Industry 4.0 as a Complex Adaptive System enabled this thesis to see and discuss its elements in relation to each other, detecting contributions such as the “dual approach” between decentralisation and centralisation. Such contributions would potentially not have been visible when researching single implementation elements in isolation.

5.9 Conclusion

Chapter 5 discussed the identified system elements of the adaptive system model in relation to 1.) centralisation and hierarchy, 2.) the diffusion of new ideas, 3.) working in teams, 4.) security and trust, 5.) open innovation, and 6.) path dependence. The system elements have been brought into the context of the current academic debate and their added value about the organisational aspects of the implementation of Industry 4.0 were elaborated. In this sense important new insights about "How a high value German manufacturing firm organises the implementation of Industry 4.0 at the firm level" as well as "Why they implemented as they did" came to the surface.

Taken together, this thesis addressed the detected research gap about missing empirical qualitative evidence on the organisational aspects of the implementation of Industry 4.0. The findings of this thesis thereby answered "how" a high value German manufacturing company implemented Industry 4.0, as well as "why" this firm implemented as it did. The developed system model captures the first collected qualitative data set that represents the organisational aspects of the implementation of Industry 4.0 as a Complex Adaptive System of interrelated system elements. The acknowledgement of important relationship characteristics in the system model delivered a "more comprehensive" perspective on the implementation of Industry 4.0, which in turn has led to new insights on influential mechanisms that interrelate with the implementation outcomes.

The new system elements of the system model demonstrate important examples for praxis on how to organise the implementation of Industry 4.0, which fills a knowledge gap in the existing literature. In addition to the detection of new system elements, such as important organisational structure changes and relationship characteristics, this thesis represents the very first that contributes to the literature by suggesting a "dual approach" between decentralisation and centralisation for the successful organisation of the implementation of Industry 4.0. The aspects detected in this qualitative study extend existing Industry 4.0 implementation frameworks, such as the one of Frank et al. (2019) or the one of Veile et al. (2020) by providing important new organisational elements that are recommended to be acknowledged in future.

This qualitative study demonstrated how workforce concerns regarding job security risk significantly influencing the emergence of system elements regarding change management during the implementation of Industry 4.0. The application of Complex Adaptive Systems Theory in combination with the holistic single case study enabled in this sense the detection of such new relationship characteristics. These relationship characteristics could potentially not have been detected with a focus on a limited set of system elements only, i.e. without the application of CAS as the theoretical lens. CAS naturally takes important relationship characteristics between system elements into account and thereby offers a more comprehensive perspective on the organisation of the implementation of Industry 4.0 in the firm. The relationships and interconnections between a potential fear of employees to lose their jobs, and new emergent system elements in the area of change management, such as the new foundation of the central department for digital transformation and the appointment of the chief digital officer, are true example for the original contribution that the application of CAS as a theoretical lens in this thesis enabled to detect and analyse. Such patterns of relationships between e.g. actors characteristics and emergent organisational structure changes have only been detected due to the application of CAS as a lens in combination with the deep and explorative single case study in this thesis. No other study was found that either applied CAS as a lens in this subject area or that detected such relationship characteristics in their research, making the application of CAS and the before named relationship patterns a true original contribution to knowledge of this thesis.

Chapter 6. Conclusion

6.1 Introduction

This chapter concludes the empirical study of this thesis and again highlights the research objective, the main findings and the contributions of this thesis. It will close by discussing potential limitations and further areas for future research.

6.2 Research objective and main findings

Understanding the organisational aspects of the implementation of Industry 4.0 in depth has been proven as a major research gap in the literature. Related studies have frequently referred to a strong demand to deliver new empirical knowledge and a more comprehensive perspective of this field. Therefore, the aim of this thesis was the examination of the organisational aspects of the implementation of Industry 4.0 in a high value German manufacturing company in a qualitative way. A holistic single case study with 35 semi-structured expert interviews enabled a deep exploration of an implementation in its real-world context at the firm level. This thesis thereby addressed the defined research gap with new empirical qualitative evidence on the organisational aspects of the implementation of Industry 4.0 from an early adopter firm, namely BERTLEI. The findings have identified the roles of important system elements and their means for the organisational system in focus. The findings demonstrated how this high value German manufacturing company implemented Industry 4.0 at the firm level, as well as why this firm implemented as it did. Nineteen important system elements were derived from the thematic data analysis and a new system model was developed that demonstrated the complex and adaptive interconnected variables which are part of, and which influence the implementation of Industry 4.0. The nineteen elements in the system model (illustrated in Figure 14) were identified as the key mechanisms that shaped the organisation of the implementation of Industry 4.0. Important organisational structure changes and personnel changes, such as the foundation of the central department for digital transformation and the appointment of the CDO, came to the surface and provided new examples of how to organise the implementation in praxis. This thesis furthermore stressed the importance of the systems thinking perspective. The systems thinking perspective offered a more comprehensive understanding of the organisational aspects of the implementation of Industry 4.0 by taking important relationship characteristics into account.

6.3 Contributions to knowledge

By bringing the identified and analysed system elements and the systems perspective as a whole into the context of the current academic debate, its added value was elaborated. This study stresses the importance of the systems thinking perspective when researching the mechanisms and complexities of the implementation of Industry 4.0 in manufacturing firms. New insights about "How a high value German manufacturing firm organised the implementation of Industry 4.0 at the firm level" as well as "Why they implemented as they did" came to the surface. The acknowledgement of important relationship characteristics resulted in a "more comprehensive" understanding of the complex organisation of the implementation of Industry 4.0 and shaped the development of the new system model. The new system model covered the three areas of actions, influences and relationships, which were discussed in relation to the theoretical themes of centralisation and hierarchy, diffusion of new ideas, working in teams, trust, open innovation and path dependence. This thesis represents the first existing study that understands the organisational aspects of the implementation of Industry 4.0 as a Complex Adaptive System of interrelated system elements which continuously evolve over time. The new system elements of the system model demonstrate important examples for praxis of how to organise the implementation of Industry 4.0. This thesis contributes to the research field as the first suggesting a "dual approach" between important decentralised as well as centralised implementation patterns for a successful process. It furthermore demonstrates how workforce concerns regarding job security significantly influence the emergence of system elements regarding change management during the implementation of Industry 4.0. In this sense, the application of Complex Adaptive Systems Theory in combination with the holistic single case study enabled the detection of such new relationship characteristics. These characteristics could potentially not have been detected without the application of CAS as the theoretical lens of this thesis. The interconnections between a potential fear of employees to lose their jobs, and new emergent system elements in the area of change management, such as the new foundation of the central department for digital transformation and the appointment of the chief digital officer, are true example for the original contribution that the application of CAS as a lens enabled to detect and analyse. No other study was found that either applied CAS as a lens in this subject area or that detected such relationship characteristics in their research. The thesis offers academic contributions to the Industry 4.0 implementation literature, as well as organisational elements recommended for practitioners when organising the implementation of Industry 4.0.

6.4 Limitations and suggestions for future research

As with all research, this thesis encapsulates a number of limitations which, in repetition and addition to the limitations highlighted in Section 3.7, at the same time open the door for future research. First of all, the use of scientific literature and in-depth qualitative data could always be extended by the consideration of other literature and other data. The restricted resources in terms of time and money available for the interviews and the thesis as a whole was an influencing factor for the results. With the provision of more resources this cross-sectional study could have been extended to more companies and to a longitudinal research project. Collecting longitudinal data would potentially lead to a better understanding of the implementation journey, rather than taking a snapshot at the time. Furthermore, the data collection of this thesis which was conducted in form of a single case study in a German manufacturing firm may include regional and company specifies and hence implies some limitations in terms of generalisability. However, there is no evidence to suggest that the patterns of the implementation of Industry 4.0 differ in its core from the patterns of the implementation in other regions and companies. Even though generalisability of this thesis contribution was demonstrated by the thematic analysis of the qualitative empirical data that referred to same content and same subjects, future studies could add secondary data from a wider range of sources to obtain a true picture of the organisation of the implementation of Industry 4.0.

The data collection technique of conducting interviews may be subject to limitations too, as interviews potentially capture problems of bias, poor recall, and poor or inaccurate articulation (Yin, 2003). However, by using an in-depth single-case study with 35 interviews as the methodological strategy for this thesis, and in combination with the pre-existing knowledge and experience about manufacturing, the breadth of sources mitigates the risk of problems with bias and low validity in the data generation process. An additional limitation of this thesis may be present in the fact that interviews were conducted with managers and employees who are responsible for the organisation of the implementation of Industry 4.0, but with office staff only, leaving a gap about the employees in terms of the shop floor workers. Interviews at the shop floor level could offer an additional perspective about the implementation of Industry 4.0, which, however, is not part of this thesis and its firm level perspective, but leaves room for future research and publications.

An alternative approach suitable for future research could be the application of Transaction Cost Economics as a theory to analyse the make or buy behaviour in the pre-implementation phase of Industry 4.0, such as indicated in an earlier study that derived from this thesis (Rüb and Bahemia, 2019). The detected transformation from the pre-Industry 4.0 pattern, i.e. a making it in-house approach, and the current Industry 4.0 pattern, i.e. the emergent behaviour of opening up towards cooperation with external partners, demonstrates the disruptive influences that the implementation of Industry 4.0 places on organisations. Analysing this behaviour through a theoretical lens of TCE may lead to a better understanding of the implementation overall. This thesis analysed the internal implementation of Industry 4.0 at a high value German manufacturing company. The firm BERTLEI showed in parallel to the internal implementation, characteristics of an Industry 4.0 solution provider. This characteristic, and how it influenced the internal implementation, seems to be worthy of further research. Additionally, the organisation of the implementation of Industry 4.0 through a "strategic" perspective seemed to be very interesting to build further research on it.

Notwithstanding its limitations, this thesis' contributions are considered to have built new significant knowledge relevant for the successful organisation of the implementation of Industry 4.0 and hence the creation of value in the firm. The thesis offers academic contributions to the Industry 4.0 implementation literature, as well as organisational elements recommended for practitioners when organising the implementation of Industry 4.0. The research was tested in parallel to its progress in order to gather feedback on its suitability by participating in the NITIM Doctoral Schools in 2017, 2018, 2019, 2020, and 2021. The research outputs were presented at the ICE IEEE Technology and Engineering Management Society Conferences in 2017, 2019 and 2020. The researcher furthermore participated at the "*WIRTSCHAFTSTAG*" Conference in Berlin on 31.08.2021 which offered, the first in-person opportunity after the *COVID-19* pandemic to listen to a variety of characters representing the leading German politicians like Peter Altmaier (CDU), and Christian Lindner (FDP), as well as perspectives of firms like SAP and Qualcomm. Seeing the consensus about the large potential that still today lies in the digital transformation and the implementation of Industry 4.0

provides new fruitful ground for further research in this field. Hence, the final version of this thesis presents the opportunity to develop a number of new publications addressing this call.

References

Abrahamson, E. (1996), "Management Fashion", *Academy of Management Review*, Vol. 21 No. 1, pp. 254–285.

Acatech (2013), *Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0: Abschlussbericht des Arbeitskreises Industrie 4.0*.

Acatech (2016a), *Industrie 4.0: International Benchmark, Options for the Future and Recommendations for Manufacturing Research*.

Acatech (2016b), *Industrie 4.0 in a Global Context: Strategies for Cooperating with International Partners*.

Acikgöz, A., Günsel, A., Bayyurt, N. and Kuzey, C. (2014), "Team Climate, Team Cognition, Team Intuition, and Software Quality. The Moderating Role of Project Complexity", *Group Decision and Negotiation*, Vol. 23, pp. 1145–1176.

Agostini, L. and Filippini, R. (2019), "Organizational and managerial challenges in the path toward Industry 4.0", *European Journal of Innovation Management*, Vol. 22 No. 3, pp. 406–421.

Akgün, A.E., Keskin, H. and Byrne, J.C. (2014), "Complex adaptive systems theory and firm product innovativeness", *Journal of Engineering and Technology Management*, Vol. 31, pp. 21–42.

Akpolat, C., Sahinel, D., Sivrikaya, F., Lehmann, G. and Albayrak, S. (2017), "CHARIOT. An IoT Middleware for the Integration of Heterogeneous Entities in a Smart Urban Factory", *Position papers of the Federated Conference on Computer Science and Information Systems*, Vol. 12, pp. 135–142.

Alexandru, V.R. (2015), "The drive for change in public organizations. A critical analysis of management fashions", *INTERNATIONAL JOURNAL OF ORGANIZATION THEORY AND BEHAVIOR*, Vol. 18 No. 4, pp. 454–493.

Anderson, P. (1999), "Complexity Theory and Organization Science", *Organization Science*, Vol. 10 No. 3, pp. 216–232.

Andrus, D.C. (2005), "The Wiki and the Blog. Towards a Complex Adaptive Intelligence Agency", *Studies in Intelligence*, Vol. 49 No. 3.

Arnold, C., Kiel, D. and Voigt, K.I. (2016), "How Industry 4.0 changes business models in different manufacturing industries", *The XXVII ISPIM Innovation Conference – Blending Tomorrow's Innovation Vintage*, pp. 1–20.

Ashton, K. (2009), “That "Internet of Things" Thing. In the real world, real things matter more than ideas.”, *RFID Journal*.

Bartodziej, C.J. (2017), *The Concept Industry 4.0: An Empirical Analysis of Technologies and Applications in Production Logistics, BestMasters*, Springer Fachmedien Wiesbaden, Wiesbaden, s.l.

Bartunek, J.M., Rynes, S.L. and Ireland, R.D. (2006), “What Makes Management Research Interesting, And Why Does It Matter?”, *Academy of Management Journal*, Vol. 49 No. 1, pp. 9–15.

Basl, J. (2017), “Pilot Study of Readiness of Czech Companies to Implement the Principles of Industry 4.0”, *Management and Production Engineering Review*, Vol. 8 No. 2, pp. 3–8.

Bauer, W., Schlund, S., Marrenbach, D. and Ganschar, O. (2014), *Industrie 4.0 - Volkswirtschaftliches Potenzial für Deutschland*, Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V., Berlin.

Bauernhansl, T. (2015), “Am Ende geht es um das Geld”, *Interaktiv – Das Kundenmagazin des Fraunhofer IPA*, No. 2, pp. 44–48.

Bauernhansl, T. (2017), “Die Vierte Industrielle Revolution – Der Weg in ein wertschaffendes Produktionsparadigma”, in Vogel-Heuser, B., Bauernhansl, T. and Hompel, M. ten (Eds.), *Handbuch Industrie 4.0: Bd. 4: Allgemeine Grundlagen*, *Springer Reference Technik*, 2. Auflage, Springer Vieweg, Berlin, pp. 1–31.

Bauernhansl, T., Emmrich, V., Paulus-Rohmer, D., Döbele, M., Schatz, A. and Weskamp, M. (2015), “Geschäftsmodell-Innovation durch Industrie 4.0. Chancen und Risiken für den Maschinen- und Anlagenbau”, *München: Wieselhuber & Partner*.

Baumol, W.J. and Benhabib, J. (1989), “Chaos. Significance, Mechanism, and Economic Applications”, *Journal of Economic Perspectives*, Vol. 3 No. 1, pp. 77–105.

Bazeley, P. (2007), *Qualitative Data Analysis with NVivo,* 2nd ed., Sage, London.

Bazeley, P. and Richards, L. (2005), *The NVivo Qualitative Project Book*, Sage, London.

Becker, J., Knackstedt, R. and Pöppelbuß, J. (2009), “Developing Maturity Models for IT Management. A Procedure Model and its Application”, *Business & Information Systems Engineering*, Vol. 1 No. 3, pp. 213–222.

Beer, S. (1959), *Cybernetics and Management*, Wiley.

Beer, S. (1966), *Decision and control: the meaning of operational research and management cybernetics*, Wiley, London.

Bertalanffy, L.V. (1951), “General System Theory. A new approach to unity of science”, *Human Biology*, Vol. 23, pp. 303–361.

Bertalanffy, L.V. (1972), “The History and Status of General Systems Theory”, *The Academy of Management Journal*, Vol. 15 No. 4, pp. 407–426.

Bhaskar, R. (1989), *Reclaiming Reality: A Critical Introduction to Contemporary Philosophy*, Verso, London.

BITKOM (2017), *Geschäftsmodelle in der Industrie 4.0: Chancen und Potenziale nutzen und aktiv mitgestalten, Faktenpapier*, Berlin.

Block, C., Freith, S., Morlock, F., Prinz, C., Kreimeier, D. and Kuhlenkötter, B. (2015), “Industrie 4.0 als soziotechnisches Spannungsfeld”, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Vol. 110 No. 10, pp. 657–660.

BMBF (2014), “Die neue Hightechstrategie. Innovationen für Deutschland”, Bundesministerium für Bildung und Forschung.

Bond, T.C. (1999), “The role of performance measurement in continuous improvement”, *International Journal of Operations and Production Management*, Vol. 19 No. 12, pp. 1318–1334.

Boukis, A. (2013), “Identifying some internal S F factors of NSD project performance”, *International Journal of Retail & Distribution Management*, Vol. 41, pp. 531–544.

Brad, S., Murar, M. and Brad, E. (2018), “Design of smart connected manufacturing resources to enable changeability, reconfigurability and total-cost-of-ownership models in the factory-of-the-future”, *International Journal of Production Research*, Vol. 56 No. 6, pp. 2269–2291.

Bradach, J.L. (1997), “Using the Plural Form in the Management of Restaurant Chains”, *Administrative Science Quarterly*, Vol. 42, pp. 276–303.

Braun, V. and Clarke, V. (2006), “Using thematic analysis in psychology”, *Qualitative Research in Psychology*, Vol. 3 No. 2, pp. 77–101.

Brown, S.L. and Eisenhardt, K.M. (1997), “The Art of Continuous Change. Linking Complexity Theory and Time-Paced Evolution in Relentlessly Shifting Organizations”, *Administrative Science Quarterly*, Vol. 42 No. 1, pp. 1–35.

Brown, S.L. and Eisenhardt, K.M. (1998), *Competing on the Edge: Strategy as Structured Chaos*, Harvard Business School, Boston.

Broy, M.(H.) (2010), *CYBER-PHYSICAL SYSTEMS: INNOVATION DURCH SOFTWARE-INTENSIVE EINGEBETTETE SYSTEME*, Springer, Berlin.

Buer, S.-V., Strandhagen, J.O. and Chan, F.T.S. (2018), “The link between Industry 4.0 and lean manufacturing. Mapping current research and establishing a research agenda”, *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924–2940.

Buijs, J. (2003), “Modelling Product Innovation Processes, from Linear Logic to Circular Chaos”, *Creativity & Innovation Management*, Vol. 12 No. 2, pp. 76–93.

Burmeister, C., Lüttgens, D. and Piller, F.T. (2016), “Business Model Innovation for Industrie 4.0. Why the "Industrial Internet" Mandates a New Perspective on Innovation”, *Die Unternehmung*, Vol. 70 No. 2, pp. 124–152.

Büschgens, T., Bausch, A. and Balkin, D.B. (2013), “Organizational Culture and Innovation. A Meta-Analytic Review. Journal of Product Innovation Management”, Vol. 30, pp. 763–781.

Charmaz, K. (2006), *Constructing Grounded Theory*, Sage, London.

Chavarría-Barrientos, D., Batres, R., Wright, P.K. and Molina, A. (2018), “A methodology to create a sensing, smart and sustainable manufacturing enterprise”, *International Journal of Production Research*, Vol. 56 No. 1-2, pp. 584–603.

Checkland, P. (1981), *Systems Thinking, Systems Practice*, John Wiley & Sons, Chichester.

Chesbrough, H. and Crowther, A.K. (2006), “Beyond high tech. Early adopters of open innovation in other industries”, *R&D Management*, Vol. 36, pp. 229–236.

Chesbrough, H.W. (2003), *Open Innovation: The new imperative for creating and profiting from technology*, Harvard Business School Press, Boston.

Chiarello, F., Trivelli, L., Bonaccorsi, A. and Fantoni, G. (2018), “Extracting and mapping industry 4.0 technologies using wikipedia”, *Computers in Industry*, Vol. 100, pp. 244–257.

Chick, S.E., Huchzermeier, A. and Netessine, S. (2014), “Europe’s Solution Factories”, *Harvard Business Review*, pp. 111–115.

Chiva-Gomez, R. (2004), “Repercussions of Complex Adaptive Systems on Product Design Management”, *Technovation*, Vol. 24 No. 9, pp. 707–711.

Choi, J.P. (1997), “Herd Behavior, the "Penguin Effect," and the Suppression of Informational Diffusion. An Analysis of Informational Externalities and Payoff Interdependency”, *RAND Journal of Economics*, Vol. 28 No. 3, pp. 407–425.

Choi, T.Y., Dooleyb, K.J. and Rungtusanatham, M. (2001), “Supply Networks and Complex Adaptive Systems. Control Versus Emergence”, *Journal of Operations Management*, Vol. 19, pp. 351–366.

Chulanova, Z.K. (2019), “Professional standards as a factor of adaptation of human resources to the industry 4.0. Approaches to development and implementation”, *Journal of Human Resource Management*, Vol. 22 No. 1.

Colapinto, C. and Porlezza, C. (2013), “Systems Theory and Innovation”, in Carayannis, E.G. (Ed.), *Encyclopedia of Creativity, Invention, Innovation and Entrepreneurship*, Springer New York, New York, pp. 1764–1768.

Cordeiro, G.A., Ordóñez, R.E.C. and Ferro, R. (2019), “Theoretical proposal of steps for the implementation of the Industry 4.0 concept”, *Brazilian Journal of Operations & Production Management*, Vol. 16 No. 2, pp. 166–179.

Coronado, P.D.U., Lynn, R., Louhichi, W., Parto, M., Wescoat, E. and Kurfess, T. (2018), “Part data integration in the Shop Floor Digital Twin. Mobile and cloud technologies to enable a manufacturing execution system”, *Journal of Manufacturing Systems*, Vol. 48, pp. 25–33.

Cunha, M.P. and Comes, J.E.S. (2003), “Order and Disorder in Product Innovation Models. Creativity & Innovation Management”, Vol. 12 No. 3, pp. 174–187.

Danjou, C., Rivest, L. and Pellerin, R. (2016), “Prendre part à la révolution manufacturière? Du rattrapage technologique à l’Industrie 4.0 chez les PME. (Industry 4.0: Paths to the Era of Digital and Connectivity)”, *CEFRIO*.

David, P.A. (1985), “Clio and the Economics of QWERTY”, *Economic History*, p. 332.

Davis, J., Edgar, T., Porter, J., Bernaden, J. and Sarli, M. (2012), “Smart manufacturing, manufacturing intelligence and demand-dynamic performance”, *Computers & Chemical Engineering*, Vol. 47, pp. 145–156.

Dekkers, R. (2005), *(R)Evolution, Organizations and the Dynamics of the Environment*, Springer, New York.

Dekkers, R. (2015), *Applied Systems Theory*, Springer.

Denzin, N. and Lincoln, Y. (2003), *Collecting and Interpreting Qualitative Materials,* 2nd ed., Sage, Thousand Oaks, California.

Dewar, R.E. and Dutton, J.E.A. (1986), “The adoption of radical and incremental innovations. An empirical analysis”, *Management Science*, Vol. 32, pp. 1422–1433.

DFKI (2011), *Im Fokus - Das Zukunftsprojekt Industrie 4.0: Handlungsempfehlung, Promotorengruppe Kommunikation, 2012*.

Dooley, K. (1997), “A Complex Adaptive Systems of Model of Organization Change”, *Nonlinear Dynamics, Psychology & Life Science*, Vol. 1 No. 1, pp. 69–97.

Dooley, K. and van de Ven, A. (1999), “Explaining Complex Organizational Dynamics”, *Organization Science*, Vol. 10 No. 3, pp. 358–372.

Drath, R. and Horch, A. (2014), “Industrie 4.0. Hit or Hype?”, *IEEE Industrial Electronics Magazine*, Vol. 8 No. 2, pp. 56–58.

Dworschak, B. and Zaiser, H. (2014), “Competences for Cyber-physical Systems in Manufacturing. First Findings and Scenarios”, *Procedia CIRP*, Vol. 25, pp. 345–350.

Eisenhardt, K. (1989), “Building Theories from Case Study Research”, *The Academy of management Review*, Vol. 14 No. 4, pp. 532–550.

Eisenhardt, K. and Graebner, M.E. (2007), “Theory Building from Cases. Opportunities and Challanges”, *Academy of Management Journal*, Vol. 50 No. 1, pp. 25–32.

Eisenhardt, K.M. and Bhatia, M.M. (2002), “Organizational Complexity and Computation”, in Baum, J.A.C. (Ed.), *Companion to Organizations*, Blackwell, Oxford, pp. 442–466.

Ettlie, J.E., Bridges, W.P. and O'Keefe, R. (1984), “Organization Strategy and Structural Differences for Radical versus Incremental Innovation”, *Management Science*, Vol. 30, pp. 682–695.

Fleisch, E. (2010), *What Is the Internet of Things?: An Economic Perspective*, Swiss Federal Institute of Technology in Zurich / University of St. Gallen.

Flyvbjerg, B. (2006), “Five Misunderstandings About Case Study Research”, *Qualitative Enquiry*, Vol. 12 No. 2, pp. 219–245.

Foerster, H. von (1960), “On Self-Organising Systems and Their Environments”, in Yovits, M.C. and Cameron, S. (Eds.), *Self-Organising Systems*, Pergamon Press, London, pp. 30–50.

Forrester, J.W. (1961), *Industrial Dynamics*, MIT Press, Cambridge, Massachusetts.

Foss, L., Gry Agnete Alsos, P. U. H. D., Woll, K. and Moilanan, M. (2013), “Creativity and implementations of new ideas”, *International Journal of Gender and Entrepreneurship*, Vol. 5, pp. 298–322.

Foss, N.J., Lyngie, J. and Zahra, S.A. (2014), “Organizational design correlates of entrepreneurship. The roles of decentralization and formalization for opportunity discovery and realization”, *Strategic Organization*, Vol. 13, pp. 32–60.

Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019), “Industry 4.0 technologies. Implementation patterns in manufacturing companies”, *International Journal of Production Economics*, Vol. 210, pp. 15–26.

Frizelle, G. and Suhov, Y.M. (2001), “An Entropic Measurement of Queueing Behaviour in a Class of Manufacturing Operations”, *Proceedings of the Royal Society of London Series. A-Mathematical Physical and Engineering Sciences*, No. 457, pp. 1579–1601.

Galanakis, K. (2006), “Innovation Process. Make sense using systems thinking”, *Technovation*, Vol. 26, pp. 1222–1232.

Galati, F. and Bigliardi, B. (2019), “Industry 4.0. Emerging themes and future research avenues using a text mining approach”, *Computers in Industry*, Vol. 109, pp. 100–113.

Ganiyusufoglu, Ö.S. (2013), *Chinese approaches to sustainable manufacturing*, In: G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions. Universitätsverl. d. TU, Berlin.

Gell-Mann, M. (1994), *The Quark and the Jaguar*, Freeman & Co., New York.

Germany Trade & Invest (GTAI) (2014), *Industrie 4.0: Smart Manufacturing for the Future*, Berlin.

Glova, J., Sabol, T. and Vajda, V. (2014), “Business Models for the Internet of Things Environment”, *Procedia Economics and Finance*, Vol. 15, pp. 1122–1129.

Gray, T. (1981), “Implementing innovations. A systems approach for integrating what is known”, *The Journal of Technology Transfer*, Vol. 6, pp. 19–32.

Grieves, M. and Vickers, J. (2017), “Digital Twin. Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems”, in Kahlen, F.-J., Flumerfelt, S. and Alves, A. (Eds.), *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, Springer International Publishing, Cham, s.l., pp. 85–113.

Gupta, P., Seetharaman, A. and Raj, J.R. (2013), “The usage and adoption of cloud computing by small and medium businesses”, *International Journal of Information Management*, Vol. 33 No. 5, pp. 861–874.

Gutierrez-Gutierrez, L. and Antony, J. (2020), “Continuous improvement initiatives for dynamic capabilities development. A systematic literature review”, *International Journal of Lean Six Sigma*, Vol. 11 No. 1, pp. 125–149.

Hamada, T. (2019), “Determinants of Decision-Makers’ Attitudes toward Industry 4.0 Adaptation”, *Social Sciences*, Vol. 8 No. 5, p. 140.

Hartmann, M. and Halecker, B. (2015), “Management of Innovation in the Industrial Internet of Things”, *XXVI ISPIM Conference - Shaping the Frontiers of Innovation Management*, pp. 1–17.

Hayes, R.H. and Wheelwright, S. (1984), *Restoring our competitive edge*, Wiley, New York.

Hazy, J.K. (2017), *Teaching Complexity and Its Practical Implications in Leadership Development Programs*, Unpublished.

Heilmann, D., Eickemeyer, L. and Kleibrink, J. (2016), “Industrie 4.0 im Internationalen Vergleich. Vergleich der Industrie 4.0 - Wettbewerbsfähigkeit Chinas, Deutschlands, Japans und der USA”, *Handelsblatt Research Institute*, pp. 1–144.

Heim, G.R. and Peng, D.X. (2010), “The impact of information technology use on plant structure, practices, and performance. An exploratory study”, *Journal of Operations Management*, Vol. 28 No. 2, pp. 144–162.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S. and Smits, R.E.H. (2007), “Functions of innovation systems. A new approach for analysing technological change”, *Technological Forecasting and Social Change*, Vol. 74, 413-432.

Hermann, M., Pentek, T. and Otto, B. (2015), *Design Principles for Industrie 4.0 Scenarios: A Literature review,* 1st ed., Dortmund.

Hermann, M., Pentek, T. and Otto, B. (2016), “Design Principles for Industrie 4.0 Scenarios”, *49th Hawaii International Conference on System Sciences 49th Hawaii International Conference on System Sciences*.

Hofmann, E. and Ruesch, M. (2017), “Industry 4.0 and the current status as well as future prospects on logistics”, *Computers in Industry*, Vol. 89, pp. 23–34.

Holland, J.H. (1995), *Hidden Order: How Adaptation Builds Complexity*, Addison-Wesley, Reading, MA.

Hoyer, C., Gunawan, I. and Reaiche, C.H. (2020), “The Implementation of Industry 4.0 - A Systematic Literature Review of the Key Factors”, *Systems Research and Behavioral Science*, Vol. 37 No. 4, pp. 557–578.

Hyland, P.W., Mellor, R. and Sloan, T. (2007), “Performance measurement and continuous improvement. Are they linked to manufacturing strategy?”, *International Journal of Technology Management*, Vol. 37 No. 4, pp. 237–246.

Industrial Internet Consortium (IIC) (2015), “Fact Sheet”, available at: http://www.iiconsortium.org/docs/IIC_FACT_SHEET.pdf (accessed 18 January 2018).

Ivanov, D., Dolgui, A., Sokolov, B., Werner, F. and Ivanova, M. (2016), “A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0”, *International Journal of Production Research*, Vol. 54 No. 2, pp. 386–402.

Ivanov, D. and Sokolov, B. (2012), “Structure dynamics control approach to supply chain planning and adaptation”, *International Journal of Production Research*, Vol. 50 No. 21, pp. 6133–6149.

Jantsch, E. (1947), “Inter- and Transdisciplinary University. A Systems Approach to Education and Innovation”, *Higher Education Quarterly*, Vol. 1, pp. 7–37.

Jerman, A. and Dominici, G. (2018), “Smart Factories from Business, Management and Accounting Perspective. A Systemic Analysis of Current Research”, *Management*, Vol. 13 No. 4, pp. 355–365.

Jones, L.B. (1962), “Curriculum innovations in a public-school system”, *Theory Into Practice*, Vol. 1, pp. 197–201.

Jung, K., Morris, K.C., Lyons, K.W., Leong, S. and Cho, H. (2015), “Mapping Strategic Goals and Operational Performance Metrics for Smart Manufacturing Systems”, *Procedia Computer Science*, Vol. 44, pp. 184–193.

Kagermann, H., Lukas, W.-D. and Wahlster, W. (2011), “Industrie 4.0. Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution”, *VDI nachrichten*, No. 13.

Kagermann, H., Wahlster, W. and Helbig, J. (2013), *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 Working Group*.

Kans, M. and Ingwald, A. (2016), “Business Model Development Towards Service Management 4.0”, *Procedia CIRP*, Vol. 47, pp. 489–494.

Kaspar, S. and Schneider, M. (2015), “Lean Und Industrie 4.0 in Der Intralogistik. Effizienzsteigerung durch Kombination der beiden Ansätze”, *Productivity Management*, Vol. 20 No. 5, pp. 17–20.

Kauffman, S.A. (1993), *The Origins of Order: Self-Organization and Selection in Evolution*, Oxford University Press, New York.

Kauffman, S.A. (1995), *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity*, Oxford University Press, New York.

Kazancoglu, Y. and Ozkan-Ozen, Y.D. (2018), “Analyzing Workforce 4.0 in the Fourth Industrial Revolution and proposing a road map from operations management perspective with fuzzy DEMATEL”, *Journal of Enterprise Information Management*, Vol. 31 No. 6, pp. 891–907.

Kiel, D., Arnold, C. and Voigt, K.-I. (2017), “The influence of the Industrial Internet of Things on business models of established manufacturing companies – A business level perspective”, *Technovation*, Vol. 68, pp. 4–19.

Kim, D.B., Denno, P.O. and Jones, A.T. (2015), “A model-based approach to refine process parameters in smart manufacturing”, *Concurrent Engineering*, Vol. 23 No. 4, pp. 365–376.

Kim, S.K. and Min, S. (2015), “Business Model Innovation Performance. When does Adding a New Business Model Benefit an Incumbent?”, *Strategic Entrepreneurship Journal*, Vol. 9 No. 1, pp. 34–57.

Kleve, H. (2010), *Konstruktivismus und Soziale Arbeit*, VS Verlag für Sozialwissenschaften, Wiesbaden.

Kolberg, D., Knobloch, J. and Zühlke, D. (2017), “Towards a lean automation interface for workstations”, *International Journal of Production Research*, Vol. 55 No. 10, pp. 2845–2856.

Kovacs, O. (2019), “Big IFs in Productivity-Enhancing Industry 4.0”, *Social Sciences*, Vol. 8 No. 2, p. 37.

Krothapalli, N. and Deshmukh, A. (1999), “Design of Negotiation Protocols for Multi-agent Manufacturing Systems”, *International Journal of Production Research*, Vol. 37 No. 7, pp. 1601–1624.

Kumar, A., Baldea, M., Edgar, T.F. and Ezekoye, O.A. (2015), “Smart Manufacturing Approach for Efficient Operation of Industrial Steam-Methane Reformers”, *Industrial & Engineering Chemistry Research*, Vol. 54 No. 16, pp. 4360–4370.

Kusiak, A. (2018), “Smart manufacturing”, *International Journal of Production Research*, Vol. 56 No. 1-2, pp. 508–517.

Labs Network Industrie 4.0 e.V. (2017), *Wissenstransfer-Event von LNI 4.0 unterstützt deutsche Unternehmen beim Erfolg von Industrie 4.0*, Berlin.

Lao, L., Ellis, M. and Christofides, P.D. (2014), “Smart manufacturing. Handling preventive actuator maintenance and economics using model predictive control”, *AIChE Journal*, Vol. 60 No. 6, pp. 2179–2196.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T. and Hoffmann, M. (2014), “Industry 4.0”, *Business & Information Systems Engineering*, Vol. 6 No. 4, pp. 239–242.

Lee, E.A. (2008), “Cyber Physical Systems. Design Challenges”, in *11th IEEE International Symposium on Object Oriented Real-Time Distributed Computing (ISORC), 2008: 5 - 7 May 2008, Orlando, Florida ; proceedings, 05.05.2008 - 07.05.2008, Orlando, FL, USA*, IEEE, Piscataway, NJ, pp. 363–369.

Lee, J., Bagheri, B. and Kao, H.-A. (2015), “A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems”, *Manufacturing Letters*, Vol. 3, pp. 18–23.

Lee, J., Kao, H.-A. and Yang, S. (2014), “Service Innovation and Smart Analytics for Industry 4.0 and Big Data Environment”, *Procedia CIRP*, Vol. 16, pp. 3–8.

Lee, S.C., Jeon, T.G., Hwang, H.-S. and Kim, C.-S. (2007), “Design and Implementation of Wireless Sensor Based-Monitoring System for Smart Factory”, *ICCSA*, pp. 584–592.

Levy, D. (1994), “Chaos Theory and Strategy:. Theory Application and Managerial Implications”, *Strategic Management Journal*, Vol. 15, 167–178 (Summer).

Liao, Y., Deschamps, F., Loures, E.d.F.R. and Ramos, L.F.P. (2017), “Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal”, *International Journal of Production Research*, Vol. 55 No. 12, pp. 3609–3629.

Lievens, A., Moenaert, R.K. and Jegers, R.S. (1999), “Linking communication to innovation success in the financial services industry. A case study analysis”, *International Journal of Service Industry Management*, Vol. 10, pp. 23–48.

Lin, C., He, D., Huang, X., Choo, K.-K.R. and Vasilakos, A.V. (2018a), “BSeIn. A blockchain-based secure mutual authentication with fine-grained access control system for industry 4.0”, *Journal of Network and Computer Applications*, No. 116, pp. 42–52.

Lin, D., Lee, C.K.M., Lau, H. and Yang, Y. (2018b), “Strategic response to Industry 4.0. An empirical investigation on the Chinese automotive industry”, *Industrial Management & Data Systems*, Vol. 118 No. 3, pp. 589–605.

Lucke, D., Görzig, D., Kacir, M., Volkmann, J., Haist, C., Sachsenmaier, M. and Rentschler, H. (2014), *Strukturstudie "Industry 4.0 für Baden-Württemberg"*, Baden-Württemberg auf dem Weg zu Industry 4.0. Stuttgart, Stuttgart.

Luhmann, N. (1984), *Soziale Systeme: Grundriß einer allgemeinen Theorie*, Suhrkamp, Frankfurt.

Luhmann, N. (2017), *Einführung in die Systemtheorie*, Carl-Auer Systeme Verlag, Heidelberg.

Madsen, D.Ø. (2019), “The Emergence and Rise of Industry 4.0 Viewed through the Lens of Management Fashion Theory”, *Administrative Sciences*, Vol. 9 No. 3, p. 71.

Madsen, D.Ø. and Stenheim, T. (2013), “Doing research on ‘management fashions’. Methodological challenges and opportunities”, *Problems and Perspectives in Management*, Vol. 11 No. 4, pp. 68–76.

Mason, J. (1996), *Qualitative Researching*, Sage, London.

Maturana, H. and Varela, F. (1980), “Autopoiesis and Cognition. The Realization of the Living Boston Studies”, in Cohen R.S. and Marx, W.W. (Eds.), *Philosophy of Science*, D. Reidel Publishing, Dordecht, p. 42.

McCarthy, I.P. (2004), “Manufacturing Strategy - Understanding the Fitness Landscape”, *International Journal of Operations and Production Management*, Vol. 24 No. 2, pp. 124–150.

McCarthy, I.P., Tsinopoulos, C., Allen, P. and Rose-Anderssen, C. (2006), “New Product Development as a Complex Adaptive System of Decisions”, *Journal of Product Innovation Management*, Vol. 23 No. 5, pp. 437–456.

McKelvey, B. (1999), “Self-Organization, Complexity, Catastrophe, and Microstate Models at the Edge of Chaos”, in Baum, J.A.C. and McKelvey, B. (Eds.), *Variations in Organization Science - in Honor of Donald T. Campbell*, Sage Publications, Thousand Oaks, CA, pp. 279–307.

Mell, P.M. and Grance, T. (2011), *The NIST definition of cloud computing*, National Institute of Standards and Technology, Gaithersburg, MD.

Miles, M.B. and Huberman, M.A. (1994), *Qualitative Data Analysis,* 2nd ed., Sage Publications, London.

Minkes, A.L. and Foxall, G.R. (2000), “Entrepreneurship and organization. Thoughts on an old theme”, *Entrepreneurship And Innovation*, Vol. 1, pp. 85–89.

Mitchell, M. (2009), *Complexity: A Guided Tour*, Oxford University Press, Oxford.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S. and Barbaray, R. (2018), “The industrial management of SMEs in the era of Industry 4.0”, *International Journal of Production Research*, Vol. 56 No. 3, pp. 1118–1136.

Mohelska, H. and Sokolova, M. (2018), “MANAGEMENT APPROACHES FOR INDUSTRY 4.0 – THE ORGANIZATIONAL CULTURE PERSPECTIVE”, *Technological and Economic Development of Economy*, Vol. 24 No. 6, pp. 2225–2240.

Morel, B. and Ramanujam, R. (1999), “Through the Looking Glass of Complexity. The Dynamics of Organizations as Adaptive and Evolving Systems Complexity”, *Organization Science*, Vol. 10 No. 3, pp. 278–293.

Morton, J.A. (1967), “A systems approach to the innovation process. Its use in the Bell System”, *Business Horizons*, Vol. 10, pp. 27–36.

Müller, J.M., Kiel, D. and Voigt, K.-I. (2018), “What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability”, *Sustainability*, Vol. 10 No. 1, p. 247.

Nayak, A., Reyes Levalle, R., Lee, S. and Nof, S.Y. (2016), “Resource sharing in cyber-physical systems. Modelling framework and case studies”, *International Journal of Production Research*, Vol. 54 No. 23, pp. 6969–6983.

Negri, E., Fumagalli, L. and Macchi, M. (2017), “A Review of the Roles of Digital Twin in CPS-based Production Systems”, *Procedia Manufacturing*, Vol. 11, pp. 939–948.

Nelson, R.R. and Winter, S.G. (1982), *An Evolutionary Theory of Change*, Belknap Press, Cambridge, Massachusetts.

Odważny, F., Szymańska, O. and Cyplik, P. (2018), “The Requirements for Implementation of the Industry 4.0 Solutions in FMCG Environmant - A Case Study”, *Scientific Journal of Logistic*, Vol. 14 No. 2, pp. 257–267.

O'Mahoney, J. and Vincent, S. (2014), “Critical realism as an empirical project. A beginner's guide”, in Edwards, P.K., O'Mahoney, J. and Vincent, S. (Eds.), *Studying organizations using critical realism: A practical guide*, Oxford University Press, pp. 1–20.

Orlikowski, W.J. and Baroudi, J.J. (1991), “Studying Information Technology in Organizations. Research Approaches and Assumptions”, *Information Systems Research*.

Osterwalder, A. (2004), “The Business Model Ontology. A Proposition in a Design Science Approach”, Thesis, *University of Lausanne*.

Pagnon, W. (2017), “The 4th Industrial Revolution – A Smart Factory Implementation Guide”, *International Journal of Advanced Robotics and Automation*, Vol. 2 No. 2, pp. 1–5.

Parsons, T. (1970), *The Social System*, Routledge & Kegan Paul, London.

Patel, P.C., Terjesen, S. and Li, D. (2012), “Enhancing effects of manufacturing flexibility through operational absorptive capacity and operational ambidexterity”, *Journal of Operations Management*, Vol. 30, pp. 201–220.

Patton, M. (1990), *Qualitative Evaluation and Research Methods*, Thousand Oaks, Sage Publications, Inc.

Pedone, G. and Mezgár, I. (2018), “Model similarity evidence and interoperability affinity in cloud-ready Industry 4.0 technologies”, *Computers in Industry*, Vol. 100, pp. 278–286.

Perrow, C. (1984), *Normal Accidents: Living with High-Risk Technologies*, Basic Books.

Petrovic, A. and Leksell, M. (2017), *Digitalized Process Innovation: Case Studies of Smart Factory Implementation*, Luleå tekniska universitet, Sweden.

Piccarozzi, M., Aquilani, B. and Gatti, C. (2018), “Industry 4.0 in Management Studies. A Systematic Literature Review”, *Sustainability*, Vol. 10 No. 10, p. 3821.

Piller, F. (2015), “Mit systematischer Geschäftsmodell-innovation von Industrie 4.0 zum Unternehmen 4.0”, *21. Internationales Holzbau-Forum IHF*, pp. 1–7.

Plattform Industrie 4.0 (2018), “Industrie 4.0”, available at: http://www.plattform-i40.de (accessed 26 April 2018).

Porter, M.E. and Heppelmann, J.E. (2014), “Wie Smarte Produkte den Wettbewerb verändern”, *Harvard Business Manager*, No. Sonderdruck aus Heft 12.

President’s Council of Advisors on Science and Technology (2014), *Accelerating U.S. Advanced Manufacturing: Report to the President*.

Prigogine, I. and Stengers, I. (1984), *Order out of Chaos*, Bantam Books, New York.

PWC (2016), “Industry 4.0. Building the digital enterprise”, available at: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf (accessed 19 December 2019).

Radzicki, M.J. (1990), “Institutional Dynamics, Deterministic Chaos, and Self-Organizing Systems”, *Journal of Economic Issues*, Vol. 15 No. 1, pp. 57–102.

Rana, G. and Sharma, R. (2019), “Emerging human resource management practices in Industry 4.0”, *Strategic HR Review*, Vol. 18 No. 4, pp. 176–181.

Robson, C. (2002), *Real World Research*, Blackwell, Oxford.

Rosendahl, R., Cal`a, A., Kirchheim, K., Lueder, A. and D’Agostino, N. (2018), “Towards Smart Factory. Multi-Agent integration on industrial standards for service-oriented communication and semantic data exchange”, *CEUR-WS*, No. 2215, pp. 124–132.

Roth, A. (2016), “Industrie 4.0 – Hype oder Revolution?”, in Roth, A. (Ed.), *Einführung und Umsetzung von Industrie 4.0: Grundlagen, Vorgehensmodell und Use Cases aus der Praxis*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–15.

Rüb, J. and Bahemia, H. (2019), “A Review of the Literature on Smart Factory Implementation”, *Conference proceedings of IEEE International Conference on Engineering, Technology and Innovation*.

Ruessmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M. (2015), “Industry 4.0. The Future of Productivity and Growth in Manufacturing Industries”, *The Boston Consulting Group*.

Rycroft, R.W. and Kash, D.E. (2002), “Path Dependence in the Innovation of Complex Technologies”, *Technology Analysis & Strategic Management*, Vol. 14 No. 1, pp. 21–35.

Saunders, M., Lewis, P. and Thornhill, A. (2012), *Research Methods for Business Students,* 6th ed., Person education limited, Harlow.

Sayer, A. (2004), *Realism and social science*, Sage Publications, London.

Schoderbek, P.P., Schoderbek, C.G. and Kefalas, A.G. (1985), *Management Systems, Conceptual Considerations*, Business Publications Inc., Plano, TX.

Schumacher, A., Erol, S. and Sihn, W. (2016), “A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises”, *Procedia CIRP*, Vol. 52, pp. 161–166.

Schumann, R. (2018), *Building the Intelligent Enterprise*, University of Applied Sciences, Constance.

Schwanninger, M. (2001), “System theory and cybernetics”, *Kybernetes*, Vol. 30, pp. 1209–1222.

Shariatzadeh, N., Lundholm, T., Lindberg, L. and Sivard, G. (2016), “Integration of Digital Factory with Smart Factory Based on Internet of Things”, *Procedia CIRP*, Vol. 50, pp. 512–517.

Sieber, J. (1992), *Planning ethically responsible research: A guide for students and internal review boards*, Sage, Newbury Park.

Siemens AG (2020), “Unternehmenspräsentation” (accessed 11 January 2021).

Silverman, D. (2009), *Doing Qualitative Research,* 3rd ed., Sage Publications, London.

Simons, H. (2009), *Case Study Research in Practice*, Sage, London.

Singh, J. and Singh, H. (2013), “Continuous Improvement Strategies. An Overview”, *Journal of Operations Management*, Vol. 12 No. 1, pp. 32–57.

Sjödin, D.R., Parida, V., Leksell, M. and Petrovic, A. (2018), “Smart Factory Implementation and Process Innovation”, *Research-Technology Management*, Vol. 61 No. 5, pp. 22–31.

Sousa Jabbour, A.B.L.d., Jabbour, C.J.C., Foropon, C. and Godinho Filho, M. (2018), “When titans meet - Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors”, *Technological Forecasting and Social Change*, No. 132, pp. 18–25.

Spath, D.(H.), Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T. and Schhlund, S. (2013), *Produktionsarbeit der Zukunft – Industrie 4.0*, Fraunhofer-Verlag, Stuttgart.

Spiegel-Online (2017), “China überholt: Deutsche Leistungsbilanz erneut auf Rekordniveau”, available at: http://www.spiegel.de/wirtschaft/unternehmen/deutschland-hat-wieder-den-groessten-exportueberschuss-der-welt-a-1132312.html (accessed 19 January 2018).

Stacey, R.D. (1995), “The Science of Complexity. An Alternative Perspective for Strategic Change”, *Strategic Management Journal*, Vol. 16 No. 6, pp. 477–495.

Staufen AG (2016), *Deutscher Industrie 4.0 Index 2015*, Köngen.

Staufen AG and Staufen Digital Neonex GmbH (2019), *German Industry 4.0 Index 2019*, STAUFEN.

Strange, R. and Zucchella, A. (2017), "Industry 4.0, global value chains and international business", *Multinatl. Bus. Rev.*, Vol. 3 No. 25, pp. 174–184.

Strozzi, F., Colicchia, C., Creazza, A. and Noè, C. (2017), "Literature review on the 'Smart Factory' concept using bibliometric tools", *International Journal of Production Research*, Vol. 55 No. 22, pp. 6572–6591.

Sun, J., Gao, M., Wang, Q., Jiang, M., Zhang, X. and Schmitt, R. (2018), "SMART SERVICES FOR ENHANCING PERSONAL COMPETENCE IN INDUSTRIE 4.0 DIGITAL FACTORY", *Scientific Journal of Logistics*, Vol. 14 No. 1, pp. 51–57.

Theorin, A., Bengtsson, K., Provost, J., Lieder, M., Johnsson, C., Lundholm, T. and Lennartson, B. (2017), "An event-driven manufacturing information system architecture for Industry 4.0", *International Journal of Production Research*, Vol. 55 No. 5, pp. 1297–1311.

Tortorella, G.L. and Fettermann, D. (2018), "Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2975–2987.

Trappey, A.J.C., Trappey, C.V., Hareesh Govindarajan, U., Chuang, A.C. and Sun, J.J. (2017), "A review of essential standards and patent landscapes for the Internet of Things. A key enabler for Industry 4.0", *Advanced Engineering Informatics*, Vol. 33, pp. 208–229.

Tupa, J., Simota, J. and Steiner, F. (2017), "Aspects of Risk Management Implementation for Industry 4.0", *Procedia Manufacturing*, Vol. 11, pp. 1223–1230.

Tuptuk, N. and Hailes, S. (2018), "Security of smart manufacturing systems", *Journal of Manufacturing Systems*, Vol. 47, pp. 93–106.

Turber, S., Vom Brocke, J., Gassmann, O. and Fleisch, E. (2014), "Designing Business Models in the Era of Internet of Things", in Hutchison, D., Kanade, T., Kittler, J., VanderMeer, D. and Yoon, V. (Eds.), *Advancing the Impact of Design Science: Moving from Theory to Practice 9th International Conference, DESRIST 2014, Miami, FL, USA, May 22-24, 2014. Proceedings*, *Lecture Notes in Computer Science / Information Systems and Applications, Incl. Internet/Web, and HCI*, Vol. 8463, Springer International Publishing, Cham, pp. 17–31.

Ulrich, W. (1983), *Critical Heuristics of Social Planning: A New Approach to Practical Philosophy*, P. Haupt, Bern.

Vachálek, J., Bartalsky, L., Rovný, O., Šišmišová, D., Morháč, M. and Lokšík, M. (2017), "The Digital Twin of an Industrial Production Line Within the Industry 4.0 Concept", *Proceedings of the 2017 21st International Conference on Process Control (PC)*, 258 - 262.

van Kranenburg, R. (2008), *The Internet of Things: A Critique of Ambient Technology and the All-seeing Network of RFID*, Institute of Network Cultures, Amsterdam.

Veile, J.W., Kiel, D., Müller, J.M. and Voigt, K.-I. (2020), "Lessons learned from Industry 4.0 implementation in the German manufacturing industry", *Journal of Manufacturing Technology Management*, Vol. 31.

Verl, A. and Lechler, A. (2014), "Steuerung aus der Cloud", in Bauernhansl, T., Hompel, M. ten and Vogel-Heuser, B. (Eds.), *Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration*, *SpringerLink*, Springer Vieweg, Wiesbaden, pp. 235–247.

Vester, F. (2000), *Die Kunst vernetzt zu denken*, Deutsche Verlags Anstalt GmbH, Stuttgart.

Vincent, S. and O'Mahoney, J. (2017), "Critical Realism and Qualitative Research. An Introductory Overview", in Cassell, C., Cunliffe, A.L. and Grandy, G. (Eds.), *The SAGE Handbook of Qualitative Business and Management Research Methods*, Sage, London, Chapter 13.

Vogel-Heuser, B., Bauernhansl, T. and Hompel, M. (Eds.) (2017), *Handbuch Industrie 4.0: Bd. 1 Produktion,* 2nd ed., Springer-Verlag, Berlin.

Vokurka, R.J. and O'Leary-Kelly, S.W. (2000), "A review of empirical research on manufacturing flexibility", *Journal of Operations Management*, Vol. 18 No. 4, pp. 485–501.

Wahl, M. (2015), "STRATEGIC FACTOR ANALYSIS FOR INDUSTRY 4.0", *Journal of Security and Sustainability Issues*, Vol. 5 No. 2, pp. 241–247.

Walsham (1993), *Interpretive Research: A Definition*.

Wan, J., Chen, B., Imran, M., Tao, F., Di Li, Liu, C. and Ahmad, S. (2018), "Toward Dynamic Resources Management for IoT-Based Manufacturing", *IEEE Communications Magazine*, Vol. 56 No. 2, pp. 52–59.

Wang, S., Ouyang, J., Di Li and Liu, C. (2017), "An Integrated Industrial Ethernet Solution for the Implementation of Smart Factory", *IEEE Access*, Vol. 5, pp. 25455–25462.

Wang, S., Wan, J., Di Li and Zhang, C. (2016a), “Implementing Smart Factory of Industrie 4.0. An Outlook”, *International Journal of Distributed Sensor Networks*, Vol. 12 No. 1.

Wang, S., Wan, J., Zhang, D., Di Li and Zhang, C. (2016b), “Towards smart factory for industry 4.0. A self-organized multi-agent system with big data based feedback and coordination”, *Computer Networks*, Vol. 101, pp. 158–168.

Webster, J. and Watson, R.T. (2002), “Analyzing the Past to Prepare for the Future. Writing a Literature Review”, *MIS Quarterly*, Vol. 26 No. 2, pp. xiii–xxiii.

Wei, Z., Song, X. and Wang, D. (2017), “Manufacturing flexibility, business model design, and firm performance”, *International Journal of Production Economics*, pp. 87–97.

Westerlund, M., Leminen, S. and Rajahonka, M. (2014), “Designing Business Models for the Internet of Things”, *Technology Innovation Management Review*, Vol. 4 No. 7, pp. 5–14.

Westkämper, E., Spath, D., Constantinescu, C. and Lentes, J. (2013), *Digitale Produktion*, Springer Berlin Heidelberg, Berlin, Heidelberg, s.l.

Weyer, S., Schmitt, M., Ohmer, M. and Gorecky, D. (2015), “Towards Industry 4.0. Standardization as the crucial challenge for highly modular, multi-vendor production systems”, *IFAC-PapersOnLine*, Vol. 48 No. 3, pp. 579–584.

Whetten, D.A. (1989), “What Constitutes a Theoretical Contribution?”, *Academy of Management Review*, Vol. 14 No. 4, pp. 490–495.

Whysall, Z., Owtram, M. and Brittain, S. (2019), “The new talent management challenges of Industry 4.0”, *Journal of Management Development*, Vol. 38 No. 2, pp. 118–129.

Wiener, N. (1948), *Cybernetics: Or Control and Communication in the Animal and the Machine*, MIT Press, Cambridge, Massachusetts.

Wu, D., Rosen, D.W., Wang, L. and Schaefer, D. (2014), “Cloud-based Manufacturing. Old Wine in New Bottles?”, *Procedia CIRP*, Vol. 17, pp. 94–99.

Xu, L.D., He, W. and Li, S. (2014), “Internet of Things in Industries. A Survey”, *IEEE Transactions on Industrial Informatics*, Vol. 10 No. 4, pp. 2233–2243.

Xu, L.D., Xu, E.L. and Li, L. (2018), “Industry 4.0. State of the art and future trends”, *International Journal of Production Research*, Vol. 56 No. 8, pp. 2941–2962.

Yakhlef, A. (2005), “Immobility of tacit knowledge and the displacement of the locus of innovation”, *European Journal of Innovation Management*, Vol. 8, pp. 227–239.

Yao, X., Jin, H. and Zhang, J. (2015), “Towards a wisdom manufacturing vision”, *International Journal of Computer Integrated Manufacturing*, Vol. 28 No. 12, pp. 1291–1312.

Yin, R.K. (2003), *Case Study Research: Design and Methods, (Bickman, L. & Rog, D. J.), Applied Social Research Methods Series*, Vol. 5, 3rd ed., Sage, Thousand Oaks, California.

Yin, R.K. (2009), *Case Study Research,* 4th ed., Sage Publications, London.

Yin, R.K. (2014), *Case Study Research Design And Methods*, Sage, Thousand Oaks, CA.

Yin, Y., Stecke, K.E. and Li, D. (2018), “The evolution of production systems from Industry 2.0 through Industry 4.0”, *International Journal of Production Research*, Vol. 56 No. 1-2, pp. 848–861.

Yoon, S., Um, J., Suh, S.-H., Stroud, I. and Yoon, J.-S. (2016), “Smart Factory Information Service Bus (SIBUS) for manufacturing application. Requirement, architecture and implementation”, *Journal of Intelligent Manufacturing*, Vol. 30 No. 1, pp. 363–382.

Zollenkop, M. and Lässig, R. (2017), “Digitalisierung im Industriegütergeschäft”, in Schallmo, D., Rusnjak, A., Anzengruber, J., Werani, T. and Jünger, M. (Eds.), *Digitale Transformation von Geschäftsmodellen: Grundlagen, Instrumente und Best Practices*, *Schwerpunkt*, Springer Fachmedien, Wiesbaden, pp. 59–95.

Zuehlke, D. (2010), “SmartFactory—Towards a factory-of-things”, *Annual Reviews in Control*, Vol. 34 No. 1, pp. 129–138.

Appendices

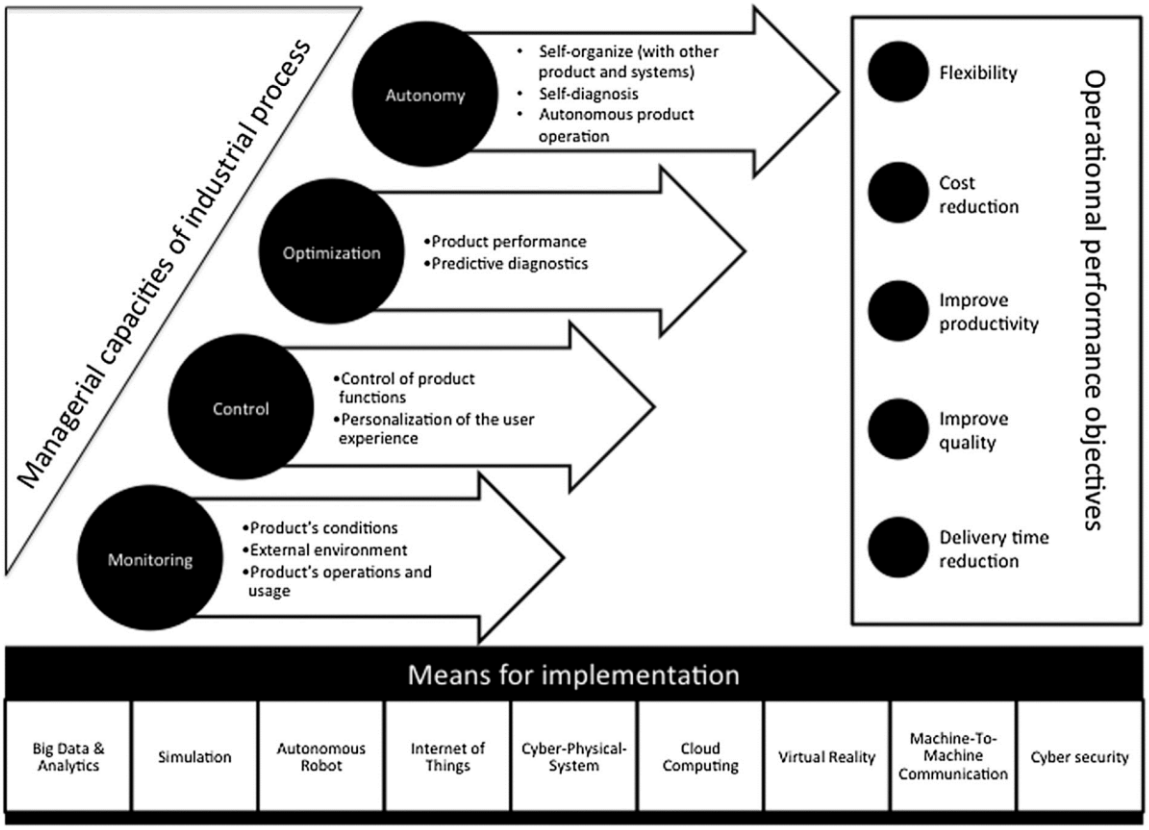
Appendix A: Neologisms inspired by Industry 4.0 (Madsen, 2019)

Area	Neologism	Reference
Work, leadership and knowledge management	HRM 4.0	Liboni et al. (2019)
	Smart HR 4.0	Sivathanu and Pillai (2018)
	Arbeit 4.0	Botthof and Hartmann (2015)
	Work 4.0	Fischer et al. (2017), Salimi (2015)
	Leadership 4.0	Kelly (2019), Prince (2017)
	Knowledge Management 4.0	Neumann (2018)
Operations, quality and logistics	Quality 4.0	Johnson (2019), Radziwill (2018)
	Lean 4.0	Mayr et al. (2018)
	Six Sigma 4.0	Schäfer et al. (2019)
	Logistics 4.0	Barreto et al. (2017), Ten Hompel and Henke (2014), Tijan et al. (2019), Winkelhaus and Grosse (2019)
	Supply Chain Management 4.0	Frazzon et al. (2019)
Industry/sector specific	Services 4.0	Paschou et al. (2018)
	Service Management 4.0	Kans and Ingwald (2016a, 2016b)
	Retail 4.0	Lee (2017)
	Fashion 4.0	Behr (2018), Bertola and Teunissen (2018)
	Agriculture 4.0	Zambon et al. (2019)
	Airport 4.0	Koenig et al. (2019)
	Pharma Industry 4.0	Ding (2018)
	Building Management 4.0	Rogers (2018)
	Construction 4.0	Maskuriy et al. (2019)
	Field Service Technician Management 4.0	Vössing and von Bischhoffshausen (2018)
	Care 4.0	Chute and French (2019)
Education	Higher Education 4.0	Xing (2019)
	Education 4.0	Almeida and Simoes (2019), Almeida and Simoes (2019), Buasuwan (2018), Ciolacu et al. (2017), Hariharasudan and Kot (2018), Mourtzis et al. (2018), Puncreobutr (2016)
	Engineering Education 4.0	Schuster et al. (2016)
	Learning 4.0	Janssen et al. (2016)
	University 4.0	Lapteva and Efimov (2016)
Innovation management	Innovation 4.0	Reischauer and Leitner (2016)
	Innovation Management 4.0	Völker et al. (2019)
Marketing and consumers	Consumer Behavior 4.0	Roblek et al. (2016)
	Marketing 4.0	Bergemann (2019), Jiménez-Zarco et al. (2019), Kotler et al. (2016), Vassileva (2017), Wereda and Wo´zniak (2019)
	Customer 4.0	Wereda and Wo´zniak (2019)
Management and governance	Controlling 4.0	Heimel and Müller (2019), Obermaier (2016)
	Enterprise 4.0	Ferreira et al. (2019)
Society	Neighborhood 4.0	Cooper and Sebake (2018)
	Revolution 4.0	Zambon et al. (2019)
	Society 4.0	Mazali (2018)

Appendix B: Clustering of Industry 4.0 technologies (Chiarello et al., 2018)

#	Label of the cluster	Constituent technologies
1	Big Data	Virtual machine, Data mining, User interface, Algorithm, Computer vision, Cryptography, Printed circuit board, Middleware, Real-time computing, Virtual reality, Augmented reality, Human–computer interaction, Multiprocessing, Decision support system, Supervised learning
2	Transactions, digital certification, digital currency	Bitcoin, Cryptocurrency, Bitcoin network, Cryptocurrency tumbler, Digital currency exchanger, Alternative currency, Dogecoin, Ethereum, Litecoin, Monero (cryptocurrency), Namecoin, Peercoin, Virtual currency, Auroracoin, Blockchain, Lisk, Primecoin, Ripple (payment protocol), Titcoin, Zerocoin
3	Program ming languages	Python (programming language), Database, Computing platform, Ruby (programming language), C Sharp (programming language), HTML, Perl, Hypertext Transfer Protocol, XML, Java (software platform), Haskell (programming language), .NET Framework, Lua (programming language), Sun Microsystems, BASIC
4	Computing	MacOS, IOS, Mainframe computer, Graphical user interface, Cloud computing, Home computer, Laptop, Solaris (operating system), Microcomputer, Personal digital assistant, QNX, Read-only memory, Tablet computer, ASCII, DOS
5	Embedded Systems	Programmable logic controller, Zilog Z80, CMOS, Zilog Z8, Toshiba TLCS, Zilog eZ80, NEC μPD780C, MOS Technology 6502, R800 (CPU), U880, Zilog Z180, Zilog Z800, Zilog Z8000, KP1858BM1, Hitachi HD64180
6	Intel	3D XPoint, Intel ADX, Intel Clear Video, Intel SHA extensions, Intel System Development Kit, Intel 1103, Intel AZ210, Intel Cluster Ready, Intel Compute Stick, Intel Display Power Saving Technology, Intel Mobile Communications, Intel Modular Server System, Intel PRO/Wireless, Intel Quick Sync Video
7	Internet of Things	Wireless sensor network, Near field communication, Arduino, NetSim, Z-Wave, OPNET, Telemetry, RIOT (operating system), Routing protocol, TinyOS, Internet of things, NesC, MiWi, Nano-RK, LinuxMCE
8	Protocols & Architec tures	1-Wire, Profibus, Smart meter, ×10 (industry standard), Modbus, Local Interconnect Network, TTEthernet, Fleet Management System, Keyword Protocol 2000, Meter-Bus, MTConnect, OPC Unified Architecture, PROFINET, RAPIEnet, SAE J1587
9	Communica tion Network and Infrastruc tures	Wi-Fi, Cellular network, Router (computing), Internet Protocol, Radiotelephone, ARPANET, Radio frequency, Digital subscriber line, General Packet Radio Service, Global Positioning System, CYCLADES, Beacon, Wireless, High Speed Packet Access, Evolution-Data Optimized
10	Production	Laser, 3D printing, Home automation, Agricultural robot, Nanorobotics, Semantic Web, Machine vision, Nanotechnology, Robotics, Information and communications technology, Speech recognition, Smart grid, Memristor, OLED, Computer-generated holography
11	Identification	Barcode, RFID, QR code, MaxiCode, Mobile tagging, Code 128, GS1 DataBar, High Capacity Color Barcode, Aztec Code, Barcode printer, Bokode, Codabar, CPC Binary Barcode, Interleaved 2 of 5, ITF-14

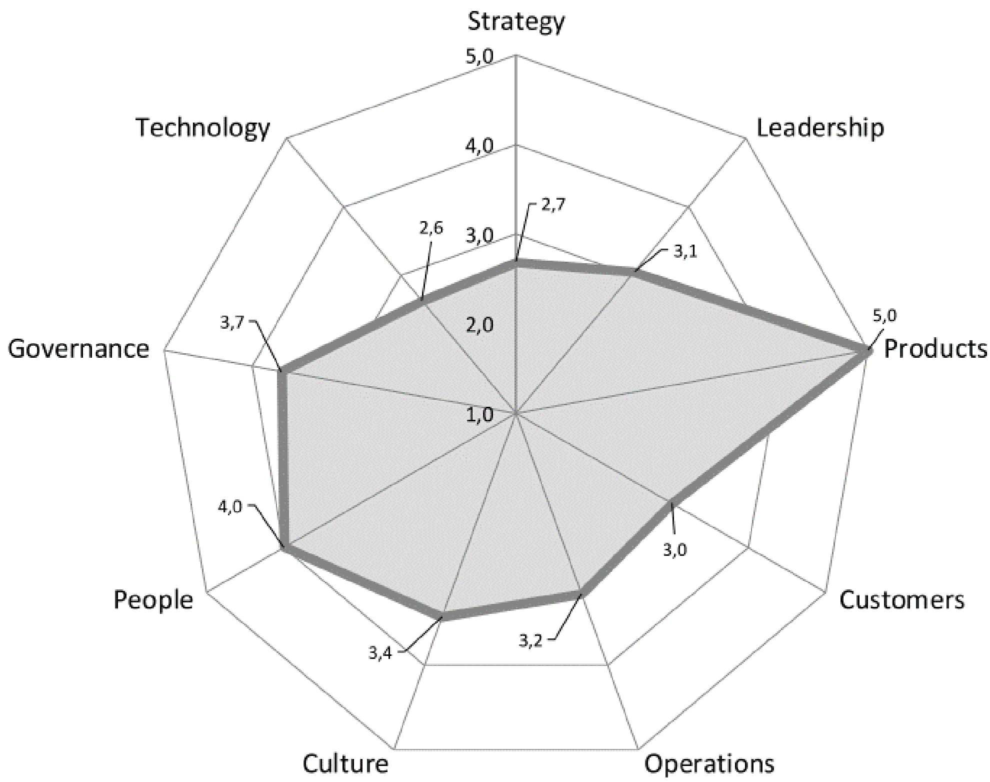
Appendix C: Implementation Framework of Industry 4.0 (Moeuf et al., 2018)



Appendix D: Evaluation sheet for the implement. of Industry 4.0 (Odważny et al., 2018)

Implementation phase	Evaluation area	Feature	Characteristic
Aspiration	Human factor	Staff qualifications	Team has qualified individuals including IT specialists and automatics engineers.
	Technical / organizational	Cooperation, communication skills	Individuals are capable to work in teams.
		Financials	Budget is sufficient for investments into staff and technology.
	Management	Data	Enterprise aspires to aggregate available data effectively.
		Machine park equipment	Sufficient technology is available: including IT solutions.
		Tools and technologies	Automation and robotics of single processes. Part of the machine park is equipped in PLC steering.
		Vertical integration	Readiness to cooperate with other departments, within enterprise.
Maturity	Human factor	Staff qualifications	Operational employees have analytic skills and operate with available IT software.
		Cooperation, communication skills	Teams gain autonomy and can easily cooperate with others.
	Technical/ organizational	Data	Software and systems are fully integrated data wise. Enterprise is implementing Big Data concept.
		Tools and technologies	-Internet of Things is implemented gradually. More elements are included in the net. -Simulation models are used in decision process and production steering. -RFID (or similar technology) is widely used in the factory for track and trace. -Monitoring and cooperation is built within machine park.
	Management	Vertical integration	Full cooperation between departments.
		Horizontal integration	Readiness to cooperate with other companies in the supply chain and potential co-operators.
Smart Factory	Human factor	Staff	No operational employees in the machine park. Staff consists of expert. Employees are controlling the process and react to system warnings if necessary.
	Technical/ organizational	Data and its correctness	-World class in aggregation, analysis and data interpretation. -Aggregated data is effectively stored. Data is valid, up to date and allows sufficient production steering.
		Tools and technologies	Full integration of all installed tools and technologies.
		Research and development	-Big investment pressure in research and development area. -Staff is being moved to such departments from the shop floor if possible (skills and knowledge wise).
		Virtualization	Simulation models used for all decision required processes.
		Real-Time Capability	Monitoring of current state and real-time capability.
		Safety	Data base is fully secured.
		Horizontal and End-to-End integration	Factory as an integral element of a supply chain cooperating with companies within the branch and also outside.
	Management	Client	High level of integration with clients. Products highly customized according to market demand.
		Organizational structure	High level of autonomy and decentralization.
		Control	Demand driven planning according to single clients' orders.

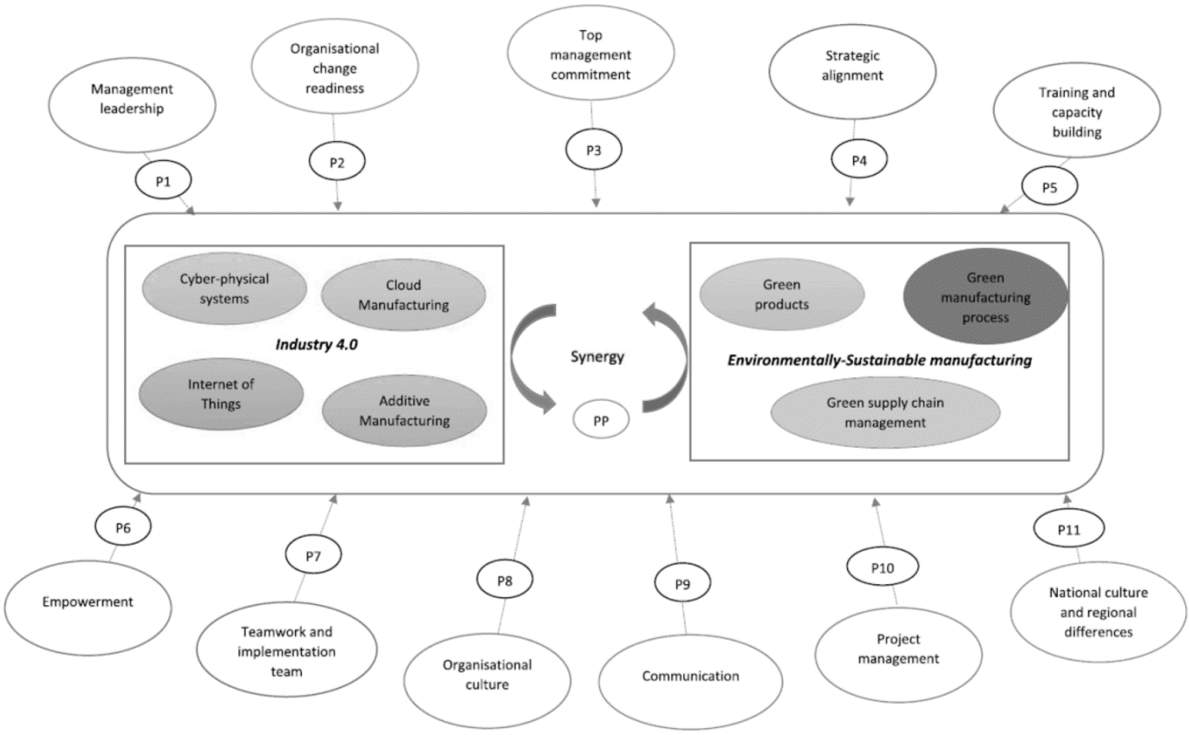
Appendix E: Example of an Industry 4.0 maturity analysis (Schumacher et al., 2016)



Appendix F: Maturity model structured in three guiding principles (Sjödin et al., 2018)

Maturity Level	People *Cultivate Digital People*	Process *Introduce Agile Processes*	Technology *Configure Modular Technology*
Level 4. Smart, predictable manufacturing	Create a culture of continuous smart factory innovation. [X, 1, 3] Create specialized roles and responsibilities geared toward predictable production. [X, 1]	Develop processes for integrating data visualization into decision making. [X, 1] Create proactive processes for forecasting and planning future production. [X, 5]	Create systems to monitor and visualize critical operational analytics. [1, 2, 5] Integrate digital system insights from external partners to enable supply chain predictability. [X, 1]
Level 3. Real-time process analytics and optimization	Organize sense-making sessions with suppliers, users, and other stakeholders. [1, 2, 4, 5] Recruit data analysts and data scientists to optimize production. [X, 1, 5]	Use insight analysis and data interpretation to streamline operational processes. [1, 2, 3, 5] Create processes for evaluating optimization opportunities. [X, 5]	Implement systems for real-time performance analysis. [1, 2, 3, 5] Implement simulation systems to test, prototype, and optimize the digital factory. [X, 5]
Level 2. Structured data gathering and sharing	Educate people to develop the ability to exploit connected data systems. [1, 3, 4] Revise production staff roles to proactively coordinate digital insights and knowledge sharing. [X, 1]	Create specialized insight-mining processes to support information gathering across departments. [1,3,4] Build cross-functional digitalization networks to facilitate knowledge sharing. [1, 2, 3, 4, 5]	Increase accuracy of data collection from technology. [1, 2, 3, 5] Create automated processes for data mining and sharing across functions. [X, 5]
Level 1. Connected technologies	Create an inclusive culture for implementation by involving workforce in vision development. [2, 3, 4] Recruit people with digitalization competencies. [1, 3, 4]	Formalize hybrid smart factory implementation processes. [X, 1] Create process for involving external actors in development of connected platform. [1, 2, 4, 5]	Apply a digital lens to map existing and new technologies. [1, 4, 5] Connect existing technological applications to create data flow. [2, 3, 5]

Appendix G: Integrative framework (Sousa Jabbour et al., 2018)



Appendix H: Barriers for the implementation of Industry 4.0 (Cordeiro et al., 2019)

Obstacles/ Challenges	Description	Authors
High investment	New technological profiles will require large investments in infrastructure and capacity building.	Oesterreich and Teuteberg (2016)
Obstacles/ Challenges	**Description**	**Authors**
New professional profile	Demand for a new professional profile with more specific and/or technical knowledge about the operation of the new intelligent manufacturing model. On the company's side, it is necessary to implement training strategies and promote a culture of sharing of good practices.	Oesterreich and Teuteberg (2016); Prause and Weigand (2016); Khan and Turowski (2016); Kagermann et al. (2013)
Employee engagement	Resistance to change and fear of exchanging people for smart equipment. Difficulty in accepting tecnology and associated knowledge.	Oesterreich and Teuteberg (2016); Khan and Turowski (2016); Kagermann et al. (2013)
Lack of standard-ization and refer-ence architectures	Concepts are still under construction. Model proposals should cover a strategic level and the standardization of technical aspects with the aim of facilitating implementation.	Oesterreich and Teuteberg (2016); Khan and Turowski (2016); Kagermann et al. (2013)
Safety	The data security is a risk factor, due to it involving a dynamic process of sharing, collaboration, mobility, large volumes of data, and various sources.	Oesterreich and Teuteberg (2016); Khan and Turowski (2016); Kagermann et al. (2013)
Communication networks	There must be an effective connectivity infrastructure available that allows access and sharing of data through a quality internet network, thereby, ensuring real-time data flow and process integration.	Oesterreich and Teuteberg (2016); Khan and Turowski (2016); Kagermann et al. (2013)
Organizational and Process Changes	A new work organization will be required to support production with mass customization. There will be a need for a collaborative working environment and continuous use of knowledge management for this intelligent manufacturing structure to be fully established.	Oesterreich and Teuteberg (2016); Khan and Turowski (2016); Brettel et al. (2014); Kagermann et al. (2013)
Legislation / Regulations	Need to develop specific legislation for these technological innovations. Particular attention should be paid to issues of corporate data protection and accountability.	Oesterreich and Teuteberg (2016); Kagermann et al. (2013)
Data processing	The systems involved in Industry 4.0 will generate an enormous amount of data from diverse sources, demanding a huge capacity of storage, processing, and management.	Khan and Turowski (2016)
Technology	The various concepts of Industry 4.0 did not evolve in a balanced way; as a result, they are currently at different levels of maturity, and some of these are still at the early stages of modeling.	Oesterreich and Teuteberg (2016), Khan and Turowski (2016)

Appendix I: Interview questions

1. When did (___) begin to implement Smart Factory and when does (___) plan to finish?
2. What are the different stages of the project? At which stage is (___) now?
3. How long did (___) prepare the Smart Factory implementation project?
4. Is the implementation project tight to fixed milestones? Or do tasks evolve over time?

5. Would you talk about the pre-implementation stage of the implementation project?
6. What are the options that were explored?
7. Please explain how the implementation was managed.
8. In which technologies did (___) invest to support the implementation of the Smart Factory?
9. Why did (___) choose to begin with these Smart Factory technologies instead of others?
10. What internal departments and people are involved in the implementation project?
11. How does the Smart Factory fit into the overall strategy of (___)?

12. Does (___) use external support in the Smart Factory implementation project?
13. What additional services (or products) does (___) require from external partners?
14. Who is negotiating with (___) before it comes to a contract?
15. Would it be rational for (___) to develop Smart Factory competencies in-house without any suppliers?
16. Did (___) set up a Smart Factory implementation team?
17. Can you elaborate on the nature and the structure of the implementation team?

18. What are important evaluations that (___) had to make prior the implementation?
19. What have been the benefits of the Smart Factory for (___)?
20. Are there some benefits which were not met?
21. How did (___) calculate the investment costs of their Smart Factory implementation project?
22. What are the critical success factors for a successful implementation?
23. What are the soft success factors that moderate a successful implementation?

Appendix J: Adjusted interview questions

1. What is your position at (___)?
2. How long have you been at (___)?
3. What is the objective of the central department for digital transformation?
4. What activities did (___) do to support its Digital Transformation?
5. What departments have been founded?
6. How large are the departments?
7. What people have been involved or employed for the project?
8. Can you place these activities on a time scale?
9. What are the milestones of the digital transformation at (___)?
10. What in the transformation project did evolve different so far, compared to how it was planned at the beginning?

11. How does (___) manage the digital transformation?
12. Do departments and factories of (___) receive much autonomy from the head quarter?
13. How does (___) motivate their employees to follow the transformation ideas?
14. Could you explain the hierarchy levels regarding the digital transformation?
15. Does (___) use external support in the Smart Factory implementation project?
16. Would it be rational for (___) to develop Smart Factory competencies in-house without any suppliers?

17. What are important evaluations that (___) had to make prior the implementation?
18. What have been the benefits of the Smart Factory for (___)?
19. Are there some benefits which were not met?
20. How did (___) calculate the investment costs of their Smart Factory implementation project?
21. What are the critical success factors for a successful implementation?
22. What are the soft success factors that moderate a successful implementation?

Appendix K: Research outputs

Studies Published for preparing the Ph.D.

Rüb, J.; Bahemia, H.; Schleyer, C. (2017), "An Examination of Barriers to Business Model Innovation", in conference proceedings: International Conference on Engineering, Technology and Innovation (ICE / IEEE ITMC), Madeira, Portugal 27.-29.06.2017.

Studies published in the process of writing the Ph.D.

Rüb, J.; Bahemia, H. (2019), "A Review of the Literature on Smart Factory Implementation", in conference proceedings: International Conference on Engineering, Technology and Innovation (ICE / IEEE ITMC), Nice, France 17.-19.06.2019.

Rüb, J.; Bahemia, H. (2020), "The Examination of the Corporate Organisation and Implementation of Industry 4.0 in a High Value German Manufacturing Firm", in conference proceedings: International Conference on Engineering, Technology and Innovation (ICE / IEEE ITMC), Cardiff, Great Britain (virtual conference due to Covid-19), 15.-17.06.2020.

Studies submitted but delayed due to Covid-19 pandemic in 2020/21

Rüb, J.; Bahemia, H. (2020), "A Complex Adaptive Systems Perspective on the Management of Industry 4.0 Implementation", in conference proceedings: R&D Management Conference 2020, Glasgow, Great-Britain [postponed].

Appendix L: Interview participant information sheet and confidentiality agreement

PARTICIPANT INFORMATION SHEET FOR INTERVIEWEES

Title of Research: Exploring the Underlying Mechanisms of Smart Factory Implementation

This research project explores the underlying mechanisms of Smart Factory implementation. We argue that the level of potential value that Smart Factory technologies release in firms depends (among other factors) on the way in which they are implemented in the firm.

You are invited to take part in an interview so that the researcher can better understand what these underlying mechanisms of Smart Factory implementation are.

What is the purpose of the study? Exploring the underlying mechanisms of Smart Factory implementation refers to the frequently stated demand to further deliver knowledge about the implementation as well as the real benefits of Smart Factory. The results shall support companies to better position themselves in the new industrial era of Industry 4.0, the IoT and the application of Smart Factories.

Do I have to take part? Participation in the study is voluntary. You are free to decline the invitation or to withdraw from the study at any time without providing an explanation. You may withdraw by contacting Julian Rüb (contact details below).

What will happen to me if I take part? If you agree to take part, you will be asked about 20 questions regarding your experience on Smart Factory implementation. With your permission, the discussion will be audio recorded. The discussion will last about 45 minutes, approximately. The audio recording and transcription will have a code number securing anonymity (i.e. you will not be identifiable) of your responses. No names will be used either in audio recording or the transcription.

What if something goes wrong? It is extremely unlikely that something will go wrong during this study. Newcastle University ensures its staff to carry out research involving people. The study has been reviewed and approved by the Newcastle University Ethics Committee. Full ethical approval has been granted for the research.

Confidentiality: Any information you supply will be held in strict confidence (password protected computer systems), and viewed only by the research team (Julian Rüb and Dr. Hanna Bahemia). The transcription support for this research will sign a confidential form too.

For any further questions regarding this research project please contact Julian Rüb via j.rueb1@newcastle.ac.uk.

If you wish to verify these details, you can contact the project supervisor Dr. Hanna Bahemia, Newcastle University Business School, 5 Barrack Road, Newcastle upon Tyne, NE1 4SE, via hanna.bahemia@newcastle.ac.uk.

Appendix M: Interview participant information sheet and confidentiality agreement

INTERVIEW CONSENT FORM

(one copy to be kept by participant, the other by the researcher)

Title of Project: Exploring the Underlying Mechanisms of Smart Factory Implementation

Name of Interviewer: Julian Rüb
Contact: j.rueb1@newcastle.ac.uk

Please initial box

1. I confirm that I have read and understand the information sheet for the above study. I have had the opportunity to consider the information and to ask questions. Any questions asked have been answered satisfactorily. ☐

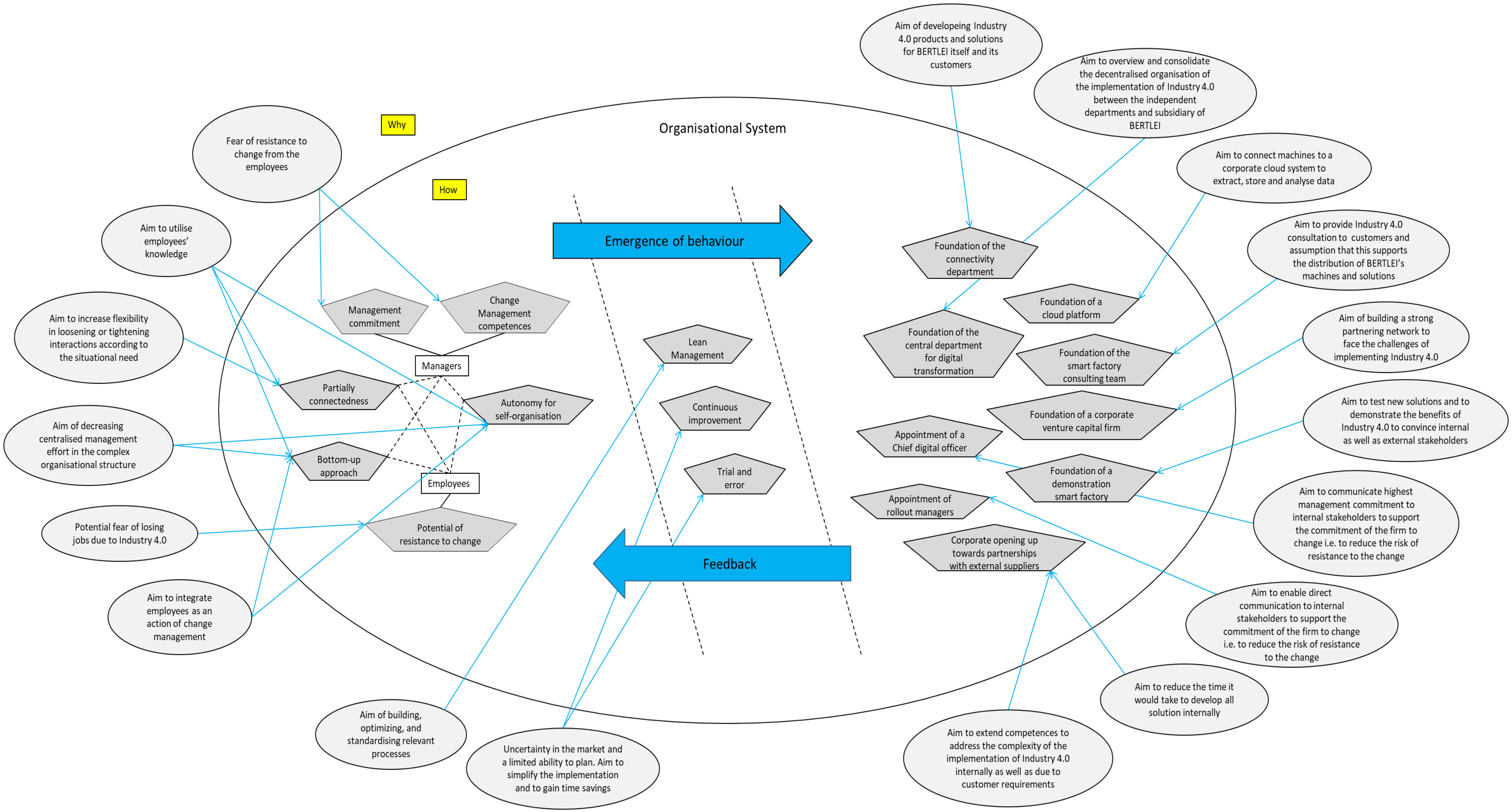
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my legal or personal rights being affected. ☐

3. I understand that the researchers will hold all audio recordings and transcripts of these collected during the study confidentially. ☐

4. I agree to take part in the above study. ☐

________________	________________	________________
Date (dd/mm/yy)	*Name of participant*	*Signature*
________________	________________	________________
Date (dd/mm/yy)	*Name of interviewee*	*Signature*

Appendix N: Emergence and feedback in the organisational system



Appendix O: Organisational system of the implementation of Industry 4.0