PhD Dissertation

Exploring the Factors that have an Impact on the Implementation of Industry 4.0

Christian Hoyer

Adelaide Business School

Faculty of the Professions

University of Adelaide

Table of Contents

Abstract

Industry 4.0 represents both a vision and a concept that paves the way to the next industrial revolution. The rise of new IT-technologies such as artificial intelligence, machine learning and cyber-physical systems build the technological foundation of what is considered a paradigm shift in how goods and services are developed, produced and delivered. While the term was often criticised in the beginning as an empty promise that solely serves marketing purposes, Industry 4.0 gained recognition fast with governments, research institutes and corporations around the globe starting to invest into the idea. However, despite all the efforts and resources spent to make the vision a reality, studies have shown that the implementation of Industry 4.0 is far from being a smooth process, as companies need to rethink their entire business strategies. In fact, the transformational process has been investigated from various angles to provide companies with a compass that guides them through this challenging transition. However, a systematic understanding of the forces and their magnetic features that steer the needle into the future is still lacking. As a consequence, companies either hesitate to embark on the transition or struggle to implement Industry 4.0 on a broader scale. In order to address this shortcoming, this thesis seeks to synthesise the strongly fragmented knowledge about the factors that have an impact on the implementation of Industry 4.0 and to evaluate their importance for companies.

The main objective of the thesis is addressed through three distinct publications. A systematic literature review has been conducted in Publication 1 to identify the factors that need to be considered when companies implement Industry 4.0. Based on this approach, the study identifies 14 factors, discusses their theoretical meaning, and proposes three categories to distinguish between them. Based upon these findings, Publication 2 assesses the importance of the previously determined implementation factors through the application of a convergent

parallel mixed-study design which is based on surveys with 140 Industry 4.0 practitioners and in-depth interviews with 16 Industry 4.0 experts. In that context, results show that the factors are not equally important and that five key factors play an elementary role when it comes to the transitional process. What is more, the findings show that the importance of certain factors varies throughout the life cycle of the transition and that the practitioners' perception has an impact on the perceived importance of the factors. Publication 3 complements the finding of the previous two studied by illustrating and visualising the relationship between the previously identified and assessed factors through the combination of network theory and systems thinking. This approach offers a new perspective on the importance of the implementation factors by showing that the importance of the examined factors is not static and that it changes depending on the relationship to other implementation factors. Consequently, the findings lay the foundations for the development of quantitative models that can be used to simulate specific implementation scenario.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree. The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Name: Christian Hoyer

Date: 15 October 2021

Acknowledgements

Now, finally coming to the best part of the thesis. My PhD journey was like a trip around the world on a luxury yacht equipped with everything that heard and soul desire. I was able to meet people from all over the globe, I had the chance to get a glance at the inner workings of the engines that power scientific research, and I was given precious time and freedom to think about my place in this world. This is a privilege only a few people have been awarded with. A privilege that was made possible by the sacrifices others have made and by their trust. There is no way I will ever take this for granted, which is why I want to pay tribute to all of those who supported me along this journey.

First of all, I would like to express my gratitude to Assoc. Prof Indra Gunawan and Dr Carmen Haule Reaiche, my supervisors. Whenever I needed guidance, they always made time to help and support me; something that I sincerely appreciate, knowing the time-consuming nature of academia. Similarly, I am thankful for their foresight. My unorthodox and unfortunately often chaotic way of working and doing research was always met with a high level of patience, respect, and encouragement. I truly learned a lot from you!

Next, I would like to thank the administrative staff of the University of Adelaide Business school for their continuous support throughout the PhD journey. In that context, a very special thank you goes out to John Staines who always made sure that we feel home and welcome, despite being thousands of kilometres away from our families and friends. You created a very special culture.

My gratitude is extended to the participants of this research for their valuable time and for their experiences they shared. Their input allowed us to see the topic of this thesis from many different perspectives.

I also welcome this opportunity to thank my friends in Germany and all the other parts in the world who supported me throughout this journey. Despite being far away, you went above and beyond to support me. I owe you a dept of gratitude, more than what can be expressed in a few pages! Similarly, I would like to express my sincere appreciation for my friends from the PhD room. I will very much miss Rajeev's wisdom and humor, the early and stimulating morning talks that I had with Ashkan and Peter, the joy Elsy, Nana, and Tiep spread and shared, Adele's as well as Luke's introductions into the Aussie culture, and Ankit's and Alyosha's rare visits. Also, my heartfelt thanks go to Binyam and Richa who made sure that my mind, soul, and of course stomach were always well fed. Thanks for being by my side from the beginning until the very last day of my PhD journey. I will miss all of you guys a lot!

I want to express my warmest thanks to my close family: my parents, siblings, and grandparents. I am indebted to you for your support throughout my life and for covering my back while I was working on my PhD and while the global pandemic made everything even more difficult at home. You all contributed to this journey in different ways, allowing me to enjoy it as much as I can; I feel humbled and grateful! It is also essential that I express my immense appreciation to my ex-partner's family, who always supported us throughout our adventure in Australia. It really means a lot to me.

Finally, I would like to express my gratitude to my ex-partner Franziska. We began this journey together and while it lasted, everything was joyful and seemed so easy; I enjoyed every second. You always believed in me, and you have been an inexhaustible source of love, encouragement, advice, and reassurance. From the bottom of my heart, this PhD is as much yours as it is mine. Thank you!

List of Figures

List of Tables

Abbreviations

AI	Artificial Intelligence
ALI	At Least Important
BC	Betweenness Centrality
BD	Balanced direct feedback loop
BID	Balanced indirect feedback loop
CC	Closeness Centrality
CLD	Causal Loop Diagram
CPS	Cyber-Physical Systems
IoT	Internet of Things
L	Average Path Length
MAS	Multi Agent System
ND	Network Density
PC	Possible Number of Connections
RD	Reinforcing direct feedback loop
RID	Reinforcing indirect feedback loop

Chapter 1. Introduction

1.1 Background

Towards the end of the 18th century, the social economy in Europe began to undergo a massive change. The mechanisation through steam-based engines led to the industrialisation of major sectors in the economy, including agriculture and manufacturing. Retrospectively, this development was coined the first industrial revolution due to its strong impact on society (Crafts 2011; Kennedy 2020; More and More 2002). Similarly, in the following two centuries, the world witnessed two more industrial revolutions. The second industrial revolution was mainly driven by new sources of energy and advancements in telecommunication technologies, whereas the third industrial revolution, which we are currently experiencing, has been characterised by the rise of computer technologies. What these revolutions share is the colossal impact on humanity (Atkeson and Kehoe 2001; Greenwood 1997; Liu and Grusky 2013). New technological advancements, efficiency boosts and improved transportation infrastructures have allowed businesses to grow continuously, increasing both the wealth and size of the population in many countries (Greenwood 1997; Liu and Grusky 2013). Today, the rise of technologies such as artificial intelligence, cyber-physical systems, big data, and machine learning are regarded as the technologies that will pave the way for the next industrial revolution, which is often referred to as Industry 4.0 (Koch et al. 2014; Lee et al. 2018; Morrar and Arman 2017).

However, so far, industrial revolutions have been defined retrospectively, after their impact on society can be feasibly assessed and measured. In contrast, Industry 4.0 does not stand for a development that already has taken place. It is a revolutionary, pre-emptive idea defined and understood as a concept that can help companies to achieve higher levels of productivity and integration, and which will eventually advance economies to similar levels as previous industrial revolutions (Kagermann et al. 2013; Li et al. 2017; Metallo et al. 2018; Vaidya et al. 2018). At its core, the concept is about increasing the levels of autonomy and integration of digital solutions by connecting machines, devices, and workforces within and beyond organisations. Accordingly, the flow of information resulting from connecting all entities can then be analysed and processed to improve the decision-making capabilities of organisations in terms of reacting to new internal and external developments, promising to make companies more flexible and efficient (Abele et al. 2015; Dalenogare et al. 2018; Fosso Wamba et al. 2015).

Based on this promising outlook, companies started investing in the concept soon after its inception in 2011. On a global scale, Industry 4.0 has fast gained relevance, with Europe and China having dedicated Industry 4.0 strategies to maintain and extend their competitive edge in the manufacturing field (Castelo-Branco et al. 2019; Feng et al. 2018; Li 2017; Santos et al. 2017). However, despite its unprecedented and widely recognised potential, the implementation of Industry 4.0 has proved to be challenging for corporations and governments (Fettermann et al. 2018; Geissbauer et al. 2018; Palazzeschi et al. 2018; Staufen AG 2018). Corporations have struggled to match high expectations with actual performance of 4.0 projects, slowing down the transition process (Basl 2017; Müller et al. 2018; Sommer 2015). Although the scientific field has been quick to react, it has yet to develop a comprehensive understanding of the concept. The challenge is for the scientific field to examine and explain the building blocks of an Industry 4.0 implementation. Against this background, this thesis seeks to address this paucity of empirical research on the implementation of Industry 4.0.

1.2 Significance of Research

As described above, the transition towards Industry 4.0 represents a massive challenge for companies, governments, and scientists (Müller et al. 2018; Sommer 2015). Despite the lack of clear definition, its future impact on the corporate sector and society is widely acknowledged. Manufacturing companies in particular, have moved beyond the question of whether they will adapt the concept, towards figuring out how they are going to manage the transition (Staufen AG 2018). The scientific field of Industry 4.0 is also highly committed to supporting companies and government institutions with this transitional process.

In its current form the research field of Industry 4.0 has already provided important insights into which factors need to be considered when implementing Industry 4.0. However, this knowledge is largely fragmented and spread out over a large number of investigations with different aims and contexts. From investigations that focus on technological challenges to studies that examine human resource issues, the implementation of Industry 4.0 has been observed from countless angles (Ahuett-Garza and Kurfess 2018; Fantini et al. 2018; Kadir and Broberg 2021). Nonetheless, so far, only a few investigations have tried to address this diffusion of knowledge itself that is resulting from Industry 4.0's interdisciplinary and complex nature. Due to this shortcoming, companies struggle to develop effective and sustainable implementation strategies and often choose to run pilot projects, which are prone to be abandoned in favour of day-to-day business (McKinsey 2018; Staufen AG 2018). Likewise, from a scientific perspective, due to the lack of a strong foundation with respect to Industry 4.0 implementation factors, developing comprehensive and effective implementation frameworks remains taxing. Consequently, investigating the factors that need to be considered for the development of Industry 4.0 specific strategies, frameworks, and use cases represents one of the primary aims of the present thesis.

Besides knowing the implementation factors, their relative importance and the relationships between them need to be further examined. A lack of a clear understanding of how vital the implementation factors are can impede the efficient use of resources, adding more barriers to the transition process. When managers need to plan and execute Industry 4.0 projects, they have to operate under resource constraints while making sure that the transition is not hurting the baseline of their daily business (Hastig and Sodhi 2020; Schneider 2018). Walking that tightrope, knowing which implementation factors are particularly important and how they affect other factors involved in the process can therefore make the difference between success and failure.

In light of the above, an increasing number of studies call for a holistic and systematic approach to Industry 4.0 to lay the foundation for a better understanding of the dynamic nature of the transition process and its atomic structure (Calabrese et al. 2021; Hou et al. 2020; Oliveira et al. 2020). The purpose of this thesis is therefore to develop and apply an holistic approach that stands on three main pillars, represented by three publications, that will be introduced in the following section.

1.3 Publications in the Thesis

Overall, the thesis seeks to explore, identify, and better understand the factors that need to be considered when organisations decide to implement the concept of Industry 4.0. This objective has been divided into three distinct publications as shown by Figure 1.

As noted in the introduction of this thesis, the knowledge about Industry 4.0 implementation factors is scattered throughout the Industry 4.0 literature. Therefore, Publication 1 aims to systematically identify and discuss the implementation factors that have already been acknowledged in previous studies. The identification process is based on a systematic literature review method proposed by Moher et al. (2015); 64 research articles are analysed out of 2,896 articles initially returned by three scientific databases searches. Besides the factor identification, the thesis also proposes a new way of defining the term Industry 4.0 and illustrates why the complexity of Industry 4.0 has several dimensions to it. The findings of Publication 1 have been further discussed in a book chapter and presented at a conference (Appendices B and C)

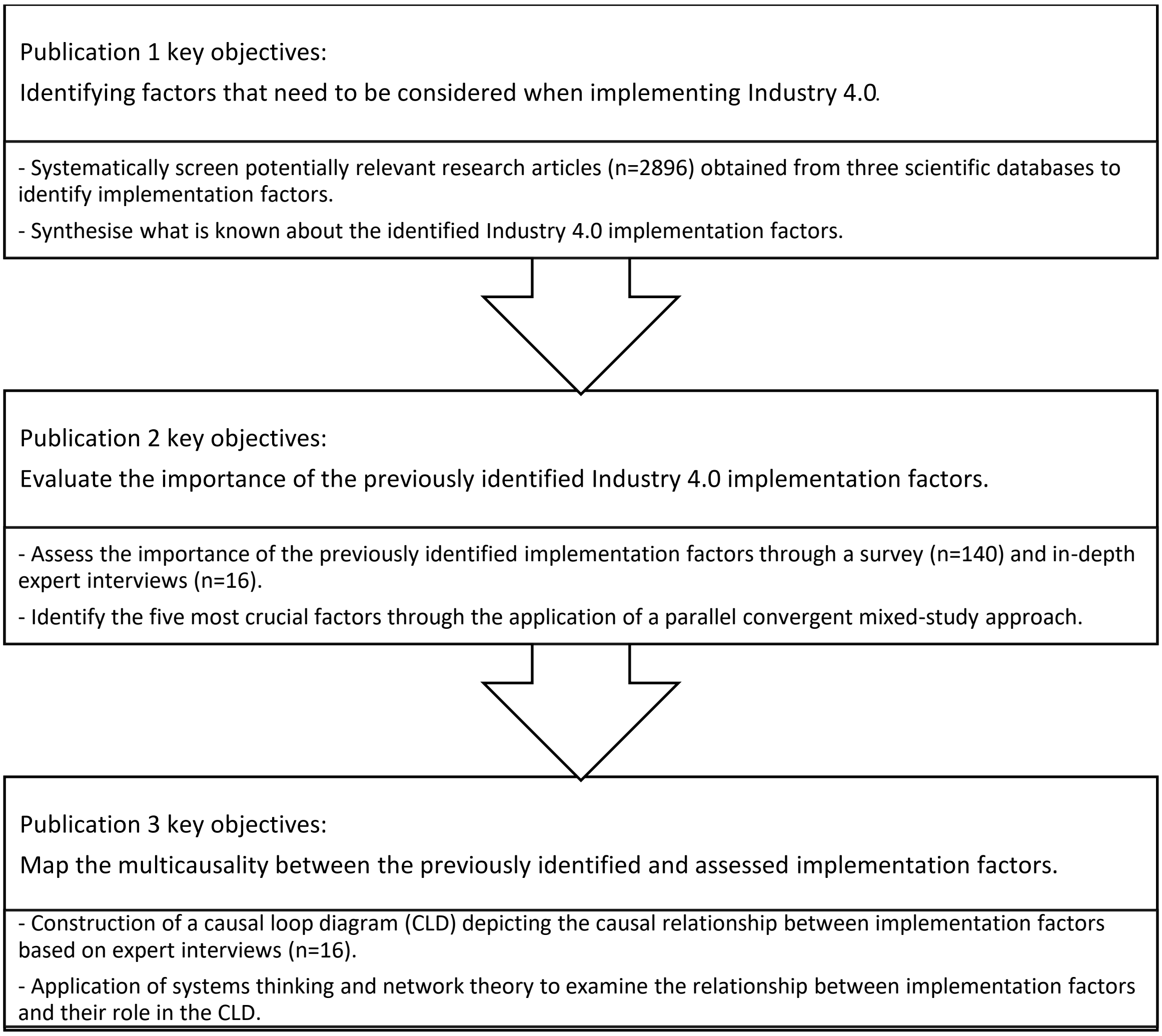

Figure 1. Key research objectives and approaches in the thesis

Based on the literature review and definition of Industry 4.0 presented in Publication 1, Publication 2 sets out to assess the importance of the previously identified implementation factors and to examine the reasons for their importance based on the experience of Industry 4.0 practitioners and experts. This knowledge is crucial as it answers the question posed in Publication 1 about whether the factors discussed in the academic literature are important to those who already work on the Industry 4.0 transition. The findings not only give practitioners a better idea of which factors should be prioritised, they also help the scientific field to recalibrate its focus, as stressed by a number of studies. In that regard, a convergent parallel mixed-methods approach is employed to validate the findings of Publication 1 and to gain a detailed understanding of the implementation factors by comparing the results of both data sources. At the same time, this approach reveals potential research gaps and contradictions between the findings from the practitioner surveys with a sample size of 140 (n=140) and from the expert interviews (n=16) (Harrison 2013; Razali et al. 2019). The surveys asked participants to rate the 14 factors identified in Publication 1 and to state at which stage of transitional period a given factor becomes particularly significant, to further understand whether the importance of a factor depends on the stage of transition. In contrast, experts were asked which factors they consider important and why, without sharing the findings from Publication 1. Additionally, when experts talked about a relationship between two factors, they were asked to elaborate on it to set the foundation for Publication 3. Finally, through the application of the described study design, Publication 2 aims to determine the five key factors that need to be prioritised when companies decide to implement Industry 4.0.

After having identified and examined Industry 4.0 implementation factors in Publication 1 and 2, the final objective of this thesis is to explore and map the multicausality between these factors, as various studies have suggested that implementation factors could exert influence on each other. Consequently, assessing the importance of the implementation factors without considering their multicausal relationship might lead to misconceptions.

Moreover, depending on which factors a company focuses on when adapting Industry 4.0, comprehending the causal relationship between these factors can further help them to refine their implementation strategy. In the same vein, studies that investigate implementation-related issues without considering the multicausal perspective might struggle to explain or interpret certain observed phenomena. Thus, Publication 3 adapts a well-established and validated systems thinking tool, referred to as a causal loop diagram (CLD), to create a visual representation of the relationship between the implementation factors according to the knowledge shared by Industry 4.0 experts (Jonker and Karapetrovic 2004; Roberts 1978). Additionally, the study adopts a novel approach that allowed the researcher to analyse the CLD with the help of network theory (McGlashan et al. 2016; Uleman et al. 2021). In this respect, the CLD was considered as a directed network to, for example, examine the centrality values for each factor and to test the network for existing clusters. A distinct advantage of using this approach is that it allows a researcher to learn more about the role of the factors within a network, complementing and testing the knowledge gained in Publication 1 and Publication 2.

1.4 Contributions

Overall, the three publications presented in this thesis extend our understanding of the implementation of Industry 4.0 by exploring and analysing the factors that represent the building blocks of the transition process, thereby laying the foundation for future research projects that seek to develop more concrete and effective implementation guidelines.

Publication 1, for the first time, systematically synthesises the widely dispersed knowledge about the implementation of Industry 4.0 and identifies 14 potentially important factors. In this process, the study summarises what is currently known about the identified factors, providing managers and scientist with a foundational understanding of the elements that need to be taken into account when engaging with the implementation of Industry 4.0. The study also reveals existing contradictions in the scientific field of Industry 4.0 that need to be addressed in future research to further extend our knowledge about the transition process. Finally, Publication 1 also demonstrates that the innate complexity of Industry 4.0 is more than just technological, further stressing the need for more holistic investigations that acknowledge the complex nature of Industry 4.0.

Building on the knowledge obtained from Publication 1, the second publication in the thesis evaluates the importance of the previously identified factors and further examines the reasons for their importance. Publication 2 shows that the previously identified factors are not equally important and discusses in further detail the five key factors that emerged from the combined findings of the survey and the expert interviews. Publication 3 also reveals that the stage of the transition affects the importance of certain factors, suggesting that the life cycle of the implementation factor should be included in future investigations. Similarly, with the help of statistical analysis, the study demonstrates that the perceived importance of the factors can change alongside certain variables, such as the participant's industry background or the fact that the participant works for an organisation that uses strategy indicators to track the implementation progress. These findings add more context to the findings of Publication 1 and can therefore be used to develop implementation guidelines that are tailored to a specific target audience and to organisations with distinctive characteristics, beyond general recommendations. Finally, besides confirming the findings of the first publication, Publication 2 also identifies a new implementation factor that has not been covered in the systematic literature review, suggesting that future studies should continue to identify potential implementation factors.

Both Publication 1 and Publication 2 contribute to the Industry 4.0 body of knowledge by identifying Industry 4.0 implementation factors and by empirically demonstrating their importance. However, findings in both studies also suggest and confirm the need to explore the interaction between the factors in order to better understand their role and importance in the transition process. Publication 3 addresses this identified gap in the literature and offers new insights into the relationship between the previously studied implementation factors. Through the application of systems thinking theory combined with network theory, Publication 3 demonstrates that a complete understanding of what constitutes the role and the importance of an implementation factor cannot be obtained without factoring in its causal relationship to other factors. In that context, the developed CLD not only visualises the dynamic relationship between the implementation factors, but also helps to explain important observations made in previous studies. The network perspective reveals that some of the previously identified factors play a leading role in enabling the efficacy of other factors. Therefore, these findings raise important theoretical issues that have a bearing on how to assess and interpret the importance of Industry 4.0 implementation factors.

1.5 Thesis structure

This thesis is presented in "by publication" format, i.e., the thesis includes three research articles in manuscript format (published and unpublished) according to the guidelines of the University of Adelaide. It is composed of five themed chapters with Chapters 2 to 4 representing the three complete research articles (Publications 1 to 3 as indicated in Figure 1). Chapter 1 has introduced the topic and presented an overview of the key objectives and main contributions. The first publication of the thesis, presented in Chapter 2, systematically reviews the Industry 4.0 literature to identify factors that need to be considered when implementing the Industry 4.0 concept. Utilising the findings of Chapter 2, Chapter 3 then continues with an evaluation of the importance of the previously identified implementation factors according to Industry 4.0 practitioners and experts, based on a convergent parallel mixed-methods study design. Chapter 4 further builds upon the previous two publications by further assessing the role and the importance of the implementation factors through the application of systems thinking and network theory. The combination of these two approaches is used to map the multicausal relationship between the previously analysed factors. The final chapter draws together the findings presented in this thesis and discusses the overarching managerial and theoretical implications. Chapter 5 also presents the limitations of the thesis and the future research opportunities arising from the main findings.

References

Abele E, Anderl R, Metternich J, Wank A, Anokhin O, Arndt A, Meudt T, Sauer M (2015) Effiziente Fabrik 4.0. ZWF 110:150–153. https://doi.org/10.3139/104.111293

Ahuett-Garza H, Kurfess T (2018) A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing. Manufacturing Letters 15:60–63. https://doi.org/10.1016/j.mfglet.2018.02.011

Basl J (2017) Pilot Study of Readiness of Czech Companies to Implement the Principles of Industry 4.0. Management and Production Engineering Review 8:817. https://doi.org/10.1515/mper-2017-0012

Calabrese A, Levialdi Ghiron N, Tiburzi L (2021) 'Evolutions' and 'revolutions' in manufacturers' implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework. Production Planning & Control 32:213–227. https://doi.org/10.1080/09537287.2020.1719715

Castelo-Branco I, Cruz-Jesus F, Oliveira T (2019) Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry 107:22–32. https://doi.org/10.1016/j.compind.2019.01.007

Crafts N (2011) Explaining the first Industrial Revolution: two views. European Review of Economic History 15:153–168. https://doi.org/10.1017/S1361491610000201

Dalenogare LS, Benitez GB, Ayala NF, Frank AG (2018) The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics 204:383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

Fantini P, Pinzone M, Taisch M (2018) Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. Computers & Industrial Engineering. https://doi.org/10.1016/j.cie.2018.01.025

Feng L, Zhang X, Zhou K (2018) Current problems in China's manufacturing and countermeasures for industry 4.0. J Wireless Com Network 2018:174. https://doi.org/10.1186/s13638-018-1113-6

Fettermann DC, Cavalcante CGS, Almeida TDd, Tortorella GL (2018) How does Industry 4.0 contribute to operations management? Journal of Industrial and Production Engineering 35:255–268. https://doi.org/10.1080/21681015.2018.1462863

Fosso Wamba S, Akter S, Edwards A, Chopin G, Gnanzou D (2015) How 'big data' can make big impact: Findings from a systematic review and a longitudinal case study. International Journal of Production Economics 165:234–246. https://doi.org/10.1016/j.ijpe.2014.12.031

Geissbauer R, Luebben E, Schrauf S, Pillsbury S (2018) Global Digital Operations Study 2018 - Digital Champions: How industry leaders build integrated operations ecosystems to deliver end-to-end customer solutions

Greenwood J (1997) The third industrial revolution: Technology, productivity, and income inequality. AEI studies on understanding economic inequality. AEI Press, Washington D.C.

Harrison RL (2013) Using mixed methods designs in the Journal of Business Research, 1990–2010. Journal of Business Research 66:2153–2162. https://doi.org/10.1016/j.jbusres.2012.01.006

Hastig GM, Sodhi MS (2020) Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. Prod Oper Manag 29:935–954. https://doi.org/10.1111/poms.13147

Hou T, Cheng B, Wang R, Xue W, Chaudhry PE (2020) Developing Industry 4.0 with systems perspectives. Syst Res Behav Sci 37:741–748. https://doi.org/10.1002/sres.2715

Jonker J, Karapetrovic S (2004) Systems thinking for the integration of management systems. Business Process Mgmt Journal 10:608–615. https://doi.org/10.1108/14637150410567839

Kadir BA, Broberg O (2021) Human-centered design of work systems in the transition to industry 4.0. Appl Ergon 92:103334. https://doi.org/10.1016/j.apergo.2020.103334

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

Kennedy C (2020) The energy embodied in the first and second industrial revolutions. Journal of Industrial Ecology 24:887–898. https://doi.org/10.1111/jiec.12994

Koch V, Kuge S, Geissbauer R, Schrauf S (2014) Industrie 4.0 - Chancen und Herausforderungen der vierten industriellen Revolution. PricewaterhouseCooper AG.

Lee M, Yun J, Pyka A, Won D, Kodama F, Schiuma G, Park H, Jeon J, Park K, Jung K, Yan M-R, Lee S, Zhao X (2018) How to Respond to the Fourth Industrial Revolution, or the Second Information Technology Revolution? Dynamic New Combinations between Technology, Market, and Society through Open Innovation. JOItmC 4:21. https://doi.org/10.3390/joitmc4030021

Li L (2017) China's manufacturing locus in 2025: With a comparison of “Made-in-China 2025” and “Industry 4.0”. Technological Forecasting and Social Change. https://doi.org/10.1016/j.techfore.2017.05.028

Li G, Hou Y, Wu A (2017) Fourth Industrial Revolution: technological drivers, impacts and coping methods. Chin. Geogr. Sci. 27:626–637. https://doi.org/10.1007/s11769-017-0890-x

Liu Y, Grusky DB (2013) The Payoff to Skill in the Third Industrial Revolution. American Journal of Sociology 118:1330–1374. https://doi.org/10.1086/669498

McGlashan J, Johnstone M, Creighton D, La Haye K de, Allender S (2016) Quantifying a Systems Map: Network Analysis of a Childhood Obesity Causal Loop Diagram. PLoS One 11:e0165459. https://doi.org/10.1371/journal.pone.0165459

McKinsey (2018) Digital Manufacturing – escaping pilot purgatory

Metallo C, Agrifoglio R, Schiavone F, Mueller J (2018) Understanding business model in the Internet of Things industry. Technological Forecasting and Social Change. https://doi.org/10.1016/j.techfore.2018.01.020

Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle P, Stewart LA (2015) Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev 4:1. https://doi.org/10.1186/2046-4053-4-1

More DC, More C (2002) Understanding the Industrial Revolution. Routledge

Morrar R, Arman H (2017) The Fourth Industrial Revolution (Industry 4.0): A Social Innovation Perspective. TIM Review 7:12–20. https://doi.org/10.22215/timreview/1117

Müller JM, Kiel D, Voigt K-I (2018) What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. Sustainability 10:247. https://doi.org/10.3390/su10010247

Oliveira BG, Liboni LB, Cezarino LO, Stefanelli NO, Miura IK (2020) Industry 4.0 in systems thinking: From a narrow to a broad spectrum. Syst Res Behav Sci 37:593–606. https://doi.org/10.1002/sres.2703

Palazzeschi L, Bucci O, Di Fabio A (2018) Re-thinking Innovation in Organizations in the Industry 4.0 Scenario: New Challenges in a Primary Prevention Perspective. Front Psychol 9:30. https://doi.org/10.3389/fpsyg.2018.00030

Razali FM, Aziz NAA, Rasli RM, Zulkefly NF, Salim SA (2019) Using Convergent Parallel Design Mixed Method to Assess the Usage of Multi-Touch Hand Gestures Towards Fine

Motor Skills Among Pre-School Children. IJARBSS 9. https://doi.org/10.6007/IJARBSS/v9-i14/7023

Roberts N (1978) Teaching Dynamic Feedback Systems Thinking: An Elementary View. Management Science 24:836–843. https://doi.org/10.1287/mnsc.24.8.836

Santos C, Mehrsai A, Barros AC, Araújo M, Ares E (2017) Towards Industry 4.0: an overview of European strategic roadmaps. Procedia Manufacturing 13:972–979. https://doi.org/10.1016/j.promfg.2017.09.093

Schneider P (2018) Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. Rev Manag Sci 125:1. https://doi.org/10.1007/s11846-018-0283-2

Sommer L (2015) Industrial revolution - industry 4.0: Are German manufacturing SMEs the first victims of this revolution? Journal of Industrial Engineering and Management 8.5 (2015). https://doi.org/10.3926/jiem.1470

Staufen AG (2018) Deutscher Industrie 4.0 Index 2018: Eine Studie der Staufen AG und der Staufen Digital Neonex GmbH. Köngen (2018).

Uleman JF, Melis RJF, Quax R, van der Zee EA, Thijssen D, Dresler M, van de Rest O, van der Velpen IF, Adams HHH, Schmand B, Kok IMCM de, Bresser J de, Richard E, Verbeek M, Hoekstra AG, Rouwette EAJA, Olde Rikkert MGM (2021) Mapping the multicausality of Alzheimer's disease through group model building. Geroscience 43:829–843. https://doi.org/10.1007/s11357-020-00228-7

Vaidya S, Ambad P, Bhosle S (2018) Industry 4.0 – A Glimpse. Procedia Manufacturing 20:233–238. https://doi.org/10.1016/j.promfg.2018.02.034

Chapter 2. Exploring the Important Implementation Factors in the Context of Industry 4.0: A Systematic Literature Review

Statement of Authorship

Statement of Authorship

Title of Paper	Exploring the Important Implementation Factors in the Context of Industry 4.0 – A Systematic Literature Review
Publication Status	☒ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Published in Systems Research and Behavioral Science, 2020

Principal Author

Name of Principal Author (Candidate)	Christian Hoyer		
Contribution to the Paper	Conducted the systematic literature review and presentation of the findings		
Overall percentage (%)	70%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15.10.2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Assoc. Prof. Indra Gunawan		
Contribution to the Paper	15% - Evaluation of research articles and contribution to theory as well as methodology		
Signature		Date	15.10.2021

Name of Co-Author	Dr. Carmen Haule Reaiche		
Contribution to the Paper	15% - Evaluation of research articles and contribution to theory as well as methodology		
Signature		Date	15.10.2021

Please cut and paste additional co-author panels here as required.

Manuscript (published in Systems Research and Behavioral Science)

Exploring the Important Implementation Factors in the Context of Industry 4.0 – A Systematic Literature Review

Christian Hoyer[a]*, Indra Gunawan[a] , Carmen Haule Reaiche[b]

[a] Adelaide Business School, University of Adelaide, Adelaide, Australia
b College of Business, Law and Governance, JCU, Australia
* Corresponding author at: Adelaide Business School, University of Adelaide, 9/10 Pulteney St, Adelaide SA 5005, Australia. Tel.: +61 452618782. Email: Christian.hoyer@adelaide.edu.au

Abstract:

Within only a couple of years, Industry 4.0 made the transition from a potential buzzword with an uncertain future to a serious manufacturing concept that is adopted by a constantly increasing number of companies. However, recent studies suggest that corporations struggle with the transitional process or even hesitate to implement Industry 4.0 at all. As a consequence, several investigations examined the potential factors that influence the implementation of Industry 4.0. Yet, a comprehensive view of the issue cannot be formed since the findings are spread throughout a number of publications, and no single study has attempted to synthesize previous investigations. Therefore, this study set out to build a solid foundation for future research and to provide orientation for practitioners and governmental institutions by building a bridge between what already has been explored and by showing how the Systems Thinking perspective can help to get a better understanding of the complex nature of Industry 4.0. Based on a systematic literature review, this study presents and discusses a comprehensive list of potential factors that influence the implementation of Industry 4.0 and strengthens the idea that future research is necessary in order to address contradictory findings and to develop efficient Industry 4.0 implementation frameworks.

2.1 Introduction

After being introduced in 2011 at a trade fair in Germany, the term Industry 4.0 has gained international attention (Roblek et al., 2016; Wang et al., 2016; Liao et al., 2017). Its importance for science, corporations, and governmental institutions is illustrated by a growing body of literature as well as by an increasing number of companies that start to engage with the topic. (Buer et al., 2018; Liao et al., 2017; Xu et al., 2018; Morton et al., 2018; Staufen AG, 2018). However, even though Industry 4.0 has gained a credit of trust since its introduction, several investigations also revealed that its complex nature leads to a number of obstacles companies have to overcome in order to benefit from the advantages Industry 4.0 promises (Müller et al., 2018a; Moktadir et al., 2018; Basl, 2017). These potential obstacles and benefits have been investigated by several studies. Yet, a comprehensive picture of which factors have an impact on the implementation has not been drawn so far. This can be explained by the fact that the majority of publications has been focused on certain factors that mattered in a particular context. For example, the study of Tortorella and Fettermann (2017) mainly revolved around the internal company perspective of an Industry 4.0 implementation as they investigated, among others, the connection between lean manufacturing experience and the transition towards Industry 4.0. In contrast, Feng et al. (2018) primarily analysed factors that cannot be controlled by corporations as they investigated the measures that should be taken by the Chinese government in order to make the implementation of Industry 4.0 more successful.

As a consequence, the findings on the factors that potentially influence the implementation of Industry 4.0 are scattered throughout a number of studies, increasing the difficulty for practitioners, scientists, and governments to get a better understanding of the underlying dynamics of an Industry 4.0 implementation. This understanding is crucial as it lays the ground for important decisions, including which research needs to be carried out in the near future, what factors are the most important to address for companies, and which government measures are necessary. Although the present work does not attempt to find final answers to these questions, it intends to create a solid basis upon which those questions can be addressed by building a bridge between the different findings that have already been published. Moreover, by presenting a comprehensive list of potential factors and by separately discussing the main findings for each factor, the present paper further attempts to shift the focus of the current, predominantly technology-focused, research towards the implementation of industry 4.0 and to provide an idea of how the "Systems Thinking" perspective can help to answer the questions above.

2.2 Theoretical Background

2.2.1 Industry 4.0

Unlike the first industrial revolutions which were defined retrospectively based on historical developments, Industry 4.0 somewhat resembles a self-fulfilling prophecy based on the future potential of current technologies and concepts. In this context, technologies such as Cyber-Physical Systems, Big-Data, and autonomous systems act as enablers for the core concept and vision of Industry 4.0, the creation of a smart environment that is based on enabling all entities within that environment to collectively share, collect, and process their information in real-time (Kagermann et al., 2013; Liao et al., 2017; Bartodziej, 2017). A smart industrial environment is not limited to one single factory nor to a single company; it ideally includes the whole supply chain, which allows companies to be more resilient and responsive to external stimuli such as changing customer's demand (Schneider, 2018; Buer et al., 2018).

Since the dawn of the first industrial revolution, each revolution has led to an increase in productivity and changed working life entirely, further illustrating the enormous expectations that are consequently linked to industry 4.0 (Buer et al., 2018; Kagermann et al., 2013; Rüttimann and Stöckli, 2016). Given these growing expectations, the term also has become a controversial subject, that has caused a still ongoing debate regarding its relevance, potential, and future impact on the economy and society (Drath and Horch, 2014; Sommer, 2015; Liao et al., 2017). At a glance, the frontline seems to run between doubts and believe, between the question of whether industry 4.0 is able to keep its promises or whether it is just a colorful label on an empty box.

However, against the background of these controversies, it is even more critical to have a clear vision of what Industry 4.0 is. Therefore, the present work refers to a balanced understanding of Industry 4.0, which is based on three main pillars: The historical context, the technologies associated with Industry 4.0, and the concept of Industry 4.0. The historical context describes the disruptive nature of Industry 4.0 and its potential impact on society based on the assumption that Industry 4.0 follows the example of previous industrial revolutions (Lee et al., 2018; Morrar and Arman, 2017). Consequently, the term fourth industrial revolution should be used to describe the historical dimension of Industry 4.0. As pointed out by Sung (2017), the distinction of both terms helps to reduce confusion. However, the technological dimension of Industry 4.0 refers to the technologies, such as Big-Data and Cyber-Physical Systems, that will be used to achieve the main goals of the concept. The concept of Industry 4.0, on the other hand, refers to how technologies are used to create an environment for businesses in which all entities are connected with each other in order to facilitate decision-making processes and to become more efficient, responsive and resilient (Kagermann et al., 2013; Liao et al., 2017; Dalenogare et al., 2018). As stressed by Buer et al. (2018), the lack of a clear vision or only having a partial understanding of Industry 4.0 leads to confusion and aggravates communication. Furthermore, they argue that particularly companies struggle to understand what Industry 4.0 is as they are often solely focused on technological aspects (Buer et al., 2018).

In light of the above, the present paper particularly refers to the implementation of the concept of Industry 4.0 rather than unilaterally focusing on single technologies. In this context, the present article proposes the intention of corporations as a key determinant to distinguish between these two scenarios. Therefore, companies that intend to implement Industry 4.0 technologies to solve isolated problems, such as increasing the accuracy of sensor data, are not classified as corporations that want to implement Industry 4.0 per se. However, since companies that want to implement Industry 4.0 on a broader level also face issues that stem from implementing single technologies, both scenarios will be considered in the reviewing process.

2.2.2 The Implementation of Industry 4.0

As previously stated, the number of companies that get engaged with the transition towards Industry 4.0 is constantly rising, a trend that was illustrated by several studies. For example, a study conducted by the Staufen AG showed that the number of German companies that did not consider the implementation Industry 4.0 decreased from 34% to 9% between 2014 and 2018. During the same period, the number of companies that started to initiate Industry 4.0 projects increased from 14% to 43% (Staufen AG, 2018). Similarly, Basl (2017) found that 40% of the responding Czech companies already started to engage with Industry 4.0 for more than one year, while 20% of the participants just started with the transition at the time of the survey. However, these numbers only reflect the situations in Germany and Czech, both countries that are rated as Industry 4.0 leaders by the World Economic Forum (World Economic Forum, 2018). Consequently, it is no surprise that studies that targeted a more international audience led to different numbers. For instance, the findings of Morton et al. (2018) suggest that the number of companies that started to implement Industry 4.0 has yet not reached the 25% mark. Similarly, the study of Geissbauer et al. (2018), which counts 1.155 participants from 26 countries, found that 31% of the participating companies already started to implement Industry 4.0 related technologies.

However, the numbers presented so far only include companies that have initiated individual Industry 4.0 projects. In contrast, the number of companies that implemented Industry 4.0 comprehensively remains low despite the euphoric predictions that have been made in recent years. For instance, in 2014, McKinsey predicted that the digitalization of the entire vertical and horizontal value chain would reach a degree above 80% within the upcoming five years (Koch et al., 2014). On the contrary, the results of the study conducted by the Staufen AG show that the number of German companies that take a broader approach towards Industry 4.0 is still low (9%) four years after the initial prediction (Staufen AG, 2018). A finding that goes along with the results of the study published in 2016 by McKinsey, which showed that only 40% of the American, German, and Japanese companies that are working on Industry 4.0 made good progress in further implementing it within one year (McKinsey Digital, 2016). These numbers illustrate the overall difficulty of combining individual Industry 4.0 projects to one approach that goes beyond the borders of single machines, departments, and factories and that are in accordance with the concept of Industry 4.0.

2.2.3 Systems Thinking and Industry 4.0

In a number of recent studies, Industry 4.0 environments such as smart factories have been characterized as complex environments (Raj et al., 2019; Teixeira de Melo et al., 2019; Bonekamp and Sure, 2016; Horváth and Szabó, 2019; Tiacci, 2020). The findings of Jäger et al. (2016) further strengthen this characterization by showing that companies assume that future challenges will be more complex due to the transition towards Industry 4.0. But what makes

Industry 4.0 complex, and how can "Systems Thinking" be applied to manage the implementation of Industry 4.0? To answer these questions, the following sections will compare the concept of Industry 4.0 with the main characteristics of complex systems and further elaborate on how Systems Thinking can help companies, scientists and governmental institutions to manage the implementation of Industry 4.0.

2.2.3.1 The Complexity of Industry 4.0

Complexity theory is a theory that finds its roots in various scientific disciplines (van Eijnatten, 2004). Instead of joining the debate about how to unify the different interpretations of the term, this work focuses on the various facets of complexity that has been examined and compiled by previous studies (Teixeira de Melo et al., 2019; Preiser, 2019; Rousseau, 2019; Dietz et al., 2020). However, as remarked by Arthur (1999):

Common to all studies on complexity are systems with multiple elements adapting or reacting to the pattern these elements create.

This ascertainment resonates with the core concept of Industry 4.0 which is, as mentioned previously, about connecting all elements within a system in order to make it more flexible, resilient and responsive (Kagermann et al., 2013; Wang et al., 2016; Sjödin et al., 2018). The goal is not limited to the overall system but also to the subsystems that are getting more information from the other subsystems they are connected to (Spath et al., 2013). To further illustrate why Industry 4.0 increases complexity, Table 1 compares the main characteristics of complex systems with the concept of Industry 4.0.

Table 1. Comparison between Complexity Characteristics and the concept of Industry 4 (Adapted from Raj et al. (2019), Castelo-Branco et al. (2019), Frank et al. (2019), Xu et al. (2018), Norman and Kuras (2006), and Yearworth (2020))

Complexity Characteristics	Description	Industry 4.0 Concept
Arrangement Variety	An ensemble of elements that can be organized in a large number of different arrangements. However, its structure cannot be inferred from the behaviour of the elements.	Industry 4.0 technologies are designed to be open and compatible with other components and systems. The arrangement depends on a number of factors such as tasks, available resources, and the overall goal of the system. The open and flexible design allows different arrangements for solving similar problems.
Open and direct Interactions	Elements directly interact with each other in an open environment by sharing information, energy or matter.	Connecting all elements to encourage interaction sits at the core of the Industry 4.0 philosophy. Industry 4.0 systems such as smart factories are designed to be open and expandable.
Changing Identity	Functions of elements can change due to pressure from other elements or changing contexts.	Industry 4.0 is about making systems more flexible by increasing the autonomy of each element. Changing demand or a faulty machine can, therefore, encourage or force other elements to adapt.
Increasing Complexity	The system's own complexity increases over time given a continuous input of resources.	The interaction between elements continually creates new pieces of information that need to be processed to lay the foundation for decision making and optimization.

While Table 1compares the vision behind Industry 4.0 with the general characteristics of complex systems, the embodiment of that vision, namely smart factories, can be viewed through a different pair of lenses. A smart factory is designed based on Industry 4.0 principles. It can be considered as a "System of Systems" (SoS) as it represents an ensemble of autonomous and independent systems that are interacting with each other (Cohen et al., 2019; Saniuk et al., 2019; Haseeb et al., 2019). This perspective further sheds light on the complexity of Industry 4.0 from a different angle as the underlying assumptions of the field of SoS are focused on the interaction between different systems that form an ensemble that is driven by a specific context such as offering specialized services to customers (Gorod et al., 2008; Henshaw, 2016; Zhichang, 2007). Since the systems that form the overall context-driven system are considered autonomous and independent, the SoS perspective can help to gain a better understanding of the complexity that arises from managing them. Conflicting goals, different operational priorities, as well as multiple levels of stakeholders, can be considered as the main drivers of complexity in a SoS (Gorod et al., 2008; Kinder et al., 2012).

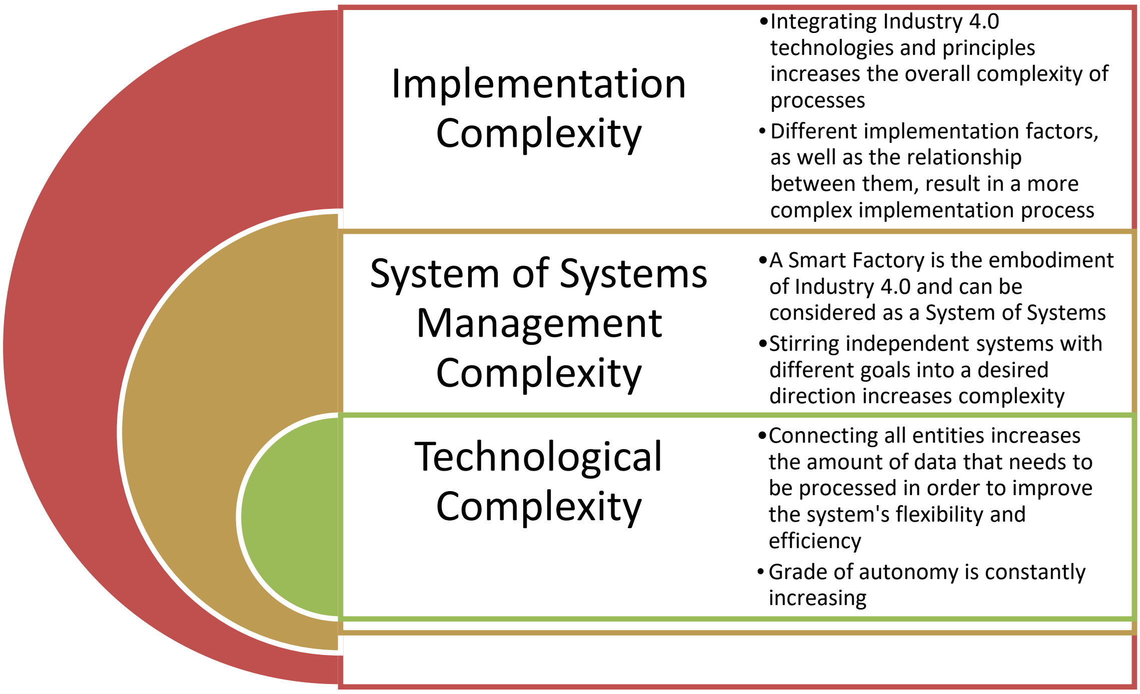

Figure 2. Industry 4.0 Complexities

Consequently, companies that want to implement Industry 4.0 not only face the complexity that is resulting from the new technologies they are integrating into their infrastructure, but also from managing the autonomous and independent systems that are resulting from this integrational process. What is more, many studies have suggested that the complexity of Industry 4.0 technologies and the complexity of managing their interaction lead to additional challenges regarding the implementation of Industry 4.0 such as helping employees to build and to work in complex environment (Freixanet et al., 2020; Hecklau et al., 2016; Roblek et al., 2016; Raj et al., 2019; Jerman et al., 2019; Jäger et al., 2016). This transition towards these complex technologies and processes can be considered as another form of complexity that is accompanied by the implementation of Industry 4.0. Therefore, the present work refers to three main types of complexity with respect to the transition towards Industry 4.0 as illustrated by Figure 2.

2.2.3.2 A Systems Thinking Perspective

The previous section brought forward the idea that corporations have to deal with different types of complexities with respect to implementing Industry 4.0 in their corporate infrastructure. Each of the three types of complexity can be approached with different sets of strategies and methodologies. However, before corporations can derive concrete plans and actions from the complexity that accompanies the implementation of Industry 4.0, they first need to be aware of the forced marriage between them. As illustrated in the previous section, systems that are designed based on Industry 4.0 principles can be considered complex, even when technology is left out of the equation. As a result, no matter which understanding companies have of Industry 4.0, they have to deal with complexity in one way or another.

Based on the above, the present work emphasizes the fact that Systems Thinking offers an important perspective on Industry 4.0 and its implementation. At first glance, this statement seems trivial. However, other authors (e.g., Norman and Kuras (2006), Punzo et al. (2020), Ladyman et al. (2013), and Bosch et al. (2013)) have highlighted the relevance of having a clear understanding of complexity and its impact on corporate processes. For instance, Kurtz and Snowden (2003) developed the Cynefin framework based on the assumption that awareness can help decisionmakers to develop new approaches towards "intractable problems". Similarly, Preiser (2019) stresses the importance of the new approaches that stem from the worldview complexity thinking presumes. Applied to the transition towards Industry 4.0, the empirical knowledge about the important factors alone is not enough considering that Industry 4.0 increases complexity. Furthermore, based on the premise that corporations are unique in terms of their goals, infrastructures, and characteristics, it can be assumed that the significance of the potential factors varies from company to company (Lee et al., 2018; Freixanet et al., 2020; Norman and Kuras, 2006). In this regard, the systems thinking perspective challenges the view that blueprints for the implementation exist. Instead, it can help to take a broader approach towards the relationship between various implementation factors and the general complexity of Industry 4.0. The latest version of the Industry 4.0 index (Staufen AG and Staufen Digital Neonex GmbH, 2019) further illustrates the need for such a change of perspective. Only 8% of the participating companies have taken a holistic approach towards Industry 4.0, while the majority of corporations still pursues individual operational projects (Staufen AG and Staufen Digital Neonex GmbH, 2019). The present work, thus, not only intends to explore important implementation factors but also promotes the need for a broader understanding of the complexity that comes with the realization of the Industry 4.0 concepts and the associated technologies. In other words, knowing the factors can be considered as necessary as understanding relationship between them as well as understanding the complexity that accompanies Industry 4.0.

2.3 Research Methodology

Even though Industry 4.0 is still a young topic, a significant amount of scientific work has been published since its introduction in the year 2011. The findings of Liao et al. (2017) and Schneider (2018) show that the majority of the research is about the evaluation of Industry 4.0 related technologies. At the same time, a growing number of scientific work starts to focus on the implementation of Industry 4.0. As illustrated in Section 2, those studies already offer first insights on how the implementation of Industry 4.0 progresses. Various studies have presented different reasons why companies decided for or against an adaptation of Industry 4.0, leading to a lack of clarity regarding which factors are relevant. A clarity that is needed to build a solid scaffolding for practitioners, scientists, and policymakers to formulate effective strategies and policies. In this context, a systematic literature review offers the necessary toolkit to clear the view on the overall problem by bringing together and evaluating the findings of all relevant sources. Furthermore, the process of identifying, selecting, and analyzing relevant resources also helps to unfold potential gaps and contradictions that need to be addressed in future investigations (Ressing et al., 2009). Therefore, it is no surprise that other areas of Industry 4.0 have been covered with a systematic literature review such as the study of Buer et al. (2018), who examined the connection between lean manufacturing and Industry 4.0. However, while several studies have applied the systematic literature method in the context of Industry 4.0, not a single study has explored the factors that are important in the context of implementing it.

The benefit of systematic literature reviews not just lies in its comprehensive but also in its transparent and reproducible nature (Ressing et al., 2009; Tranfield et al., 2003). The structure of this method is based on the PRISMA statement by Moher et al. (2015) and has been visualized with the PRISMA flowchart that is shown in . It illustrates the process of identifying, selecting, and analyzing relevant resources.

2.3.1 Data collection

Before starting with the actual collection of references, appropriate search terms, and electronic databases had to be selected. It is important that the combination of search terms reflects the main objective of this paper. Therefore, a list of general industry 4.0 related search terms has been combined with implementation-specific terms. Table 2 shows the result of this twofold approach.

Table 2. Search terms (Industry 4.0 related AND research objective related)

Databases	Industry 4.0 related terms (including plural versions*)	Research objective related terms
Scopus	***Industry 4.0***	**Implementation**
AND	***OR***	**OR**
ProQuest	***Industrie 4.0***	**Adaptation**
AND	***OR***	**OR**
Web of Science	***The fourth industrial revolution***	**Readiness**
	OR	
	The 4th industrial revolution	
	OR	
	Cyber-Physical System*	
	OR	
	Cyber-Physical Production System*	
	OR	
	Smart Factory*	
	OR	
	Smart Industry*	
	OR	
	Factory of the future*	
	OR	
	Integrated industry*	
	OR	
	Smart industry*	
	OR	
	Industrial internet	
	OR	
	Smart Industry*	
	OR	
	Production 4.0	

Industry 4.0 related search terms, on the other hand, have been selected based on the findings of Liao et al. (2017), who identified the most frequent words related to Industry 4.0. Moreover, the list Industry 4.0 related terms has been extended based on the findings of Schneider (2018) and Buer et al. (2018), who also conducted a systematic literature review on specific areas within Industry 4.0. On the other hand, the implementation-specific terms have been selected based on the findings of Bala and Venkatesh (2015), Lai and Mahapatra (1997),

and Erol et al. (2016). The term adaptation was considered due to the socioeconomic implications that go along with the expected implementation of industry 4.0. Those implications include, for instance, changing job requirements that have to be addressed either by companies and the government (Mazali, 2017; Fantini et al., 2018). The term readiness, on the other hand, describes the current status of the companies' ability to adapt to new technological environments and shifting markets (Pourabdollahian et al., 2016). Consequently, both terms are two sides of the same medal.

Building on the works of Buer et al. (2018), Roblek et al. (2016), and Liao et al. (2017), the databases Scopus, ProQuest and Web of Science were selected since they have returned the most results when it comes to industry 4.0 related topics.

As mentioned previously, the goal of using a systematic literature review method is to identify industry 4.0 implementation factors from relevant and reliable sources. In order to achieve this goal, inclusion and exclusion criteria have been defined based on the findings of Meline (2006); they represent the four main filters the references had to go through (Figure 3).

After selecting the three primary databases, their general settings were used to return book chapters, journal papers, and conference proceedings which were peer-reviewed, written in English or German, and not published before the term industry 4.0 was mentioned the first time in the year 2011 (Kagermann et al., 2013; Liao et al., 2017). Additionally, eleven references from other sources have been added to this list; they are mostly studies from governmental institutions or universities that have not been published through scientific journals. Secondly, by using the reference manager Endnote, 979 duplicates have been removed.

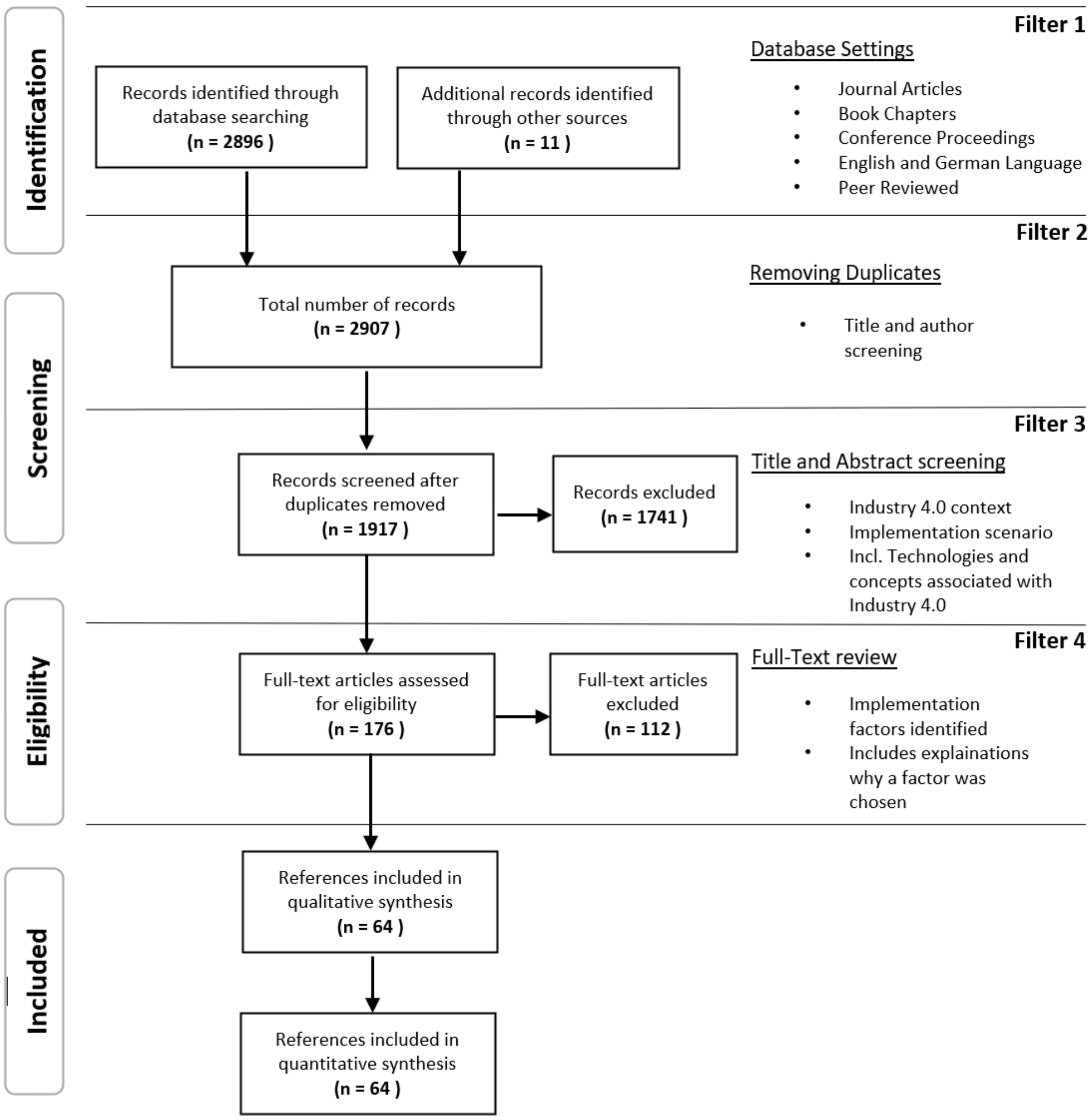

Figure 3. The PRISMA flowchart illustrates the systematic reference selection process (Adapted from Moher et al. (2015))

Thirdly, the titles and the abstracts of the 1917 remaining references were screened and assessed based on whether they are addressing the implementation of Industry 4.0 associated technologies and concepts as they were described in the previous section. Consequently, papers that referred to technologies and concepts without addressing their implementation have been filtered. In this context, 566 references were removed as they introduced new ways of how to use and optimize Industry 4.0 technologies without addressing their implementation. 790 references, on the other hand, were removed because they solely introduced and described new Industry 4.0 technologies without addressing their implementation. Furthermore, 332 references were filtered since they presented frameworks of how to design and use certain technologies without focusing on their implementation. 59 references were removed due to the fact that no industry 4.0 context could be identified. Finally, 246 full-text references were collected and reviewed which led to the exclusion of 114 references. They did not identify important industry 4.0 factors or were not able to give satisfactory explanations of why factors were considered, leaving a total of 62 references for the following analysis.

It is worth noting that the findings of Maghazei and Netland (2017) offer a plausible explanation for the strong technology focus of the field Industry 4.0 by putting current trends into a historical context. During the third industrial revolution, science first started with the evaluation of advanced manufacturing technologies before addressing implementation related subjects due to the corporations´ need for information whether a particular technology is suitable for using it in an industrial environment (Pourabdollahian et al., 2016).

2.3.2 Factor categorization and analysis

After the initial set of 1031 references was filtered, the remaining papers had to be analyzed in order to identify, code and, categorize the factors that either have a positive or negative impact on the probability of an industry 4.0 implementation. The program Citavi was used to collect the references and to categorize the implementation factors together with the reasoning behind the relevance of those factors. As a result, three main categories alongside 14 factors were identified (Table 3). This system of classification was chosen for the purpose of showing the three main angles from which an industry 4.0 implementation can be observed.

The category "external factors" contains all the factors that cannot be influenced by single companies. Illustrating this, it is difficult for a single company to determine which IT-protocol becomes the industry standard or to which extent the government provides funding options. However, factors that, on the other hand, can be influenced by single companies have been categorized as internal factors such as the decision to consider industry 4.0 on a strategic level. Besides external and internal factors, some findings suggested that the characteristics of a company, such as the size or the sector the company is operating in, can influence the likelihood of an industry 4.0 implementation. Therefore, a third category has been created.

Table 3. Industry 4.0 implementation factors

Factors	References
External Factors	
Political Support	Müller et al. (2018a); Li (2017); Infosys (2015); Lin et al. (2018); Deloitte Insights (2018); Sung (2017); Odważny et al. (2018); Schumacher et al. (2016); Lichtblau et al. (2015); Choi and Choi (2018); Dvouletý et al. (op. 2017); Feng et al. (2018); Issa et al. (2017); Ślusarczyk (2018); Jäger et al. (2016), Natalia Pantielieieva et al. (2018)
IT- Standardisation and Security	Infosys (2015); Sung (2017); Odważny et al. (2018); Lichtblau et al. (2015); Müller et al. (2018b); Gökalp et al. (2017); Ahuett-Garza and Kurfess (2018); Choi and Choi (2018); Cimini et al. (2017); Feng et al. (2018); Schumacher et al. (2016); Abele et al. (2015); Ślusarczyk (2018); Benias and Markopoulos (9/23/2017 - 9/25/2017); Benzerga et al. (2018); Jäger et al. (2016); Khan and Turowski (2016); Moktadir et al. (2018); Nagy et al. (2018); Philipp Autenrieth et al. (2018); Vaidya et al. (2018); Zawadi Chengula et al. (2018)
Corporate and Institutional Cooperation	Müller et al. (2018a);Li (2017); Deloitte Insights (2018); Sung (2017); Schumacher et al. (2016); Prudential (2017); Feng et al. (2018); Issa et al. (2017); Ślusarczyk (2018); Moica et al. (2018); Natalia Pantielieieva et al. (2018); Sjödin et al. (2018); Zawadi Chengula et al. (2018)
Cost Assessment and Available Funding Options	(2017); Müller et al. (2018a); Li (2017); Sung (2017); Lichtblau et al. (2015); Prudential (2017); Schneider (2018); Choi and Choi (2018); Issa et al. (2017); Ślusarczyk (2018); Braun et al. (2018); Hamzeh et al. (2018); Jäger et al. (2016); Moktadir et al. (2018); Nagy et al. (2018); Sjödin et al. (2018); Vaidya et al. (2018); (Ślusarczyk, 2018)
Available Knowledge and Education	Sung (2017); Prudential (2017); Mueller et al. (2017); Schneider (2018); Choi and Choi (2018); Cimini et al. (2017); Feng et al. (2018); Schumacher et al. (2016); Lichtblau et al. (2015); Ślusarczyk (2018); Cala et al. (2018); Hamzeh et al. (2018); Jäger et al. (2016); Khan and Turowski (2016); Moica et al. (2018); Nagy et al. (2018)
Pressure to Adapt	Basl (2017); Lin et al. (2018); Hamidi et al. (2018); Feng et al. (2018); Davies et al. (2017); Jäger et al. (2016); Sjödin et al. (2018)
Internal Factors	

Perceived Implementation Benefits	Basl (2017); Müller et al. (2018a); Infosys (2015); Lin et al. (2018); Deloitte Insights (2018); Buer et al. (2018); Kolberg and Zuehlke (2015); Xu et al. (2018); Odważny et al. (2018); Samaranayake et al. (2017); Müller et al. (2018b); Prudential (2017); Li et al. (2017); Ahuett-Garza and Kurfess (2018);Choi and Choi (2018); Feng et al. (2018); Ślusarczyk (2018); Benzerga et al. (2018); Fettermann et al. (2018); Hamzeh et al. (2018); Khan and Turowski (2016); Moica et al. (2018); Moktadir et al. (2018); Nagy et al. (2018); Sjödin et al. (2018)
Strategic Consideration	Basl (2017); Müller et al. (2018a); Lin et al. (2018); Tortorella and Fettermann (2017);Buer et al. (2018); Odważny et al. (2018); Schumacher et al. (2016); Lichtblau et al. (2015); Erol et al. (2016); Hamidi et al. (2018); Cimini et al. (2017); Moica et al. (2018); Moktadir et al. (2018); Nagy et al. (2018); Zawadi Chengula et al. (2018)
IT-Infrastructure Maturity	Müller et al. (2018a); Sung (2017); Odważny et al. (2018); Schumacher et al. (2016); Lichtblau et al. (2015); Mueller et al. (2017); Chan et al. (2017); Leyh et al. (2016);Ahuett-Garza and Kurfess (2018); Segura-Velandia et al. (2016); Cala et al. (2018); Hamzeh et al. (2018); Moktadir et al. (2018); Philipp Autenrieth et al. (2018); Sjödin et al. (2018); Vaidya et al. (2018); Zawadi Chengula et al. (2018); Badri et al. (2018); Bogner et al. (2016)
Internal Knowledge and Skills Development	Basl (2017); Müller et al. (2018a); Deloitte Insights (2018); Ustundag and Cevikcan (2018); Odważny et al. (2018);Schumacher et al. (2016); Lichtblau et al. (2015); Hamidi et al. (2018); Prudential (2017); Cimini et al. (2017); Infosys (2015); Samaranayake et al. (2017); Ślusarczyk (2018); Braun et al. (2018); Issa et al. (2018); Khan and Turowski (2016); Moica et al. (2018); Moktadir et al. (2018); Nagy et al. (2018); Palazzeschi et al. (2018); Sjödin et al. (2018)
Lean Manufacturing Experience	Tortorella and Fettermann (2017); Ustundag and Cevikcan (2018); Kolberg and Zuehlke (2015); Sanders et al. (2016); Chan et al. (2017); Davies et al. (2017); Dombrowski et al. (2017)
Occupational Health and Safety	Badri et al. (2018); Kagermann et al. (2013); Müller et al. (2018b); Ahuett-Garza and Kurfess (2018); Cala et al. (2018)
Company Characteristics	
Industry Sector	Müller et al. (2018a);Tortorella and Fettermann (2017);Infosys (2015); Buer et al. (2018); Lichtblau et al. (2015); Müller et al. (2018b); Lin et al. (2018); Carolis et al. (2017); Bogner et al. (2016)
Company Size	Müller et al. (2018a); Tortorella and Fettermann (2017); Lin et al. (2018); Lichtblau et al. (2015); Sommer (2015); Braun et al. (2018); Hamzeh et al. (2018); Moica et al. (2018); Bogner et al. (2016)

Note: Some articles are counted more than once because they cover more than one type of issue.

Apart from analyzing which factors can be identified in the current literature, it is also important to look at how those factors were identified. The rationale for this is to provide more information on who the main contributors to this scientific discourse are. In this context, Table 4 shows that a significant portion of the listed references used surveys, expert interviews, and case studies to assess the relevance of the factors, indicating a healthy and robust connection between the scientific and the corporate world. All of the surveys and expert interviews included practitioners and experts from academia.

Furthermore, the sample also indicates that industry 4.0 gained momentum in the year 2017. In contrast, publications that were focused on industry 4.0 related technologies, such as Big Data, already started to gather pace right after its introduction in the year 2011 (Fosso Wamba et al., 2015). As was pointed out earlier, the work of Maghazei and Netland (2017) proposes a possible explanation and shows that the focus on technologies is not a new phenomenon.

Table 4. Classification of articles by research approach

Factors identified through	Author
Survey	Basl (2017);Tortorella and Fettermann (2017); Infosys (2015); Lin et al. (2018);Deloitte Insights (2018); Schumacher et al. (2016); Lichtblau et al. (2015); Hamidi et al. (2018); Müller et al. (2018b); Prudential (2017); Schneider (2018); Choi and Choi (2018); Braun et al. (2018); Hamzeh et al. (2018); Jäger et al. (2016); Khan and Turowski (2016);
Literature Review	Li (2017); Ustundag and Cevikcan (2018); Buer et al. (2018); Kolberg and Zuehlke (2015); Sanders et al. (2016); Sung (2017); Xu et al. (2018); Odważny et al. (2018); Samaranayake et al. (2017); Mueller et al. (2017); Li et al. (2017); Gökalp et al. (2017); Leyh et al. (2016); Sommer (2015); Ahuett-Garza and Kurfess (2018); Cimini et al. (2017); Dvouletý et al. (op. 2017); Feng et al. (2018); Abele et al. (2015); Braun et al. (2018); Cala et al. (2018); Dombrowski et al. (2017); Fettermann et al. (2018); Khan and Turowski (2016); Moktadir et al. (2018); Natalia Pantielieieva et al. (2018); Palazzeschi et al. (2018); Philipp Autenrieth et al. (2018); Vaidya et al. (2018); Badri et al. (2018); Cala et al. (2018)
Expert Interview	Schumacher et al. (2016); Lichtblau et al. (2015); Issa et al. (2018); Carolis et al. (2017); Khan and Turowski (2016); Moktadir et al. (2018); Zawadi Chengula et al. (2018)

Case Study	(Müller et al., 2018a); Chan et al. (2017); Segura-Velandia et al. (2016) ; Issa et al. (2017); Issa et al. (2018); Moica et al. (2018); Philipp Autenrieth et al. (2018); Sjödin et al. (2018)

Note: Some articles are counted more than once because they cover more than one type of issue.

2.4 Discussion of the Identified Factors

This section is divided into three main parts, each of which presents the results relating to one of the three presented implementation categories. Furthermore, each identified factor (Table 5) within a category will be discussed. The purpose of this approach is to present a comprehensive overview of the factors that have been identified within the systematic literature review by giving more details about why the identified factors are considered relevant. In addition, conflicting findings will be highlighted in order to identify potential research gaps that need to be addressed in the future.

Table 5. Summary of the Implementation Factors

#	FACTORS	FURTHER DETAILS
1	**Political Support**	E.g., setting legal boundaries and achieving a wider broadband deployment.
2	**IT-Standardization and Security**	E.g., data security, and standardization of communication protocols.
3	**Corporate and Institutional Cooperation**	E.g., cooperation between companies and universities.
4	**Cost Assessment and Available Funding Options**	E.g., in order to overcome financial barriers.
5	**Available Knowledge and Education**	E.g., role models, methods, use cases, and frameworks.
6	**Pressure to Adapt**	E.g., maintaining the competitive edge and external pressure from customers.
7	**Perceived Implementation Benefits**	E.g., Increasing operational flexibility and efficiency.
8	**Strategic Consideration**	E.g., having a dedicated industry 4.0 strategy.
9	**IT-Infrastructure Maturity**	E.g., having an open and flexible IT-infrastructure that facilitates the integration of new technologies.
10	**Internal Knowledge and Skills Development**	E.g., internal promotion of skills that are related to the transition towards industry 4.0.
11	**Lean Manufacturing Experience**	Lean Manufacturing experience might increase the probability of a thriving Industry 4.0 implementation.
12	**Occupational Health and Safety**	Implementing Industry 4.0 might increase the risks related to occupational health and safety.
13	**Industry Sector**	Some industry sectors might be more likely to implement Industry 4.0.
14	**Company Size**	The size of a corporation might have an impact on the implementation of Industry 4.0

2.4.1 External Factors

2.4.1.1 Political Support

The analysis of the relevant papers has shown that all authors who mentioned the factor political support emphasized the importance of the government as an enabler of the implementation of Industry 4.0. Both scientists and practitioners together drew a homogeneous picture of a government that has a substantial impact on the fourth industrial revolution.

The field of responsibilities of political institutions is wide and complex. Therefore it is not surprising that the factor political support turned out to have the most interrelation with other factors. For instance, when it comes to the available funding options in a country, governments can represent a reliable source for financial support. Coupled with other measures like reducing taxes for industry 4.0 related research, political institutions can help to overcome financial barriers that slow down the transitional process towards industry 4.0 as the studies of Choi and Choi (2018), and Prudential (2017) have illustrated. However, besides facilitating funding related issues, there is also a consensus that political institutions are responsible for creating an appropriate environment for companies intending to be engaged in the transitional process. This includes setting legal boundaries that rather have supporting opposed to limiting effects, achieving a wider broadband deployment, and creating a social system that is capable to deal with the fourth industrial revolution in terms of education (Sung, 2017; Infosys, 2015; Feng et al., 2018; Ashrafi and Kuilboer, 2018; Krempel and Beyerer, 2018; Natalia Pantielieieva et al., 2018).

2.4.1.2 IT-Standardization and Security

Similar to the factor political support, the authors who identified IT-standardization and security considered it as one of the biggest challenges regarding the implementation of industry

4.0. The rationale for this lies in the main goal of industry 4.0 itself. As was pointed out in the introduction to this paper, connecting all entities within a company requires the use of certain key technologies like big data or cloud computing. Using these novel technologies increases the amount of data that will be shared, collected and processed and therefore also increases the overall vulnerability of the systems that are managing the data (Goel and Chen, 2008; Akter et al., 2016; Khan and Turowski, 2016; Philipp Autenrieth et al., 2018). In a study that set out to determine what the main drivers of the implementation of industry 4.0 are, Müller et al. (2018b) identified data security concerns as one of the main obstacles in terms of adapting industry 4.0. Along the same line, Odważny et al. (2018) and Jäger et al. (2016) argue that securing and managing data inappropriately could result in system crashes that lead a whole production stop. However, besides security concerns, companies are also struggling with the lack of standardization of new technologies, laws, and communication protocols (Abele et al., 2015). Not only that the lack of standardization makes the implementation of industry 4.0 technologies more difficult from a technological standpoint, but it also forces companies to take financial risks related to the acquisitions of industry 4.0 assets (Infosys, 2015; Pourabdollahian et al., 2016; Vaidya et al., 2018). Since it is not sure whether the acquired systems will be compatible with other systems in the near future, companies have to deal with an additional amount of uncertainty. Reducing those asset acquisition-related uncertainties in the context of standardization is therefore considered as one of the most important measures to take in order to accelerate the implementation of industry 4.0.

2.4.1.3 Corporate and Institutional Cooperation

During the analysis, several studies have reported the need for more cooperation between companies, universities and governments to address industry 4.0 related implementation problems (Natalia Pantielieieva et al., 2018; Moica et al., 2018; Sjödin et al., 2018; Zawadi

Chengula et al., 2018). Companies are at the center of the implementation of industry 4.0; however, as the analysis of the references has shown, there is a set of factors beyond their influence. For instance, in a survey that was conducted by Prudential (2017), 36% of the participants stated that cooperation with industry partners is crucial in order to address the skill gap that is caused by the fourth industrial revolution. Also, 27% of the participants mentioned collaboration with the educational sector as an important approach to deal with the challenge. A broadly similar point has also recently been made by Feng et al. (2018), who proposed the German vocational education system as a potential role model for other countries.

Another significant aspect of cooperation in the context of industry 4.0 was identified by Issa et al. (2017) and Müller et al. (2018a). By sharing resources and building collaborations with other companies, SMEs can decrease the overall risks that come with developing, testing, and producing new technologies and products. Compared to larger corporations, SMEs struggle more with those activities since they require additional financial and human resources. In this context, Issa et al. (2017) promote the initiative I4KMU, a project that facilitates and encourages cooperation between SMEs and test environments by establishing an online matching system based on the characteristics and needs of the companies to outbalance the distinctive disadvantages of SMEs.

2.4.1.4 Cost Assessment and Available Funding Options

The implementation of new technologies poses a massive challenge for many companies. The analysis of the selected references shows that industry 4.0 technologies are no exception and that companies are facing two main issues in this regard.

Firstly, financial constraints combined with the high cost of industry 4.0 associated technologies and systems build a strong barrier for companies that want to be engaged with industry 4.0 (Ślusarczyk, 2018; Pourabdollahian et al., 2016; Vaidya et al., 2018). The findings of Prudential (2017) illustrate this aspect by showing that 31% of the participants in their survey reported high costs of implementation to be the main source of their hesitation. Other authors such as Sung (2017) or Odważny et al. (2018) note that particularly the complexity of industry 4.0 infrastructures, as well as the difficulties to maintain security standards during the transformation, are leading to increased financial efforts.

Secondly, due to the complexity of industry 4.0 technologies, companies are also facing difficulties when they want to assess the profitability of their future investments. Schneider (2018) argues that the non-linear nature of transformation towards industry 4.0 and the fact that new business opportunities might result from the investment along the line are responsible for the underlying uncertainty linked to industry 4.0. However, studies indicate that companies that were able to deal with the uncertainty and that started with the implementation of industry 4.0 still faced financial issues. In this context, Lichtblau et al. (2015) reported that more than 63,4% of the companies that are aware of the uncertainty of industry 4.0 claimed that high costs are stopping them from going further with their industry 4.0 engagement. The study of Choi and Choi (2018) came to a similar result. Out of 140 SMEs who gained positive experiences by implementing industry 4.0, 102 claimed that financial barriers kept them from reaching higher levels of Industry 4.0 maturity.

As the findings of Pourabdollahian et al. (2016) suggest, these funding related issues in the context of new technologies are not a new problem as they also played a major role during the third industrial revolution. However, how to address these old issues in a new industry 4.0 context remains to be answered.

2.4.1.5 Available Knowledge and Education

As previously stated, the ability to evaluate industry 4.0 related investments is crucial to companies. In this context, use cases, methodologies, frameworks, and role models are important sources of information upon which companies can build solid decisions (Mueller et al., 2017; Schneider, 2018; Cimini et al., 2017). However, use cases are usually tailored to the individual needs and visions of a corporation, which therefore makes it difficult to transfer the gathered knowledge to other companies. Furthermore, due to the innovative character of industry 4.0, the number of existing role models and use cases is still limited. Thus, the development of implementation methodologies and frameworks should address these issues by considering a larger audience. However, other findings suggest that companies are not only struggling with finding suitable sources of information but also with recruiting a workforce that processes the necessary knowledge (Ślusarczyk, 2018; Khan and Turowski, 2016). Within their study, Choi and Choi (2018) found that the lack of industry 4.0 experts has a negative impact on the ability to implement industry 4.0. The study of Prudential (2017) came to similar results and showed that companies are concerned about the effects of a transition towards industry 4.0 on recruiting skilled employees. To address this issue, Feng et al. (2018) suggest that investments in education and R&D should be increased by the government and corporations.

2.4.1.6 Pressure to Adapt

In a changing environment, the ability to adapt to new developments is important in terms of either maintaining or gaining a completive edge (Liu et al., 2018; Davies et al., 2017). However, the analysis of the literature indicates that external pressure not only forces but also prevents corporations from implementing industry 4.0. What first seems counterintuitive can be explained with the help of the findings of Deloitte Insights (2018). In their survey, participants expressed concerns about investing in long-term projects like the implementation of industry 4.0 since their strategies are mostly focused on delivering financial results in the short term. In the same vein, Davies et al. (2017) state that the negligence of future customers' needs is often the result of a too strong focus on current mainstream customers. In contrast, the findings of Lin et al. (2018) and Hamidi et al. (2018) illustrate that external pressure can also have positive effects on the implementation of industry 4.0. Especially the general need to remain competitive, which can be intensified by factors such as customers' demand or building infrastructures that allow cooperation, was identified as a driver for the implementation of industry 4.0 technologies. Together these results provide interesting insights into how external sources can cause conflicts in the decision-making of organizations.

2.4.2 Internal Factors

2.4.2.1 Perceived Implementation Benefits

The factor perceived implementation benefits revolves around the question of why companies actively want to implement Industry 4.0. Throughout the analysis of the literature, various answers that provide a better understanding of the hopes that are connected to industry 4.0 have been given. In their study, Lin et al. (2018) were able to confirm their hypothesis that perceived benefits have a positive impact on the usage of industry 4.0 technologies. In fact, perceived benefits turned out to be the most significant factor, a less than surprising result. However, the more interesting perspective literature has to offer in that regard are the reasons to adapt themselves.

While some studies have shown that corporations particularly want to increase their profits or their operational efficiency and flexibility (Sishi and Telukdarie, 2017; Ahuett-Garza and Kurfess, 2018), other studies have offered a more diverse picture. In this context, the findings of Müller et al. (2018b) drew a distinction between benefits that are related to operational, strategic, environmental, and social opportunities. Depending on individual characteristics like the goals of a company or the sector they are operating in, the purpose and therefore, the perceived benefits might change, further illustrating the individual nature of this factor. In this context, the findings of Kolberg and Zuehlke (2015) and Wagner et al. (2017) represent another useful example. They suggest that industry 4.0 can enable and improve lean principles, which makes the implementation of Industry 4.0 more likely for companies that intend to implement or to improve lean manufacturing. This view is supported by Tortorella and Fettermann (2017), whose results show that companies with lean manufacturing experience are more likely to implement industry 4.0. However, these data must be interpreted with caution because further investigations are required in order to rule out the influence of other factors. Therefore, shedding light on this factor can prevent corporations from making dangerous decisions.

2.4.2.2 Strategic Consideration

As explained earlier and as the number of potential factors indicates, companies who want to implement industry 4.0 have to deal with many obstacles. The process of developing a strategy can help to identify those potential hurdles and to overcome them. Therefore, it is no surprise that a number of authors stressed the importance of addressing the implementation of industry 4.0 on a strategical level (Moica et al., 2018). In this context, the findings of Tortorella and Fettermann (2017) suggest, the lack of a dedicated strategy leads to misunderstandings and wrong expectations towards the overall concept of industry 4.0. This aspect became apparent when some participants of their survey who have not perceived an increase in their operational performance during the last three years and who had a low level of industry 4.0 implementation, still claimed that they already have widely implemented it. Because of these contradictory claims, the authors concluded that this particular group of participants misunderstood and/or misused the concepts and technologies associated with industry 4.0. To address this problem, the authors of the study suggested that aligning a dedicated industry 4.0 strategy with the overall corporate strategy can prevent companies from having a flawed understanding of the underlying concepts and dynamics. A suggestion that also has been made by Erol et al. (2016), who advise companies to choose a broad strategical approach towards industry 4.0 rather than only considering technological aspects for isolated environments.

When it comes to the question of how companies perceive the importance of an Industry 4.0 strategy, the findings of Hamidi et al. (2018) show that companies also consider strategy as an essential factor. In contrast, the study of Lichtblau et al. (2015) reported that 40% of the participants did not have a dedicated industry 4.0 strategy, while 20% were still developing one.

The main questions raised by the presented findings are how important the factor strategic consideration is compared to other factors and which building blocks are essential for developing a successful Industry 4.0 strategy.

2.4.2.3 IT-Infrastructure Maturity

As indicated previously, technologies such as cloud computing, machine learning, and big data are not just characterized by their ability to process and interpret immense amounts of data in real-time, but also by their complexity itself. In this context, the meaning behind IT-maturity refers to the companies' ability to manage the emerging complexity caused by industry 4.0 associated technologies. On this basis, the findings of Samaranayake et al. (2017) show that this ability is the sum of a number of factors such as the skills and the knowledge of employees, the compatibility of currently used technologies, and the stability of the internet connection. Similarly, Lichtblau et al. (2015) presented different ways of how companies can prepare themselves for the transition towards industry 4.0. Depending on their existing experience and

IT-infrastructure as well as on which technologies they intend to use, different solutions have been proposed.

Another important aspect of IT-maturity can be inferred from the findings of Chan et al. (2017). In their case study about simulating lean manufacturing and industry 4.0 processes, the companies' IT-infrastructure turned out to be the limiting factor regarding collecting data. Consequently, the authors concluded that a more advanced infrastructure would allow more accurate simulations and process optimizations, further illustrating the importance and the evolutionary nature of IT-infrastructures. Similarly, other authors argued that IT-maturity is an ongoing process and that the more flexible and the more open an IT-infrastructure is, the fewer issues companies will face while implementing industry 4.0 technologies (Xu et al., 2018; Sung, 2017).

Overall, the analysis of the literature shows that IT-maturity has been recognized as one of the most important challenges regarding the implementation of industry 4.0. This view is shared by all authors who were listed under this factor. Nonetheless, the question of how important IT-maturity is compared to other factors remains to be answered.

2.4.2.4 Internal Knowledge and Skills Development

The history of industrial revolutions shows that with each milestone, not only markets were disrupted but also the skills that were required to produce and to deliver goods for those new markets. Therefore, it is hardly a surprise that even international institutions like the OECD or the World Economic Forum assume that skill requirements will change as a result of industry 4.0 (Ustundag and Cevikcan, 2018; Sung, 2017). In this context, the factor skills and knowledge refers to the efforts made by a company to address the aforementioned disruptive process by promoting industry 4.0 related skills and knowledge.

As the analysis of the literature shows, some authors have already started to identify important skills that should be promoted by the corporate world in order to be prepared for the transition towards industry 4.0. While the findings of Deloitte Insights (2018) are suggesting that companies do not think that industry 4.0 will have a significant impact on their workforce, other studies demonstrated the overall importance of the topic for corporations (Lichtblau et al., 2015; Hamidi et al., 2018; Prudential, 2017).

Based on the assumption that the level of automation and the use of smart devices, as well as advanced IT-systems, will increase, specific skills become more important. Amongst others, these skills include working across organizational boundaries and the ability to interact with complex systems, as shown by the findings of Prudential (2017). Furthermore, Ustundag and Cevikcan (2018) believe that due to fast-changing business environments, cultural skills will gain more importance over time.

When it comes to general knowledge about industry 4.0, companies show a high awareness. However, as the findings of Basl (2017) and Müller et al. (2018a) indicate, this knowledge is unequally distributed among the workforces of corporations. Particularly managers showed a higher degree of basic knowledge compared to the rest of the workforce. Likewise, the findings of Hamidi et al. (2018; Issa et al., 2017; Zawadi Chengula et al., 2018) maintain that there is a lack of knowledge of industry 4.0 among employees despite having a large set of skills. Whether this disequilibrium has the potential to curb the transition towards industry 4.0 and whether a more balanced distribution has positive effects remains to be answered.

2.4.2.5 Lean Manufacturing Experience

The analysis of the literature shows that there is a consensus among scientists regarding the compatibility of industry 4.0 and lean manufacturing. This compatibility is mainly based on the shared objectives of increasing the overall flexibility and productivity of a company (Buer et al., 2018; Kolberg and Zuehlke, 2015). Additionally, both philosophies prefer decentralized structures over large and complex systems (Krafcik, 1988; Santos et al., 2017). A study to set out the interdependencies and correlations between the two approaches by analysing 260 Industry 4.0 use cases, further illustrated their compatibility by showing how certain Lean Manufacturing principles such as the zero-waste principle correlate with the application of Industry 4.0 technologies (Dombrowski et al., 2017).

Besides their compatibility, recent studies suggest that not only lean manufacturing can be improved with industry 4.0 but also that industry 4.0 can be improved with lean manufacturing (Buer et al., 2018; Tortorella and Fettermann, 2017; Karre et al., 2017). This dynamic relationship is further exemplified in studies focusing on implementing Industry 4.0 into lean manufacturing environments. For instance, Sanders et al. (2016) and Kolberg and Zuehlke (2015) argue that the implementation of industry 4.0 can help companies to achieve higher levels of lean manufacturing due to the potential of Industry 4.0 technologies and the goals both philosophies share.

As a result of the dynamic relationship between Industry4.0 and lean manufacturing, the question arises whether companies who are applying or intending to apply lean principles are also more likely to implement industry 4.0. This question formed the central focus of a study by Tortorella and Fettermann (2017) in which the authors found evidence that supports the argument that lean manufacturing experience leads to a higher probability of implementing industry 4.0. However, this particularly applied to companies that were able to gather experience with lean manufacturing for more than two years. Furthermore, since the study was conducted in one country and did not consider the influence of industry sectors, more research needs to be done to understand the dynamic between lean manufacturing experience and the implementation of industry 4.0.

2.4.2.6 Occupational Health and Safety

The analysis of the literature has also shown that the implementation of those technologies can jeopardize the overall working safety and, as a consequence, potentially decrease the probability of implementing Industry 4.0. In this context, Badri et al. (2018) stressed the importance of the potential risk that is linked to the implementation of Industry 4.0 technologies and further argued that the topic deserves more academic attention as it represents only a small fraction of the overall research.

The analysis of the literature shows further that the risks involved in implementing Industry 4.0 can either be physical and psychological nature. While, for instance, an increased use of robots can also increase the risks of potential accidents, psychological risks are, among other things, referred to the anxiety of losing one's job, to the lack of trust in recently implemented systems, and to the transparency of data (Badri et al., 2018; Müller et al., 2018b; Bauernhansl et al., op. 2014).

Industry 4.0 has the potential to accelerate the change of work organization towards a more complex work environment (Badri et al., 2018). Therefore, it is crucial to consider the potential risks regarding occupational health and safety before developing or implementing new technologies. As Bauernhansl et al. (op. 2014) pointed out, subsequent adjustments can lead to high costs or even can become unfeasible. Furthermore, it is important to address potential psychological risks by creating working environments that offer employees emotional and behavioural support (Ahuett-Garza and Kurfess, 2018; Cala et al.). However, the question that remains is whether risks related to occupational health and security play a significant role in the decision making of enterprises with the intention to implement Industry 4.0.

2.4.3 Company Characteristics

As the review of the literature revealed, besides internal and external factors, the size of the company and the sector the company is mainly operating in can have an impact on the probability of implementing industry 4.0 as well. Policymakers can make use of this knowledge in order to increase the efficiency of their industry 4.0 strategies by addressing the specific corporate infrastructure of their countries or by addressing the specific needs of certain industry sectors.

2.4.3.1 Industry Sector

Recent research suggests that the sector companies are operating in has an impact on the probability of whether they will implement industry 4.0 (Buer et al., 2018; Infosys, 2015). In their investigation into what drives the implementation of industry 4.0, Müller et al. (2018b) were able to illustrate this connection. They found that depending on the sector, companies claimed to face different implementation challenges and opportunities. From this result, it can be derived that depending on the industry sector, some companies might face more challenges than others. In this context, the findings of Buer et al. (2018) and Müller et al. (2018a) show that particularly repetitive and highly automated production environments are suitable for the integration of industry 4.0 technologies and concepts. However, more research is necessary to illustrate the differences between sectors in terms of the implementation of industry 4.0. Furthermore, it is not clear how important this factor is compared to other factors.

2.4.3.2 Company Size

Does the size of the company have an impact on the probability of whether it will implement industry 4.0? The analysis of the literature offers no clear answer to this question. While some authors were able to demonstrate the correlation between the size of a company and the readiness of implementing industry 4.0, other authors were not able to confirm this hypothesis. Therefore, there is conflicting evidence on the relationship between the two factors.

In his examination of companies' ability to meet the challenges associated with industry 4.0, Sommer (2015) has illustrated that this ability strongly depends on the size of companies. Similarly, Lichtblau et al. (2015) have found that the industry 4.0 readiness of a corporation correlates with its size and that larger companies are showing higher readiness levels. In both studies, it is stated that industry 4.0 is particularly challenging for smaller companies due to various reasons, such as the lack of resources. In this regard, Müller et al. (2018a), Braun et al. (2018), and Hamzeh et al. (2018) argue that this lack of resources impedes smaller firms from identifying future opportunities as they are more forced to focus on their daily business.

However, the findings of Lin et al. (2018), Bogner et al. (2016), and Tortorella and Fettermann (2017) were not able to confirm the assumptions that can be derived from the findings above. In both studies, the size of a company had no significant impact on the implementation of Industry 4.0. Nonetheless, these findings are not offering a final answer to the question posed at the beginning. Both studies shared limitations that have to be addressed in the future, such as the limited number of sectors and countries that were involved in the studies.

2.5 Conclusions

This paper presents the first comprehensive set of potential factors that need to be considered when it comes to the implementation of industry 4.0. The main aim of this examination was to build a bridge between the existing knowledge in order to contribute to and to stimulate further the scientific discussion about the difficulties that revolve around the implementation of industry 4.0. In contrast to other studies that approached this topic from the readiness perspective or that tried to focus on certain factors, the present study intended to use a more extensive approach by combining previous findings and stressing the importance of the systems thinking perspective. As a result, the systematic literature review revealed and discussed several gaps that need to be addressed in future examinations.

However, the findings also clearly indicate that organizations that decide to integrate concepts and technologies associated with the fourth industrial revolution face a number of issues that not always can be addressed by corporations themselves. Since society is benefiting from a prospering economy, it is of common interest of scientists, practitioners, and governmental institutions to address the presented issues and to keep a vital conversation alive. Furthermore, this literature review also strengthens the idea that the identified factors are interrelated in a complex manner and that some factors might be more important than others. For instance, the analysis of the literature has shown that particularly governmental institutions are perceived as important in the context of solving industry 4.0 related issues that can also be the result of other identified factors. However, the importance of the presented factors cannot be derived from the number of publications they have been addressed in. Therefore, future investigations are necessary in order to assess the importance of each factor in different environments as proposed by several authors such as Müller et al. (2018b), Frank et al. (2019), and Tortorella and Fettermann (2017).

2.5.1 Implications

Throughout the literature review, a set of potential implementation factors has been identified and discussed. From these findings, several implications emerged. First, an understanding of Industry 4.0 is crucial, as misconceptions and wrong expectations can have a negative impact on the transitional process. As described in section 2, Industry 4.0 is more than the sum of technologies associated with it. Therefore, corporations should consider developing a strategy that helps them to understand all the important aspects of Industry 4.0. This strategy should not be focused on individual projects but rather aligned with the main strategy of the corporation. In this context, systems thinking has been introduced as a new perspective that can help companies to understand the complexity that arises from Industry 4.0. However, some findings suggest that knowledge about Industry 4.0 is distributed unevenly within corporations (Hamidi et al., 2018; Issa et al., 2017). This disequilibrium has the potential to divide workforces; consequently, resulting fears must be taken seriously and addressed by the management. Governments and scientists, on the other hand, can support this process of addressing the knowledge gap by further promoting a broader understanding of Industry 4.0. While case studies and use cases can give organizations an idea about what can be expected from Industry 4.0, governments can support programs that raise the awareness of the topic. Secondly, cooperation can help to accelerate the development of standards and to decrease the financial uncertainty that is associated with Industry 4.0. In this regard, the compatibility of future technologies with current IT-infrastructures is one of the major concerns. Assessing which communication protocols are efficient, safe, and within the scope of a legal framework that will provide data security is a task that cannot be handled by single companies. Therefore, the exchange of information between corporations, science, and governments is crucial. As mentioned in the previous section, financial uncertainty, however, not only results from lacking standards but also developing and testing new systems and business models. In this context, the project I4KMU was mentioned as an excellent example of creating a platform that encourages companies to work on these issues together in order to decrease the overall uncertainty. As a consequence, managers are advised to cooperate not only with other companies but also with governmental institutions and scientists. Another promising approach to decrease financial risks connected to industry 4.0 is to consider safety as an integral part of the development and implementation of new systems. It is important to understand the potential impact of new technologies on the overall safety as addressing those aspects afterward imply high expenditures. Thirdly, the findings suggest that certain types of experiences can support the transition towards Industry 4.0. This is particularly true for the lean manufacturing experience. Promoting the similarities between the Industry 4.0 concept and lean manufacturing can, therefore, encourage companies to make use of their existing knowledge. Finally, the role of the government is essential in the context of Industry 4.0. From infrastructure to education, to economic alleviations, to cooperation, the findings indicate that governmental institutions can set the boundaries for an environment that increases the probability of a successful implementation of Industry 4.0.

2.5.2 Limitations and Future Research

Before discussing the main findings of this paper, a number of important limitations need to be considered. First, Industry 4.0 is still a young topic, and as the findings of Maghazei and Netland (2017) have suggested, the main focus of science is still on assessing the capabilities of industry 4.0 technologies rather than on how to implement them, leading to a still small body of available literature. Secondly, this study is limited by the references that were selected from three scientific databases. Therefore, relevant findings might have been overseen.

In order to fortify the foundation on which future research can be constructed, not only the identification of further factors but also the examination of the dynamic relationship between the different factors with the help of systems thinking becomes vital. While the systems perspective has been proposed to gather a more realistic view on these dynamics, the questions when, why, and in which environment a certain factor becomes important still need to be answered before more efficient implementation strategies can be developed. In this regard, the present study strengthens the idea that the stage of the transition, as well as the sector and the size of the corporation, affect the importance of certain factors (Müller et al., 2018b; Frank et al., 2019; Tortorella and Fettermann, 2017). Future studies, therefore, should compare the importance of the identified factors in different industry sectors while considering the individual stage of the transition as well as the size of the corporations. This would further allow developing frameworks that address the specific needs of corporations that exhibit individual characteristics.

However, the review of the literature also revealed that not only the dynamics between and around the factors are important, but also that the factors themselves should be in the focus of scientific investigations. While all authors listed under a particular factor agreed upon its importance, the reasoning behind its importance varied, as illustrated with contradictory findings regarding the size of corporations. Practitioners, scientists, and governments are all working with limited resources that force them to build priorities since not all issues can be addressed at the same time with the same amount of attention. Therefore, evaluating industry 4.0 implementation factors in more detail not only allows organizations to build priorities between factors but also between different measures that are associated with those factors.

References

Abele, E., Anderl, R., Metternich, J., Wank, A., Anokhin, O., Arndt, A., Meudt, T., Sauer, M., 2015. Effiziente Fabrik 4.0. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 110 (3), 150–153, DOI: 10.3139/104.111293.

Ahuett-Garza, H., Kurfess, T., 2018. A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing. Manufacturing Letters, 15, 60–63, DOI: 10.1016/j.mfglet.2018.02.011.

Akter, S., Wamba, S.F., Gunasekaran, A., Dubey, R., Childe, S.J., 2016. How to improve firm performance using big data analytics capability and business strategy alignment? International Journal of Production Economics, 182, 113–131, DOI: 10.1016/j.ijpe.2016.08.018.

Arthur, W.B., 1999. Complexity and the economy. science, 284 (5411), 107–109.

Ashrafi, N., Kuilboer, J.-P., 2018. A Comparative Study of Privacy Protection Practices in the US, Europe, and Asia. International Journal of Information Security and Privacy, 12 (3), 1–15, DOI: 10.4018/IJISP.2018070101.

Badri, A., Boudreau-Trudel, B., Souissi, A.S., 2018. Occupational health and safety in the industry 4.0 era: A cause for major concern? Safety Science, 109, 403–411, DOI: 10.1016/j.ssci.2018.06.012.

Bala, H., Venkatesh, V., 2015. Adaptation to Information Technology: A Holistic Nomological Network from Implementation to Job Outcomes. Management Science, DOI: 10.1287/mnsc.2014.2111.

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

Basl, J., 2017. Pilot Study of Readiness of Czech Companies to Implement the Principles of Industry 4.0. Management and Production Engineering Review, 8 (2), 817, DOI: 10.1515/mper-2017-0012.

Bauernhansl, T., Michael ten Hompel, Birgit Vogel-Heuser (Eds.), op. 2014. Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung, Technologien und Migration. Wiesbaden: Springer Vieweg.

Benias, N., Markopoulos, A.P., 9/23/2017 - 9/25/2017. A review on the readiness level and cyber-security challenges in Industry 4.0. In: 2017 South Eastern European Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM). IEEE, 1–5.

Benzerga, S., Hauf, D., Pretz, M., Bounfour, A., 2018. When Energy Revolution Meets Digital Transformation. In: Czarnowski, I., Howlett, R.J., Jain, L.C. (Eds.). Intelligent Decision Technologies 2017. Cham: Springer International Publishing, 65–81.

Bogner, E., Voelklein, T., Schroedel, O., Franke, J., 2016. Study Based Analysis on the Current Digitalization Degree in the Manufacturing Industry in Germany. Procedia CIRP, 57, 14–19, DOI: 10.1016/j.procir.2016.11.004.

Bonekamp, L., Sure, M., 2016. Consequences of Industry 4.0 on Human Labour and Work Organisation. Journal of Business and Media Psychology, 30–44.

Bosch, O.J.H., Nguyen, N.C., Maeno, T., Yasui, T., 2013. Managing Complex Issues through Evolutionary Learning Laboratories. Systems Research and Behavioral Science, 30 (2), 116–135, DOI: 10.1002/sres.2171.

Braun, A., Ohlhausen, P., Alt, C., Bahlinger, D., Chaves, D.C., Egeler, M., Gramespacher, S., Matzka, J., Steinbeck, J., Weber, C., 2018. Der Weg zur Industrie 4.0-Roadmap. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 113 (4), 254–257, DOI: 10.3139/104.111888.

Buer, S.-V., Strandhagen, J.O., 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, 3 (4), 1–17, DOI: 10.1080/00207543.2018.1442945.

Cala, A., Luder, A., Boschi, F., Tavola, G., Taisch, M., 2018. Migration towards digital manufacturing automation — An assessment approach. 2018 IEEE Industrial Cyber-Physical Systems 5/15/2018 - 5/18/2018, 714–719, DOI: 10.1109/ICPHYS.2018.8390795.

Carolis, A.D., Macchi, M., Negri, E., Terzi, S., 2017. "Engineering, technology & innovation management beyond 2020: new challenges, new approaches". conference proceedings. 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC) :

Castelo-Branco, I., Cruz-Jesus, F., Oliveira, T., 2019. Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry, 107, 22–32, DOI: 10.1016/j.compind.2019.01.007.

Chan, W.K., D'Ambrogio, A., Zacharewicz, G., Mustafee, N., Wainer, G., Page, E.H. (Eds.), 2017. Integrating Simulation-Based Optimization, Lean, And The Concepts of Industry 4.0. 2017 Winter Simulation Conference : WSC turns 50: simulation everywhere! : December 3-6, 2017, Red Rock Casino Resort & Spa, Las Vegas, NV. Piscataway, NJ: IEEE.

Choi, Y.-H., Choi, S.-H., 2018. A Study of Crossing the Chasm in applying Smart Factory System for SMEs. International Journal of Pure and Applied Mathematics, 118 (19), 469–487.

Cimini, C., Pinto, R., Cavalieri, S., 2017. The business transformation towards smart manufacturing: a literature overview about reference models and research agenda. IFAC-PapersOnLine, 50 (1), 14952–14957, DOI: 10.1016/j.ifacol.2017.08.2548.

Cohen, Y., Naseraldin, H., Chaudhuri, A., Pilati, F., 2019. Assembly systems in Industry 4.0 era: a road map to understand Assembly 4.0. The International Journal of Advanced Manufacturing Technology, 105 (9), 4037–4054, DOI: 10.1007/s00170-019-04203-1.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics, 204, 383–394, DOI: 10.1016/j.ijpe.2018.08.019.

Davies, R., Coole, T., Smith, A., 2017. Review of Socio-technical Considerations to Ensure Successful Implementation of Industry 4.0. Procedia Manufacturing, 11, 1288–1295, DOI: 10.1016/j.promfg.2017.07.256.

Deloitte Insights, 2018. The Fourth Industrial Revolution is here - are you ready?

Dietz, T., Klamroth, K., Kraus, K., Ruzika, S., Schäfer, L.E., Schulze, B., Stiglmayr, M., Wiecek, M.M., 2020. Introducing multiobjective complex systems. European Journal of Operational Research, 280 (2), 581–596, DOI: 10.1016/j.ejor.2019.07.027.

Dombrowski, U., Richter, T., Krenkel, P., 2017. Interdependencies of Industrie 4.0 & Lean Production Systems: A Use Cases Analysis. Procedia Manufacturing, 11, 1061–1068, DOI: 10.1016/j.promfg.2017.07.217.

Drath, R., Horch, A., 2014. Industrie 4.0: Hit or Hype? [Industry Forum]. IEEE Industrial Electronics Magazine, 8 (2), 56–58, DOI: 10.1109/MIE.2014.2312079.

Dvouletý, O., Lukeš, M., Mísař, J. (Eds.), op. 2017. Proceedings of the 5th International Conference , Innovation Management, Entrepreneurship and Sustainability - IMES, 25 - 26 May, 2017 Prague, Czech Republic. Praha: Vysoká škola ekonomická.

Erol, S., Schumacher, A., Sihn, W. (Eds.), 2016. Strategic guidance towards Industry 4.0 – a three-stage process model.

Fantini, P., Pinzone, M., Taisch, M., 2018. Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. Computers & Industrial Engineering, DOI: 10.1016/j.cie.2018.01.025.

Feng, L., Zhang, X., Zhou, K., 2018. Current problems in China's manufacturing and countermeasures for industry 4.0. EURASIP Journal on Wireless Communications and Networking, 2018 (1), 174, DOI: 10.1186/s13638-018-1113-6.

Fettermann, D.C., Cavalcante, C.G.S., Almeida, T.D.d., Tortorella, G.L., 2018. How does Industry 4.0 contribute to operations management? Journal of Industrial and Production Engineering, 35 (4), 255–268, DOI: 10.1080/21681015.2018.1462863.

Fosso Wamba, S., Akter, S., Edwards, A., Chopin, G., Gnanzou, D., 2015. How 'big data' can make big impact: Findings from a systematic review and a longitudinal case study. International Journal of Production Economics, 165, 234–246, DOI: 10.1016/j.ijpe.2014.12.031.

Frank, A.G., Dalenogare, L.S., Ayala, N.F., 2019. Industry 4.0 technologies: Implementation patterns in manufacturing companies. International Journal of Production Economics, 210, 15–26, DOI: 10.1016/j.ijpe.2019.01.004.

Freixanet, J., Rialp, A., Churakova, I., 2020. How do innovation, internationalization, and organizational learning interact and co-evolve in small firms? a complex systems approach. Journal of Small Business Management, 7 (3), 1–34, DOI: 10.1111/jsbm.12510.

Geissbauer, R., Luebben, E., Schrauf, S., Pillsbury, S., 2018. Global Digital Operations Study 2018 - Digital Champions. How industry leaders build integrated operations ecosystems to deliver end-to-end customer solutions.

Goel, S., Chen, V., 2008. Can business process reengineering lead to security vulnerabilities: Analyzing the reengineered process. International Journal of Production Economics, 115 (1), 104–112, DOI: 10.1016/j.ijpe.2008.05.002.

Gökalp, E., Şener, U., Eren, P.E., 2017. Development of an Assessment Model for Industry 4.0: Industry 4.0-MM. In: Mas, A., Mesquida, A., O'Connor, R.V., Rout, T., Dorling, A. (Eds.). Software process improvement and capability determination. 17th International Conference, SPICE 2017, Palma de Mallorca, Spain, October 4-5, 2017, Proceedings. Cham, Switzerland: Springer, 128–142.

Gorod, A., Sauser, B., Boardman, J., 2008. System-of-Systems Engineering Management: A Review of Modern History and a Path Forward. IEEE Systems Journal, 2 (4), 484–499, DOI: 10.1109/JSYST.2008.2007163.

Hamidi, S.R., Aziz, A.A., Shuhidan, S.M., Aziz, A.A., Mokhsin, M. (Eds.), 2018. SMEs Maturity Model Assessment of IR4.0 Digital Transformation.

Hamzeh, R., Zhong, R., Xu, X.W., 2018. A Survey Study on Industry 4.0 for New Zealand Manufacturing. Procedia Manufacturing, 26, 49–57, DOI: 10.1016/j.promfg.2018.07.007.

Haseeb, M., Hussain, H.I., Ślusarczyk, B., Jermsittiparsert, K., 2019. Industry 4.0: A Solution towards Technology Challenges of Sustainable Business Performance. Social Sciences, 8 (5), 154, DOI: 10.3390/socsci8050154.

Hecklau, F., Galeitzke, M., Flachs, S., Kohl, H., 2016. Holistic Approach for Human Resource Management in Industry 4.0. Procedia CIRP, 54, 1–6, DOI: 10.1016/j.procir.2016.05.102.

Henshaw, M., 2016. SYSTEMS OF SYSTEMS, CYBER-PHYSICAL SYSTEMS, THE INTERNET-OF-THINGS… WHATEVER NEXT? Insight, 19 (3), 51–54.

Horváth, D., Szabó, R.Z., 2019. Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? Technological Forecasting and Social Change, 146, 119–132, DOI: 10.1016/j.techfore.2019.05.021.

Infosys, 2015. Industry 4.0: The state of the nation.

Issa, A., Hatiboglu, B., Bildstein, A., Bauernhansl, T., 2018. Industrie 4.0 roadmap: Framework for digital transformation based on the concepts of capability maturity and alignment. Procedia CIRP, 72, 973–978, DOI: 10.1016/j.procir.2018.03.151.

Issa, A., Lucke, D., Bauernhansl, T., 2017. Mobilizing SMEs Towards Industrie 4.0-enabled Smart Products, 63, 670–674, DOI: 10.1016/j.procir.2017.03.346.

Jäger, J., Schöllhammer, O., Lickefett, M., Bauernhansl, T., 2016. Advanced Complexity Management Strategic Recommendations of Handling the “Industrie 4.0” Complexity for Small and Medium Enterprises. Procedia CIRP, 57, 116–121, DOI: 10.1016/j.procir.2016.11.021.

Jerman, A., Pejić Bach, M., Aleksić, A., 2019. Transformation towards smart factory system: Examining new job profiles and competencies. Systems Research and Behavioral Science, 20 (3), 484, DOI: 10.1002/sres.2657.

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

Karre, H., Hammer, M., Kleindienst, M., Ramsauer, C., 2017. Transition towards an Industry 4.0 State of the LeanLab at Graz University of Technology. Procedia Manufacturing, 9, 206–213, DOI: 10.1016/j.promfg.2017.04.006.

Khan, A., Turowski, K., 2016. A Perspective on Industry 4.0: From Challenges to Opportunities in Production Systems. International Conference on Internet of Things and Big Data, 441–448, DOI: 10.5220/0005929704410448.

Kinder, A., Barot, V., Henshaw, M., Siemieniuch, C., 2012. System of Systems:“Defining the system of interest”.

Koch, V., Kuge, S., Geissbauer, R., Schrauf, S., 2014. Industrie 4.0 - Chancen und Herausforderungen der vierten industriellen Revolution.

Kolberg, D., Zuehlke, D., 2015. Lean Automation enabled by Industry 4.0 Technologies. International Federation of Automatic Control.

Krafcik, J.F., 1988. Triumph of the Lean Production System. Sloan Management Review (41).

Krempel, E., Beyerer, J., 2018. The EU General Data Protection Regulation and its Effects on Designing Assistive Environments. In: Unknown (Ed.). Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference on - PETRA '18. New York, New York, USA: ACM Press, 327–330.

Kurtz, C.F., Snowden, D.J., 2003. The new dynamics of strategy: Sense-making in a complex and complicated world. IBM systems journal, 42 (3), 462–483.

Ladyman, J., Lambert, J., Wiesner, K., 2013. What is a complex system? European Journal for Philosophy of Science, 3 (1), 33–67, DOI: 10.1007/s13194-012-0056-8.

Lai, V.S., Mahapatra, R.K., 1997. Exploring the research in information technology implementation. Information & Management, 32 (4), 187–201, DOI: 10.1016/S0378-7206(97)00022-0.

Lee, M., Yun, J., Pyka, A., Won, D., Kodama, F., Schiuma, G., Park, H., Jeon, J., Park, K., Jung, K., Yan, M.-R., Lee, S., Zhao, X., 2018. How to Respond to the Fourth Industrial Revolution, or the Second Information Technology Revolution? Dynamic New Combinations between Technology, Market, and Society through Open Innovation.

Journal of Open Innovation: Technology, Market, and Complexity, 4 (3), 21, DOI: 10.3390/joitmc4030021.

Leyh, C., Schäffer, T., Bley, K., Forstenhäusler, S., 2016. SIMMI 4.0 – A Maturity Model for Classifying the Enterprise-wide IT and Software Landscape Focusing on Industry 4.0. In: Proceedings of the 2016 Federated Conference on Computer Science and Information Systems. IEEE, 1297–1302.

Li, G., Hou, Y., Wu, A., 2017. Fourth Industrial Revolution: technological drivers, impacts and coping methods. Chinese Geographical Science, 27 (4), 626–637, DOI: 10.1007/s11769-017-0890-x.

Li, L., 2017. China's manufacturing locus in 2025: With a comparison of “Made-in-China 2025” and “Industry 4.0”. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.05.028.

Liao, Y., Deschamps, F., Loures, E.d.F.R., 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, 55 (12), 3609–3629, DOI: 10.1080/00207543.2017.1308576.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., Schmitt, K., Schmitz, E., Schröter, M., 2015. Industrie 4.0 READINESS.

Lin, D., Lee, C.K.M., Lau, H., Yang, Y., 2018. Strategic response to Industry 4.0: an empirical investigation on The Chinese automotive industry. Industrial Management & Data Systems, 34 (5), 0, DOI: 10.1108/IMDS-09-2017-0403.

Liu, J., Gong, Y., Zhu, J., Zhang, J., 2018. A DEA-based approach for competitive environment analysis in global operations strategies. International Journal of Production Economics, 203, 110–123, DOI: 10.1016/j.ijpe.2018.05.029.

Maghazei, O., Netland, T., 2017. Implementation of Industry 4.0 Technologies: What Can We Learn from the Past? In: Lödding, H., Riedel, R., Thoben, K.-D., Cieminski, G.v., Kiritsis, D. (Eds.). Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing. Cham: Springer International Publishing, 135–142.

Mazali, T., 2017. From industry 4.0 to society 4.0, there and back. AI & SOCIETY, 16 (5), 548, DOI: 10.1007/s00146-017-0792-6.

McKinsey Digital, 2016. Industry 4.0 after the initial hype. Where manufacturers are finding value and how they can best capture it.

Meline, T., 2006. Selecting Studies for Systematic Review: Inclusion and Exclusion Criteria. CONTEMPORARY ISSUES IN COMMUNICATION SCIENCE AND DISORDERS, 33, 21–27.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L.A., 2015. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Systematic reviews, 4, 1, DOI: 10.1186/2046-4053-4-1.

Moica, S., Ganzarain, J., Dorleta, I., Ferencz, P., 2018. Change Made in Shop Floor Management to Transform a Conventional Production System into an “Industry 4.0”. Case studies in SME automotive production manufacturing. Piscataway, NJ: IEEE.

Moktadir, M.A., Ali, S.M., Kusi-Sarpong, S., Shaikh, M.A.A., 2018. Assessing challenges for implementing Industry 4.0: Implications for process safety and environmental protection. Process Safety and Environmental Protection, 117, 730–741, DOI: 10.1016/j.psep.2018.04.020.

Morrar, R., Arman, H., 2017. The Fourth Industrial Revolution (Industry 4.0): A Social Innovation Perspective. Technology Innovation Management Review, 7 (11), 12–20, DOI: 10.22215/timreview/1117.

Morton, D., Wherley, S., Ben-Bassat, A., Ben-Assa, A., Reshef, O., 2018. TRENDS IN DIGITAL MANUFACTURING. Implementing Industry 4.0 & building the Digital Factory.

Mueller, E., Chen, X.-L., Riedel, R., 2017. Challenges and Requirements for the Application of Industry 4.0: A Special Insight with the Usage of Cyber-Physical System. Chinese Journal of Mechanical Engineering, 30 (5), 1050–1057, DOI: 10.1007/s10033-017-0164-7.

Müller, J.M., Buliga, O., Voigt, K.-I., 2018a. Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.12.019.

Müller, J.M., Kiel, D., Voigt, K.-I., 2018b. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. Sustainability, 10 (1), 247, DOI: 10.3390/su10010247.

Nagy, J., Oláh, J., Erdei, E., Máté, D., Popp, J., 2018. The Role and Impact of Industry 4.0 and the Internet of Things on the Business Strategy of the Value Chain—The Case of Hungary. Sustainability, 10 (10), 3491, DOI: 10.3390/su10103491.

Natalia Pantielieieva, Sergii Krynytsia, Yulia Zhezherun, Mykhailo Rebryk, Liudmyla Potapenko, 2018. Proceedings of 2018 IEEE 9th International Conference on Dependable Systems, Services and Technologies. DESSERT'2018 : Ukraine, Kyiv, May 24-27, 2018. Piscataway, NJ: IEEE.

Norman, D.O., Kuras, M.L., 2006. Engineering complex systems. In: Complex Engineered Systems. Springer, 206–245.

Odważny, F., Szymańska, O., Cyplik, P., 2018. SMART FACTORY: THE REQUIREMENTS FOR IMPLEMENTATION OF THE INDUSTRY4.0 SOLUTIONS IN FMCG ENVIRONMENT – CASE STUDY. Scientific Journal of Logistics.

Palazzeschi, L., Bucci, O., Di Fabio, A., 2018. Re-thinking Innovation in Organizations in the Industry 4.0 Scenario: New Challenges in a Primary Prevention Perspective. Frontiers in psychology, 9, 30, DOI: 10.3389/fpsyg.2018.00030.

Philipp Autenrieth, Christian Lorcher, Christian Pfeiffer, Tobias Winkens, Ludwig Martin, 2018. Conference proceedings ICE/IEEE ITMC. 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) : Stuttgart, 17.06.-20.06.2018. Piscataway, NJ: IEEE.

Pourabdollahian, G., Jäger, A., Horvat, D., Simons, M., van de Velde, E., Copani, G., Kroll, H., Naumanen, M., Wastyn, A., 2016. An analysis of drivers, barriers and readiness factors of EU companies for adopting advanced manufacturing products and technologies. Luxembourg: Publications Office.

Preiser, R., 2019. Identifying general trends and patterns in complex systems research: An overview of theoretical and practical implications. Systems Research and Behavioral Science, 36 (5), 706–714, DOI: 10.1002/sres.2619.

Prudential, 2017. Manufacturing In Motion: Transforming For A New Industrial Era.

Punzo, G., Tewari, A., Butans, E., Vasile, M., Purvis, A., Mayfield, M., Varga, L., 2020. Engineering Resilient Complex Systems: The Necessary Shift Toward Complexity Science. IEEE Systems Journal, 1–10, DOI: 10.1109/JSYST.2019.2958829.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A.B., Rajak, S., 2019. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 107546, DOI: 10.1016/j.ijpe.2019.107546.

Ressing, M., Blettner, M., Klug, S.J., 2009. Systematic Literature Reviews and Meta-Analyses. Deutsches Aerzteblatt Online, DOI: 10.3238/arztebl.2009.0456.

Roblek, V., Meško, M., Krapež, A., 2016. A Complex View of Industry 4.0. SAGE Open, 6 (2), 215824401665398, DOI: 10.1177/2158244016653987.

Rousseau, D., 2019. A vision for advancing systems science as a foundation for the systems engineering and systems practice of the future. Systems Research and Behavioral Science, 36 (5), 621–634, DOI: 10.1002/sres.2629.

Rüttimann, B.G., Stöckli, M.T., 2016. Lean and Industry 4.0—Twins, Partners, or Contenders? A Due Clarification Regarding the Supposed Clash of Two Production Systems. Journal of Service Science and Management, 09 (06), 485–500, DOI: 10.4236/jssm.2016.96051.

Samaranayake, P., Ramanathan, K., Laosirihongthong, T., 2017. Implementing Industry 4.0 - A Technological Readiness Perspective. IEEE IEEM2017 : 10-13 Dec, Singapore. Piscataway, NJ: IEEE.

Sanders, A., Elangeswaran, C., Wulfsberg, J., 2016. Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. Journal of Industrial Engineering and Management, 9 (3), 811, DOI: 10.3926/jiem.1940.

Saniuk, S., Saniuk, A., Cagáňová, D., 2019. Cyber Industry Networks as an environment of the Industry 4.0 implementation. Wireless Networks, 39 (10), 822, DOI: 10.1007/s11276-019-02079-3.

Santos, C., Mehrsai, A., Barros, A.C., Araújo, M., Ares, E., 2017. Towards Industry 4.0: an overview of European strategic roadmaps. Procedia Manufacturing, 13, 972–979, DOI: 10.1016/j.promfg.2017.09.093.

Schneider, P., 2018. Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. Review of Managerial Science, 125 (2–4), 1, DOI: 10.1007/s11846-018-0283-2.

Schumacher, A., Erol, S., Sihn, W., 2016. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. Procedia CIRP, 52, 161–166, DOI: 10.1016/j.procir.2016.07.040.

Segura-Velandia, D., Neal, A., Conway, P., West, A., 2016. Industrie 4.0 implementations in the Automotive Industry. Proceedings of the 14th International Conference on Manufacturing Research, incorporating the 31st National Conference on Manufacturing Research, September 6 - 8, 2016, Loughborough University, UK, Volume 3.

Sishi, M.N., Telukdarie, A., 2017. Implementation of industry 4.0 technologies in the mining industry: A case study. In: IEEM2017. 2017 IEEE International Conference on Industrial Engineering & Engineering Management : 10-13 Dec, Singapore. [Piscataway, New Jersey]: IEEE, 201–205.

Sjödin, D.R., Parida, V., Leksell, M., Petrovic, A., 2018. Smart Factory Implementation and Process Innovation. Research-Technology Management, 61 (5), 22–31, DOI: 10.1080/08956308.2018.1471277.

Ślusarczyk, B., 2018. Industry 4.0 – Are We Ready? Polish Journal of Management Studies, 232–248.

Sommer, L., 2015. Industrial revolution - industry 4.0: Are German manufacturing SMEs the first victims of this revolution? Journal of Industrial Engineering and Management, 8 (5), DOI: 10.3926/jiem.1470.

Spath, D., Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T., Schlund, S., 2013. Produktionsarbeit der Zukunft-Industrie 4.0. Fraunhofer Verlag Stuttgart.

Staufen AG, 2018. Deutscher Industrie 4.0 Index 2018. Eine Studie der Staufen AG und der Staufen Digital Neonex GmbH.

Staufen AG, Staufen Digital Neonex GmbH, 2019. GERMAN INDUSTRY 4.0 INDEX 2019.

Sung, T.K., 2017. Industry 4.0: A Korea perspective. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.11.005.

Teixeira de Melo, A., Caves, L.S.D., Dewitt, A., Clutton, E., Macpherson, R., Garnett, P., 2019. Thinking (in) complexity: (In) definitions and (mis)conceptions. Systems Research and Behavioral Science, 11 (4), 959, DOI: 10.1002/sres.2612.

Tiacci, L., 2020. Object-oriented event-graph modeling formalism to simulate manufacturing systems in the Industry 4.0 era. Simulation Modelling Practice and Theory, 99, 102027, DOI: 10.1016/j.simpat.2019.102027.

Tortorella, G.L., Fettermann, D., 2017. Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. International Journal of Production Research, 22 (2), 1–13, DOI: 10.1080/00207543.2017.1391420.

Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. British Journal of Management, 14 (3), 207–222, DOI: 10.1111/1467-8551.00375.

Ustundag, A., Cevikcan, E., 2018. Industry 4.0. Managing the digital transformation. Cham: Springer.

Vaidya, S., Ambad, P., Bhosle, S., 2018. Industry 4.0 – A Glimpse. Procedia Manufacturing, 20, 233–238, DOI: 10.1016/j.promfg.2018.02.034.

van Eijnatten, F.M., 2004. Chaordic systems thinking. The Learning Organization, 11 (6), 430–449, DOI: 10.1108/09696470410548791.

Wagner, T., Herrmann, C., Thiede, S., 2017. Industry 4.0 Impacts on Lean Production Systems. Procedia CIRP, 63, 125–131, DOI: 10.1016/j.procir.2017.02.041.

Wang, S., Wan, J., Zhang, D., Di Li, Zhang, C., 2016. Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. Computer Networks, 101, 158–168, DOI: 10.1016/j.comnet.2015.12.017.

World Economic Forum, 2018. Readiness for the Future of Production Report 2018.

Xu, L.D., Xu, E.L., Li, L., 2018. Industry 4.0: state of the art and future trends. International Journal of Production Research, 20 (8), 1–22, DOI: 10.1080/00207543.2018.1444806.

Yearworth, M., 2020. The theoretical foundation(s) for Systems Engineering? Systems Research and Behavioral Science, 17 (1), S11, DOI: 10.1002/sres.2667.

Zawadi Chengula, Miguel Angel Rubio Morato, Thilo Thurner, Yannick Wiedensohler, Ludwig Martin, 2018. Conference proceedings ICE/IEEE ITMC. 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) : Stuttgart, 17.06.-20.06.2018. Piscataway, NJ: IEEE.

Zhichang, Z., 2007. Complexity science, systems thinking and pragmatic sensibility. Systems Research and Behavioral Science, 24 (4), 445–464, DOI: 10.1002/sres.846.

Chapter 3. Transition Towards Industry 4.0: Applying a Mixed-Methods Approach to Identify the Key Implementation Factors

Statement of Authorship

Statement of Authorship

Title of Paper	Transition Towards Industry 4.0: Applying a Mixed-Methods Approach to Identify the Key Implementation Factors
Publication Status	☐ Published ☐ Accepted for Publication ☒ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Submitted to Research Policy

Principal Author

Name of Principal Author (Candidate)	Christian Hoyer		
Contribution to the Paper	Literature review, data collection and analysis.		
Overall percentage (%)	70%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15.10.2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Assoc. Prof. Indra Gunawan		
Contribution to the Paper	15% - support in developing a quantitative approach and theoretical and Theoretical underpinnings of the research		
Signature		Date	15.10.2021

Name of Co-Author	Dr. Carmen Haule Reaiche		
Contribution to the Paper	15% - support in developing a qualitative approach and qualitative analysis		
Signature		Date	15.10.2021

Please cut and paste additional co-author panels here as required.

Manuscript submitted to Research Policy (ISSN: 0048-7333):

The initial research design was prepared and discussed by all authors. The statistical analysis was performed by the main author and supervised by the first co-author. Similarly, the qualitative analysis was performed by the main author and supervised by the second co-author. All results of the analysis have been evaluated by the three authors in preparation for the discussion section. It was decided to submit the paper to the Research Policy journal due to the increasing relevance of Industry 4.0 for governmental decision makers.

Transition Towards Industry 4.0: Applying a Mixed-Methods Approach to Identify the Key Implementation Factors

Christian Hoyer[a]*, Indra Gunawan[a] , Carmen Haule Reaiche[b]

[a] *Business School, University of Adelaide, Adelaide, Australia*

[b] *College of Business, Law and Governance, JCU, Australia*

** Business School, University of Adelaide, Adelaide*

Abstract

Today, productive processes are being prepared for what has been coined the Fourth Industrial Revolution. Industry 4.0 development seeks to achieve a high level of operational efficiency, productivity, and automation of production systems in the way it facilitates processes to improve operational flexibility and in turn cater for the ongoing growth of customer's demands. However, despite the existence of a common objective, the literature does not present a consensus on how this transformation process should be approached. In order to shed more light on this shortfall, this study sets out to examine the key factors that have an impact on the implementation of Industry 4.0. Based on a previous systematic literature review, this article aims to evaluate and identify the main contributing factors for successful Industry 4.0 transition and how managers can adopt them. Evidence for this research is presented through a convergent parallel mixed-methods study based on a survey of 140 participants and 16 semi-structured interviews with Industry 4.0 experts. The results indicate that there are five key factors for managers to consider when leading the transition towards Industry 4.0: perceived benefits, strategic consideration, IT-standardisation and security, available knowledge and education, and inter-institutional cooperation.

3.1 Introduction

In 2011, the German National Society of Science and Engineering marked the beginning of the Fourth Industrial Revolution, also referred to as Industry 4.0; a concept that defines Industry 4.0 as a process of creating smart manufacturing environments in which decentralised decision-making processes take place in real time (Kagermann et al.; Lee et al. 2018). Based on the idea that modern technologies will successively increase the level of autonomy of machines, tools, and other devices, these smart environments are designed to complete operational tasks more efficiently while being more resilient and flexible (Wang et al. 2016; Cimini et al. 2017). Therefore, adapting the Industry 4.0 concept will change the way data are collected, processed and ultimately used to form operational decisions. However, implementing and purposefully using technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Cyber-Physical Systems (CPS) while managing the operations of the traditional day-to-day business represents an additional burden for managers. Recent evidence suggests that companies, particularly in manufacturing, struggle with implementing Industry 4.0 (Fromhold-Eisebith et al. 2021; Müller, Kiel, Voigt 2018; Horváth and Szabó 2019; Raj et al. 2019). For example, the most recent release of the German Industry 4.0 Index shows that while the number of companies implementing Industry 4.0 on an operational level increased from 31% to 48% in four years, only 8% applied a comprehensive operational approach (Staufen AG and Staufen Digital Neonex GmbH 2019). In other words, most companies working on the transition towards Industry 4.0 approach it with isolated projects and thereby do not draw on its full potential—an ongoing trend since its inception. As a result, despite feeling the growing pressure to adapt, the vast majority of corporations has either not yet embarked upon the transition towards Industry 4.0 or is struggling to move forward to a comprehensive implementation (Staufen AG and Staufen Digital Neonex GmbH 2019; McKinsey 2018; MPI

Group 2020).

In light of these and similar findings, a number of researchers have stressed the importance of systematically exploring the transition towards Industry 4.0 and then provide companies with guidance on how to do so successfully (Müller, Kiel, Voigt 2018; Horváth and Szabó 2019; Castelo-Branco et al. 2019). Responding to this call for further research, our previous study set out to systematically identify and synthesise the Industry 4.0 implementation factors that have already been discussed in the literature. In that study, we identified and discussed a set of 14 potential implementation factors (Hoyer et al. 2020). In this study, we have extended our research by exploring how these factors are perceived by Industry 4.0 experts and practitioners who already worked on its implementation. Their views and experiences are of great value as these can aid the overall understanding and identification of which factors need to be considered when working on the implementation of Industry 4.0, and whether they are equally important in the first place. Thus, the primary aim of the present study was to examine the importance of the previously presented factors to identify a set of key factors that managers should be focusing on. Equipped with this knowledge, they can derive concrete actions that facilitate the transition process. However, only knowing the key factors does not provide sufficient guidance. Consequently, to further put the resulting ratings into perspective and to validate our previous findings, we employed a mixed methods approach targeted at key Industry 4.0 experts who named and elaborated on the factors that they consider important. The mixed-methods approach consisted of using both a survey and semi-structured interviews.

The combined findings of this convergent parallel study design, therefore, do not just present a list of key factors, but also show why these factors are important to consider for those who are undertaking and managing the transition. Furthermore, this study sought to answer the research questions regarding *when* the previously identified factors become particularly important and whether the perception of the importance of the factors change across different groups (Castelo-Branco et al. 2019; Hoyer et al. 2020; Müller, Buliga, Voigt 2018).

This article proceeds as follows: Section 2 briefly elaborates on the benefits of Industry 4.0, and on the status quo of Industry 4.0 implementation studies. In Section 3, we further describe the study design. Section 4 presents the results of the qualitative and quantitative analysis before the findings of both sources are further discussed and used to identify the key factors in Section 5. Finally, we conclude this paper with a summary of the implications for managers.

3.2 Theoretical Background

3.2.1 The Benefits of Industry 4.0

Much of the current literature on Industry 4.0 is centred around the benefits that arise from the potential of new technologies, including improved product quality, increased efficiency of operations, and more flexible processes, among others (Nürk 2019; Polge et al. 2020). Technologies like CPS, AI, Big Data and Machine learning are presented as the foundations for various kinds of autonomous systems that will become the new norm in manufacturing environments (Hastig and Sodhi 2020; Zhang et al. 2020). From collaborative robots to Multi Agent Systems (MAS) to social IoT, these autonomous systems are designed to provide managers with the means to monitor and improve processes in real time (Moeuf et al. 2017; Ahuett-Garza and Kurfess 2018). These autonomous systems will introduce new forms of interaction between smart digital devices and humans and consequently also introduce direct changes to the way operational level workers execute their tasks (Zhang et al. 2020; Tamas and

Murar 2019). As a result, many researchers expect Industry 4.0 to potentially change how companies are organised and managed.

In a similar vein, previous studies have assessed how Industry 4.0 can be combined with other, already well-established and applied, manufacturing philosophies such as Kaizen and Lean Manufacturing (Rüttimann and Stöckli 2016; Rossini et al. 2019). Hence, Industry 4.0 will not only introduce new technologies and concepts, but also has the potential to enhance proven methods and approaches. In that context, various investigations have studied the compatibility between Lean Manufacturing and Industry 4.0 and concluded that both approaches can benefit from each other (Fettermann et al. 2018b; Buer et al. 2018). For instance, the concept of the Augmented Operator shows how smart devices can reduce the time between failure occurrence and failure notification by giving operators and managers real time updates on the status of CPS-enhanced machines and sensors. While continuously reducing the time between failure occurrence and failure notification is a traditional Lean task, enhancing it with permanently shared real time data and autonomous systems that can learn from these occurrences belongs to the Industry 4.0 concept (Vidal-Balea et al. 2020; Wyrwicka and Mrugalska 2018; Cohen et al. 2019).

Together, these studies illustrate how Industry 4.0 will change how organisations manage their operations. In the context of digital transformation, managers are not only confronted with selecting, implementing, and organising new technologies, but also with assessing how Industry 4.0 can enhance their current manufacturing approaches. The vast scope of the transition towards Industry 4.0 therefore constitutes a great challenge for companies, and a greater part of the literature has emphasised the importance of further investigating this process in order to provide practical guidance and to set the foundation for further research (Zhang et al. 2020; Li 2020).

3.2.2 Implementation of Industry 4.0

Data from several studies suggest that the implementation of Industry 4.0 is and will remain one the most important topics for the manufacturing industry for the foreseeable future. For example, the European Patent Office (EPO) has revealed that the growth rate of patents related to Industry 4.0 technologies has rapidly increased over the last decade. This growth rate is five times higher than the annual increase in international patent families, illustrating how Industry 4.0 is becoming more dominant in this area (European Patent Office 2020). This result is in accord with the most recent findings of an ongoing study of the MPI Group, which not only demonstrate that manufacturers have increasingly moved towards Industry 4.0 since the beginning of their research in 2016, but also that the vast majority of participants have stated that Industry 4.0 will have a significant impact on their businesses in the next five years (MPI Group 2020). However, while these studies clearly indicate that implementing Industry 4.0 technologies and concepts will remain an integral part of corporations' agendas, other studies have shown that this transition process poses an immense challenge for corporations. Highlighting this problem, the German Industry 4.0 Index presented findings that showed that companies struggle to implement Industry 4.0 on a wider basis despite having worked on single projects for years (Staufen AG 2019).

Similarly, there is a growing body of literature that recognises the barriers that companies face when moving towards the implementation of Industry 4.0 (Raj et al. 2020; Schumacher et al. 2019; Sony and Naik 2020). Accordingly, these studies focus on identifying and analysing these barriers to gain a better understanding of the root causes that slow down or even prevent companies from beginning the transition process. In our previous study, we synthesised these findings so that they can be used as a foundation for future research that aims at further identifying the key implementation factors (Hoyer et al. 2020). Overall, we identified

14 potential implementation factors and divided them into three categories for greater clarity. In the following section we describe how these 14 factors were implemented and extended into our current study design (Table 6).

Table 6. Industry 4.0 Implementation Factors by Hoyer et al. (2020)

External Factors	Internal Factors	Company Characteristics
Political Support	Perceived Benefits	Industry Sector
IT-Standardisation	Strategic Consideration	Company Size
Institutional Cooperation	IT-Maturity	
Available Funding Options Available	Skills Development	
Knowledge	Lean Manufacturing Experience	
Pressure to Adapt	Occupational Health and Safety	

3.3 Methods

Our previous literature review provided an overview of the key factors that have been discussed in the field. This was a critical starting point for our research; however, we still needed to confirm whether the resulting list of critical factors was complete, and how these factors are actually perceived by practitioners and experts who already work on Industry 4.0 projects. To address these secondary research questions we adopted a convergent parallel mixed-methods approach, as illustrated by Figure 4. We sought to explore whether certain factors are perceived as more important than others, based on the evaluation of experienced practitioners. However, to do so, we wanted to expand our sample beyond just the classic disciplines and industry sectors common in this type of research, because Industry 4.0 stretches well past these traditional borders (Fromhold-Eisebith et al. 2021; Müller, Kiel, Voigt 2018). By covering a wide range of participants with different backgrounds, skills, and levels of experience, we could further explore whether certain criteria, such as years of Industry 4.0 experience, change the perceived importance of a given factor. For us to gain a deeper understanding of the implementation factors, we needed to give the experts enough room to express their thoughts and concerns; something that could not be implemented into the survey without significantly increasing the time required to complete it, and potentially decreasing the return ratio. Therefore, besides distributing a survey to experienced practitioners, we also opted to simultaneously conduct semi-structured interviews with Industry 4.0 experts. Both data sources are considered of equal importance, collected simultaneously but analysed independently (Harrison 2013; Hong et al. 2017; Razali et al. 2019).

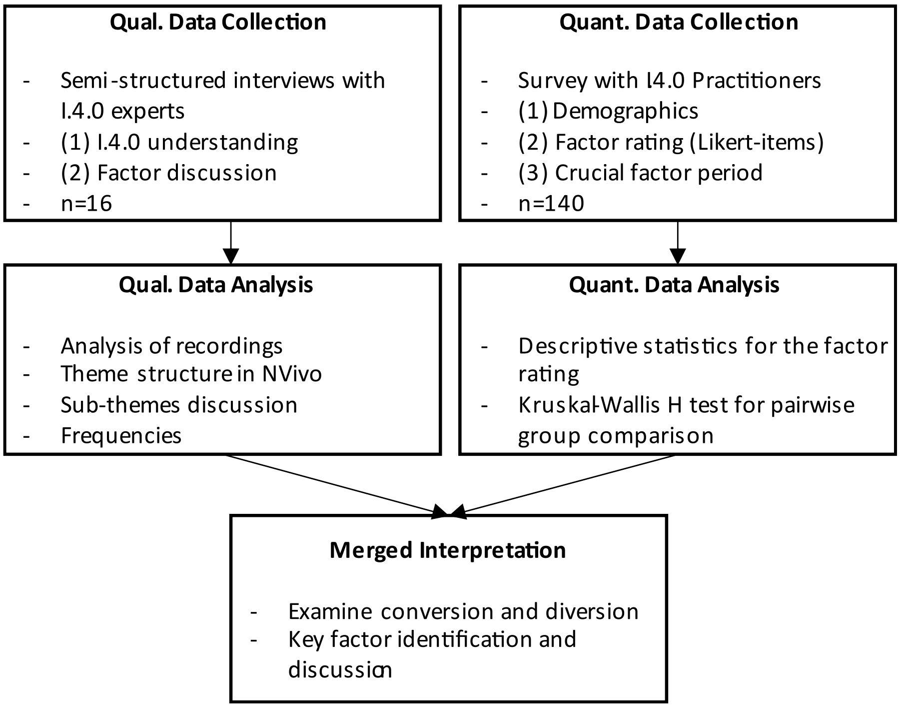

Figure 4. Convergent Parallel Study Design

This study design provides a more complete and comprehensive understanding of the implementation factors by evaluating the two methods in a complementary approach (Stentz et al. 2012). While the goal of the survey was to provide insight into the general perception of the identified factors amongst a wide range of practitioners with Industry 4.0 experience, the focus of the expert interviews was on validating the results of the survey and incorporating existing findings to explain not just which factors must be considered when implementing Industry 4.0 but also why they must be considered. Prior to data collection, we obtained the appropriate ethics approval. We also ensured participant anonymity by deidentifying their personal information.

3.3.1 Participants and Data Collection

3.3.1.1 Survey

To achieve a better understanding of how important the identified factors are perceived by those experienced with Industry 4.0, we first had to develop a set of criteria that enabled us to find suitable candidates for the survey (Dennis 2014; Sargeant 2012). This is a challenging task that a number of researchers have been confronted with in recent investigations focused on Industry 4.0 (Tortorella and Fettermann 2017; Bartodziej 2017). Building on their proposed approaches, we decided to target respondents from various industry sectors. While manufacturing-dominant sectors seem to be the stronghold of Industry 4.0, many investigations have already illustrated its long reach beyond classic domains (Raj et al. 2020). It was more important for our study that participants were experienced with Industry 4.0 technologies, such as CPS and/or Industry 4.0 projects.

The webpages of *Plattform Industrie 4.0* as well *LinkedIn* were used to select and contact suitable participants who met the presented criteria. In total, 693 practitioners were contacted via email or the platforms directly, out of which 140 returned valid answers. The resulting response rate of 20.20% sits right between the previous Industry 4.0 investigations of Rossini et al. (2019) (16%) and Tortorella and Fettermann (2017) (25%). We collected the responses between the end of October 2019 and early January 2020 through Qualtrics, a platform designed to develop and distribute surveys.

Table 7 summarises the profile of the survey participants, showing that the majority of respondents worked for a company with more 1,000 employees (57%). Interestingly, more than the half of the respondents (56%) stated that their corporation has at least started to implement an Industry 4.0 strategy, aligning with the findings of the Staufen AG (2019). Conversely, 6% reported that no Industry 4.0 strategy exists in their corporation. In a similar vein, 71% of the participants indicated that their corporation uses a set of Industry 4.0 strategy indicators to track the implementation of their Industry 4.0 strategy. Consequently, it is not surprising that the majority of respondents (66%) had more than three years of experience in working on Industry 4.0 projects. Only 3% of the participants had worked on Industry 4.0 projects for less than a year. In terms of sectors, almost a third of the respondents worked in the IT sector.

The questionnaire was divided into three main parts. In the first part, participants were asked to provide background information, such as their job function. In the second and major part, the focus was on rating the importance of the factors identified through the systematic literature review by presenting participants each factor as a single Likert item that ranged from 1 (not important) to 5 (very important). To ensure that participants shared the same understanding of the implementation factors, an explanation was provided. In the final part, we asked respondents to state at which stage of the transition they think the previously rated factor becomes most significant, ranging from 1 (at the beginning of the transition) to 5 (the factor remains important throughout the entire transition). As discussed earlier, the implementation of Industry 4.0 is considered a time intensive and complex process; as a result, this question was included to reflect this dynamic nature and to account for the fact that the importance of a factor might depend on the stage of transition.

Table 7. Survey Participants Demographics (n=140)

Demographics	n	%	Demographics	n	%
Firm Size			**Role**		
1–49	32	23	Individual contributor	23	17
50–249	17	12	Team Lead	21	15
250–999	11	8	Manager (less than 3 years of experience)	10	7

1000–4999	21	15	Manager (more than 3 years of experience)	29	21
5000 or more	59	42	Leader (looks after a region or business area)	14	10
			Executive/C-Suite	14	10
Implementation Indicators			Partner	2	1
No	41	29	Owner	21	15
Yes—Giving some orientation	67	48	Others	5	4
Yes—Appropriate system	32	23			
			Department		
Sector			Human Resources	2	1
Machinery	16	11	Information Technology	22	16
Automotive	21	15	Administration	2	1
Aviation	5	4	Sales	17	12
Chemical	4	3	Marketing	12	9
Medical	3	2	Research and Development	18	13
Energy and Environmental	2	1	Manufacturing	16	11
IT and communication	46	33	Engineering	19	14
Electronics	23	16	Others	32	23
Others	20	14			
			Strategy Status		
Industry 4.0 Experience			No strategy exists	6	4
Less than 1 Year	6	3	Pilot initiatives launched	26	19
At least 1 Year but less than 3 years	56	31	Strategy in development	20	14
At least 3 Year but less than 5 years	60	33	Strategy formulated	10	7
At least 5 Year but less than 10 years	58	33	Strategy in implementation	43	31
			Strategy implemented	34	25

3.3.1.2 Expert Interviews

Bartodziej (2017), in an empirical study to determine the influence of a set of functions on end-to-end digital integration, illustrated the difficulty of distinguishing between Industry 4.0 experts and other groups, such as persons that possess a special expertise. In the study, it was argued that this difficulty mainly arises from the complex and heterogeneous nature of Industry 4.0, which is why the we focused on participants with access to a broader field of Industry 4.0 technologies, consequently leading to a broader understanding of the topic. Since the complexity and the heterogeneity of Industry 4.0 increases over time due to various factors, such as more and more sectors adapting it and the increasing amount of data that is being processed, we decided to refine his approach and to build on the notion that an Industry 4.0 expert must have a broad understanding of the topic (Bogner et al. 2009; Lee et al. 2018). Therefore, experts with extensive knowledge about a specific concept related to Industry 4.0, such as Big Data or AI, did not automatically qualify for an interview. A set of criteria was developed to make sure that only experts who had a significant amount of experience in the field of Industry 4.0 as a wider concept would be selected, which included having a broader understanding of the entire implementation cycle.

First, the interviews were not limited to experts with an industry background. Experts working in academia or government institutions, or on Industry 4.0 initiatives were considered equally important as they are all involved in the process of implementing Industry 4.0 on a broader scale (Sung 2017; Kipper et al. 2021). Second, potential participants had to have worked on Industry 4.0 projects in a leading position for more than five years. These projects did not have to be focused on implementing Industry 4.0; however, candidates who fulfilled that criterion were prioritised. Third, we focused on participants who were actively involved in committees, associations, and/or initiatives that support the transition towards Industry 4.0. This criterion was chosen to make sure that we covered a wider range of experiences regarding Industry 4.0, not just main professions. Finally, we accepted a variety of different professional backgrounds, as long as the other conditions were met.

As mentioned earlier, we decided to proceed with semi-structured interviews to give interviewees sufficient opportunity to express their thoughts on the factors that they considered important. In that regard, the interviewer asked open questions about which factors they consider crucial when it comes to the implementation of Industry 4.0. In contrast to the quantitative survey, participants were not informed about the factors previously identified from the literature, so that we could use their responses to validate the other two sources of data. At the same time, by asking the interviewees to elaborate on why they mentioned certain factors, we could gather more information on what makes their mentioned factors important. The interviews lasted around 60 minutes.

At the beginning of each interview, interviewees were asked to discuss their experience with Industry 4.0, how they would define the term, and what Industry 4.0 means to them. The next part of the interview was then tailored around the implementation factors and what makes them important. Each participant was also asked if there were any other factors they wanted to mention before ending the interview.

3.3.2 Data Analysis

3.3.2.1 Survey Data

The goal of the quantitative analysis was to find out how practitioners rate the 14 previously identified Industry 4.0 implementation factors and to determine whether differences in the factor ratings occur between groups of participants with particular characteristics such as Industry 4.0 experience or their role in the corporation. How participants rated the factors was assessed through descriptive statistics, specifically frequency counts and percentages. On the other hand, a Kruskal-Wallis H test was run to analyse the relationships between demographic variables and factor ratings.

The statistical testing process was supported by version 26 of SPSS. At the beginning of the analysis, we reviewed the survey for missing data before summarising the overall rating of the factors through the descriptive approach. After summarising the data and confirming that no data was missing, we then checked if all the assumptions of the Kruskal-Wallis H test were met.

3.3.2.2 Interview Data

Thematic analysis was used to analyse the 16 interviews that were audio recorded and transcribed by the team of researchers using NVivo 12, which is a software developed to analyse the relationships between emerging themes, categories, and codes (Hilal, AlYahmady Hamed, and Saleh Said Alabri 2013). In the first round of analysis, the audio recordings were carefully analysed while following the interview transcripts. In the second round, we determined and discussed naturally apparent codes and themes. These codes and themes were then reviewed by the authors again in order to merge identical codes and to prepare the data for the next round of analysis. In the third round of analysis, the emerged themes were compared against the set of factors previously identified in the systematic literature review. Themes that did not share similarities with the criteria presented in the systematic review and the explanations given to the survey participants were converted into new factors. Sub-themes served to determine the different facets of the factors discussed by participants. In the last round of analysis, the final structure of themes and codes was discussed. Upon completion of the coding process, we examined how often each theme/factor was referenced by the interviewees as well as how many interviewees mentioned a given theme/factor. We took this frequencies-based approach so that the factor ratings from the survey could be compared with the results of the qualitative analysis, as discussed previously. Evidence from the interviews will be presented adopting a narrative format (Polkinghorne 1995; Sandelowski 1991).

3.4 Results

3.4.1 Quantitative Results

Table 8. Industry 4.0 Implementation Factor Ranking

Rank	Factors	Not Important	Slightly Important	Moderately Important	Important	Very Important	ALI

1	Perceived Implementation Benefits	0.0	2.9	5.7	32.1	59.3	91.4
2	Strategic Consideration	0.7	2.9	9.3	23.6	63.6	87.2
3	IT-Standardization and Security	2.9	2.9	8.6	20.0	65.7	85.7
4	Internal Knowledge and Skills Development	2.9	4.3	11.4	40.7	40.7	81.4
5	Available Knowledge and Education	2.9	6.4	10.7	35.7	44.3	80.0
6	IT-Infrastructure Maturity	2.9	7.1	15.7	32.9	41.4	74.3
7	Corporate and Institutional Cooperation	1.4	5.0	19.3	41.4	32.9	74.3
8	Pressure to Adapt	2.9	12.1	19.3	37.9	27.9	65.8
9	Political Support	2.9	16.4	20.7	46.4	13.6	60.0
10	Cost Assessment and Available Funding Options	4.3	12.9	27.1	32.1	23.6	55.7
11	Occupational Health and Safety	5.7	20.0	22.9	24.3	27.1	51.4
12	Industry Sector	12.9	17.1	19.3	32.9	17.9	50.8
13	Lean Manufacturing Experience	4.3	15.0	30.0	27.9	27.9	50.8
14	Company Size	20.7	21.4	25.0	23.6	9.3	32.9

Table 8 provides an overview of how the survey respondents (n=140) rated each of the 14 factors (presented as a percentage). In order to create a ranking based on the responses, we introduced the “At least important” score (ALI), which combined the percentages of the participants who rated a given factor as either “Important” or “Very Important”. In that way, we were able to highlight and illustrate the importance of each factor according to our research question. Furthermore, using the mean as a measure for central tendency would not have created any additional meaning in terms of interpreting the Likert items, as stressed by Harpe (2015). While the ALI also lacks the ability to measure the central tendency, it facilitates the interpretation of the results by focusing on one side of the spectrum, illustrating what percentage of the sample considered the factor import or very important.

Overall, Table 8 shows that the importance of the factors varies significantly. What is more, a closer inspection reveals that the factors ranked from 1 to 3 are rated above the 85% mark, and the factors ranked from 4 to 7 stabilise around the 80% mark. After that, the ratings drop significantly; however, only one of the presented factors has an ALI score below 50%.

Table 9. Industry 4.0 Transition Periods

Rank	Factors	At the beginning	After major steps have been taken	Towards the end of the transition	During the whole transition	I don't know
1	Perceived Implementation Benefits	17.9	17.9	17.1	42.9	4.3
2	Strategic Consideration	23.6	12.9	4.3	53.6	5.7
3	IT-Standardization and Security	23.6	14.3	4.3	55.0	2.9
4	Internal Knowledge and Skills Development	24.3	12.9	7.9	50	5.0
5	Available Knowledge and Education	30.7	12.1	4.3	49.3	3.6
6	IT-Infrastructure Maturity	22.9	21.4	3.6	48.6	3.6
7	Corporate and Institutional Cooperation	22.1	20.0	2.9	50.7	4.3
8	Pressure to Adapt	30.7	12.9	4.3	40.7	11.4
9	Political Support	43.6	10.7	2.1	37.9	5.7
10	Cost Assessment and Available Funding Options	45.0	10.0	2.1	31.4	11.4
11	Occupational Health and Safety	10	12.9	9.3	51.4	16.4
12	Industry Sector	20	8.6	1.4	47.1	22.9
13	Lean Manufacturing Experience	30.0	15.0	2.9	36.4	15.7
14	Company Size	21.4	7.9	1.4	50.0	19.3
-	Average	26.1	13.5	4.8	46.1	9.4

Besides rating each of the presented factors, we also asked participants to state at which phase of the Industry 4.0 transition period they think a given factor becomes particularly important. Table 9 summarises the results from that section of the survey and shows that for 12 of the 14 factors most respondents stated that the importance of a given factor remains unchanged throughout the transition period. Only political as well as financial support seem to be more important at the beginning of the transition compared to the remaining phases. What further stands out is that, on average, less than 5% of the factors become important towards the end of the transition, indicating that most factors are either important before that phase or remain important throughout the entire transition.

Turning now to the Kruskal-Wallis H test, Table 10 shows whether the factor ratings were statistically significantly different for a given group. For the groups that returned values of $p<0.05$ for a given factor, we then continued with Dunn's (1964) procedure, including a Bonferroni correction for multiple comparisons. This is a post hoc analysis for each pairwise comparison and signals a differences between two or more groups (Sheskin 2020; András Vargha and Harold D. Delaney 1998). Additionally, the distribution of the ratings was assessed by visual inspections of the corresponding box plots. While a similar distribution allowed us to further compare the medians of each group, none of the assessed box plots showed an equal distribution (Sheskin 2020). Therefore, we specified the ALI score for each group in order to provide a general overview of how the presented factor ratings changed across a given pair.

Overall, the test revealed that 8 of the 14 factors did not show a significant change in rating across the presented groups ($p > 0.05$). Similarly, "Job Function" and "Strategy Status" had no impact on the rating of any of the factors. However, the remaining factors and groups returned statistically significant differences. Individual p-values will be specified at the end of each group comparison.

Starting with "Number of Employees", differences in ratings occurred in three factors. For the factor "IT-Standardization", $p = .00$, the post hoc analysis revealed statistically significant differences in factor ratings between firm size 1–49 (ALI=62.5) and 5,000 or more employees (ALI=93.3) ($p = .000$), and 1–49 and 1,000–4,999 employees (ALI=95.2) ($p = .037$), indicating that smaller companies perceive the importance of IT-standardisation and security less important compared to larger corporations. Similarly, the factor "IT-Infrastructure Maturity", $p = .015$, showed a difference in factor ratings between firm size 1–49 (ALI=53.1) and 5,000 or more employees (ALI=80.3) ($p = .010$). Finally, for the factor "Lean Manufacturing Experience", $p = .022$, a difference in rating between the groups 1-49 (ALI=37.9) and 5,000 or more (ALI=66.1) ($p = .031$) could be observed.

Continuing with the group “Industry 4.0 Experience”, only the factor “Implementation Benefits”, *p* = .008, turned out to have different ratings across groups. The group that had at least 1 but less than 3 years of experience (ALI=79.5) and the group with at least 5 but less than 10 years of experience (ALI-95.8) (*p* = .036) rated the factor differently. In a similar vein, different ratings could be observed for the pairing of the group with at least 1 but less than 3 years of experience and the group with at least 3 but less than 5 years of experience (ALI=96) (*p* = .009).

While the first part of the Kruskal-Wallis test showed a difference in ratings for the factor “Available Knowledge and Education” in the “Job Role” group, *p* = .041, the post hoc evaluation did not lead to differences between any given pair. In contrast, a difference in rating, together with a positive post hoc analysis, was observed for the factors “Company Sector” (*p* = .024) and “Company Size” (*p* = .009) across the “Industry 4.0 Strategy Indicators” groups. In terms of company sector, the difference in the strategy indicator group occurred between the group that has a system of Industry 4.0 indicators in place that provides some orientation, (ALI=30.3) and the group that has an appropriate system of Industry 4.0 indicators (ALI=68.8) (*p* = .023). Likewise, there was a difference between the group that has some indicators (ALI=22.4) and the group that has an appropriate set of indicators (ALI=43.8) *(p=.024)* for the factor “Company Size” *(p=.009)*. Additionally, the rating of the factor showed differences between the group that has some indicators in place and the group that stated that they do not have any indicators in place (ALI=47.5) *(p=.049)*.

Finally, the rating for the factors “Available knowledge and Education” (*p* = .000) and “Lean Manufacturing Experience” (*p* = .002) changed across the “Industry Sector” groups. For the factor referring to the availability of knowledge, a difference between the electronic sector (ALI=52.2) and information and communications technology sector (ALI=93.4) (*p* = .000) was observed. On the other hand, for the factor referring to lean manufacturing experience, a difference between the information and communications technology sector (ALI=39.1) and the automotive sector (ALI=85.8) (p = .008) was found.

Table 10. Pairwise Comparison Between Groups and Factors

#	Factors	Number of Employees	Job Function	Industry 4.0 Experience	Responsibility	Strategy Status	Strategy Indicators	Sector
1	Perceived Implementation Benefits	0.574	0.667	0.008	0.624	0.458	0.812	0.53
2	Strategic Consideration	0.151	0.636	0.959	0.056	0.708	0.653	0.423
3	IT-Standardization and Security	0	0.058	0.316	0.104	0.772	0.661	0.052
4	Internal Knowledge	0.21	0.309	0.386	0.697	0.121	0.934	0.734
5	Available Knowledge and Education	0.736	0.529	0.469	0.041	0.936	0.976	0
6	IT-Infrastructure Maturity	0.015	0.362	0.264	0.167	0.779	0.436	0.059
7	Corporate and Institutional Cooperation	0.905	0.79	0.689	0.758	0.858	0.123	0.745
8	Pressure to Adapt	0.748	0.541	0.289	0.336	0.594	0.293	0.987
9	Political Support	0.682	0.866	0.487	0.361	0.811	0.16	0.182
10	Cost Assessment and Available Funding Options	0.21	0.357	0.094	0.148	0.824	0.892	0.216
11	Occupational Health and Safety	0.05	0.688	0.192	0.163	0.592	0.619	0.224
12	Industry Sector	0.357	0.375	0.541	0.063	0.498	0.024	0.064
13	Lean Manufacturing Experience	0.022	0.398	0.385	0.131	0.44	0.721	0.002
14	Company Size	0.468	0.414	0.255	0.281	0.326	0.009	0.504

Taken altogether, the results of the quantitative analysis answers three interesting questions that emerged from the systematic review of Industry 4.0 research. First, the findings suggest that the factors discussed in the literature are not perceived as equally important by experienced practitioners. Second, for the vast majority of factors, the importance does not change throughout the transition process. Finally, the importance of some factors varies across certain groups. For example, lean manufacturing experience was considered more important by participants working in the automotive industry compared to participants working in the communications technology sector.

3.4.2 Qualitative Findings

In the first round of coding, 18 themes and 82 sub-themes emerged from the review of the transcripts. After the identified codes and themes were evaluated and discussed, we reduced the number themes to 14 themes and the number of sub-themes to 67. After the second round of analysis, themes and sub-themes were further discussed and compared against the factors identified in the literature review. Table 11 shows the outcome of that process with "*n*" displaying how many times each sub-theme was addressed by the interviewees. Unexpectedly, out of the 14 factors identified in the systematic literature review, 13 were discussed by the Industry 4.0 experts. While they did not address the fact that the industry sector could play an important role when it comes to implementing Industry 4.0, they talked about the importance of the attitude and mindset of corporations as a factor that needs to be taken into consideration.

Table 11 highlights how many times each of the identified factors was mentioned as well as how many participants talked about each of them. From this overview, it can be observed that some factors were discussed significantly more than others. For example, while only one participant talked about occupational health and safety, all participants talked about the importance of implementation benefits. Moreover, the number of references further indicates how intensively certain factors were discussed, revealing four particularly prominent factors; "Perceived Implementation Benefits", "IT-Standardisation and Security", Corporate and Institutional Cooperation" and "Available Knowledge and Education".

Table 11. Frequency of Addressed Sub-Themes in the Expert Interviews

Sub-Themes	***n***	**Sub-Themes**	***n***
Perceived Implementation Benefits		**Company Size**	

New business opportunities	36	Lack of Resources	10
Productivity & Process Efficiency Boost	35	Lack of Understanding AND Initiative	7
Improved data accuracy & availability	18	Difficult access to Funding	5
Customer retention	16	Cooperation Difficulties	4
Ability to compete	15	Operational Focus	2
More individualisation & smaller batch sizes	11	Negotiation Power	1
Traceability & Transparency	8	Flexibility	1
Quality Increase	7	**Political Support**	
Flexibility	4	Facilitate cooperation and initiatives	14
Sustainability	3	Legal boundaries & Data Privacy	14
IT-Standardization and Security		International competitiveness	8
Data Privacy and Ownership	31	Support for SMEs	8
Interoperability	21	Shrinking population & Skill shortage	6
Data Safety	13	Broadband and 5G expansion	5
Broadband Expansion	11	Promoting Industry 4.0	3
Dependency and Power Imbalance	10	Shaping new working environments	1
Corporate and institutional cooperation		**Strategic Consideration**	
Science and Corporations	20	Day to Day Business	19
Cooperation through initiatives	19	Pilot Purgatory	19
Interdisciplinary cooperation	10	Need for comprehensive approaches	8
Cooperation with Competitors	8	Including the human factor	7
Government AND Companies AND Science	8	Strategic Initiative	4
Government and Corporate World	3	**IT infrastructure maturity**	
National AND International Cooperation	2	Data Usability and Accessibility	21
Available knowledge and education		Networking as enabler	16
Education Programs and Infrastructure	21	Brownfield & Compatibility	11
Support Programs and Initiatives	15	Data Quality	5
Test Environments and Use Cases	12	**Internal Knowledge & Skills Development**	
Availability of Qualified Personnel	8	Knowhow management	21
General Understanding of Industry 4.0	6	New Job Requirements	20
Finding a Partner	6	Continuing Education	4
Attitude and Mindset		**Cost Assessment and Available Funding**	
Attitude towards change	26	Cost Assessment	10
Company Culture	9	Lack of financial Resources	9
Innovation Mindset	4	Funding Autocracy	5
Pressure to adapt		**Lean Manufacturing Experience**	
Media Presence	20	Lean Similarities	5
Customer Pressure	11	**Occupational Health and Safety**	
Market Pressure	9	Fear of losing one’s Job	1

A variety of perceptions were expressed, but most answers revolved around new business models resulting from the implementation of Industry 4.0 and how companies mainly start to implement Industry 4.0 in order to increase their efficiency, summarized under the most discussed factor "Perceived Implementation Benefits".

The second factor that was widely discussed was "IT-Standardization and Security". In the context of Industry 4.0, new business models often rely on the processing and sharing of data. In that regard, participants expressed their concerns regarding data privacy and ownership. As one interviewee stated:

> *We need global standards for data privacy and ownership. It should not matter, not even for the data privacy lovers among us, that our data are stored in Asia for example.* (P4)

Another common view among experts was that the interoperability of systems plays an important role when implementing Industry 4.0 technologies and concepts, as illustrated by the following comment:

> *The same problems can be encountered in almost every system and IT-infrastructure: What language does it speak and how can we use it?* (P6)

The third factor that was often reported was "Corporate and Institutional Cooperation". Here, experts elaborated on the importance of Industry 4.0 initiatives that give companies the opportunity to work on Industry 4.0 standards together with other companies and institutions:

> *The model inspired by the German Plattform Industrie 4.0 becomes internationally more popular. It aims to bring all important parties to the negotiation table so it can be discussed which direction certain developments and standards should take.* (P5)

The need for more cooperation between academic institutions and companies was also highlighted. A common view among interviewees was that research institutes should support companies with the development and understanding of Industry 4.0 technologies and processes. However, participants also noted that this form of cooperation can often be accompanied by a number of difficulties. Commenting on how academic institutes should approach the corporate world, one of the experts said:

> *I think research institutes should introduce internal incentives that encourage projects with corporations. In that regard, I advise them to understand and present themselves as service providers. Furthermore, they should adjust their language, which often is a crucial barrier.* (P10)

Finally, the factor "Available Knowledge and Education" was among the most discussed themes across all interviews. Experts mainly showed concern over the capability of education systems to prepare workers for new working environments. In that regard, they stressed the importance of making the current education infrastructure more flexible so that it suits the continuously changing needs of the economy, as illustrated by one participant:

> *I still do not understand why bachelor and master students in engineering have to study an excessive amount of mathematics. Instead, they should learn how to use simulation tools. What is the point understanding differential equations when they actually should be able to interpret the results of simulated systems?* (P12)

In summary, what emerges from the qualitative results reported here validate the findings of the previously conducted systematic review. With the exception of the "Industry Sector" factor, all identified factors were discussed by the interviewees. A critical finding has been the identification of an additional factor referring to the company's mindset and attitude toward Industry 4.0. In addition, the identified sub-themes further illustrate why a given factor is considered important and which facets need to be taken into account when implementing Industry 4.0.

Table 12. Frequency of Mentioned Factors in the Expert Interviews

Factor	**Number of Participants mentioning it**	**References**
Perceived Implementation Benefits	16	153

IT-Standardization and Security	14	86
Corporate and Institutional Cooperation	16	70
Available Knowledge and Education	14	68
Company Size	12	60
Political Support	15	59
Strategic Consideration	11	57
IT- Infrastructure Maturity	13	53
Internal Knowledge and Skills Development	13	51
Attitude and Mindset	12	48
Pressure to Adapt	14	47
Cost Assessment and Available Funding Options	8	24
Lean Manufacturing Experience	3	5
Occupational Health and Safety	1	1
Industry Sector	0	0

Regarding the importance of each factor, the findings show that some factors were discussed more often than others. This can be perceived as indicative findings, therefore, to enhance the interpretation of these data, a mixed-method study approach was adopted. The next section discusses the results of the qualitative findings together with the quantitative findings.

3.5 Discussion

The present study was designed to identify and evaluate the key factors contributing to an effective Industry 4.0 implementation. Building on the findings of our previous study, we presented 14 factors identified from the literature as being critical for Industry 4.0 transition to an audience of experienced practitioners through a survey. By asking them to rate the importance of these factors and state when those factors become particularly important, we achieved to get a better understanding of how practitioners perceive the overall importance of the identified factors. In order to validate these results and to obtain a clearer picture of why certain factors are considered crucial, we also conducted interviews at the same time with Industry 4.0 experts who had a broad understanding about the implementation cycle. Hence, interviewees were asked open questions regarding the implementation of Industry 4.0 without mentioning any of the previously identified factors as discussed in Section 0. The findings of this qualitative approach suggest that the initial list of 14 factors reflects the experience and the evaluation of the experts, with only one factor not being discussed. In addition, two other critical findings emerged. First, we were able to identify an additional factor, that we labelled “Attitude and Mindset”, that was not uncovered by our initial systematic review. Second, the factor “Company Size” was among the top five discussed factors in the interviews, despite having received the lowest ALI score.

While, so far, each of the two approaches may explain certain aspects of an effective transition towards Industry 4.0, the key factors can only be identified and discussed by examining both approaches in context. Therefore, this section begins with the completion of the key factor identification process by merging and interpreting the two complementary approaches. Subsequently, we will discuss each of the resulting key factors in more detail.

3.5.1 Key Factors Identification Through Synthesis

By using the ALI scores (see Table 8) to evaluate the importance of the factors according to the quantitative dataset collected through the survey, it can be seen that 7 factors are around, or exceed 75%. The scores of the remaining factors then drop significantly. Similarly, by determining how many times each of the interviewees referred to one of the factors in the qualitative dataset, it can be seen that 7 factors are close to 60 references before the scores drop towards and below 50 references per factor.

Further assessing the two datasets, it becomes evident that 5 factors are among the top 7 factors of both datasets, as illustrated by Figure 5. In other words, out of the 15 identified implementation factors in both datasets, 5 factors received a high ALI score combined with a high interview reference score. These factors will be further evaluated and discussed as they seem to be at the core of an effective Industry 4.0 implementation according to both experienced practitioners and Industry 4.0 experts. The focus will be on why these factors should become part of a manager's decision-making. However, we will close this section by briefly discussing other critical findings that emerged from the analysis.

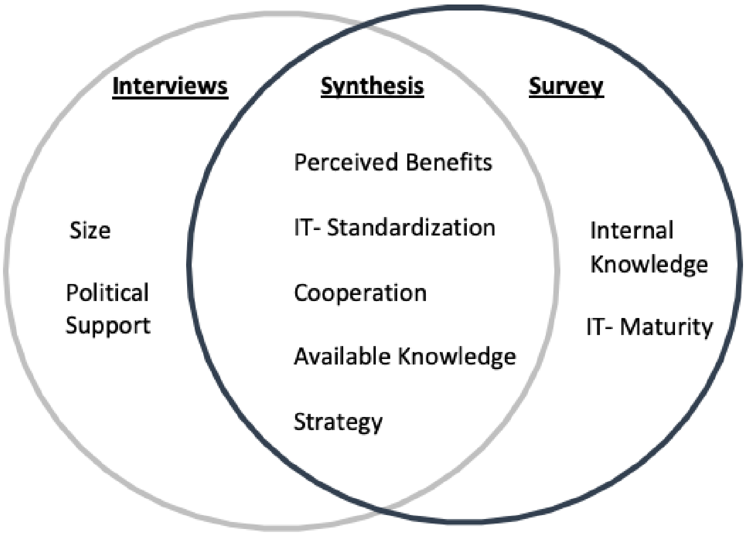

Figure 5. Implementation Factors after Synthesis of Qualitative and Quantitative Data

3.5.2 Perceived Benefits

With more than 90% of all survey participants stating that the factor is at least important, and with almost twice as many references as the second most discussed factor, "Perceived Benefits" emerged as one of the most dominant factors in our examination. In terms of when the factor becomes most important, most participants think that the importance level remains stable throughout the transition (see Figure 6), which is supported by the findings of the qualitative analysis. Industry 4.0 experts particularly highlighted long-term goals such as maintaining the ability to compete or increase the overall efficiency and flexibility of the company as major benefits of implementing Industry 4.0. However, experts also stressed the importance of having a clear and comprehensive understanding of how Industry 4.0 technologies and concepts can support companies to achieve their goals, a process that is located at the beginning of a transition. Alluding to the problem that this elementary process is often underestimated, interviewees said:

> *In terms of assessing the potential of Industry 4.0, I worked with many companies that lack a clear vision of what they want, thinking that buying a new machine from their supplier will make them more efficient. Instead, they should ask themselves how digitalization can be incorporated in their products? Can we improve our selling platforms? Is there a way we can understand our customers better and can this be implemented into our processes? In my opinion, a lot of potential remains untouched.* (P05)

> *When it comes to Industry 4.0, it is important to figure out what creates value in an organization and which approach is beneficial. Since the term itself created a hype, it became even more important for companies to clearly evaluate what the term means for themselves and how it should be put into practice.* (P09)

While the combination of findings suggests that “Perceived Benefits” plays a major role across different transition periods, a clear vision must be formed before beginning the transition process. This implies that managers need to build implementation approach on a comprehensive understanding of the organisation’s vision. In this context, the process of identifying potential business models and areas that benefit from the use of Industry 4.0 technologies represents the starting point of the transition process. In contrast, the benefits highlighted by experts are strongly connected to the long-term success of corporations such as increasing the flexibility of operational processes. Hence, both aspects should be taken into consideration when implementing Industry 4.0, despite the seemingly contradictory nature of the factor’s transition timeline. Furthermore, the Kruskal-Wallis test showed that participants with more experience tended to rate the factor higher, indicating that the impact of this factor might be underestimated by those with less Industry 4.0 experience.

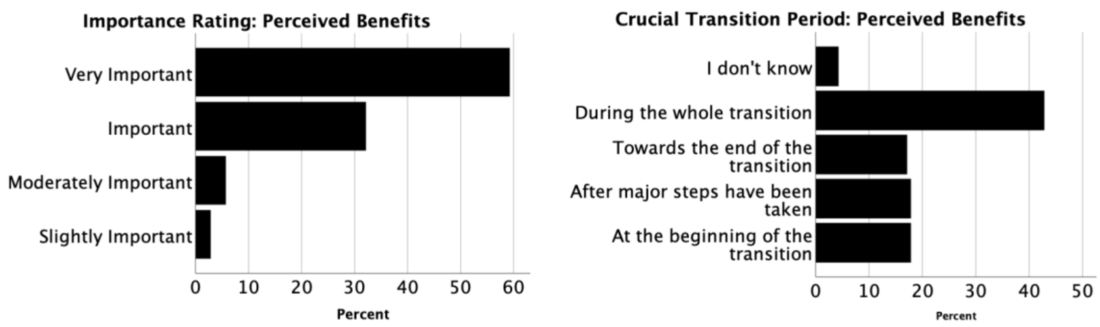

Figure 6. Perceived Benefits: Factor Rating and Crucial Transition Period

3.5.3 IT-Standardization and Security

The factor “IT-Standardization and Security” received the highest very important rating among all factors in the survey and was the second most discussed factor in the interviews (Figure 7). Uncertainty regarding data privacy and data ownership as well as interoperability were reported as major challenges in the context of moving towards Industry 4.0. Technologies that allow decentralised data-driven dynamic decision-making in real time such as IoT devices and artificial intelligence require significant amounts of collected and processed data (Xu and Duan 2019; Nürk 2019). Thus, with data becoming more valuable and essential, corporations need clear data privacy and ownership rules, as stressed by most of the interviewees. However, it was also stressed that no ideal legal solution existed and that companies, therefore, need to actively manage the uncertainty surrounding this topic, as interviewees said:

> *The topics data management and data privacy are a difficult balancing act. At the moment, we must figure out how create a useful data economy that respects the ownership of data. Because that economy is necessary to make processes more efficient with the help of Industry 4.0.* (P14)

> *It can become a major problem when companies share their data without taking all the necessary precautions regarding the use of their data.* (P02)

In a similar vein, interviewees reported a lack of machine communication and software standards. Companies would, consequently, often face an increased amount of uncertainty regarding the future compatibility of their newly acquired systems. Additionally, their current

IT infrastructures are often not compatible with solutions that allow them to move towards Industry 4.0 technologies. As a result, interviewees further stressed the importance of industry standards and that companies should be open to cooperate with competitors to address these problems together, as illustrated by the comments below:

> *…Industry standards are urgently needed in order to be able to provide data, share data, and to create more efficient interfaces...* (P04)

> *…With regards to developing standards and joint interfaces, it is advisable to cooperate with competitors as long as it does not have an impact on a company's competitiveness…* (P02)

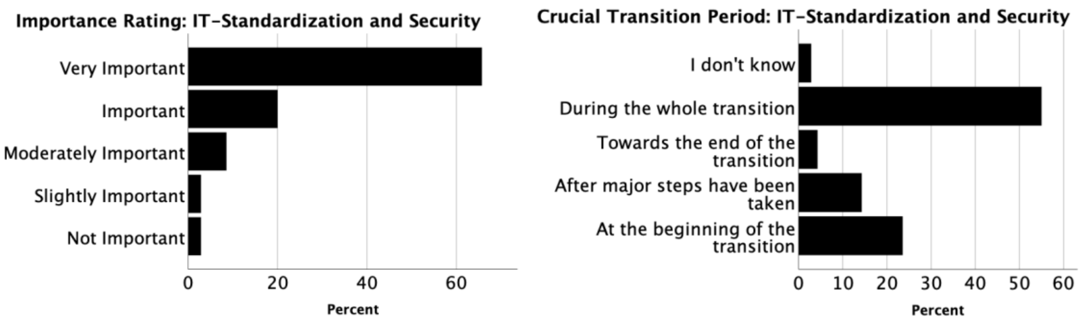

Figure 7. IT-Standardization and Security: Factor Rating and Crucial Transition Period

Overall, this is a somewhat troubling result for managers as no standard solutions exist to solve the two major identified challenges related to this factor. On the one hand, when it comes to data ownership and privacy, companies need thoroughly examine which data can be shared, while taking all the necessary precautions. On the other hand, because no industry-wide standard for certain applications exists, managers have to strategically plan the extension of their company's infrastructure. In that regard, they not only need to manage the interoperability of their systems within their own infrastructure, but also need to consider the compatibility of their systems with customers and suppliers. Cooperation with other companies can even accelerate the process of developing appropriate industry and privacy standards.

Nevertheless, until more solid solutions are available, further extending the capabilities of one's own infrastructure according to the Industry 4.0 philosophy, seems to come at a difficult-to-evaluate cost. Different data privacy and ownership regulations in different parts of the world, and the uncertainty resulting from the future compatibility of systems, seem to be a firm component of this new data-driven economy, offering a potential explanation as to why the vast majority of practitioners stated that the factor remains important across all transition periods.

3.5.4 Cooperation

Almost 75% of the survey participants considered "Corporate and Institutional Cooperation" as at least important (Figure 8). Along similar lines, all Industry 4.0 experts emphasised the importance of cooperation when it comes to the transition towards Industry 4.0. Three main themes emerged from the interviews: cooperation between science and corporations, cooperation through initiatives, and having a interdisciplinary focus.

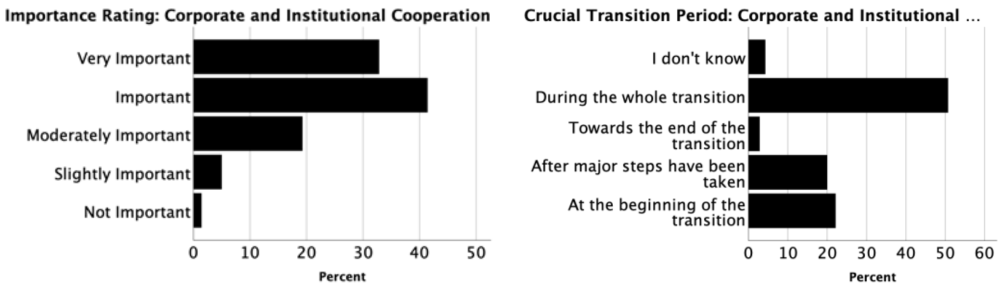

Figure 8. Cooperation: Factor Rating and Crucial Transition Period

First, interview participants highlighted the potential resulting from research institutions' ability to communicate the meaning of Industry 4.0. On that basis, they also emphasised the need to develop potential use cases tailored to the needs of individual corporations. However, in that context, Industry 4.0 experts also stressed the difficulty for companies to find a suitable partner due to a lack of experience with this type of cooperation as well as a lack of openness. Commenting on that issue, one interviewee mentioned:

> *Companies often struggle to find a research institution that understands their needs and that can offer enough expertise. Unfortunately, while there are many ways to find the right partner, companies often are not aware of them.* (P05)

Second, interviewees recognised that cooperation with initiatives such as "Plattform Industrie 4.0" was a promising way for companies to learn about the concept of Industry 4.0, to find partners for joint research, to test new technologies, and to identify potential use cases. Consequently, the role of Industry 4.0 initiatives was rated as vital among Industry 4.0 experts. The comment below further illustrates their expectations about these initiatives:

> *It is extremely important that these initiatives not only promote the awareness and the understanding of Industry 4.0. They also need to demonstrate what can be done with it and motivate companies to develop new ideas.* (P14)

Finally, Industry 4.0 experts not only stressed the importance and the potential of cooperation between different disciplines, but also stated that Industry 4.0 had already helped to initiate a change in their thinking. For example, the requirements for new industry machines have drastically increased as they need to be integrated into highly digitalised infrastructures, resulting in a more diverse team constellation, as illustrated by the comments of one interviewee:

> *The traditional make or buy decision, in my opinion, has changed and the existing boundaries between knowledge domains continue to dissolve. Developing a machine does not only require engineers but also software developers and data scientists. Compared to the last 20 years, companies need more heterogeneous teams of experts in order to develop Industry 4.0 capable products.* (P02)

Overall, the findings further reveal why cooperation is crucial for an effective implementation of Industry 4.0. The processes of developing standards, identifying use cases, and producing Industry 4.0 compatible products can all be supported and accelerated by inter-institutional cooperation and interdisciplinarity. For corporations that intend to evolve their DNA towards Industry 4.0, cooperation seems indispensable. It can therefore be assumed that managers need to actively support the process of further dissolving the traditional boundaries between disciplines in order to successfully manage the implementation of Industry 4.0 technologies and concepts. Also, cooperation with research institutes and Industry 4.0 initiatives has been identified as the most promising method to address the more fundamental problems that are often beyond a manager's direct control. However, the findings indicate that companies often struggle with finding partners, further illustrating the need for a proactive approach that encourages and facilitates cooperation.

3.5.5 Available Knowledge and Education

The factor "Available knowledge and education" was considered as at least important by 80% of the survey participants and was referred to 68 times by Industry 4.0 experts during the interviews. Interestingly, almost one-third of the survey participants stated that the factor is particularly important at the beginning (see Figure 9). This aligns with the interviewees' comments about the need for use cases and test environments that help companies to develop their own Industry 4.0 goals and ideas—a process that sits at the beginning of the transition. For example, one interviewee said:

> *Ideally, we should provide access to our reference labs to more companies. Furthermore, we also need to discuss and develop more joint projects. However, at the moment, we are only giving seminars to some companies we already formed a relationship with as we are simply lacking the financial capacities. We organize some events every two years, but that is far from sufficient.* (P11)

However, the most dominant theme that was discussed by Industry 4.0 experts refers to education infrastructure. Interviewees pointed out that education systems no longer suit the needs of the corporate world, and they expect the situation to become even more aggravated due to the increasing speed of change in staffing requirements. Talking about this issue, interviewees said:

> *The way the entire education sector is structured does no longer meet the requirements of corporation and this will get worse in the future.* (P15)

> *…I think what is taught will become obsolete even faster than before, which is why it often becomes unavoidable for employees to go through continuous training. This is also reason why me and my colleagues designed and initiated a master program in a continuous training format.* (P12)

Whereas the need for use cases indicates that the factor should be particularly considered at the beginning of the transition, new styles of education such as continuous learning suggest that this factor will not lose it significance after the initial phase of the transition, potentially explaining why most practitioners stated that the factor remains important after initial steps have been taken (see Figure 9).

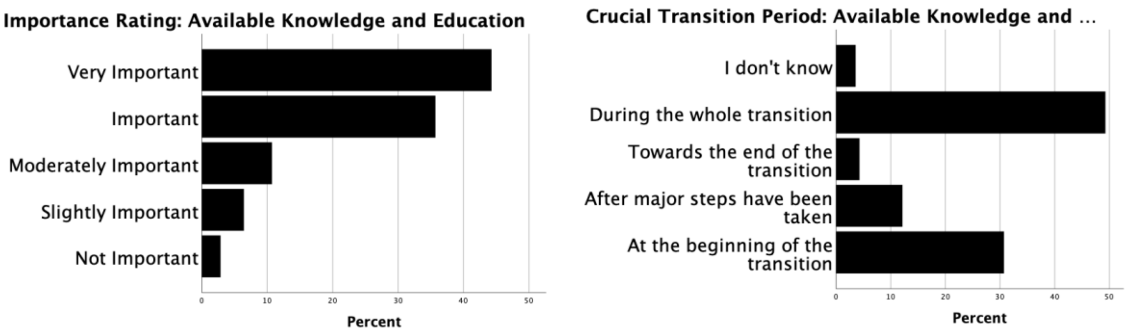

Figure 9. Available Knowledge: Factor Rating and Crucial Transition Period

Apart from the current state of education systems and the availability of test environments and use cases, Industry 4.0 experts also discussed the importance of support programs and initiatives. As discussed earlier, while these support programs and initiatives can support companies with developing their own Industry 4.0 DNA and strategy, interviewees further stressed the lack of accessibility to and availability of these programs, as one interviewee stated:

> *One Entrepreneur told me that applying for support programs often would require him to hire employees who would only work on that task. However, that often makes these programs obsolete.* (P10)

What emerges from these results is that managers need to find an internal solution for an external problem. With education systems struggling to meet the requirements of a fast-paced changing digital economy and with the difficulties of accessing support programs, actively preparing the already existing workforce for future challenges becomes fundamental. Other authors have tried to address this fundamental problem by proposing different models that help companies to implement a sustainable learning infrastructure. What these models share is a reliance on digital solutions that facilitate the on-the-job learning based on a tailored learning strategy for each employee (Kadir and Broberg 2021).

3.5.6 Strategic Consideration

In the survey, the factor "Strategic Consideration" received the highest very important rating and the second highest ALI score (see Figure 10). Also, strategy was one of the dominant topics in the interviews. Furthermore, most survey participants stated that considering Industry 4.0 at a strategical level remains important during the entire transition. What seems counterintuitive at first, can be put into perspective through the participants' claims that Industry 4.0 is more than a project and that it should be managed and treated like a transformation of the entire business; it is a task that requires a holistic approach rather than breaking Industry 4.0 into use cases. As a result, it is not surprising that Industry 4.0 experts discussed two main reasons why companies often lack an appropriate and dedicated strategy.

First, it was stressed that corporations are often trapped in their day-to-day business and success. According to the interviewees, this means that plans to implement Industry 4.0 are often put on hold or even abandoned due to the positive order situation. Talking about this issue, interviewees said:

Particularly traditional corporations fail to implement Industry 4.0 into their daily business because they rather fully focus on operative processes. For example, we often see companies applying for Industry 4.0 funding, which requires a lot preparation, and, in the end, they decide to cancel the process due to a new order from a customer. This often leads to delays, which is a fundamental issue. (P05)

As long as businesses are going well, even when there is a small decline in orders from customers, companies tend to not initiate change. (P12)

Besides the fact that companies seem to prioritise their daily business over developing an appropriate strategy, interviewed experts pointed out that there is a general issue with how companies approach Industry 4.0. Interviewees suggested that instead of developing an Industry 4.0 strategy, companies often move towards Industry 4.0 with the help of small and isolated projects. These projects often do not do Industry 4.0 justice and lead to what some experts called a "Pilot Purgatory". As interviewees said:

It is crucial that companies have a clear focus on an Industry 4.0 strategy as well as on the target architecture. Otherwise, they will enter the state of a pilot purgatory, as demonstrated by McKinsey. (P08)

In terms of Industry 4.0, companies often only think of use cases without seeing the bigger picture. Consequently, those companies are developing small use cases from which only small subsets will be implemented as other, more cost-effective, solutions are always available on the market. However, the benefit lies in understanding Industry 4.0 as a whole and to combine the development of different use cases. (P05)

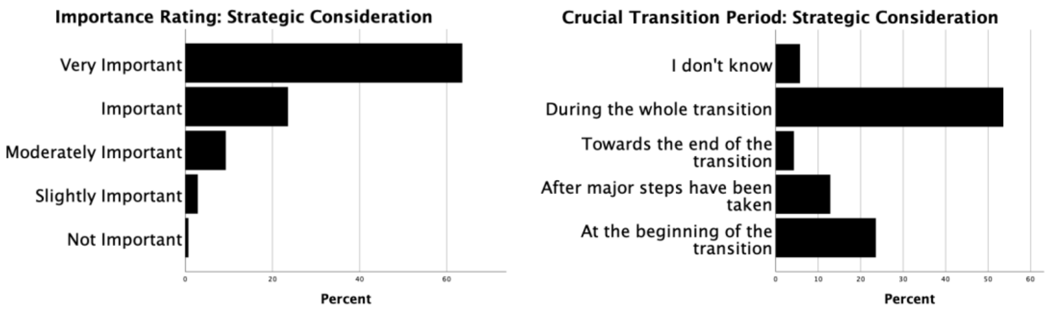

Figure 10. Strategic Consideration: Factor Rating and Crucial Transition Period

In the context of Industry 4.0, "Pilot Purgatory" refers to companies that have a number of IoT projects underway but fail to organise a proper rollout or sometimes even to see the overall benefit of the projects (McKinsey 2018). Interviewees firmly stressed the importance of Industry 4.0 strategies as they help companies to manage the transition more effectively and to get a better understanding of how Industry 4.0 can help their businesses.

Together these results indicate that the transition towards Industry 4.0 without strategy is an approach that is prone to fail. Managers should avoid breaking the transition down into different use cases and projects without a proper strategy that combines these single elements into a comprehensive vision for the company. Managers also face the difficulty of managing the transition while having a strong focus on the day-to-day business. Industry 4.0 experts pointed out that this is often a priority issue, with success sometimes becoming a blockade for change. Developing a dedicated Industry 4.0 strategy can help to identify and articulate these issues, facilitating the process and putting expectations of isolated projects into a wider and more sustainable context. Both pilot purgatory and day-to-day business create an on/off relationship with the implementation of Industry 4.0 technologies and concepts; an Industry 4.0 strategy should take these issues into account and provide orientation for the entire implementation cycle.

3.5.7 Further Critical Findings

Besides the five key factors, two other critical findings emerged from the analysis. First, there was a lack of consensus between experts and practitioners when it came to importance of the size of a company. While this factor was considered the least import according to the survey, interviewees referred to it comparatively often, being amongst the five most referenced factors. In our previous study, we pointed out that different studies came to different conclusions with regards to whether the size of company is important in the context of implementing Industry

4.0. Considering the overall compatibility of the two datasets, we did not expect this to be as clearly reflected in our current findings. Thus, further investigations are required to obtain a deeper understanding of the effect of size on the implementation of Industry 4.0.

Second, the factor “Attitude and Mindset” emerged from our interviews with experts. While not being among the most discussed factors, its impact on the transition and its importance for practitioners should still be further assessed in future investigations. Interestingly, experts pointed out that Industry 4.0 is often perceived as a threat, encouraging companies to wait as long as possible before initiating the transition. However, they also stressed that raising awareness of the opportunities can have a positive effect in that context.

3.6 Conclusions

The concept of Industry 4.0 has so far withstood the test of time. With an increasing number of companies expecting Industry 4.0 to have a significant impact on their businesses, and with the ever-growing availability of new technological solutions, the term has matured and became an inherent part of management decisions.

For managers working at the frontline of the transition process, these developments have not only created future opportunities, but also resulted in substantial and seemingly overwhelming challenges. From selecting compatible technology solutions to preparing the workforce to work in a smart environment that is driven by real time data processing and autonomous systems, the scope of implementing Industry 4.0 seems vast and demanding (Kumar et al. 2018).

To face these challenges, managers need to have a better understanding of the underlying dynamics of the transition towards Industry 4.0, as stressed by a number of authors (Fettermann et al. 2018a; Li 2020). Through a convergent parallel study design, our study identified five key factors that managers should focus on when outlining and managing the transition towards Industry 4.0. This mixed study approach was a key strength of our investigation as we were not only able to test and validate our previous findings, but also present a more detailed picture of the implementation of Industry 4.0 by combining two sources of data.

Besides identifying the key factors, we were also able to show why these factors are considered important by interviewing Industry 4.0 experts. Furthermore, our findings indicate that the perception of the importance of certain factors changes across groups and that the importance of most of the factors remains stable throughout the entire transition period. Finally, these findings were interpreted together to derive concrete recommended actions for managers, which will be summarised in the next section.

3.6.1 Implications for Managers

Confirming the findings of a recent study by Müller, Buliga, Voigt (2018), we identified "Perceived Benefits" as the most dominant factor in our analysis. However, in addition to what has already been said about this factor, we were able to show that this factor is not only important in terms of identifying potential benefits, such as increasing the overall flexibility, but also that mangers must align these benefits with the overall vision of the corporation. This implies that the vision itself must be understood and geared towards the concept of Industry 4.0, a task that goes beyond the initial phase of the transition and beyond selecting promising technologies and business models. The factor "Strategic Consideration" has illustrated the consequence of neglecting this process. Industry 4.0 experts have stressed that approaching Industry 4.0 strategically is inevitable, which is confirmed by previous investigations (Cohen et al. 2019; Raj et al. 2020). Otherwise, managers are likely to manoeuvre single and isolated projects to the open sea from where the overall purpose of these projects cannot be seen. To avoid this so called "Pilot Purgatory", managers are therefore advised to first articulate dedicated Industry 4.0 implementation strategies that can then act as the foundation upon which these projects can be built and connected (McKinsey 2018). Our findings suggest that day-to-day business and current success seem to be the natural enemy of dedicated Industry 4.0 strategies. Mangers and companies, consequently, need to resist the temptation of treating Industry 4.0 like spare-time work.

Another key finding that emerged from our analysis was that the continuously growing number of available Industry 4.0 software and hardware solutions introduce a major problem for managers. Against the background of missing industry standards and a lack of data ownership regulations, managing the increasing expectations of customers and suppliers becomes even more demanding. Offering new data-driven services and integrating new technologies in existing IT infrastructures require a significant amount of research in terms of compatibility and the value of data that will be shared. In that context, the findings that emerged from the key factor "Corporate and Institutional Cooperation" suggest that managers need to encourage cooperation with research institutes, Industry 4.0 initiatives, and even competitors in order to actively manage missing standards and regulations. Moreover, our findings also indicate that the form of cooperation within companies will change dramatically as a result of moving towards Industry 4.0. Smart Factories and Smart Products require cooperation between different disciplines and professions, further reshaping the role of managers who increasingly need to mediate between different parties. Likewise, our findings indicate that this diplomatic responsibility will also be crucial when companies decide to develop new solutions and standards with other institutions.

Finally, the findings of this study strengthen the idea that managers not only need to manage the implementation of Industry 4.0 technologies and concepts, but also the implementation of an internal learning infrastructure that is capable of continuously preparing the existing workforce for the changes induced by Industry 4.0. As highlighted by other studies and confirmed by our own findings emerging from the factor “Available Knowledge and Education”, the availability of qualified personal and the ability of the education system to serve the fast-evolving needs of an increasingly digitalised economy are factors that managers cannot rely on (Kadir and Broberg 2021; Kipper et al. 2021). Therefore, to mitigate the risk of slowing down the transition due to a lack of qualified personnel, our findings suggest that this challenge must be approached strategically and with the same rigour as the other identified key areas.

3.6.2 Future Work and Limitations

While this study was able to identify and discuss a set of key factors, several questions still remain to be answered. First, and most importantly, the dynamic relationship between the key and other factors needs to be further examined. Our findings indicate an existing relationship between certain factors. For example, cooperation was mentioned as the key factor to solve the problems caused by the lack of IT standards. Second, the findings regarding factor “Company Size” remain inconclusive as the factor received the lowest ALI score whilst being among the top five discussed factors in the expert interviews. Interestingly, in our previous study, we noted that there are contradicting findings in the literature regarding the question of whether the size of the company matters when it comes to implementing Industry 4.0; this factor needs to be investigated further. Third, an additional factor emerged from our data analysis: “Attitude and Mindset”. This factor addresses how companies view Industry 4.0 and how they approach change. The impact and the perceived importance of this factor, therefore, need to be further assessed. Finally, despite not being among the top five, the factors “Political Support”, “IT-Infrastructure Maturity”, and “Internal Knowledge and Skills Development” still received a high score in at least one of the datasets, which is why they should not be excluded in future studies.

In terms of limitations, the number of participants was below our expectations (n=140). Therefore, caution must be applied when it comes to differences between groups regarding the perceived importance of the presented factors. Due to the fact that Industry 4.0 is still a relatively new phenomenon, finding participants that share the required characteristics represented a major challenge. As Industry 4.0 becomes more established, future studies, therefore, should aim for larger samples sizes, as we expect that more differences between the analysed groups exist. Furthermore, our data collection period ended two months before the outbreak of COVID-19. Potential changes in how practitioners view the importance of certain factors as a result of new economic developments were not included in the present study. Finally, the findings are based on the subjective perception of our study participants, introducing possibilistic uncertainty. While our overall findings are based on three independent data sources to reduce this type of uncertainty, future studies should not just focus on larger sample sizes to investigate the changing importance of the factors as a result of different participant backgrounds and implementation scenarios, but also to further examine the overall importance of the presented factors.

References

Ahuett-Garza, H., Kurfess, T., 2018. A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing. Manufacturing Letters, 15, 60–63, DOI: 10.1016/j.mfglet.2018.02.011.

András Vargha and Harold D. Delaney, 1998. The Kruskal-Wallis Test and Stochastic Homogeneity.

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

Bogner, A., Littig, B., Menz, W. (Eds.), 2009. Interviewing experts. Basingstoke [England], New York: Palgrave Macmillan.

Buer, S.-V., Strandhagen, J.O., 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, 3 (4), 1–17, DOI: 10.1080/00207543.2018.1442945.

Castelo-Branco, I., Cruz-Jesus, F., Oliveira, T., 2019. Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry, 107, 22–32, DOI: 10.1016/j.compind.2019.01.007.

Cimini, C., Pinto, R., Cavalieri, S., 2017. The business transformation towards smart manufacturing: a literature overview about reference models and research agenda.

Cohen, Y., Naseraldin, H., Chaudhuri, A., Pilati, F., 2019. Assembly systems in Industry 4.0 era: a road map to understand Assembly 4.0. The International Journal of Advanced Manufacturing Technology, 105 (9), 4037–4054, DOI: 10.1007/s00170-019-04203-1.

Dennis, B.K., 2014. Understanding Participant Experiences: Reflections of a Novice Research Participant. International Journal of Qualitative Methods, 13 (1), 395–410, DOI: 10.1177/160940691401300121.

European Patent Office, 2020. Patents and the Fourth Industrial Revolution. The global trends enabling the data-driven economy.

Fettermann, D.C., Cavalcante, C.G.S., Almeida, T.D.d., Tortorella, G.L., 2018a. How does Industry 4.0 contribute to operations management? Journal of Industrial and Production Engineering, 35 (4), 255–268, DOI: 10.1080/21681015.2018.1462863.

Fettermann, D.C., Cavalcante, C.G.S., Almeida, T.D.d., Tortorella, G.L., 2018b. How does Industry 4.0 contribute to operations management? Journal of Industrial and Production Engineering, 35 (4), 255–268, DOI: 10.1080/21681015.2018.1462863.

Fromhold-Eisebith, M., Marschall, P., Peters, R., Thomes, P., 2021. Torn between digitized future and context dependent past – How implementing 'Industry 4.0' production technologies could transform the German textile industry. Technological Forecasting and Social Change, 166, 120620, DOI: 10.1016/j.techfore.2021.120620.

Harpe, S.E., 2015. How to analyze Likert and other rating scale data. Currents in Pharmacy Teaching and Learning, 7 (6), 836–850, DOI: 10.1016/j.cptl.2015.08.001.

Harrison, R.L., 2013. Using mixed methods designs in the Journal of Business Research, 1990–2010. Journal of Business Research, 66 (11), 2153–2162, DOI: 10.1016/j.jbusres.2012.01.006.

Hastig, G.M., Sodhi, M.S., 2020. Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. Production and Operations Management, 29 (4), 935–954, DOI: 10.1111/poms.13147.

Hilal, AlYahmady Hamed, and Saleh Said Alabri, 2013. Using NVivo for data analysis in qualitative research. International interdisciplinary journal of education, 2(2), 181–186.

Hong, Q.N., Pluye, P., Bujold, M., Wassef, M., 2017. Convergent and sequential synthesis designs: implications for conducting and reporting systematic reviews of qualitative and quantitative evidence. Systematic reviews, 6 (1), 61, DOI: 10.1186/s13643-017-0454-2.

Horváth, D., Szabó, R.Z., 2019. Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? Technological Forecasting and Social Change, 146, 119–132, DOI: 10.1016/j.techfore.2019.05.021.

Hoyer, C., Gunawan, I., Reaiche, C.H., 2020. The Implementation of Industry 4.0 - A Systematic Literature Review of the Key Factors. Systems Research and Behavioral Science, 37 (4), 557–578, DOI: 10.1002/sres.2701.

Kadir, B.A., Broberg, O., 2021. Human-centered design of work systems in the transition to industry 4.0. Applied ergonomics, 92, 103334, DOI: 10.1016/j.apergo.2020.103334.

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

Kipper, L.M., Iepsen, S., Dal Forno, A.J., Frozza, R., Furstenau, L., Agnes, J., Cossul, D., 2021. Scientific mapping to identify competencies required by industry 4.0. Technology in Society, 64, 101454, DOI: 10.1016/j.techsoc.2020.101454.

Kumar, S., Mookerjee, V., Shubham, A., 2018. Research in Operations Management and Information Systems Interface. Production and Operations Management, 27 (11), 1893–1905, DOI: 10.1111/poms.12961.

Lee, M., Yun, J., Pyka, A., Won, D., Kodama, F., Schiuma, G., Park, H., Jeon, J., Park, K., Jung, K., Yan, M.-R., Lee, S., Zhao, X., 2018. How to Respond to the Fourth Industrial Revolution, or the Second Information Technology Revolution? Dynamic New

Combinations between Technology, Market, and Society through Open Innovation. Journal of Open Innovation: Technology, Market, and Complexity, 4 (3), 21, DOI: 10.3390/joitmc4030021.

Li, F., 2020. Leading digital transformation: three emerging approaches for managing the transition. International Journal of Operations & Production Management, 40 (6), 809–817, DOI: 10.1108/IJOPM-04-2020-0202.

McKinsey, 2018. Digital Manufacturing – escaping pilot purgatory.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., Barbaray, R., 2017. The industrial management of SMEs in the era of Industry 4.0. International Journal of Production Research, 92, 1–19, DOI: 10.1080/00207543.2017.1372647.

MPI Group, 2020. Industry 4.0 Drives Productivity and Profitability for Manufacturers. Findings from the MPI 2020 Industry 4.0 Study, 1.

Müller, J.M., Buliga, O., Voigt, K.-I., 2018a. Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.12.019.

Müller, J.M., Kiel, D., Voigt, K.-I., 2018b. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. Sustainability, 10 (1), 247, DOI: 10.3390/su10010247.

Nürk, J., 2019. Smart Information System Capabilities of Digital Supply Chain Business Models. European Journal of Business Science and Technology, 5 (2), 143–184, DOI: 10.11118/ejobsat.v5i2.175.

Polge, J., Robert, J., Le Traon, Y., 2020. A Case Driven Study of the Use of Time Series Classification for Flexibility in Industry 4.0. Sensors (Basel, Switzerland), 20 (24), DOI: 10.3390/s20247273.

Polkinghorne, D.E., 1995. Narrative configuration in qualitative analysis. International Journal of Qualitative Studies in Education, 8 (1), 5–23, DOI: 10.1080/0951839950080103.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A.B., Rajak, S., 2019. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 107546, DOI: 10.1016/j.ijpe.2019.107546.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A.B., Rajak, S., 2020. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 224, 107546, DOI: 10.1016/j.ijpe.2019.107546.

Razali, F.M., Aziz, N.A.A., Rasli, R.M., Zulkefly, N.F., Salim, S.A., 2019. Using Convergent Parallel Design Mixed Method to Assess the Usage of Multi-Touch Hand Gestures Towards Fine Motor Skills Among Pre-School Children. International Journal of Academic Research in Business and Social Sciences, 9 (14), DOI: 10.6007/IJARBSS/v9-i14/7023.

Rossini, M., Costa, F., Tortorella, G.L., Portioli-Staudacher, A., 2019. The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers. The International Journal of Advanced Manufacturing Technology, 102 (9-12), 3963–3976, DOI: 10.1007/s00170-019-03441-7.

Rüttimann, B.G., Stöckli, M.T., 2016. Lean and Industry 4.0—Twins, Partners, or Contenders? A Due Clarification Regarding the Supposed Clash of Two Production Systems. Journal of Service Science and Management, 09 (06), 485–500, DOI: 10.4236/jssm.2016.96051.

Sandelowski, M., 1991. Telling stories: narrative approaches in qualitative research. Image--the journal of nursing scholarship, 23 (3), 161–166, DOI: 10.1111/j.1547-5069.1991.tb00662.x.

Sargeant, J., 2012. Qualitative Research Part II: Participants, Analysis, and Quality Assurance. Journal of graduate medical education, 4 (1), 1–3, DOI: 10.4300/JGME-D-11-00307.1.

Schumacher, A., Nemeth, T., Sihn, W., 2019. Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises. Procedia CIRP, 79, 409–414, DOI: 10.1016/j.procir.2019.02.110.

Sheskin, D., 2020. Handbook of parametric and nonparametric statistical procedures. Boca Raton: Chapman & Hall/CRC.

Sony, M., Naik, S., 2020. Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model. Technology in Society, 61, 101248, DOI: 10.1016/j.techsoc.2020.101248.

Staufen AG, 2019. Studie: Industrie 4.0 Index 2019.

Staufen AG, Staufen Digital Neonex GmbH, 2019. GERMAN INDUSTRY 4.0 INDEX 2019.

Stentz, J.E., Plano Clark, V.L., Matkin, G.S., 2012. Applying mixed methods to leadership research: A review of current practices. The Leadership Quarterly, 23 (6), 1173–1183, DOI: 10.1016/j.leaqua.2012.10.001.

Sung, T.K., 2017. Industry 4.0: A Korea perspective. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.11.005.

Tamas, L., Murar, M., 2019. Smart CPS: vertical integration overview and user story with a cobot. International Journal of Computer Integrated Manufacturing, 32 (4-5), 504–521, DOI: 10.1080/0951192X.2018.1535196.

Tortorella, G.L., Fettermann, D., 2017. Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. International Journal of Production Research, 22 (2), 1–13, DOI: 10.1080/00207543.2017.1391420.

Vidal-Balea, A., Blanco-Novoa, O., Fraga-Lamas, P., Vilar-Montesinos, M., Fernández-Caramés, T.M., 2020. Creating Collaborative Augmented Reality Experiences for Industry 4.0 Training and Assistance Applications: Performance Evaluation in the Shipyard of the Future. Applied Sciences, 10 (24), 9073, DOI: 10.3390/app10249073.

Wang, S., Wan, J., Di Li, Zhang, C., 2016. Implementing Smart Factory of Industrie 4.0: An Outlook. International Journal of Distributed Sensor Networks, 12 (1), 3159805, DOI: 10.1155/2016/3159805.

Wyrwicka, M.K., Mrugalska, B., 2018. "INDUSTRY 4.0"—TOWARDS OPPORTUNITIES AND CHALLENGES OF IMPLEMENTATION. DEStech Transactions on Engineering and Technology Research (icpr), DOI: 10.12783/dtetr/icpr2017/17640.

Xu, L.D., Duan, L., 2019. Big data for cyber physical systems in industry 4.0: a survey. Enterprise Information Systems, 13 (2), 148–169, DOI: 10.1080/17517575.2018.1442934.

Zhang, F., Wu, X., Tang, C.S., Feng, T., Dai, Y., 2020. Evolution of Operations Management Research: from Managing Flows to Building Capabilities. Production and Operations Management, 29 (10), 2219–2229, DOI: 10.1111/poms.13231.

Chapter 4. Exploring the Relationships Between Industry 4.0 Implementation Factors through Systems Thinking and Network Analysis

Statement of Authorship

Statement of Authorship

Title of Paper	Exploring the Relationship Between Industry 4.0 Implementation Factors through Systems Thinking and Network Analysis
Publication Status	☐ Published ☐ Accepted for Publication ☒ Submitted for Publication ☐ Unpublished and Unsubmitted w ork w ritten in manuscript style
Publication Details	Submitted to Management Science

Principal Author

Name of Principal Author (Candidate)	Christian Hoyer		
Contribution to the Paper	Literature review, data collection, methodology development and analysis		
Overall percentage (%)	70%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15.10.2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Assoc. Prof. Indra Gunawan		
Contribution to the Paper	15% - support in developing the research methodology and the theoretical foundation		
Signature		Date	15.10.2021

Name of Co-Author	Dr. Carmen Haule Reaiche		
Contribution to the Paper	15% - support in developing the research methodology and the theoretical foundation		
Signature		Date	15.10.2021

Please cut and paste additional co-author panels here as required.

Manuscript (submitted to Management Science)

Exploring the Relationship Between Industry 4.0 Implementation Factors through Systems Thinking and Network Analysis

Christian Hoyer[a]*, Indra Gunawan[a] , Carmen Haule Reaiche[b]

[a] *Business School, University of Adelaide, Adelaide, Australia*

[b] *College of Business, Law and Governance, JCU, Australia*

* *Business School, University of Adelaide, Adelaide*

Abstract:

Based on the utilisation of new technologies that connect all entities within and beyond an organisation, the concept of Industry 4.0 provides companies with the technological and theoretical means to enhance data-driven decision-making procedures, thereby allowing companies to achieve higher productivity, flexibility and efficiency. In order to facilitate the transformation process, several studies have identified some of the factors that need to be considered when implementing Industry 4.0. However, the dynamic relationship between these factors has yet to be understood and addressed in order to provide companies with the in-depth knowledge needed to effectively manage the transition. Recent investigations have repeatably demonstrated that most corporations fail to implement the concept on a broader level beyond isolated projects. The principal aim of our research is therefore to map out the complex relationships between the previously identified Industry 4.0 implementation factors, by adapting a novel approach that combines network analysis with the adoption of causal loop diagrams. The construction of the causal loop diagram is based on the insights gathered from in-depth interviews with Industry 4.0 experts working for corporations, governmental organisations and research institutes. Results show that the roles of Industry 4.0 implementation factors are not static, and what role they play depends on their position in the network and centrality measures, complementing the findings of previous investigations about the drivers of change. Furthermore, our findings indicate that multiple intervention points exist, shedding more light on how to develop more effective implementation strategies.

Keywords: Industry 4.0; Systems Thinking; Causal Loop Diagram; Network Analysis; Complexity

4.1 Introduction

In early 2000, Mendelson (2000) discussed the increasing importance of corporations being able to process data collected from internal and external environments, allowing them to improve their decision-making and their reaction time with respect to internal and external changes. Eleven years later, Industry 4.0 was born—a worldwide recognised concept that builds on that very principle (Kagermann et al. 2013, Lasi et al. 2014). Industry 4.0 is often associated with a number of key technologies such as artificial intelligence (AI), cyber-physical systems (CPS), and big data (Dalenogare et al. 2018, Raj et al. 2019). However, at its core, Industry 4.0 is a concept that promises to transform entire business models and the way goods are developed, produced, and distributed. The aforementioned technologies are therefore not what constitutes Industry 4.0, but what allows the essential concept of Industry 4.0 to be put into practice (Calabrese et al. 2021, Castelo-Branco et al. 2019b, Da Silva et al. 2020). This concept is about connecting as many entities as possible, such as machines and sensors, within and beyond an organisation to process and channel the resulting stream of information to augment the decision-making capabilities of workers and entire factories, including their customers and suppliers. Consequently, Industry 4.0-related technologies are needed to connect devices, to process information and to increase the pace as well as the accuracy of companies' decision-making processes both on micro and macro levels (Bai et al. 2020, Kagermann et al. 2013, Vaidya et al. 2018). Given this upcoming paradigm shift, it is no surprise that governments and corporations around the world have started to invest in the concept in order to cement and even further extend their competitive advantage (Lee et al. 2018, Lin et al. 2018). However, previous research has established that the transition towards

Industry 4.0 is complex and that companies are still struggling with implementation (Hirsch-Kreinsen 2016, Raj et al. 2020, Staufen AG 2019). As a result, there is a growing body of literature that tries to identify potential implementation barriers and ways to overcome them instead of solely focusing on the potential of Industry 4.0 technologies (Müller, Kiel, and Voigt 2018, Stentoft et al. 2021).

In the beginning, Industry 4.0 research was predominantly geared towards the special characteristics of the manufacturing sector, but then more and more studies started discussing its usefulness in other areas. This research trend can also be observed for other manufacturing philosophies, such as lean manufacturing (Buer et al. 2018, Distelhorst et al. 2017, Santos et al. 2015). Therefore, since its inception in 2011, the scientific field of Industry 4.0 has been in constant motion. Besides becoming more diverse with respect to its usability beyond the manufacturing sector, the field has also moved away from a purely technological approach to solve Industry 4.0 implementation related issues, towards an approach that considers other factors as equally important. Thus, instead of simply assessing which Industry 4.0 technologies can help companies to become more efficient and flexible, a number of studies have brought forward the idea that a successful implementation of the Industry 4.0 concept and technologies depends on a number of factors, such as how companies train their workforce and in which ways they perceive Industry 4.0 as beneficial (Cimini et al. 2021, Cugno et al. 2021, Raj et al. 2019). Initially, most of these implementation factors were discussed in isolation, without considering how their causal relationship to other factors might influence the overall implementation process. However, the field has recently started to shift again, with more studies indicating that certain implementation factors exert influence on other factors (Bakhtari et al. 2021). For example, the findings of Cimini et al. (2021) demonstrated that the introduction of new Industry 4.0 technologies can have an impact on how companies organise and train their workforce. In a similar vein, Büchi et al. (2020) showed how more openness, with respect to how companies use their IT infrastructure, improves the way companies seize opportunities.

Findings like these illustrate the risks involved in not recognising the underlying dynamic relationship between Industry 4.0 implementation factors. Recommending corporations to focus on a given set of factors without providing them with a deeper grasp of how these factors interact with others may lead to false expectations and ineffective or incomplete implementation strategies (Bakhtari et al. 2021, Calabrese et al. 2021). Although previous investigations have acknowledged this issue, research has yet to systematically study the complexity that arises from the interdisciplinary nature of the Industry research field, 4.0 as well as the multicausality of the implementation factors (Hoyer et al. 2020). Hence, this study sets out to obtain a more comprehensive understanding of the multicausal relationship between previously identified and well-studied Industry 4.0 implementation factors. Furthermore, we seek to explore how the roles and the individual importance of factors change when considered as part of a larger network of implementation factors instead of examined individually.

To account for the interdisciplinary DNA of Industry 4.0 and its implementation, we apply systems thinking by developing a causal loop diagram (CLD) based on the findings of our previously published systematic literature review and semi-structured interviews that we conducted with Industry 4.0 experts to learn more about the relationship between the factors which emerged as critical for Industry 4.0. We then analyse the characteristics of the CLD with the help of network theory to learn more about the characteristics of the network and the roles of the implementation factors within that network.

The remaining part of this study is organised as follows: Section 2 further discusses the application of systems thinking in the field of Industry 4.0. Our research approach, including the acquisition of data, is outlined in Section 3. Along with the numerical results from our network analysis, we present the final CLD, including identified feedback loops, in Section 4. We then continue discussing the key findings of the study in Section 5, before we conclude the study and outline suggestions for future research in Section 6.

4.2 Systems Thinking and the Implementation of Industry 4.0

The existing body of knowledge on Industry 4.0 suggests that the reasons for its complexity are manifold. From a technological perspective, the concept of Industry 4.0 requires organisations to make decisions based on an increasing amount of data shared and processed by a growing number of smart devices (Hoyer et al. 2020, Kagermann et al. 2013, Sjödin et al. 2018). However, as advocated by Whysall et al. (2019) and Freixanet et al. (2020), this continuing technological evolution creates a gap between what technologies can achieve and the competencies required by employees to work effectively in such an evolving environment, adding another layer of complexity to the implementation of Industry 4.0. What is more, Oliveira et al. (2020) argued that this internal perspective of complexity with respect to adapting Industry 4.0 must be extended, as the implementation process interacts with external factors such as economic growth and human capital. Hou et al. (2020) argued that these different elements of complexity inherent to Industry 4.0 must interact seamlessly to achieve a successful implementation process.

Although numerous approaches exist to address, evaluate, and comprehend complexity, all of the authors mentioned above regard systems thinking as the most promising among them in the context of Industry 4.0. Due to its flexibility, systems thinking has also been employed in other scientific disciplines such as neuro sciences, education and management (Jonker and Karapetrovic 2004, Mahaffy et al. 2019, Uleman et al. 2021). As pointed out by McGlashan et al. (2016), systems science offers a wide range of qualitative techniques to capture the shared understanding of a given topic, and a variety of quantitative methods to generate simulations (Berry et al. 2018). Similarly, Kenzie et al. (2018) referred to systems thinking as an appropriate tool for the synthesis of information gathered from different stakeholders and disciplines with the goal to develop a model that reflects their shared understanding of a complex system. This model can also help to identify gaps in theoretical and empirical knowledge that need to be addressed in future research (Cabrera et al. 2008, Jones et al. 2011).

One specific and validated systems thinking tool that helps to visualise the synthesis of the shared understanding of a complex phenomenon is the CLD (Roberts 1978, Spector et al. 2001). In the present study, we use this tool to map out the causal relationship between Industry 4.0 implementation factors based on the shared understanding of Industry 4.0 experts with various backgrounds. More specifically, we aim to develop a visual grounded model that illustrates the dynamic relationship between Industry 4.0 implementation factors, by showing the direction of each relationship as well as whether a given factor either exerts a positive or negative influence on another factor. Both polarity as well as the direction of a causal relationship are based on the statements of our interview participants.

Therefore, to construct the CLD, we conduct semi structured interviews with Industry 4.0 experts with various Industry 4.0 backgrounds. In that context, we focus on interview participants who are also engaged with Industry 4.0-related activities such as working on Industry 4.0 initiatives. In a similar vein, our previously conducted systematic review drew from a wide spectrum of different Industry 4.0 studies, reflecting what is known about the implementation factors according to the existing body of Industry 4.0 literature.

4.3 Methods

To gain a better understanding of the relationships between the previously investigated implementation factors, we developed a three-stage research approach. First, based on the results of our systematic literature review and the findings of our Industry 4.0 survey of practitioners, we conducted interviews with Industry 4.0 experts to learn more about the factors themselves and the relationship between them. Second, based on their explanations, we used the program Vensim PLE 8.2.1 to visualise the connections between the factors. Finally, we identified causal loops and used NetworkX for Python and Gephi 0.9.2 to analyse the overall structure of the CLD, which was interpreted as a directed network based on the studies of Uleman et al. (2021) and McGlashan et al. (2016).

4.3.1 Expert Interviews

Many studies have explored which factors are crucial to consider when it comes to implementing Industry 4.0 (Lin et al. 2018, Müller, Kiel, and Voigt 2018). In our previous investigations, we synthesised this knowledge through a systematic literature review and conducted a survey to measure the perceived importance of each identified factor. However, these investigations were not able to draw reliable conclusions with respect to the potential relationship between the identified factors. Therefore, in the current study, we chose a qualitative approach to gain a deeper understanding of the various facets of the implementation factors and their interconnectedness. To allow each participant to fully express their thoughts and ideas, we decided to adopt the semi-structured interview method. As pointed out by Adams (2015), semi-structured interviews are suitable for adding depth to quantitative examinations such as survey findings, which typically struggle to ask open questions that can put quantitative findings into a broader perspective, and therefore well aligned with our research objectives.

In our interviews, we asked participants to discuss the Industry 4.0 implementation factors that they consider crucial. After asking them why they think these factors are important, we asked them if there were any other factors they would like to discuss, before we proceeded with asking them about the relationship between the factors they mentioned. However, in order to make them feel more comfortable, we opened each interview with questions about the participants' experience with Industry 4.0 and how they would define it (Adams 2015). Following the recommendation of McIntosh and Morse (2015), every question was asked in the same way and in the depicted order to ensure replicability between interviews. Whenever a participant talked about a relationship between factors or the importance of a specific factor, we gave them the opportunity to elaborate by inviting them to share more details. On average, each interview lasted 55 minutes.

A number of criteria were considered when selecting the participants for our interviews. Due to the multifaceted nature of Industry 4.0, our goal was to interview experts with a wide spectrum of Industry 4.0 knowledge and experience (Bartodziej 2017, Bogner et al. 2009, Lee et al. 2018). We build upon the approach of Bartodziej (2017) who distinguished between specialists and experts by the number of Industry 4.0 technologies they worked with. In the following paragraph, we will describe the selection criteria we added to this approach.

First, to qualify as an expert, the number of Industry 4.0 technologies they have worked with was not considered the main factor. Instead, our main focus was on finding experts who experienced in implementing Industry 4.0. Consequently, the study was not limited to participants with an industry background, as the implementation of Industry 4.0 takes place at different levels (Luthra and Mangla 2018, Raman and Rathakrishnan 2019, Sung 2017). For example, a number of initiatives and government support programs exist to promote the implementation of Industry 4.0. In that context, participants working for the government, researchers conducting research on the implementation of Industry 4.0, and managers working on Industry 4.0 initiatives were equally considered for our study, as long as they fulfilled the remaining selection criteria. Second, we specifically looked for participants with more than five years of experience with Industry 4.0 projects in a leading position with the assumption that they would have solved problems that were not only limited to technological issues. Third, we prioritised participants engaged with Industry 4.0 beyond their profession. This includes being part of Industry 4.0 committees, initiatives, and associations.

To find suitable candidates, we used the database of the Hanover Industrial Fair, due to its significance in the field of Industry 4.0, as well as other databases that provided publicly accessible information, such as the webpage "Plattform Industrie 4.0". These databases provided lists of keynote speakers, presentations, seminars and projects focusing on Industry 4.0. We selected and contacted 30 suitable candidates after cross-checking their profiles with the help of additional publicly available information, such as company webpages; 16 agreed to an interview. Following the recommendations of Symon and Cassell (2012), we considered this number sufficient, taking into account that we had two additional sources of data with which we could compare the results. At the time of the interviews, 9 participants worked for a corporation, 4 worked for an Industry 4.0-related initiative, and 3 worked as university researchers. All of our participants fulfilled all of our criteria.

After transcribing the audio recorded interviews, we used thematic analysis to identify emerging themes with respect to the implementation factors. We used the findings of our systematic literature review to classify the implementation factors and added new factors to the list when a factor that was discussed by one or more participants did not match the description of our systematic synthesis. The analysis comprised three steps. In the first step, we followed the interviews and captured emerging themes and relationships with the program Nvivo 12, which not only allowed us to capture themes, but also the relationship between them. Then, we further analysed and discussed the emerging themes to merge similar codes and connections. In the third step, we compared the emerged themes, sub-themes, and connections with the findings of our systematic literature review again. The final list of themes was then used to design the CLD.

4.3.2 Causal Loop Diagram

Causal loop diagrams were designed to visualise how variables are interconnected in a given system, thereby helping to elicit the mental models of groups and/or individuals. From understanding the complexity of the COVID-19 pandemic to comprehending policy intervention, CLDs have been used to examine a variety of complex systems (Roxas et al. 2019, Sahin et al. 2020).

The goal of the present study is to better understand the complex relationship between Industry 4.0 implementation factors by developing a CLD that is based on the experience of Industry 4.0 experts, combined with the insights of a previously conducted systematic literature review and a survey distributed among Industry 4.0 practitioners.

Based on the responses of our interview partners, we used the program Vensim to draw the causal connection between the identified implementation factors. These connections are represented by directed arrows, whereby solid lines show positive causal relationships and dotted lines show negative causal relationships. A positive causal connection indicates that if a causal factor, “A”, moves in one direction, the factor it is connected to, “B”, moves in the same direction. In contrast, if a connection is negative, an increase of A results in a decrease of B (Kiani et al. 2009, Uleman et al. 2021).

After drawing the connections, we continued with the identification of feedback loops. These feedback loops are indicators for a sequence of change that can further amplify the original momentum (reinforcing feedback loops) or push back against it (balancing feedback loops). For example, if a product gets positive reviews, sales increase which further increases the number of positives reviews, therefore reinforcing the initial impulse of change. On the other hand, balancing feedback loops imply a self-regulating behaviour. For example, while hunger increases the consumption of food, the consumption of food decreases the feeling of being hungry. Reinforcing and balancing sequences are initiated by introducing change to one factor whereby the sequences of change can go through an unlimited number of factors (Kiani et al. 2009). When it comes to Industry 4.0 implementation factors, it might be particularly important to identify reinforcing feedback loops that introduce positive change to the system and thereby make an effective implementation of Industry 4.0 more likely. Balancing feedback loops, on the other hand, can be crucial when it comes to targeting factors with a negative influence, such as the potential job loss anxiety of employees.

In our systematic literature review, we distinguished between internal and external implementation factors to account for the fact that some of the identified implementation factors are under the direct control of corporations that want to implement Industry 4.0, whereas other factors such as "Political Support" cannot be directly influenced by corporations. We integrated that categorisation into our CLD to be able to identify feedback loops that include internal as well as external implementation factors, therefore offering a new perspective that has not been discussed in the field of Industry 4.0 yet. For example, these cross-scale feedback loops can help to further understand why Industry 4.0 support programs are not able to directly address the barriers corporations face, as recently observed by Cugno et al. (2021). In contrast, we referred to feedback loops that either comprise internal or external implementation factors as “within scale”. We adopted this approach from the investigation of Uleman et al. (2021), who also differentiated between direct and indirect loops. Direct feedback loops consist of two implementation factors, whereas indirect feedback loops consist of more than two implementation factors.

4.3.3 Network Analysis

In 2016, McGlashan et al. (2016) demonstrated how quantitative network analysis can be used to examine the structure of a CLD to learn more about its properties and the underlying dynamics between the variables in the system. This approach was then adopted and further refined by Uleman et al. (2021), who added additional steps to the analysis to study the robustness of their CLD. For the present study, we build on both approaches to analyse the relationship between the previously identified and examined Industry 4.0 implementation factors. In the following section, we describe the measures and techniques used to analyse the CLD and test its robustness.

4.3.3.1 Structural Metrics

Structural metrics are used to describe the overall topology of the network and can help to better understand how change in one factor might cause change in other factors (Hansen et al. 2011, McGlashan et al. 2016).

“Network Density” (ND) is a measure that shows the fractions of connection between the “Actual Number of Implementation Factors” in the CLD (AC) relative to the “Maximum Possible Number of Connections Between the Factors” (PC), where *n* represents the number of factors. The higher the density, in other words, the closer the actual number of connections between factors gets to the theoretical maximum number of possible connections, the higher the chance that introducing change to one factor will cause change in other parts of the network.

As a consequence, the lower the density of a given network, the more intervention points need to be identified and targeted in order to cause change in other factors and parts of the network (McGlashan et al. 2016, Metcalf and Casey 2016).

$$PC = n\frac{n-1}{2}; ND = \frac{AC}{DC} \quad (1)$$

The “Degree Distributions” simply refers to the number of directed causal connections leading to or exiting a given factor. The degree distribution is, therefore, divided into in-degree distribution and out-degree distribution and shows the level of involvement of a given factor in the network. As argued by McGlashan et al. (2016), this means that factors with a high in-degree and/or out-degree can serve as important hubs in the network from which change can be initiated due to their interconnectedness.

The “Average Path Length” (L) depicts the smallest number of connections between any given implementation factors in the network. The distance d_{ij} between two chosen factors *i* and *j* includes all directed connection on the shortest path in the network between these two factors. If there is no connection between a pair of factors, then d_{ij} = *N* (Xiong 2012). The average path length is a strong indicator of how efficiently change spreads from one factor to the other. Consequently, less effort is necessary to spread change from one factor to others when the average path length is small (McGlashan et al. 2016).

$$L = \frac{1}{N(N-1)} \sum_{ij=1,\ i \neq j}^{N} d_{ij} \quad (2)$$

“Network Modularity” is a measure that helps to identify clusters in the network and shows their level of segregation. Therefore, if a given network exhibits a high level of modularity, clusters should be targeted individually to introduce change, and factors with high betweenness centrality (BC) should be targeted to spill over change from one cluster to another

(McGlashan et al. 2016). To calculate the modularity of the CLD, we used the algorithm proposed by Blondel et al. (2008), which is based on the approach developed by Leicht and Newman (2008). In a partition of a directed network, the modularity Q_d is defined as follows:

$$Q_d = \frac{1}{m}\sum_{i,j}\left[A_{ij} - \frac{d_i^{in} d_j^{out}}{m}\right]\delta(c_i, c_j) \tag{3}$$

A_{ij} stands for the existing connection between two chosen factors i and j, whereas d_i^{in} and d_j^{out}stand for the in- and out degree of i and j respectively. The variable m represents the number of connections within the network and c_i is defined as the cluster the factor i belongs to (Blondel et al. 2008, Leicht and Newman 2008).

4.3.3.2 Network Centrality Measures

While structural measures provide insight into the general topology of the entire network, centrality measures can reveal the importance of each factor in the network. However, depending on the centrality measure applied, importance has a different meaning. Following the approaches of McGlashan et al. (2016) and Uleman et al. (2021), we focused on "Betweenness Centrality" BC and "Closeness Centrality" (CC) to identify factors that either lie on and/or have the shortest paths in the network.

The importance of high BC factors arises from their potential to act as a bridge between other factors and clusters in the network (Ahmed 2017, Uleman et al. 2021). It shows how many times a factor can be found on the shortest path between other factor in the network. Therefore, the more often a given factors lies on the shortest paths between other factors, the more that factor can be used to mediate the flow of information within the network (Hansen et al. 2019, McGlashan et al. 2016). The BC for a chosen factor *v*, is calculated as followed:

$$BC_v = \frac{1}{(N-1)(N-2)}\sum_{s,t}\frac{\sigma(s,t|v)}{\sigma(s,t)} \quad (4)$$

N represents the total number implementation factors within the network, whereas $\sigma(s,t)$ is defined as the total number of shortest paths between two chosen factors s and t. The expression $\sigma(s,t|v)$ stands for the number of shortest paths going through factor v (Hansen et al. 2019, Uleman et al. 2021).

In contrast to betweenness centrality, closeness centrality measures how close each factor is to other factors in the network. It can therefore help to identify factors that influence the entire network at the highest speed. In that context, Uleman et al. (2021) and McGlashan et al. (2016) recommended using this measure to identify efficient spreaders of information that can be used to initiate potential interventions. However, in high density networks, variables have similar CC scores, making the measure less effective (Ahmed 2017, Hansen et al. 2019). The CC of a chosen variable v is calculated as follows:

$$CC_v = (n-1)\frac{1}{\sum_{u=1}^{n-1} d(v,u)} \quad (5)$$

The number of reachable factors in the network is represented by $(n-1)$, whereas $d(v,u)$ is defined as the distance of the shortest path from a chosen factor v to u. After calculating the shortest paths between all the factors in the network, a score is assigned to each implementation factor with respect to the number of its shortest paths (Hansen et al. 2019).

4.3.3.3 Robustness Test

To test the structural robustness of the centrality measures, we adopted the approach that was recently proposed by Uleman et al. (2021). In their study, they created mutated CLDs by introducing five random mutations to the connections between the variables in the network. These mutations were equiprobably implemented by rewiring the connection between a random set of factors and by randomly adding new connections to the adjacency matrix of the

CLD. Similarly, existing connections can be randomly removed from the CLD. For example, instead of A having a directed connection to B, the connection can be either removed entirely from the CLD or changed to a new connection where A directly connects to C. Furthermore, a not already existing connection between two factors can be added to the CLD.

Following this method, we created 300 mutated CLDs by introducing five random changes to the final adjacency matrix of the CLD, as described above, in order to test the robustness of the centrality measures to random perturbations. This test was done by calculating the centrality measures of each of the mutated CLDs. These measures were then used to calculate the interquartile ranges of each factor's CC and BC to construct error bars (Uleman et al. 2021).

4.4 Results

Table 13 portrays the factor relationships that emerged from the analysis of the qualitative data obtained from a set of 16 interviews. As previously described in the methods section, out of the 13 initial factors that have been mentioned as part of a relationship with other factors, 10 factors have been further divided into sub-themes to illustrate which specific facet of a given factor was addressed by the interviewees. For example, we broke down the factor "Perceived Implementation Benefits" into three sub-themes as some interviewees were specifically referring to an organisation's desire to improve their efficiency with the implementation of Industry 4.0, while others were referring to the opportunity of creating new business models when discussing its impact on other factors. Table 13 shows the resulting sub-themes that emerged from the interviews and that have been used to construct the final CLD (**Error! Reference source not found.**), whereby n shows how many times a given factor was mentioned in connection with other factors.

Table 13. Implementation Factors integrated into the CLD

Sub-Themes	n	Sub-Themes	n
1. Political Support	42	**7. Perceived Implementation Benefits**	60
		7.1 New Business Models	
2.1 IT-Standardization	32	7.2 Need for New Technologies	
2.2 Data Ownership and Privacy Rules		7.3 Improving Productivity and Efficiency	
2.3 Broad Band and 5G Expansion			
		08. Strategic Consideration	27
3. Corporate and Institutional Cooperation	57		
3.1 Availability of Cooperation Platforms		**9. IT-Infrastructure Maturity**	19
3.2 Inter-Institutional Cooperation			
		10. Internal Knowledge and Skills Development	17
04. Cost Assessment and Available Funding Options	21	10.1 Industry 4.0 Related Skill Promotion	
4.1 Cost of Transition		10.2 Internal HR Capacity	
4.2 Financial Support and Initiatives			
4.3 Financial Support for I.4.0. Initiatives		**11. Lean Manufacturing Experience**	6
		11.1 Lean Performance	
05. Available Knowledge and Education	39	11.2 Lean Experience	
5.1 Availability of Skilled Workers			
5.2 Education System		**12. Occupational Health and Safety**	4
5.3 Availability of Industry 4.0 Knowledge		12.1. Safety and Job Loss Anxiety	
06. Pressure to adapt	19	**13. Attitude and Mindset**	15
6.1 Market Pressure to Adapt Industry 4.0		13.1 Openness to Change and Cooperation	
6.2 Customer Demand for Current		13.2 Scepticism Towards Change	

Overall, we consider the inclusion of 25 factors into the CLD appropriate, highlighting the 65 existing connections between them. As discussed in the previous section, we divided the CLD into two clusters based on our findings from the systematic literature review (Hoyer et al. 2020).

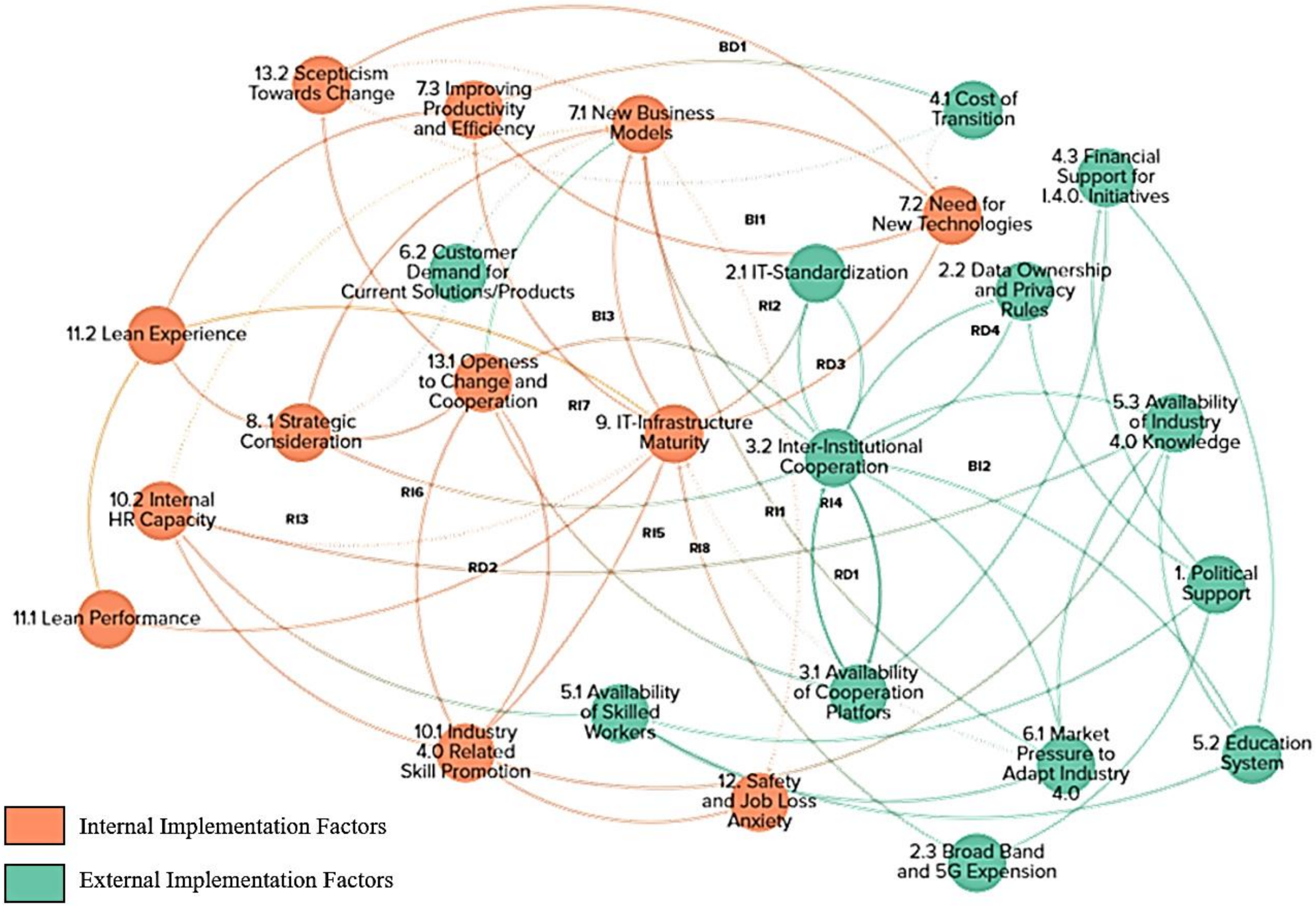

Figure 11. Industry 4.0 Implementation Factors CLD: Internal Factors are in green and external factors are in orange

4.4.1 Causal Loop Diagram Structure

The density of the final network is 0.1, meaning that the network contains 10% of all the possible edges if all the nodes in the network were completely interconnected. As pointed out by Uleman et al. (2021), this sparse network topology demands a more strategic approach when it comes to identifying and using potential leverage-critical points in the system. This notion is supported by McGlashan et al. (2016) who argued that compared to dense networks, sparse networks are more likely to require multiple points of intervention in order to introduce change in the overall system. One important reason for this can be explained by the so called "bus factor", which refers to the potential decrease of a given network's overall efficiency as well as its capability of sharing information after certain nodes have been removed from the system (Coplien and Harrison 2004). Sparse networks are more vulnerable to this problem, as with decreasing density, the number of alternative routes from one node to another decreases accordingly. With respect to the implementation of Industry 4.0, this could mean that not taking into consideration certain key factors can lead to a more challenging and less efficient transition towards Industry 4.0. This can eventuate if the ignored factor(s) potentially has the only connection to a key factor with a strong impact on a desired outcome produced by the overall system.

Consequently, the overall importance of an Industry 4.0 implementation factor should also be determined through the role that this would play in the overall network in a specific outcome context. This finding supports the paper's aim of offering a broader understanding of Industry 4.0, something the literature has been calling for (Cimini et al. 2021, Kagermann et al. 2013, Li 2020). However, it is important to note that while the low density of the network requires more attention and planning when it comes to finding the optimal implementation strategy, it can also be argued that the low density is an indicator of the robustness of the overall

CLD. In this context, Uleman et al. (2021) mentioned that although all factors in a CLD are indirectly connected through a common theme, only direct causal relationships should be included.

The observed average path length in the CLD is 3.518, meaning that the average causal distance between two factors is 3.518 connections. Consequently, almost all implementation factors are interconnected within a short number of edges, indicating a smooth flow of information. However, the diameter of the network shows that the longest distance between two factors in the network is 8 causal connections.

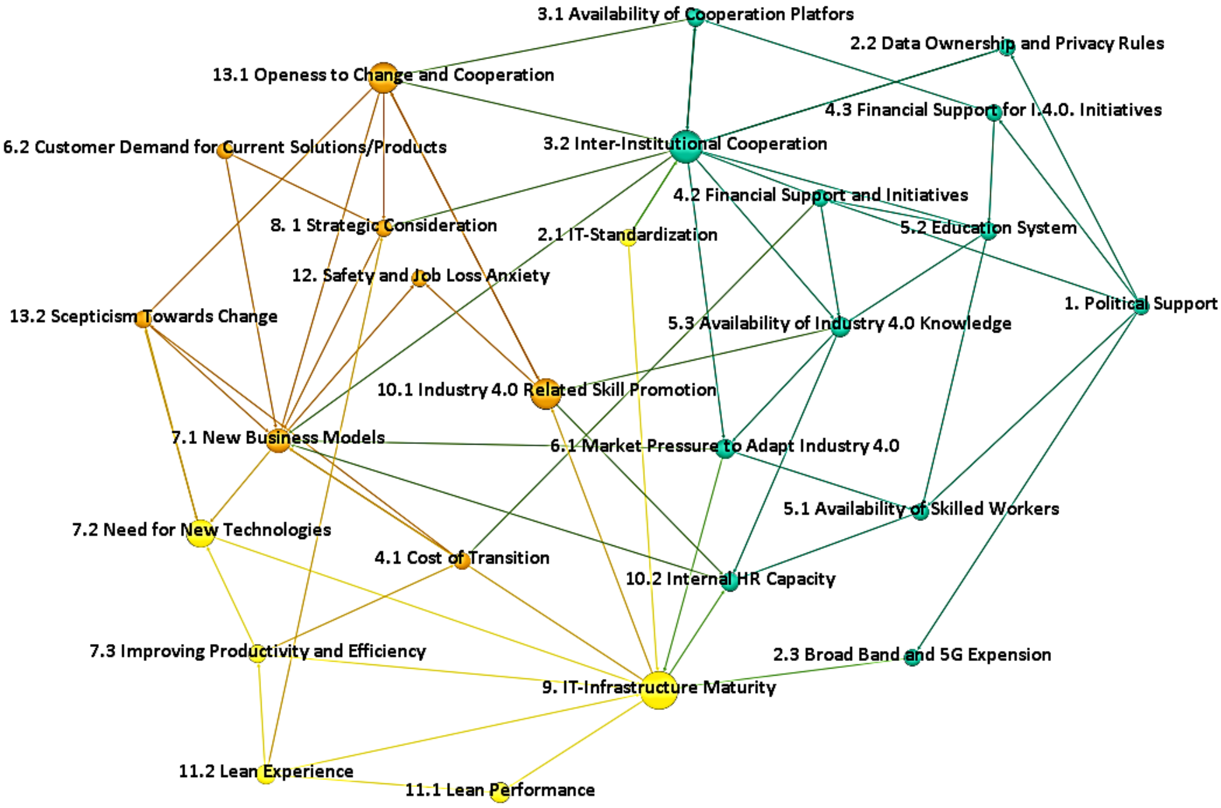

Figure 12. Network Modularity and Centrality Analysis (each cluster is shown in a different colour)

As described in the methods section, we used the algorithm proposed by Blondel et al. (2008), incorporated in our used network analysis tool. We calculated a modularity of 0.332, indicating that different clusters within the network exist. Upon further analysis, we identified three clusters, which are shown in Figure 12. Interestingly, while there are two main clusters that reflect the exact division between internal and external implementation factors, a third cluster was identified. This cluster builds a sub-cluster within the internal cluster and seems to comprise implementation factors that are more relevant for the operational aspects of Industry 4.0 such as “Lean Performance” and “Improving Productivity and Efficiency”.

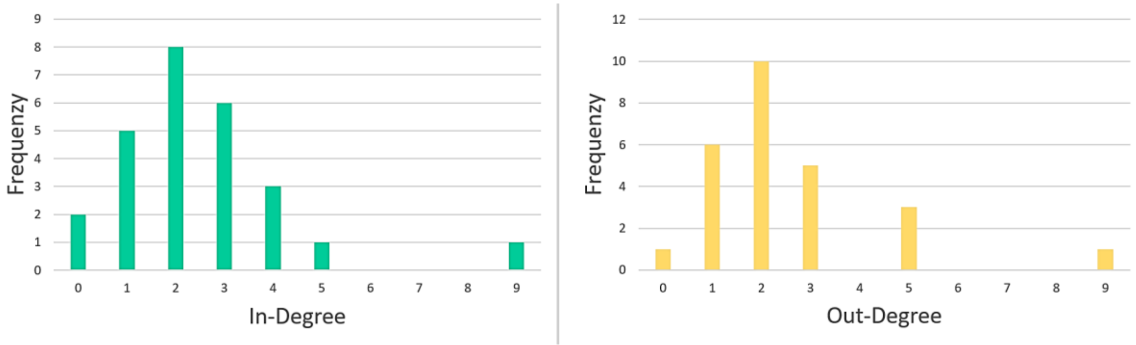

Figure 13. Distribution of Factor In- and Out-Degree

The degree distributions as well as the individual in- and out-degree values are shown in Figure 13. In both cases, the degrees range from 0 to 9 with most factors having a degree of 2. Similarly, in both cases, only a few larger hubs can be observed, leading to a heavy-tailed degree distribution (Hansen et al. 2019, Metcalf and Casey 2016). Moreover, only one factor was found to not have an impact on at least one other factor. As stated by McGlashan et al. (2016), factors with an out-degree of 0 are less likely to occur than factors with an in-degree of 0, as shown in the presented CLD.

4.4.2 Variable Centrality

The network analysis returned the highest BC for the factor “IT-Infrastructure Maturity” (Figure 14). Therefore, it lies directly on the shortest path that connects various factors with each other (Hansen et al. 2011, Hansen et al. 2019, Layton and Watters 2015). A closer look reveals that the factor seems to act as a bridge between the inner workings of corporations and the factors that have a more strategic component, such as the creation of new business models.

Therefore, despite its comparatively low individual reference score (Table 13) in combination with other factors, the analysis shows that its importance changes when the implementation of Industry 4.0 is considered as a complex system. In fact, the connection between "IT-Infrastructure Maturity" and "Perceived Implementation Benefits" was found to be the connection that Industry 4.0 experts most referred to, indicating that the execution of implementation plans is connected to the capabilities of the local infrastructure. As one expert stated: *"This topic is essential for us. The better and the more efficiently our machines our connected with each other based on an overarching system solution, the better we can survive on the market."*

In the same vein, "Inter-Institutional Cooperation" may have a similar role, acting as a junction between internal and external implementation factors. Its high BC indicates that in order to have a strong impact on corporations from the outside and vice versa, "Inter-Institutional Cooperation" may offer the most efficient paths to achieve these goals. The fact that this factor also has the highest CC is one of the most striking results found, as it strengthens the idea that cooperation represents a crucial platform through which both corporations and outside parties can address key issues related to Industry 4.0 across internal and external boundaries. Consequently, the factor not only sits on a number of shortest paths between external and internal factors, but it also shows that "Inter-Institutional Cooperation" is very close to all other factors in the network, making it crucial for implementation strategies. According to network theory, this, on average, short distance to other factors in the network gives cooperation a position from which information spreads quickly (McKnight 2014). For the implementation of Industry 4.0, this result not only indicates that cooperation is often part of the solution when it comes to implementing Industry 4.0 effectively, but may also indicate that cooperation is a promising starting point for Industry 4.0 strategies (Hansen et al. 2019, McGlashan et al. 2016). Commenting on the overall importance of inter-institutional cooperation, one expert said: "*I believe that cooperation between corporations, governmental institutions, scientific institutions as well as labour unions can help to achieve a smoother transition towards Industry 4.0 compared to the second and the third industrial revolution.*" While cooperation was amongst the seven most important factors in our previous investigation, six other implementation factors, such as "Perceived Benefits" and "Strategic Consideration" were considered significantly more important. Similarly, in recent implementation studies that, among other things, investigated Industry 4.0 readiness or identified potential barriers, cooperation was not, if at all, acknowledged as a key factor. This discrepancy between existing studies and our results might be due to the perspective offered by the network analysis that is offered by the network analysis that accounts for the complexity of implementing Industry 4.0 and the potential relationship between the identified factors.

Besides cooperation, the factors "Openness to Change", "Political Support" and "IT-Standardization" emerged from the analysis as key factors with high CC, indicating on the one hand that from a corporation's perspective, incorporating measures that encourage an open mindset towards Industry 4.0 may be the strongest leverage point in terms of having an impact on as many implementation factors as possible. Or as one of the interviewee put it: "*If we don't find a way to be more open towards Industry 4.0, our chance to lose increases drastically*".

On the other hand, our findings further verify the results of a wide range of studies that have argued that the standardisation of IT solutions and communication protocols are a base condition for realising a successful and efficient Industry 4.0 implementation (Abele et al. 2015, p. 153, Benzerga et al. 2018, p. 69, Khan and Turowski 2016, p. 445). One expert alluded to the notion that most companies have to ask themselves two basic questions when it comes to the state of their IT-infrastructure: “*Which language does it speak and what can be done with it*”.

Elaborating now on the factor “Political Support”, the results show that despite its high CC, it has a BC of 0, indicating that the factor can have a significant impact on the system, while changes in the system do not impact the factor itself. Although it is a widely-held view that political institutions play an important role when it comes to Industry 4.0, our findings may offer an additional explanation as to why the support of political institutions is crucial. Its exogenous nature combined with a high CC suggests that the factor has many and short connections to other influential factors in the network, therefore taking a special role when it comes to trigger change (Metcalf and Casey 2016, Uleman et al. 2021). Most experts emphasised how political initiatives can encourage corporations to implement Industry 4.0. For example, one interviewee stated: “*Industry 4.0 spread across the entire globe thanks to the involvement of governments. Even in China, where the concept was directly incorporated in their China 2025 strategy. This provided good momentum for corporations to invest in Industry 4.0.*”

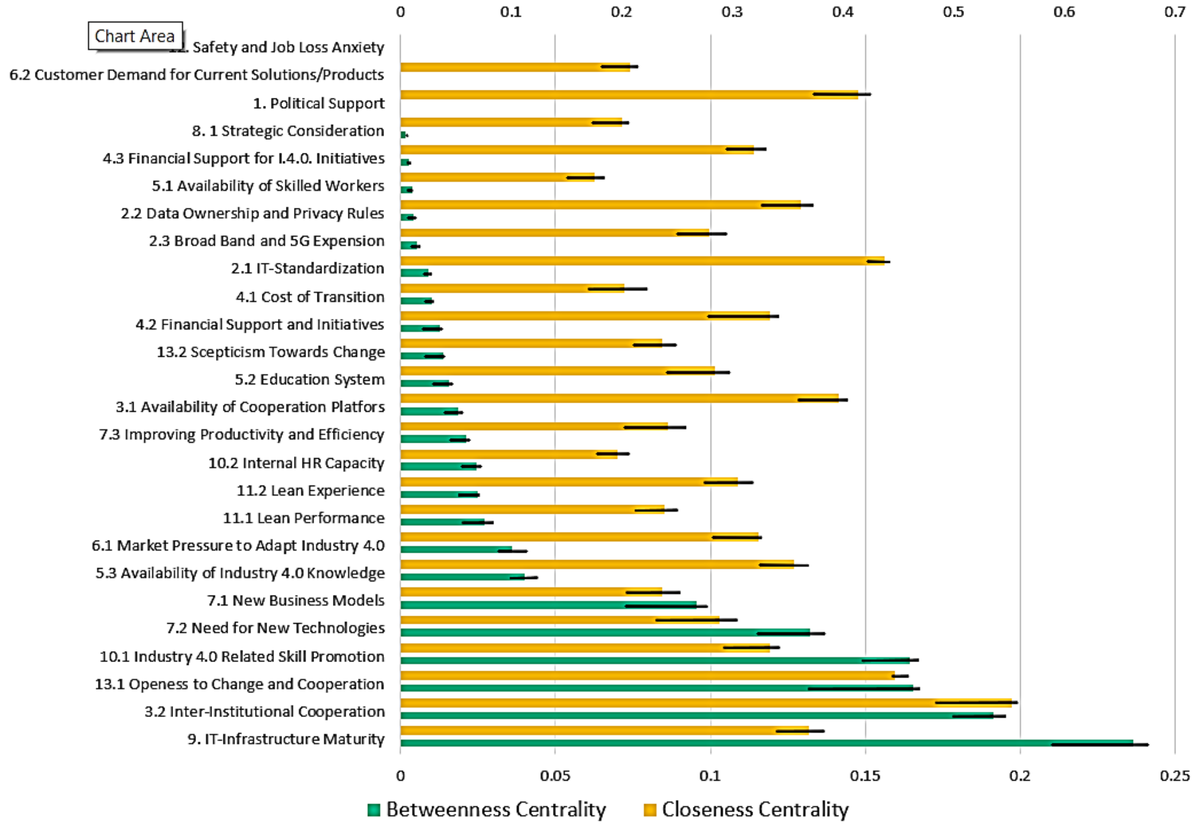

Figure 14. Factor Variability including Interquartile Range of the Mutated CLDs (represented by black error bars)

Testing the robustness of the centrality measures, we included the interquartile range of the mutated CLDs for each factor in Figure 14, showing that the error bars only rarely overlap and therefore suggesting that small errors in connecting the implementation factors will not lead to different qualitative interpretations (Uleman et al. 2021).

4.4.3 Feedback Loops

Adopting Vensim as a supportive tool, we analysed all the existent loops that go through a given factor. The results of the CLD analysis are summarised in Table 11. However, for focus and clarity, only feedback loops up to five factors have been included in the table.

As shown in **Error! Reference source not found.**, both direct and indirect balancing (BD & BID) as well as reinforcing (RD & RID) feedback loops are present in the CLD (see **Error! Reference source not found.**). Direct feedback

Table 14. Feedback loops in the causal loop diagram (Fig. 1)

Loop	1st variable	2nd variable	3rd variable	4th variable
RD1	3.1 Availability of Cooper. Platforms	3.2 Inter Institutional Cooperation	-	-
RD2	13.1 Openness to Change and Coop.	10.1 Industry 4.0 related skill promotion	-	-
RD3	3.2 Inter Institutional cooperation	2.1 IT-Standardization	-	-
RD4	3.2 Inter Institutional cooperation	2.2 Data Ownership and Privacy Rules	-	-
RI1	3.2 Inter Institutional cooperation	3.1 Availability of Cooperation Platforms.	13.1 Openness to Change and Coop.	-
RI2	7.1 New Business Models	7.2 Need for new technologies	9. IT-Infrastructure Maturity	-
RI3	9. IT-Infrastructure Maturity	11.1 Lean Performance	11.2 Lean Experience	-
RI4	9. IT-Infrastructure Maturity	7.2 Need for new technologies	7.3 Improving Productivity and Efficiency	-
RI5	3.2 Inter Institutional cooperation	5.3 Availability of Industry 4.0 Knowledge	10.1 Industry 4.0 related skill promotion	13.1 Openness to Change and Coop.
RI6	7.3 Improving Productivity and Efficiency	7.2 Need for new technologies	9. IT-Infrastructure Maturity	11.1 Lean Performance
RI7	7.1 New Business Models	7.2 Need for new technologies	9. IT-Infrastructure Maturity	10.1 Industry 4.0 related skill promotion
RI8	6.1 Market Pressure to Adapt Industry 4.0	9. IT-Infrastructure Maturity	10.1 Industry 4.0 related skill promotion	13.1 Openness to Change and Coop.
BI1	13.2 Scepticism Towards Change	7.2 Need for new technologies	7.1 New Business Models	-
BI2	4.1. Cost of Transition	7.2 Need for new technologies	9. IT-Infrastructure Maturity	7.3 Improving Productivity and Efficiency
BI3	7.1 New Business Models	7.2 Need for new technologies	9. IT-Infrastructure Maturity	10.2 Internal HR Capacity

loops are defined as feedback loops between two variables whereas indirect feedback loops include more than two variables (Uleman et al. 2021). Before we extend our discussion on the overall findings, the following part of the paper describes different feedback loops considered important across feedback loops as well as intersections identified in the CLD.

4.4.4 Within-Scale Feedback Loops

Following the approach of Uleman et al. (2021), we define within scale feedback loops as loops that take place within the cluster of internal or external implementation factors. For example, as Figure 15 shows, the development of new business models not only increases the need for new technologies, but also the capabilities of a corporation's IT infrastructure resulting from introducing these new technologies—a process that exclusively happens within the boundaries of an organisation. Meanwhile, the feedback loop also proposes that an improved infrastructure gives organisations more opportunities to develop new business models. Similar to several implementation studies, the particular importance of new business models and optimisation opportunities was a recurrent theme amongst the interviewed group of Industry 4.0 experts. This was also reflected in our previous investigation that showed that these aspects are considered the most crucial according to Industry 4.0 practitioners (Lin et al. 2018, Müller, Buliga, and Voigt 2018). In contrast, a number of Industry 4.0 readiness studies have stressed the importance of the enabling features that sophisticated infrastructures have on the creation of new business models (Castelo-Branco et al. 2019a, Pacchini et al. 2019, Stentoft et al. 2021). In this context, the CLD/network perspective not only supports both notions, but also illustrates the dynamic and reinforcing relationships between these factors. In addition, this also shows that the creation of new business models further triggers the need to expand an ongoing loop of business model development, suggesting that both theories are part of the same process. Another interesting aspect of this relationship is that the reinforcing nature of the loop is enabled by the fact that using more capable infrastructures requires organisations to upskill their workforce, which, according to the interviewees, leads to more openness towards Industry 4.0. Finally, the higher level of openness then encourages organisations to develop new business models, which has also been forwarded through evidence presented in a recent investigation by Büchi et al. (2020).

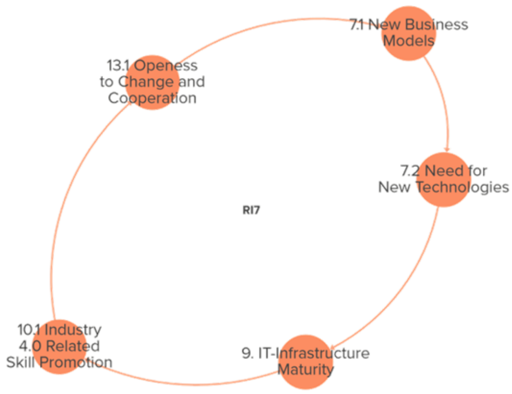

Figure 15. RI7: Example of a Within Scale Loop

4.4.5 Cross Scale Feedback Loops

Turning now to an example for an indirect cross feedback loop, RI5 shows a causal chain between internal and external implementation factors (see Figure 16). More specifically, the internal promotion of skills of an organisation can benefit from the availability of accessible Industry 4.0 knowledge, for example, in the form of qualified graduates entering the job market or external workshops. While this is an expected and well-documented relationship, a surprising finding is that organisations seem to have an impact on the availability of skilled workers that goes beyond a simple supply and demand logic—cooperation and collaboration also seem to play factors. Further, the results suggest that an open mindset towards cooperation with education providers, competitors, and government institutions leads to an improved accessibility of use cases, workshops, and training opportunities. Through cooperation, companies can therefore positively influence the availability of external knowledge that helps them to train and educate their own workforce. As one interviewed expert, talking about this dynamic, one interviewee stated: "*The corporate sector has to do more. Looking at current stage of educations programs including schools, apprenticeships etc., there is a dislocation between what is available and what is actually needed. Therefore, I think that there must be a vigorous exchange between the two fractions so that we can move together on a shared road.*"

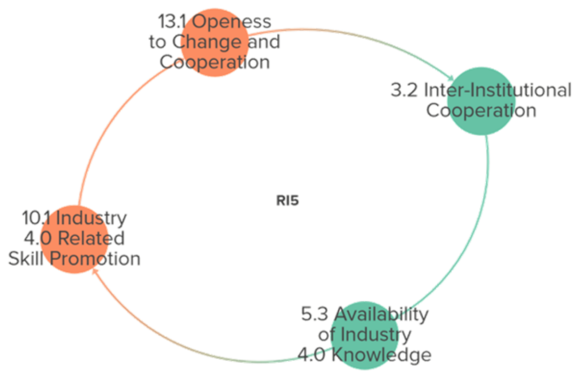

Figure 16. Example of a Cross Scale Loop

While the previously discussed feedback loop RI7 shows that upskilling employees might be a key factor when it comes to the creation of new business models, RI5 offers one potential answer as to how companies can effectively promote new Industry 4.0 skills, despite the high dependency on external providers.

4.4.6 Loop Intersections

When it comes to loop intersections, we refer to them as implementation factors that cause an effect on the network through the various feedback loops to which they are directly connected. As discussed earlier, high centrality is a strong indicator of how influential a node/factor is within the network. Unsurprisingly, "Infrastructure Maturity" and "Inter-Institutional Cooperation" exhibited the highest number of loops in the system. Consequently, both factors and their influence on the network will be illustrated.

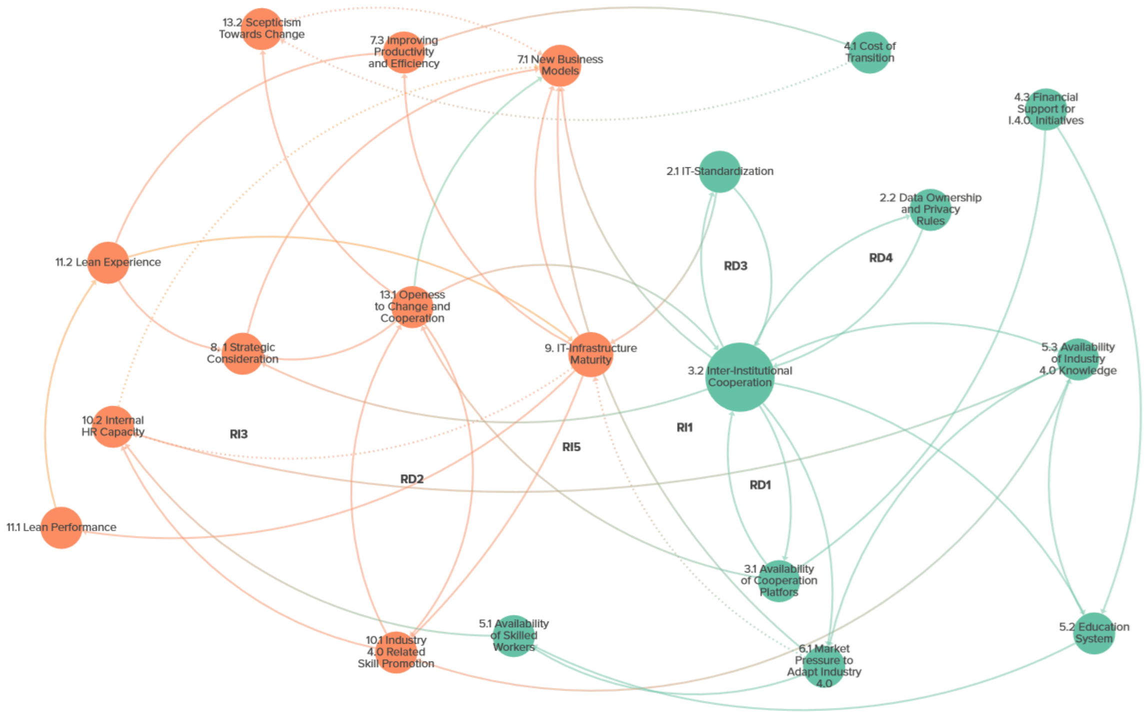

Figure 17. Loops Connected to Inter-Institutional Cooperation

Starting with Inter-Institutional cooperation, Figure 17 summarises all the factors and feedback loops that are connected. What stands out is that cooperation seems to take a key role when it comes to the standardisation of IT solutions and communication (RD3, RD4). The interviewed experts argued that the lack of existing IT standards forces companies to invest more time and resources into identifying IT solutions that are compatible with the infrastructures of their customers and suppliers. They further argued that cooperation, even with direct competitors, seems inevitable as the most optimal solution always involves players outside of an organisation. As one interviewee put it: "When it comes to, for example, standardised data interfaces, it is crucial to cooperate with competitors."

Although exceeding the number of five factors per loop and therefore harder to identify, inter-institutional cooperation was found to also be connected to several cross-scale loops. For instance, inter-institutional cooperation is part of the feedback loops that comprise the strategic consideration of Industry 4.0 as well as the identification of new business models, indicating that even internal implementation processes might show a certain level of dependency on outside factors. While this adds further complexity to the implementation of Industry 4.0, it may help to understand certain phenomena, such as the fact that Industry 4.0-specific incentives do not seem to address specific barriers that companies face when implementing Industry 4.0 (Cugno et al. 2021).

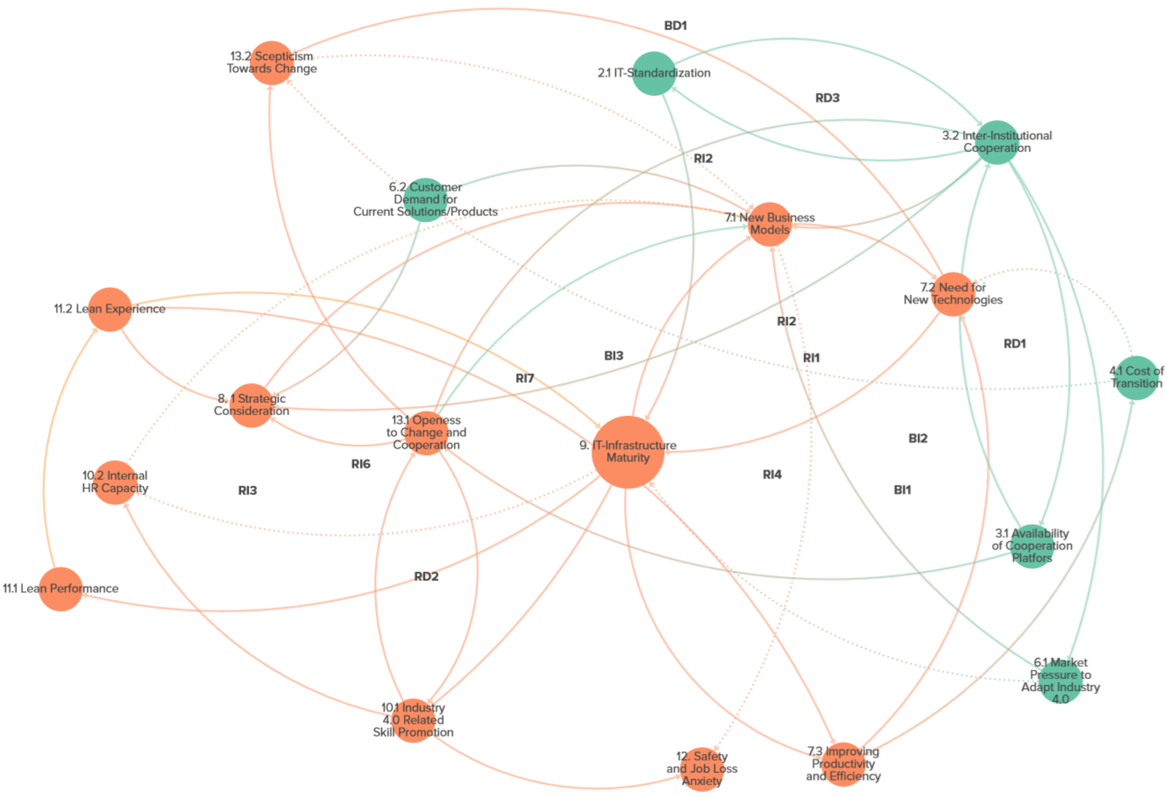

Figure 18. Loops Connected to IT-Infrastructure Maturity

In contrast to “Inter-Institutional Cooperation”, “IT-Infrastructure Maturity” (Figure 18) mainly exerts its influence on the internal part of the system and is only connected to a small number of cross-scale loops such as RI8. Nonetheless, as illustrated earlier, its overall impact on the network is strong, indicating that internal implementation processes and endeavours in particular are directly connected to the maturity and capability of the company’s infrastructure. In that regard, Figure 19 provides new insights into already well-studied relationships. For example, a number of have researchers argued that Industry 4.0 not only benefits from Lean

Manufacturing experience, but that getting started with Industry 4.0 will ultimately improve the performance of already applied Lean principles in an organisation (Buer et al. 2018, Ciliberto et al. 2021, Fettermann et al. 2018, Shahin et al. 2020). While this relationship is also reflected in our findings (RI3 and RI6), the CLD further indicates that this relationship might influence and be influenced by other internal feedback loops that include the maturity of an organisation's infrastructure. For example, RI6 suggests that the maturity level of an organisation's IT infrastructures is positively influenced by an organisation's desire to optimise their processes, which increases the need for new technologies that help to incorporate lean principles more efficiently. This finding provides additional context to the already well-established relationship and can help to improve understanding of the underlying causal chain. In a similar vein, the feedback loop RI9 shows that Lean Manufacturing also has a positive impact on "Strategic Consideration", which helps organisations to gain a deeper, and at the same time, broader understanding of Industry 4.0. Consequently, this broader strategic approach can then help organisations to identify new and better integrated business models, which encourages companies to further improve their IT infrastructure. Commenting on the importance of Industry 4.0 strategies in the context of developing new business models, one interviewee argued: "*Similar to the transition towards Lean Management, Industry 4.0 must be approached consistently; small projects here and there are pointless.*"

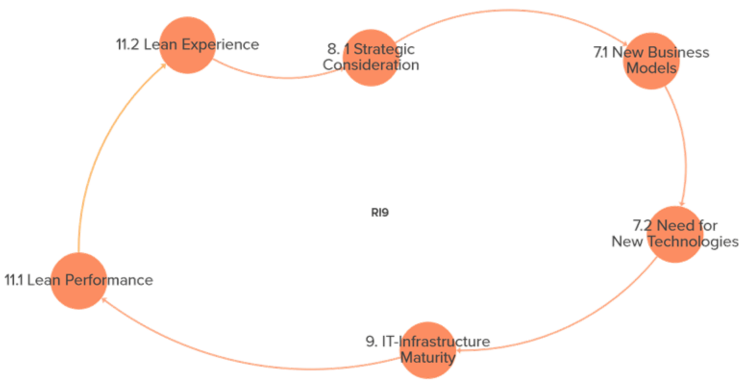

Figure 19. Feedback Loop Illustrating the Connection between Strategy and Lean Experience

4.5 Discussion

Based on the approaches of McGlashan et al. (2016) and Uleman et al. (2021), we analysed our CLD using well-established network analysis methods. Through examining the topological constitution of the CLD, a number of interesting observations could be made that will have implications for the field of Industry 4.0.

The analysis of the mutated CLDs show that the connections between factors are robust despite their qualitative roots. As suggested by Uleman et al. (2021), this means that small errors with respect to the connection will most likely not lead to different conclusions. Furthermore, we tested the relevance of the factors themselves in our previous investigation through a survey that was based on a systematic literature review. Consequently, our findings further suggest that in order to implement Industry 4.0 successfully, the relevance and importance of previously identified implementation factors can only be comprehensively understood by acknowledging their relationship to other factors. However, this also means that companies face a high degree of complexity when they approach Industry 4.0.

Recent studies have come to the conclusion that a systematic approach to Industry 4.0 is inevitable (Freixanet et al. 2020, Hou et al. 2020, Oliveira et al. 2020). For example, Neumann et al. (2021) argued that since companies tend to enter unsafe states when they are engaged with process innovation, unanticipated system risks are even more likely to occur when approaching Industry 4.0 through isolated steps. This accords with our findings that shed new light on how the implementation factors influence each other within the system. For instance, in **Error! Reference source not found.**, it can be seen that developing business m odels (factor 7.1) may also lead to job loss anxiety among employees (factor 12). A sole focus on developing new business model, without considering the impact on other factors such as “Internal Promotion of Industry 4.0 Skills”, could therefore lead to a stronger resistance against change and to lower productivity, as suggested by our interviews and the findings of Saniuk et al. (2021).

The density of the presented CLD is low, indicating that the implementation of Industry 4.0 through one factor will likely not affect as many other factors as in dense networks. According to network theory, this means that to introduce change in the system effectively, multiple leverage points must be identified (Hansen et al. 2011, Hansen et al. 2019). Hence, corporations should not only approach Industry 4.0 more strategically to avoid unanticipated risks, but also exert enough influence on the entire network so that change can take place. This further strengthens the idea that comprehensive approaches should be chosen over single projects, despite seeming more practical on the surface, as illustrated by the most recent German Industry 4.0 Index, which shows that most corporations move toward Industry 4.0 through individual and operational projects (Staufen AG 2019).

Our modularity test based on the approach proposed by Blondel et al. (2008) showed that the network is divided, not only confirming our initial separation between external and internal implementation factors, but also suggesting that a third cluster may exist. This third cluster is consistent with the growing body of Operations Management literature that is mainly focused on increasing the overall flexibility and efficiency of operations with the help of Industry 4.0, as illustrated by the findings of Zhang et al. (2020) and Hastig and Sodhi (2020). A possible explanation that complements those observations might lie in the nature of the factor "Perceived Implementation Benefits". The factor was divided into subclusters to account for the fact that our interview partners treated the desire to build new business models differently from the desire to increase the overall efficiency of processes, which is consequently also reflected by their respective connections to other factors in the CLD. This could mean that the differentiation between operational and business model-oriented goals is more important with respect to Industry 4.0 strategy development than previously assumed (Masood and Sonntag 2020). However, before drawing definite conclusions about this emerging cluster, more research needs to be conducted to better understand what distinguishes this cluster from the other two.

The calculated modularity of 0.332 gives further insight into the importance of factors within the network that have high betweenness centrality. Since our findings further strengthen the idea that implementing Industry 4.0 involves a number of factors that can be found either within or outside of the factory gates and that multiple leverage points may be necessary to effectively introduce change to the system, high betweenness centrality factors can help to spread change across different clusters (McGlashan et al. 2016).

The fact that all, except one, interviewed Industry 4.0 experts advocated for a more systematic approach to Industry 4.0 that involves multidisciplinary cooperation across institutions, offers a sound explanation for the high BC value of "Inter-Institutional Cooperation" and its central position in the network. Moreover, combined with its high out-degree, it is no surprise that "Inter-Institutional Cooperation" is the main hub in the network that connects the external implementation cluster with the internal one. Recent studies have presented evidence that cooperation plays a major role when it comes to overcoming certain implementation barriers, such as the lack of know-how and experience with smart technologies as well as new IT standards (Masood and Sonntag 2020, Saniuk et al. 2021, Stentoft et al. 2021). Moreover, the findings of Cugno et al. (2021) have shown that incentives such as Industry 4.0 support and awareness programs are not effectively targeting the barriers companies need to overcome while moving towards Industry 4.0, indicating a lack of coordination between key players such as the corporate sector and government institutions. In that context, our CLD offers new insights as to which implementation processes would directly benefit from cooperation, which could be used to tailor support programs around the needs of corporations. Furthermore, the discussed network structure of the CLD puts forward the idea that even when support programs are aimed at a specific barrier, such as the lack of skilled workers, they need to consider multiple factors in order to effectively target this Industry 4.0-related barrier. In that regard, our developed CLD can facilitate the identification of implementation factors that need to be acknowledged in order to develop more effective approaches.

While more and more studies recognise the importance of broader Industry 4.0 approaches and the importance of cooperation, initially, the field of Industry 4.0 was mainly focused on technological innovations and how companies can assess their readiness to integrate these new technologies into their infrastructures (Basl 2017, Lichtblau et al. 2015, Schumacher et al. 2016). Our research is still consistent with that part of the Industry 4.0 literature, illustrated by the high BC value and the high out-degree centrality of the factor "IT-Infrastructure Maturity". In the findings section, we demonstrated that every internal implementation factor is either directly dependant on the IT infrastructure of the organisation or indirectly connected to it through a short causal loop. It is probable therefore that every organisation's attempt to move towards Industry 4.0 stands and falls with their ability to efficiently manage and scale their IT-infrastructure, which may further help to explain why a great deal of Industry 4.0 literature is still focused on Industry 4.0 technologies (Ghobakhloo 2020, Nara et al. 2021). However, our findings also show that "IT-Infrastructure" has the second highest in-degree, which is unusual for high out-degree variables in a network and indicative of a dynamic and complex relationship to other factors. For example, we showed that while factors related to lean management and the creation of new business models highly depend on the infrastructure maturity, they also directly exert effects on the IT infrastructure.

Therefore, our findings broadly support the notion that the maturity of an IT infrastructure should not only be assessed based on its technological capabilities, but also based on their relationship to other implementation factors and drivers, as proposed by other recent investigations (Pozzi et al. 2021, Stentoft et al. 2021, Wagire et al. 2021).

Another compelling finding that has emerged from our centrality analysis is that the factor "New Business Models" has shown by far the highest in-degree among all factors and a comparatively low out-degree. This finding is unexpected as on the basis of our systematic literature review, we cautiously assumed that the creation of new Industry 4.0 business models would have an impact on other implementation factors (Hoyer et al. 2020). In contrast, the results of this study assert that more factors causally influence the creation of Industry 4.0-related business models, rather than the other way around. As a result, the degree to which other implementation factors influence the creation of new business models becomes more important than we previously assumed (Lin et al. 2018, Müller, Kiel, and Voigt 2018). However, what remains unchanged is the overall importance of the factor. As pointed out by McGlashan et al. (2016), factors with high indegree centrality can serve as a central hub for change in a network and therefore be viewed as an important factor to consider when implementing Industry 4.0. This is further reflected by the results of our previous survey in which the factor "Perceived Benefits" emerged as the most important implementation factor according to experienced Industry 4.0 practitioners.

4.6 Conclusions

The aim of the present research was to examine and map out the complexity inherent in the implementation of Industry 4.0 through the application of network analysis to a CLD developed based on in-depth interviews with Industry 4.0 experts. Our study has shown that a comprehensive grasp of the importance of Industry 4.0 implementation factors cannot be obtained without considering the role of each factor in a multicausal network. In that regard, through the application of network analysis, we determined the specific properties of the CLD to derive potential intervention points in the network to introduce and spread change more efficiently. These insights not only help to explain why focusing on one implementation factor can cause negative side effects, but also which factors are crucial to achieve a more effective implementation of Industry 4.0. The combination of systems thinking and network theory has allowed us to shed more light on the specific functions of previously investigated implementation factors. At the same time, through the identification of feedback loops, our findings demonstrate that the role of a given factor is not static, as it changes depending on which other factors it is connected to.

Our modularity test further supports the notion that the internal transformation process interacts with external implementation factors. The presented CLD can therefore be used to further expand our understanding of how external implementation factors exert influence on internal implementation processes and vice versa, thereby providing external key players, such as government institutions, with a more comprehensive understanding of how specific measures influence the transition process of corporations. Taken together, our findings therefore highlight the importance of approaching the implementation of Industry 4.0 in a systematic manner that accounts for its complexity. Scientific investigations should favour the application of holistic and interdisciplinary approaches to further improve our understanding of the underlying dynamics of implementing Industry 4.0. Similarly, we recommend that corporations and governments need to change their perspectives on Industry 4.0. Isolated use cases and pilot projects may be beneficial to assess the potential of certain technologies, but they fail to make allowances for the various factors that need to be considered to have a sustainable impact. Our findings suggest that strategic approaches that acknowledge the dynamic behaviour of complex adaptive systems are more likely to have a strong enough effect on the overall system to introduce lasting change.

4.6.1 Future Work and Limitations

The construction of our CLD was based on interviews with Industry 4.0 experts. Although we adapted the methods and recommendations from McGlashan et al. (2016) and Uleman et al. (2021) to increase the overall robustness of our approach and compared the results against the findings of our systematic literature review, a certain level of subjectivity cannot be avoided with respect to how the presented implementation factors are connected. Furthermore, a major challenge of CLDs is to find the right level of detail to avoid either difficult to comprehend or overly simplified representations of reality (Richards et al. 2021). The introduction of mutated CLDs to test how changing existing and adding new connections to the network influences the centrality measures of the presented CLD, however, has shown a strong resilience against random permutations, making alternative qualitative conclusions less likely (Uleman et al. 2021). As proposed by Uleman et al. (2021), conducting systematic reviews on every connection identified in the network might further strengthen the model.

Another important limitation of CLDs is their static nature when it comes to emergent behaviour, non-intuitive quantitative results and time delays (Richards et al. 2021, Richardson 1986, Sterman 2002). These factors can alter the properties of a given network by, for instance, changing the calculated centrality measures of variables within the network and thereby affecting the overall dynamic of the system. In future research, we will therefore aim to quantitively define the connections between Industry 4.0 implementation factors by collecting empirical data on implementation processes, to simulate different implementation scenarios, making it more suitable for practical application. Both the size of a corporation as well as the sector it is operating in are of particular interest in that regard, as their importance with respect to Industry 4.0 is still a subject of debate, as illustrated by our previous study (Hoyer et al. 2020). The resulting complex system dynamic model can then be used to develop implementation frameworks that consider the different characteristics of corporations and their Industry 4.0-specific goals, a component that all of the currently existing models lack. Furthermore, these quantitative models can then be used to study the portrayed feedback loops. Finally, as the field of Industry 4.0 is constantly evolving, we plan to further update the CLD alongside recent developments. Therefore, we support the notion shared by McGlashan et al. (2016) and Allender et al. (2015) that CLDs rarely reach a final stage as they change together with the evolving problem.

References

Abele, E., Anderl, R., Metternich, J., Wank, A., Anokhin, O., Arndt, A., Meudt, T., Sauer, M., 2015. Effiziente Fabrik 4.0. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 110 (3), 150–153, DOI: 10.3139/104.111293.

Adams, W.C., 2015. Conducting Semi-Structured Interviews. In: Newcomer, K.E., Hatry, H.P., Wholey, J.S. (Eds.). Handbook of Practical Program Evaluation. Hoboken, NJ, USA: John Wiley & Sons, Inc, 492–505.

Ahmed, S.E., 2017. Big and complex data analysis. Methodologies and applications / S. Ejaz Ahmed, editor. Cham, Switzerland: Springer.

Allender, S., Owen, B., Kuhlberg, J., Lowe, J., Nagorcka-Smith, P., Whelan, J., Bell, C., 2015. A Community Based Systems Diagram of Obesity Causes. PloS one, 10 (7), e0129683, DOI: 10.1371/journal.pone.0129683.

Bai, C., Dallasega, P., Orzes, G., Sarkis, J., 2020. Industry 4.0 technologies assessment: A sustainability perspective. International Journal of Production Economics, 229, 107776, DOI: 10.1016/j.ijpe.2020.107776.

Bakhtari, A.R., Waris, M.M., Sanin, C., Szczerbicki, E., 2021. Evaluating Industry 4.0 Implementation Challenges Using Interpretive Structural Modeling and Fuzzy Analytic Hierarchy Process. Cybernetics and Systems, 52 (5), 350–378, DOI: 10.1080/01969722.2020.1871226.

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

Basl, J., 2017. Pilot Study of Readiness of Czech Companies to Implement the Principles of Industry 4.0. Management and Production Engineering Review, 8 (2), 817, DOI: 10.1515/mper-2017-0012.

Benzerga, S., Hauf, D., Pretz, M., Bounfour, A., 2018. When Energy Revolution Meets Digital Transformation. In: Czarnowski, I., Howlett, R.J., Jain, L.C. (Eds.). Intelligent Decision Technologies 2017. Cham: Springer International Publishing, 65–81.

Berry, H.L., Waite, T.D., Dear, K.B.G., Capon, A.G., Murray, V., 2018. The case for systems thinking about climate change and mental health. Nature Climate Change, 8 (4), 282–290, DOI: 10.1038/s41558-018-0102-4.

Blondel, V.D., Guillaume, J.-L., Lambiotte, R., Lefebvre, E., 2008. Fast unfolding of communities in large networks. Journal of Statistical Mechanics: Theory and Experiment, 2008 (10), P10008, DOI: 10.1088/1742-5468/2008/10/P10008.

Bogner, A., Littig, B., Menz, W. (Eds.), 2009. Interviewing experts. Basingstoke [England], New York: Palgrave Macmillan.

Büchi, G., Cugno, M., Castagnoli, R., 2020. Smart factory performance and Industry 4.0. Technological Forecasting and Social Change, 150, 119790, DOI: 10.1016/j.techfore.2019.119790.

Buer, S.-V., Strandhagen, J.O., 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, 3 (4), 1–17, DOI: 10.1080/00207543.2018.1442945.

Cabrera, D., Colosi, L., Lobdell, C., 2008. Systems thinking. Evaluation and program planning, 31 (3), 299–310, DOI: 10.1016/j.evalprogplan.2007.12.001.

Calabrese, A., Levialdi Ghiron, N., Tiburzi, L., 2021. ‘Evolutions’ and ‘revolutions’ in manufacturers’ implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework. Production Planning & Control, 32 (3), 213–227, DOI: 10.1080/09537287.2020.1719715.

Castelo-Branco, I., Cruz-Jesus, F., Oliveira, T., 2019a. Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry, 107, 22–32, DOI: 10.1016/j.compind.2019.01.007.

Castelo-Branco, I., Cruz-Jesus, F., Oliveira, T., 2019b. Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry, 107, 22–32, DOI: 10.1016/j.compind.2019.01.007.

Ciliberto, C., Szopik-Depczyńska, K., Tarczyńska-Łuniewska, M., Ruggieri, A., Ioppolo, G., 2021. Enabling the Circular Economy transition: a sustainable lean manufacturing recipe for Industry 4.0. Business Strategy and the Environment, DOI: 10.1002/bse.2801.

Cimini, C., Boffelli, A., Lagorio, A., Kalchschmidt, M., Pinto, R., 2021. How do industry 4.0 technologies influence organisational change? An empirical analysis of Italian SMEs. Journal of Manufacturing Technology Management, 32 (3), 695–721, DOI: 10.1108/JMTM-04-2019-0135.

Coplien, J.O., Harrison, N., 2004. Organizational patterns of agile software development. Upper Saddle River, NJ: Pearson Prentice Hall.

Cugno, M., Castagnoli, R., Büchi, G., 2021. Openness to Industry 4.0 and performance: The impact of barriers and incentives. Technological Forecasting and Social Change, 168, 120756, DOI: 10.1016/j.techfore.2021.120756.

Da Silva, V.L., Kovaleski, J.L., Pagani, R.N., Silva, J.D.M., Corsi, A., 2020. Implementation of Industry 4.0 concept in companies: empirical evidences. International Journal of Computer Integrated Manufacturing, 33 (4), 325–342, DOI: 10.1080/0951192X.2019.1699258.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics, 204, 383–394, DOI: 10.1016/j.ijpe.2018.08.019.

Distelhorst, G., Hainmueller, J., Locke, R.M., 2017. Does Lean Improve Labor Standards? Management and Social Performance in the Nike Supply Chain. Management Science, 63 (3), 707–728, DOI: 10.1287/mnsc.2015.2369.

Fettermann, D.C., Cavalcante, C.G.S., Almeida, T.D.d., Tortorella, G.L., 2018. How does Industry 4.0 contribute to operations management? Journal of Industrial and Production Engineering, 35 (4), 255–268, DOI: 10.1080/21681015.2018.1462863.

Freixanet, J., Rialp, A., Churakova, I., 2020. How do innovation, internationalization, and organizational learning interact and co-evolve in small firms? a complex systems approach. Journal of Small Business Management, 7 (3), 1–34, DOI: 10.1111/jsbm.12510.

Ghobakhloo, M., 2020. Industry 4.0, digitization, and opportunities for sustainability. Journal of Cleaner Production, 252, 119869, DOI: 10.1016/j.jclepro.2019.119869.

Hansen, D., Shneiderman, B., Smith, M.A., Himelboim, I., 2019. Analyzing Social Media Networks with NodeXL. Insights from a Connected World / Derek Hansen, Ben Shneiderman, Marc A. Smith, Itai Himelboim.

Hansen, D.L., Shneiderman, B., Smith, M.A., 2011. Calculating and Visualizing Network Metrics. In: Analyzing Social Media Networks with NodeXL. Elsevier, 69–78.

Hastig, G.M., Sodhi, M.S., 2020. Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. Production and Operations Management, 29 (4), 935–954, DOI: 10.1111/poms.13147.

Hirsch-Kreinsen, H., 2016. Digitization of industrial work: development paths and prospects. Journal for Labour Market Research, 49 (1), 1–14, DOI: 10.1007/s12651-016-0200-6.

Hou, T., Cheng, B., Wang, R., Xue, W., Chaudhry, P.E., 2020. Developing Industry 4.0 with systems perspectives. Systems Research and Behavioral Science, 37 (4), 741–748, DOI: 10.1002/sres.2715.

Hoyer, C., Gunawan, I., Reaiche, C.H., 2020. The Implementation of Industry 4.0 - A Systematic Literature Review of the Key Factors. Systems Research and Behavioral Science, 37 (4), 557–578, DOI: 10.1002/sres.2701.

Jones, N.A., Ross, H., Lynam, T., Perez, P., Leitch, A., 2011. Mental Models: An Interdisciplinary Synthesis of Theory and Methods. Ecology and Society, 16 (1), DOI: 10.5751/ES-03802-160146.

Jonker, J., Karapetrovic, S., 2004. Systems thinking for the integration of management systems. Business Process Management Journal, 10 (6), 608–615, DOI: 10.1108/14637150410567839.

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

Kenzie, E.S., Parks, E.L., Bigler, E.D., Wright, D.W., Lim, M.M., Chesnutt, J.C., Hawryluk, G.W.J., Gordon, W., Wakeland, W., 2018. The Dynamics of Concussion: Mapping Pathophysiology, Persistence, and Recovery With Causal-Loop Diagramming. Frontiers in neurology, 9, 203, DOI: 10.3389/fneur.2018.00203.

Khan, A., Turowski, K., 2016. A Perspective on Industry 4.0: From Challenges to Opportunities in Production Systems. International Conference on Internet of Things and Big Data, 441–448, DOI: 10.5220/0005929704410448.

Kiani, B., Gholamian, M., Hamzehei, A., Hosseini, S., 2009. USING CAUSAL LOOP DIAGRAM TO ACHIEVE A BETTER UNDERSTANDING OF E-BUSINESS MODELS. International Journal of Electronic Business Management, 7, 159–167.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., Hoffmann, M., 2014. Industry 4.0. Business & Information Systems Engineering, 6 (4), 239–242, DOI: 10.1007/s12599-014-0334-4.

Layton, R., Watters, P.A., 2015. Algorithms for automating open source intelligence (OSINT). Rockland: Syngress.

Lee, M., Yun, J., Pyka, A., Won, D., Kodama, F., Schiuma, G., Park, H., Jeon, J., Park, K., Jung, K., Yan, M.-R., Lee, S., Zhao, X., 2018. How to Respond to the Fourth Industrial Revolution, or the Second Information Technology Revolution? Dynamic New Combinations between Technology, Market, and Society through Open Innovation. Journal of Open Innovation: Technology, Market, and Complexity, 4 (3), 21, DOI: 10.3390/joitmc4030021.

Leicht, E.A., Newman, M.E.J., 2008. Community structure in directed networks. Physical review letters, 100 (11), 118703, DOI: 10.1103/PhysRevLett.100.118703.

Li, F., 2020. Leading digital transformation: three emerging approaches for managing the transition. International Journal of Operations & Production Management, 40 (6), 809–817, DOI: 10.1108/IJOPM-04-2020-0202.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., Schmitt, K., Schmitz, E., Schröter, M., 2015. Industrie 4.0 READINESS.

Lin, D., Lee, C., Lau, H., Yang, Y., 2018. Strategic response to Industry 4.0: an empirical investigation on The Chinese automotive industry. Industrial Management & Data Systems, 34 (5), 0, DOI: 10.1108/IMDS-09-2017-0403.

Luthra, S., Mangla, S.K., 2018. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. Process Safety and Environmental Protection, 117, 168–179, DOI: 10.1016/j.psep.2018.04.018.

Mahaffy, P.G., Matlin, S.A., Holme, T.A., MacKellar, J., 2019. Systems thinking for education about the molecular basis of sustainability. Nature Sustainability, 2 (5), 362–370, DOI: 10.1038/s41893-019-0285-3.

Masood, T., Sonntag, P., 2020. Industry 4.0: Adoption challenges and benefits for SMEs. Computers in Industry, 121, 103261, DOI: 10.1016/j.compind.2020.103261.

McGlashan, J., Johnstone, M., Creighton, D., La Haye, K. de, Allender, S., 2016. Quantifying a Systems Map: Network Analysis of a Childhood Obesity Causal Loop Diagram. PloS one, 11 (10), e0165459, DOI: 10.1371/journal.pone.0165459.

McIntosh, M.J., Morse, J.M., 2015. Situating and Constructing Diversity in Semi-Structured Interviews. Global qualitative nursing research, 2, 2333393615597674, DOI: 10.1177/2333393615597674.

McKnight, W., 2014. Information management strategies for gaining a competitive advantage with data. Amsterdam: Elsevier.

Mendelson, H., 2000. Organizational Architecture and Success in the Information Technology Industry. Management Science, 46 (4), 513–529, DOI: 10.1287/mnsc.46.4.513.12060.

Metcalf, L., Casey, W., 2016. Cybersecurity and applied mathematics. Rockland: Syngress.

Müller, J.M., Buliga, O., Voigt, K.-I., 2018a. Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.12.019.

Müller, J.M., Kiel, D., Voigt, K.-I., 2018b. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. Sustainability, 10 (1), 247, DOI: 10.3390/su10010247.

Nara, E.O.B., Da Costa, M.B., Baierle, I.C., Schaefer, J.L., Benitez, G.B., do Santos, L.M.A.L., Benitez, L.B., 2021. Expected impact of industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry. Sustainable Production and Consumption, 25, 102–122, DOI: 10.1016/j.spc.2020.07.018.

Neumann, W.P., Winkelhaus, S., Grosse, E.H., Glock, C.H., 2021. Industry 4.0 and the human factor – A systems framework and analysis methodology for successful development. International Journal of Production Economics, 233, 107992, DOI: 10.1016/j.ijpe.2020.107992.

Oliveira, B.G., Liboni, L.B., Cezarino, L.O., Stefanelli, N.O., Miura, I.K., 2020. Industry 4.0 in systems thinking: From a narrow to a broad spectrum. Systems Research and Behavioral Science, 37 (4), 593–606, DOI: 10.1002/sres.2703.

Pacchini, A.P.T., Lucato, W.C., Facchini, F., Mummolo, G., 2019. The degree of readiness for the implementation of Industry 4.0. Computers in Industry, 113, 103125, DOI: 10.1016/j.compind.2019.103125.

Pozzi, R., Rossi, T., Secchi, R., 2021. Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies. Production Planning & Control, 1–21, DOI: 10.1080/09537287.2021.1891481.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A.B., Rajak, S., 2019. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 107546, DOI: 10.1016/j.ijpe.2019.107546.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A.B., Rajak, S., 2020. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 224, 107546, DOI: 10.1016/j.ijpe.2019.107546.

Raman, A., Rathakrishnan, M. (Eds.), 2019. Redesigning higher education initiatives for industry 4.0. Hershey PA: Information Science Reference.

Richards, C.E., Lupton, R.C., Allwood, J.M., 2021. Re-framing the threat of global warming: an empirical causal loop diagram of climate change, food insecurity and societal collapse. Climatic Change, 164 (3-4), DOI: 10.1007/s10584-021-02957-w.

Richardson, G.P., 1986. Problems with causal-loop diagrams. System Dynamics Review, 2 (2), 158–170, DOI: 10.1002/sdr.4260020207.

Roberts, N., 1978. Teaching Dynamic Feedback Systems Thinking: An Elementary View. Management Science, 24 (8), 836–843, DOI: 10.1287/mnsc.24.8.836.

Roxas, F.M.Y., Rivera, J.P.R., Gutierrez, E.L.M., 2019. Locating Potential Leverage Points In A Systems Thinking Causal Loop Diagram Toward Policy Intervention. World Futures, 75 (8), 609–631, DOI: 10.1080/02604027.2019.1654784.

Sahin, O., Salim, H., Suprun, E., Richards, R., MacAskill, S., Heilgeist, S., Rutherford, S., Stewart, R.A., Beal, C.D., 2020. Developing a Preliminary Causal Loop Diagram for Understanding the Wicked Complexity of the COVID-19 Pandemic. Systems, 8 (2), 20, DOI: 10.3390/systems8020020.

Saniuk, S., Caganova, D., Saniuk, A., 2021. Knowledge and Skills of Industrial Employees and Managerial Staff for the Industry 4.0 Implementation. Mobile Networks and Applications, DOI: 10.1007/s11036-021-01788-4.

Santos, Z.G.d., Vieira, L., Balbinotti, G., 2015. Lean Manufacturing and Ergonomic Working Conditions in the Automotive Industry. Procedia Manufacturing, 3, 5947–5954, DOI: 10.1016/j.promfg.2015.07.687.

Schumacher, A., Erol, S., Sihn, W., 2016. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. Procedia CIRP, 52, 161–166, DOI: 10.1016/j.procir.2016.07.040.

Shahin, M., Chen, F.F., Bouzary, H., Krishnaiyer, K., 2020. Integration of Lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises. The International Journal of Advanced Manufacturing Technology, 107 (5-6), 2927–2936, DOI: 10.1007/s00170-020-05124-0.

Sjödin, D.R., Parida, V., Leksell, M., Petrovic, A., 2018. Smart Factory Implementation and Process Innovation. Research-Technology Management, 61 (5), 22–31, DOI: 10.1080/08956308.2018.1471277.

Spector, J., Christensen, D.L., Sioutine, A.V., McCormack, D., 2001. Models and simulations for learning in complex domains: using causal loop diagrams for assessment and evaluation. Computers in Human Behavior, 17 (5-6), 517–545, DOI: 10.1016/S0747-5632(01)00025-5.

Staufen AG, 2019. Studie: Industrie 4.0 Index 2019.

Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., Haug, A., 2021. Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. Production Planning & Control, 32 (10), 811–828, DOI: 10.1080/09537287.2020.1768318.

Sterman, J.D., 2002. All models are wrong: reflections on becoming a systems scientist. System Dynamics Review, 18 (4), 501–531, DOI: 10.1002/sdr.261.

Sung, T.K., 2017. Industry 4.0: A Korea perspective. Technological Forecasting and Social Change, DOI: 10.1016/j.techfore.2017.11.005.

Symon, G., Cassell, C., 2012. Qualitative organizational research. Core methods and current challenges / Gillian Symon & Catherine Cassell. London: SAGE.

Uleman, J.F., Melis, R.J.F., Quax, R., van der Zee, E.A., Thijssen, D., Dresler, M., van de Rest, O., van der Velpen, I.F., Adams, H.H.H., Schmand, B., Kok, I.M.C.M. de, Bresser, J. de, Richard, E., Verbeek, M., Hoekstra, A.G., Rouwette, E.A.J.A., Olde Rikkert, M.G.M., 2021. Mapping the multicausality of Alzheimer's disease through group model building. GeroScience, 43 (2), 829–843, DOI: 10.1007/s11357-020-00228-7.

Vaidya, S., Ambad, P., Bhosle, S., 2018. Industry 4.0 – A Glimpse. Procedia Manufacturing, 20, 233–238, DOI: 10.1016/j.promfg.2018.02.034.

Wagire, A.A., Joshi, R., Rathore, A.P.S., Jain, R., 2021. Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. Production Planning & Control, 32 (8), 603–622, DOI: 10.1080/09537287.2020.1744763.

Whysall, Z., Owtram, M., Brittain, S., 2019. The new talent management challenges of Industry 4.0. Journal of Management Development, 38 (2), 118–129, DOI: 10.1108/JMD-06-2018-0181.

Xiong, G., 2012. Service science, management, and engineering. Theory and applications. Amsterdam, Hangzhou China: Elsevier/AP; Zhejiang University Press.

Zhang, F., Wu, X., Tang, C.S., Feng, T., Dai, Y., 2020. Evolution of Operations Management Research: from Managing Flows to Building Capabilities. Production and Operations Management, 29 (10), 2219–2229, DOI: 10.1111/poms.13231.

Chapter 5. Conclusion

5.1 Introduction

The main goal of the thesis was to identify the factors that play an important role when it comes to the implementation of Industry 4.0 and to understand why they are important, thereby laying the foundations for future research that takes into account the complexity that is inherent in Industry 4.0. The body of research is increasingly recognising that future investigations need to acknowledge the complex and interdisciplinary nature of Industry 4.0, resulting from the multicausal relationships between the implementation factors and the broad spectrum of Industry 4.0 applications. The thesis aimed to approach this task systematically by utilising validated research methods geared towards gaining a deeper and, at the same time, broader understanding of a chosen matter. Through this research design, this thesis sheds new light on the importance of the previously identified implementation factors. The present investigation also provides an extensive examination of the relationship between the factors that have been rated by Industry 4.0 practitioners and discussed by Industry 4.0 experts. Moreover, the findings further solidify the notion that the importance of a factor cannot be entirely understood without considering its relationship to other factors, leading to significant theoretical and managerial implications. In the section that follows, the main research findings and key implications will be summarised. The chapter will conclude with a discussion of future research opportunities and the limitations of the present research approach.

5.2 Summary of research findings

Taken together, the three presented studies offer a fresh perspective on the elements that make the implementation of Industry 4.0 complex and challenging. Publication 1 synthesised the findings of Industry 4.0-related studies across a variety of disciplines, showing that three important categories of implementation factors have been discussed so far (Figure 20).

Furthermore, the study proposed three different complexity layers of Industry 4.0: implementation complexity, system of systems management complexity, and technological complexity. Similarly, Publication 1 highlighted the lack of a clear definition of Industry 4.0 by showing that the term combines three core layers that need to be kept apart to avoid confusion: the historical layer, the conceptual layer, and the technological layer.

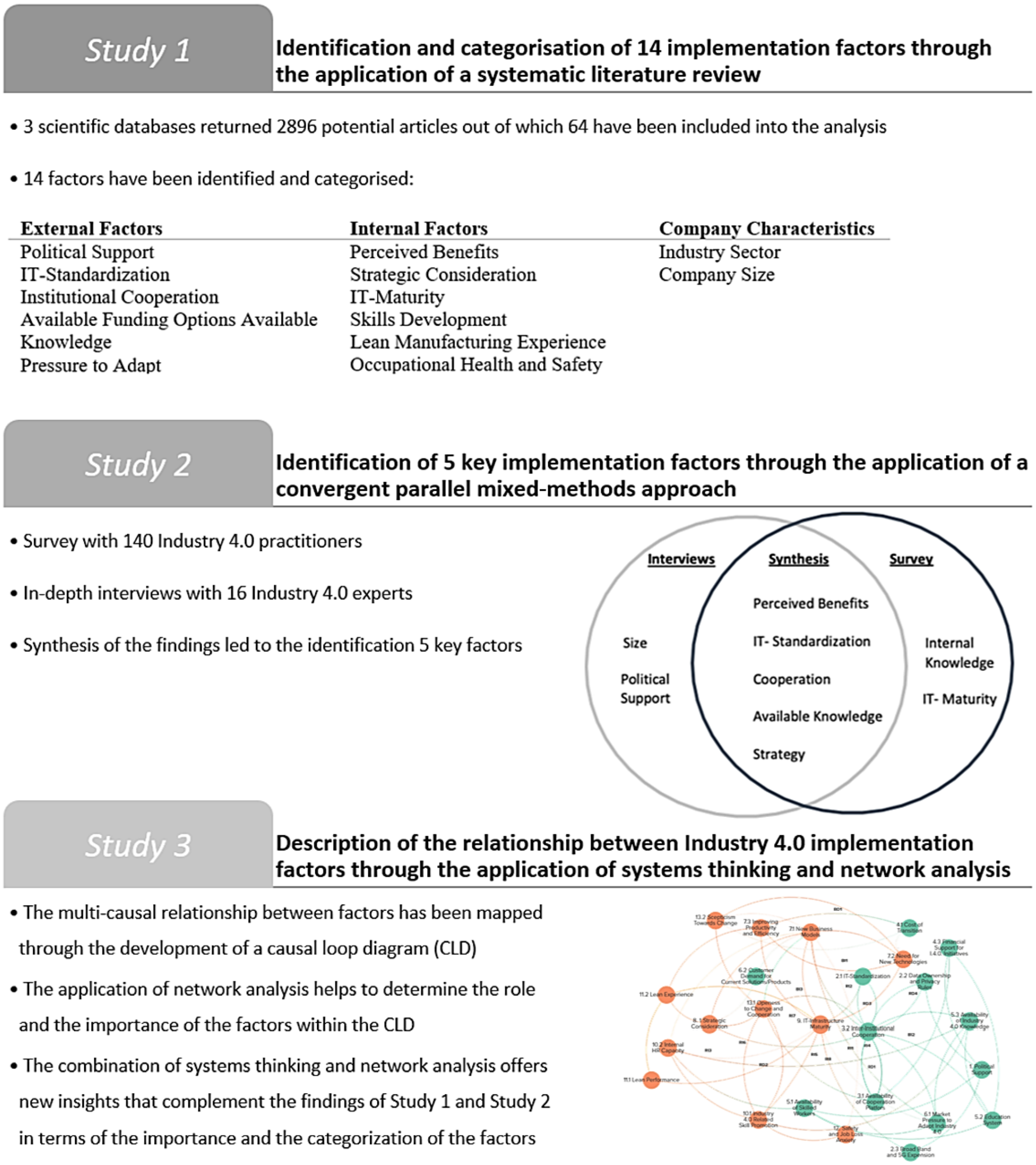

Figure 20. Summary of the key findings in the thesis

Publication 1 laid the groundwork for Publication 2, which was designed to address these shortcomings by examining the importance of the implementation factors according to Industry 4.0 practitioners and experts. Using a mixed-methods approach, the study not only quantitively demonstrated that the identified implementation factors are not similarly important, but also provided qualitative evidence as to what constitutes their importance. Most significantly though, Publication 2 identified a set of five key factors with the highest importance scores in the practitioner survey and the in-depth expert interviews, providing valuable insights into which implementation factors need to be examined further and considered when developing dedicated implementation strategies (Figure 20). Finally, Publication 3 complemented the findings of the two previous studies by assessing the relationship between the identified implementation factors. Publication 3 was able to demonstrate that the current understanding of the implementation factors and the transition process is incomplete. By combining systems thinking with network theory, it was shown that the roles and the importance of the implementation factors are not static and therefore must be interpreted based on their positions in the network as well as on their causal relationships to other factors. This was illustrated through the identification of feedback loops within the constructed CLD, which showed that one factor can be part of and relevant for multiple implementation processes and strategies, thereby playing different roles. Furthermore, by calculating the centrality values for each factor, it was highlighted which factors exert the most influence on other factors. Both findings expand our understanding of the criteria that determine the importance of the investigated implementation factors.

5.3 Research Implications

5.3.1 Theoretical Contributions

Although the field of Industry 4.0 has made significant steps forward since its inception in 2011, it also has experienced some growing pains (Maghazei and Netland 2017; Schneider 2018). A major goal of this thesis was therefore to contribute to the emerging body of knowledge by addressing some of the most significant gaps. In the following section, the major contributions and implications resulting from this endeavour will be emphasised.

First, the thesis has presented the first systematic review of Industry 4.0 implementation factors, synthesising what has already been discussed in the field and thereby addressing the existing fragmentation of knowledge in the field. The findings revealed that technological and financial issues may be important, but not the only factors that matter when it comes to implementing Industry 4.0. In total, 14 implementation factors were identified and discussed. Against this background, the extensive review of the literature also brought forward the idea that the term Industry 4.0 has three dimensions, which may help to explain the lack of widely accepted definition until now. Through the findings of Publication 2, the thesis was able to confirm the *raison d'être* of the previously identified implementation factors, as interview partners discussed the same factors previously identified in the systematic review. It is important to note that the interviewees were only asked which factors they consider important to avoid any form of bias. However, one additional factor emerged from the interviews that was not identified in the review of the literature, showing that the attitude towards change should be further investigated and considered when moving towards Industry 4.0. Finally, Publication 3 confirmed our initial categorisation of factors. Through a network cluster analysis, it was shown that internal implementation factors interact more with internal implementation factors, whereas external factors exhibited stronger connections to external factors. Consequently, Publication 3 supported the proposed differentiation between internal and external implementation. Future investigations aimed at developing implementation frameworks are therefore advised to focus on internal factors when it comes to the organisation's perspective, whereas more emphasis should lie on external factors in the context of developing effective support programs and initiatives. Moreover, factors with high centrality values such as "Inter-Institutional Cooperation" should be considered when it comes to solving issues that require both the help of the corporate sector as well as external key players, such as government institutions and research institutes.

Second, the results from our empirical study have confirmed that the presented implementation factors are not equally important. Experienced Industry 4.0 practitioners were asked to rate the factors according to their importance and to state at which stage of the transition they consider the factor to be most important. Through the application of a convergent parallel mixed-methods approach, these findings were then compared with the results from our interviews, showing that experts and practitioners mainly agree on the importance of the factors. As a result, Publication 2 was able to present the five most important factors according to the survey and the interviews, providing scientists and practitioners with more orientation when it comes to the questions of which implementation factors should be the centre of attention. In that context, the expert interviews helped to expand our understanding of why the identified factors are crucial for transition towards Industry 4.0 beyond what has already been discussed in the literature. What is more, through the application of the Kruskal-Wallis test, our findings show that the perceived importance of certain factors changes according to certain survey participant attributes, such as years of experience and industry sector, stressing the need to lay more emphasis on the context of the implementation of Industry 4.0 (Li 2020; Müller et al. 2018).

Finally, the thesis has raised important questions about the nature of the complexity of Industry 4.0 and its implementation. Recent findings have increasingly stressed the need to have a more holistic perspective of Industry 4.0 (Cimini et al. 2021; Raj et al. 2020). Sharing that notion, the thesis was based on a research design that considered the implementation of Industry 4.0 as a dynamic process. From a systematic literature review to a mixed-methods design to the combination of systems thinking and network analysis, the three studies were conducted to gain a broader and deeper understanding of that dynamic process. While the first two studies were focused on the identification and the importance of Industry 4.0 implementation factors, the final study mapped out the multicausal relationship between the factors. As such, the thesis contributes to the existing body of literature by describing how the identified factors are connected to each other and how they exert influence on each other and the overall network, suggesting that a comprehensive grasp of the importance and the function of the implementation factors cannot be obtained without considering their relationships with other factors. Through the identification of feedback loops and factors with high centrality values in the CLD, the thesis has also provided a deeper insight into the reasons why the transition process is so challenging. Besides knowing the implementation factors, future investigation also needs to consider the role that factors play in the proposed CLD and the adjacent factor's influence on these observed factors, increasing the overall difficulty of developing effective frameworks. Recent findings have shown that addressing the needs of companies that have embarked on implementing Industry 4.0 is demanding and that government institutions fail to introduce effective measures (Bakhtari et al. 2021; Castelo-Branco et al. 2019; Pozzi et al. 2021). The discussed feedback loops revealed some unexpected effects that might explain why support programs and incentives struggle to land where corporations face challenges that slow down or even stop the transition motion. In a similar vein, the centrality measures revealed some important points for intervention, illustrating which factors have the most significant and widest impact on others, further explaining why they are crucial when it comes to implementing Industry 4.0.

Overall, the thesis has introduced a novel perspective to the field of Industry 4.0 and demonstrated that acknowledging the complexity inherent in Industry 4.0 leads to new insights that complement and add to the rapidly expanding field.

5.3.2 Practical Implications

Besides the contribution to knowledge, the findings of the three studies provide important considerations for companies that want to implement Industry 4.0 and for government institutions that want to assist their local economy with the transition process. The major implications are discussed below.

First, the findings have shown that Industry 4.0 is constituted of more than just a wide range of technologies. In fact, only two of the identified implementation factors are directly related to either technological challenges or opportunities. Hence, managers should consider a more holistic approach towards Industry 4.0 and go through a controlled technology withdrawal. The thesis has provided a comprehensive overview of the building blocks that play an important role for the implementation of Industry 4.0. Moreover, Publication 2 has shed more light on the key factors that should be prioritised, offering managers more in-depth knowledge relevant for strategy articulation (Schneider 2018). In a similar vein, Publication 3 complements the findings of the first two studies by presenting more evidence that initiating change depends on a number of factors, depending on the influence these factors exert on other factors in the CLD presented in **Error! Reference source not found.** (Stentoft et al. 2021). A dditionally, Publication 3 discussed a number of feedback loops, illustrating how factors influence each other. Managers can use this knowledge to develop broader and more effective Industry approaches by considering the wider implications of implementing Industry 4.0 beyond technological advancements. Publication 3 also illustrated the key role of the factor "IT-Infrastructure Maturity", deduced from its high betweenness centrality in a sparse network. Consequently, technology matters in terms of how well managers are able to align the existing technological capabilities of their organisations' infrastructures with future business models, while shifting the focus away from the potential of future technologies towards the core competencies of an organisation.

Second, many findings have framed Industry 4.0 as a mainly technological and financial challenge for corporations (Braun et al. 2018; Jäger et al. 2016; Moktadir et al. 2018; Vaidya et al. 2018). However, as the field evolves, it becomes clearer that this view is flawed as it only explains a small proportion of the challenges that companies actually face during the implementation of Industry 4.0, as illustrated by recent investigations (Da Silva et al. 2020; Nara et al. 2021; Neumann et al. 2021). Supporting that notion, the thesis has presented a list of factors that reflect the challenges and the opportunities tied to the transition towards Industry 4.0, consequently further raising the question of which factors corporations should focus on to address the multitude of challenges. Publication 2 and Publication 3 have proposed inter-institutional cooperation as one of the most vital factors to consider in order to address critical implementation challenges. Its importance mainly arises from the increasing need of coordination between different disciplines and industry challenges that cannot be solved by managers themselves, such as defining industry standards for machine communication. As highlighted in Publication 2, companies that incorporate the philosophy of Industry 4.0 into their products and services must increasingly rely on IT specialists working together with engineers. Likewise, the coordination between different departments as well as between suppliers and customers will intensify with the introduction of Industry 4.0 to improve efficiency and service quality (Issa et al. 2018). Accordingly, the diplomatic duties of managers will take up more space both within and outside of the organisation. This idea is further encouraged by the findings of Publication 3, which indicated that the factor is highly interconnected with almost all other factors, elevating it to the nexus of Industry 4.0 implication. The emerging role of cooperation therefore must be taken into consideration when planning out the transition towards Industry 4.0, as many of the difficulties for managers lie in finding internal solutions for external problems. For example, "IT-Standardisation and Security" was identified as one of the most crucial factors according to practitioners and experts. In this connection, experts stated that the lack of standardisation increases the level of difficulty for managers to select technological solutions that are compatible with the IT infrastructures of all of their key suppliers and customers. This increases the amount of research on coordination for managers internally, as they are not able to define industry-wide standards on their own.

Third, Publication 2 revealed that both Industry 4.0 practitioners and experts consider "Perceived Implementation Benefits" as the principal implementation factor. In that context, new business model opportunities and the ability to design more efficient and productive processes have emerged as the dominant facets of the factor. Publication 3 confirmed this finding by showing that other implementation factors were mentioned together with these two facets exclusively besides the need for new technologies. Although this seems logical as these facets reflect the main incentives to adopt Industry 4.0, the findings of the thesis have further revealed important managerial implications. For example, Publication 2 showed that the importance of the factor “Perceived Benefits’ remains important throughout the entire transition period, suggesting that the factor is more than an initial motivator. In a similar vein, Publication 3 showed that the same factor does not influence many other factors but at the same time is influenced by most of them, illustrating its fragile and permanent nature. These findings further strengthen the idea that business models and Industry 4.0-related goals must be deeply embedded in the vision of the organisation and tailored around the capabilities of their IT infrastructure as well as the knowledge of the workforce. Organisations therefore must acknowledge the vulnerability of the factor resulting from changes introduced to other factors.

Finally, with respect to gaining a broader understanding of Industry 4.0, the findings of Publication 2 suggested that government organisations need to extend their programs for Industry 4.0 support initiatives such as test environments and use cases. These programs are considered the most effective way to help companies develop their Industry 4.0 ideas (Xu et al. 2018). Publication 2 further suggested that the gap between what the education infrastructure can deliver and what is in demand in the job market is continuously growing, adding more difficulties for companies that are still at the beginning of the transition. Unsurprisingly, the findings indicated that the need for knowledge from external sources peaks during the initiation phase. As a result, companies that experience limited access to skilled workers and support programs are less likely to obtain a comprehensive grasp of industry that enables them to articulate a broad and sustainable Industry 4.0 strategy. Furthermore, our findings suggest that these circumstances increase the ubiquitous temptation to focus on daily business and to approach Industry 4.0 through isolated projects. A vicious cycle that can broken by encouraging companies to adopt a broader perspective of Industry 4.0 and by promoting support programs that address the main challenges of an Industry 4.0 implementation. In this context, Publication 3 confirmed the central role of government support by illustrating its strong causal influence on external implementation factors in particular.

5.4 Future Research Agenda and Research Limitations

The thesis has successfully demonstrated that the implementation of Industry 4.0 depends on many factors that are not equally important. Furthermore, the thesis has illustrated and mapped out the multicausal relationships between the implementation factors. These findings build the foundation for future research that relies on developing effective implementation frameworks and guidelines. The thesis has also thrown up interesting questions in need of future research, but many overarching limitations that represent opportunities for future investigations will also be noted.

First, although the thesis has shown a broad consensus between Industry 4.0 experts and Industry 4.0 practitioners with respect to the importance of the implementation factors, a larger sample size for the surveys could further highlight the difference in importance perception among different groups. For example, due to the large variance in speed of adaption throughout different industry sectors, it is difficult to obtain an equal amount of survey responses across these sectors. Since Industry 4.0 is still a young concept, previous studies that have surveyed Industry 4.0 practitioners have faced similar issues (Rossini et al. 2019; Tortorella and Fettermann 2017). However, thanks to its popularity, it is reasonable to assume that the adaptation of Industry 4.0 will continue to grow, allowing for larger sample sizes. Future examinations can therefore further investigate the impact of the variables tested in the survey, such as time, industry sector, and profession. The resulting data can be used to account for the dynamic nature of Industry 4.0 to develop more accurate and company-specific implementation frameworks.

Second, Publication 1 showed that there is a lack of consensus in the literature with respect to what extent the size of a company affects the implementation of Industry 4.0. Interestingly, instead of shedding light on this issue, Publication 2 further solidified this gap by showing that Industry 4.0 practitioners do not consider the size as important whereas experts have argued that the factor is critical. More empirical evidence is therefore required to evaluate the impact of this factor. Besides the companies themselves, government institutions can use the resulting knowledge to develop implementation strategies based on the characteristics of their local economy.

Third, the implementation of Industry 4.0 as a research topic has recently gained momentum. It is therefore to be expected that new factors may emerge alongside new research findings, potentially changing the dynamic of the presented CLD in Publication 3. Accordingly, the presented findings in the thesis should be viewed as a static snapshot of a dynamic and ongoing process. The thesis therefore encourages future research to continue to explore potential implementation factors alongside their importance. With the discovery of a new factor in Publication 2, it was illustrated that the initial list of factors is incomplete, despite the application of a systematic literature review in Publication 1.

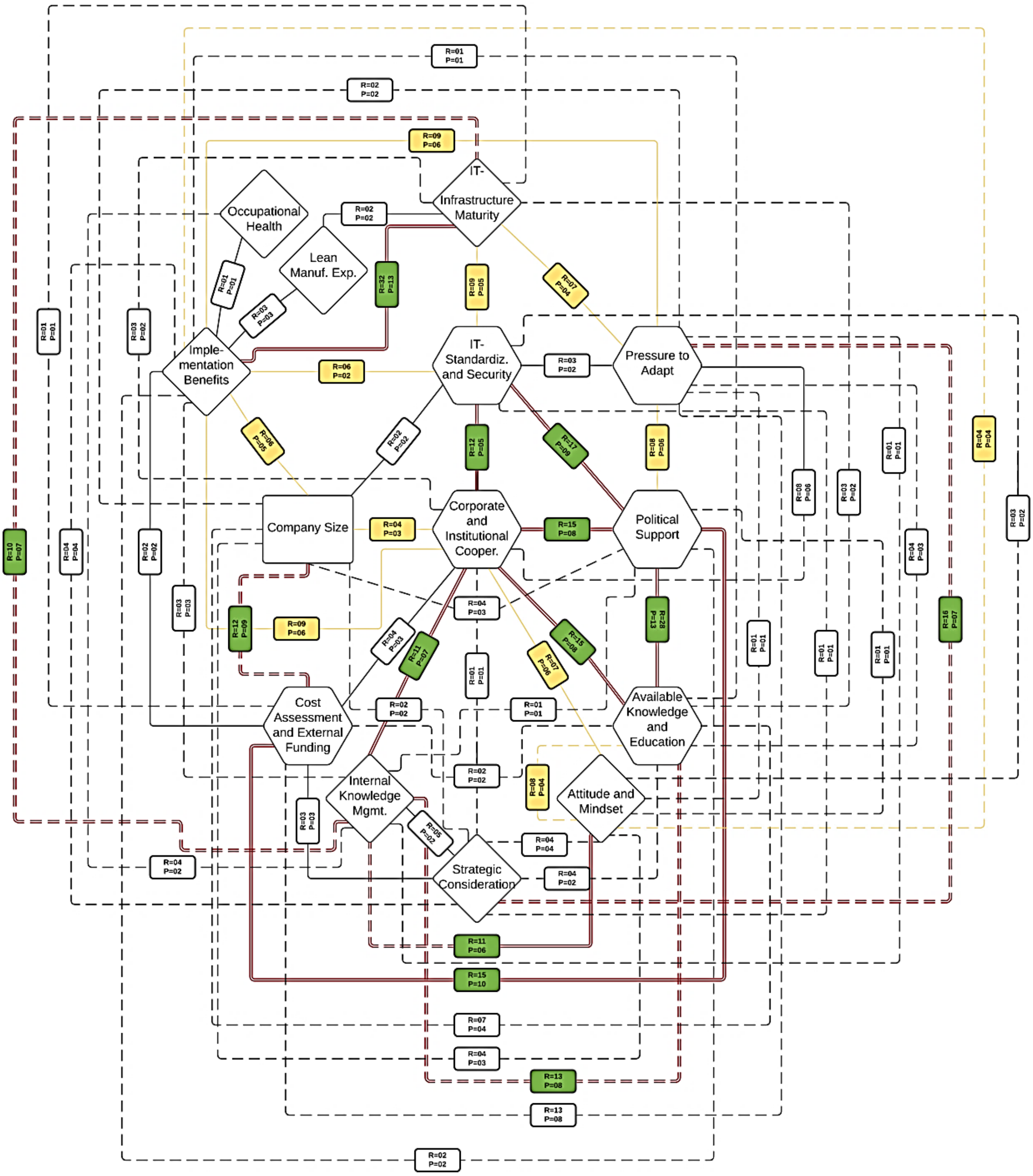

Figure 21. Strength of connections between implementation factors (green/red signals an above average strength, yellow an average strength, and white a below average strength)

Finally, Publication 3 has laid the foundation for the development of accurate and dynamic systems thinking models and hypothesis generation. Fed with quantitative data, these computational models can help to simulate scenario-based implementation processes that further examine the underlying dynamic relationship between the presented factors. For instance, the recent study of Richards et al. (2021) has shown that CLDs can be extended by adding the strength of the connection between two variables. The findings of Publication 3 can serve as a foundation to quantitatively explore how strong the connections are based on quantitative data. Figure 21 illustrates the strength of the connections by capturing how often a connection was mentioned (R) in the interviews of Publication 3 as well as how many participants mentioned it (P). Combined with additional empirical evidence, the accuracy of the proposed CLD can be further improved. However, despite adapting novel approaches that test the robustness of the implementation CLD, it is still an incomplete reflection of reality, like any other model (Sterman 2002). For example, its qualitative nature and the division of the factors into sub-factors further extend the spectrum of possible flaws in the model. Therefore, future research should not only use the insights discussed in this thesis to develop new systems thinking models, but also focus on further developing the presented CLD to increase the overall accuracy and predictability of future simulations.

References

Bakhtari AR, Waris MM, Sanin C, Szczerbicki E (2021) Evaluating Industry 4.0 Implementation Challenges Using Interpretive Structural Modeling and Fuzzy Analytic Hierarchy Process. Cybernetics and Systems 52:350–378. https://doi.org/10.1080/01969722.2020.1871226

Braun A, Ohlhausen P, Alt C, Bahlinger D, Chaves DC, Egeler M, Gramespacher S, Matzka J, Steinbeck J, Weber C (2018) Der Weg zur Industrie 4.0-Roadmap. ZWF 113:254–257. https://doi.org/10.3139/104.111888

Castelo-Branco I, Cruz-Jesus F, Oliveira T (2019) Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry 107:22–32. https://doi.org/10.1016/j.compind.2019.01.007

Cimini C, Boffelli A, Lagorio A, Kalchschmidt M, Pinto R (2021) How do industry 4.0 technologies influence organisational change? An empirical analysis of Italian SMEs. JMTM 32:695–721. https://doi.org/10.1108/JMTM-04-2019-0135

Da Silva VL, Kovaleski JL, Pagani RN, Silva JDM, Corsi A (2020) Implementation of Industry 4.0 concept in companies: empirical evidences. International Journal of Computer Integrated Manufacturing 33:325–342. https://doi.org/10.1080/0951192X.2019.1699258

Issa A, Hatiboglu B, Bildstein A, Bauernhansl T (2018) Industrie 4.0 roadmap: Framework for digital transformation based on the concepts of capability maturity and alignment. Procedia CIRP 72:973–978. https://doi.org/10.1016/j.procir.2018.03.151

Jäger J, Schöllhammer O, Lickefett M, Bauernhansl T (2016) Advanced Complexity Management Strategic Recommendations of Handling the “Industrie 4.0” Complexity for

Small and Medium Enterprises. Procedia CIRP 57:116–121. https://doi.org/10.1016/j.procir.2016.11.021

Li F (2020) Leading digital transformation: three emerging approaches for managing the transition. IJOPM 40:809–817. https://doi.org/10.1108/IJOPM-04-2020-0202

Maghazei O, Netland T (2017) Implementation of Industry 4.0 Technologies: What Can We Learn from the Past? In: Lödding H, Riedel R, Thoben K-D, Cieminski Gv, Kiritsis D (eds) Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing, vol 513. Springer International Publishing, Cham, pp 135–142

Moktadir MA, Ali SM, Kusi-Sarpong S, Shaikh MAA (2018) Assessing challenges for implementing Industry 4.0: Implications for process safety and environmental protection. Process Safety and Environmental Protection 117:730–741. https://doi.org/10.1016/j.psep.2018.04.020

Müller JM, Buliga O, Voigt K-I (2018) Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change. https://doi.org/10.1016/j.techfore.2017.12.019

Nara EOB, Da Costa MB, Baierle IC, Schaefer JL, Benitez GB, do Santos LMAL, Benitez LB (2021) Expected impact of industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry. Sustainable Production and Consumption 25:102–122. https://doi.org/10.1016/j.spc.2020.07.018

Neumann WP, Winkelhaus S, Grosse EH, Glock CH (2021) Industry 4.0 and the human factor – A systems framework and analysis methodology for successful development. International Journal of Production Economics 233:107992. https://doi.org/10.1016/j.ijpe.2020.107992

Pozzi R, Rossi T, Secchi R (2021) Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies. Production Planning & Control:1–21. https://doi.org/10.1080/09537287.2021.1891481

Raj A, Dwivedi G, Sharma A, Lopes de Sousa Jabbour AB, Rajak S (2020) Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics 224:107546. https://doi.org/10.1016/j.ijpe.2019.107546

Rossini M, Costa F, Tortorella GL, Portioli-Staudacher A (2019) The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers. Int J Adv Manuf Technol 102:3963–3976. https://doi.org/10.1007/s00170-019-03441-7

Schneider P (2018) Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. Rev Manag Sci 125:1. https://doi.org/10.1007/s11846-018-0283-2

Stentoft J, Adsbøll Wickstrøm K, Philipsen K, Haug A (2021) Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. Production Planning & Control 32:811–828. https://doi.org/10.1080/09537287.2020.1768318

Sterman JD (2002) All models are wrong: reflections on becoming a systems scientist. Syst. Dyn. Rev. 18:501–531. https://doi.org/10.1002/sdr.261

Tortorella GL, Fettermann D (2017) Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. International Journal of Production Research 22:1–13. https://doi.org/10.1080/00207543.2017.1391420

Vaidya S, Ambad P, Bhosle S (2018) Industry 4.0 – A Glimpse. Procedia Manufacturing 20:233–238. https://doi.org/10.1016/j.promfg.2018.02.034

Xu LD, Xu EL, Li L (2018) Industry 4.0: state of the art and future trends. International Journal of Production Research 20:1–22. https://doi.org/10.1080/00207543.2018.1444806

Appendices

A. Ethics Approval

THE UNIVERSITY *of* ADELAIDE

RESEARCH SERVICES
OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY
THE UNIVERSITY OF ADELAIDE

LEVEL 4, RUNDLE MALL PLAZA
50 RUNDLE MALL
ADELAIDE SA 5000 AUSTRALIA

TELEPHONE +61 8 8313 5137
FACSIMILE +61 8 8313 3700
EMAIL hrec@adelaide.edu.au

CRICOS Provider Number 00123M

Our reference 33272

07 November 2018

Associate Professor Indra Gunawan
Entrepreneurship, Commercialisation and Innovation Centre

Dear Associate Professor Gunawan

ETHICS APPROVAL No: H-2018-246
PROJECT TITLE: Exploring the factors that have an impact on the implementation of Industry 4.0

The ethics application for the above project has been reviewed by the Low Risk Human Research Ethics Review Group (Faculty of Arts and Faculty of the Professions) and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research (2007)* involving no more than low risk for research participants.

You are authorised to commence your research on: 07/11/2018
The ethics expiry date for this project is: 30/11/2021

NAMED INVESTIGATORS:

Chief Investigator:	Associate Professor Indra Gunawan
Student - Postgraduate Doctorate by Research (PhD):	Mr Christian Hoyer
Associate Investigator:	Dr Carmen Haule Reaiche
Associate Investigator:	Dr Scott Gordon

CONDITIONS OF APPROVAL: Thank you for your responses to the matters raised. The revised application provided on 07/11/18 has been approved.

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled Annual Report on Project Status is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the information sheet and the signed consent form to retain. It is also a condition of approval that you immediately report anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol or project investigators; and
- the project is discontinued before the expected date of completion.

Yours sincerely,

Dr Anna Olijnyk
Convenor

Dr Jungho Suh
Convenor
The University of Adelaide

B. Book Chapter (Artificial Intelligence in Industry 4.0)

Statement of Authorship

Title of Paper	Implementing Industry 4.0 - The Need for a Holistic Approach
Publication Status	☒ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Published in Artificial Intelligence in Industry 4.0 (Springer Nature)

Principal Author

Name of Principal Author (Candidate)	Christian Hoyer		
Contribution to the Paper	Conducted the systematic literature review and presentation of the findings		
Overall percentage (%)	70%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15.10.2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Assoc. Prof. Indra Gunawan		
Contribution to the Paper	15% - Evaluation of research articles and contribution to theory as well as methodology		
Signature		Date	15.10.2021

Name of Co-Author	Dr. Carmen Haule Reaiche		
Contribution to the Paper	15% - Evaluation of research articles and contribution to theory as well as methodology		
Signature		Date	15.10.2021

Please cut and paste additional co-author panels here as required.

Chapter 1
Implementing Industry 4.0—The Need for a Holistic Approach

Christian Hoyer, Indra Gunawan, and Carmen Haule Reaiche

Abstract Recent studies have shown that corporations around the world are aware of the topic industry 4.0 and the possible implications associated with it, such as more flexible, resilient, and productive manufacturing sites. While the outlook seems positive, the findings of several studies have also documented that most of the companies that are aware of industry 4.0 technologies and concepts still have not started to implement them. At the same time, corporations that are already engaged with the transition faced a considerable number of challenges. These challenges have been the subject of several investigations since the introduction of Industry 4.0 and illustrate why corporations seem to hesitate with initiating the transitional process. What is more, these findings also show that while some factors slow down the adaptation of new technologies and concepts related to Industry 4.0, other factors seem to have positive effects and even make a potential implementation more likely. However, to the frustration of practitioners, scientists, and governments, the current landscape of Industry 4.0 implementation research resembles a puzzle that has not been put together yet. As a result, the current status of the implementation of Industry 4.0 is difficult to comprehend at best as the referring knowledge and expertise are widely dispersed throughout a number of different publications. Furthermore, the potential dynamic between implementation factors cannot be examined if elements are treated as isolated and individual phenomena. In order to shed more light on this shortfall, this study set out to explore the factors that have an impact on the implementation of industry 4.0 and to build a solid foundation for future research that is mainly focused on a more coherent and complete understanding of the transition towards Industry 4.0 by acknowledging the dynamic between the already identified factors.

C. Hoyer · I. Gunawan (✉) · C. H. Reaiche
Business School, University of Adelaide, 9/10 Pulteney St, Adelaide, SA 5005, Australia
e-mail: indra.gunawan@adelaide.edu.au

C. Hoyer
e-mail: christian.hoyer@adelaide.edu.au

C. H. Reaiche
e-mail: carmen.reaiche@adelaide.edu.au

A. Dingli et al. (eds.), *Artificial Intelligence in Industry 4.0*,
Studies in Computational Intelligence 928,
https://doi.org/10.1007/978-3-030-61045-6_1

1.1 Introduction

Industry 4.0, also referred to as the Fourth Industrial Revolution, gained international attention after its introduction in the year 2011. This attention is not only coming from the scientific world, which is mostly engaged with technological aspects of Industry 4.0, but also from corporations and governments. While corporations are interested in how Industry 4.0 can make them more efficient and responsive, governmental institutions, on the other hand, are mainly focused on supporting their local business infrastructures in order to save and create jobs [11, 20, 30]. In this regard, some findings suggest that the technical focus of scientists results from the need of corporations to understand the potential and usability of new technological innovations before they consider integrating them [13]. However, studies also have shown that identifying the potential of certain technologies is not the only factor corporations consider when it comes to the implementation of Industry 4.0 [17, 18, 28]. In this context, a wide variety of potential factors that have an impact on the implementation of Industry 4.0 have been identified within the Industry 4.0 literature. These factors not only potentially make the implementation of Industry 4.0 more or less likely but also more or less successful. A comprehensive list of the factors as well as the knowledge illustrating why these factors are relevant in the context of implementing Industry 4.0, therefore, can help corporations, scientists, and governments to deal with the transition towards Industry 4.0 more efficiently. Yet, an investigation which compiles and validates the factors that have already been identified has not been carried out. Therefore, this paper will discuss how future investigations can close the resulting gap and shift the focus of Industry 4.0 more towards its implementation by creating a foundation for future research.

After an initial review of the literature, different categories of Industry 4.0 research emerged. One the one hand, Industry 4.0 readiness studies have presented different areas companies should focus on before implementing Industry 4.0. These studies are particularly focused on the measures that can be taken by corporations such as investing in a more open IT-infrastructure or in the promotion of employees. On the other hand, studies that assessed the opportunities and challenges of an Industry 4.0 implementation also presented external perspectives, such as the role of the government or the standardization of communication. The third category of studies focused on the implementation of Industry 4.0 technologies in certain environments, such as a production line of an automobile manufacturer. These studies offer a better understanding of the benefits corporations are expecting from implementing Industry 4.0 as well as which obstacles they faced during the transition. However, little attention has been paid to combine these findings in order to gain a comprehensive understanding of the factors that have an impact on the Implementation of Industry 4.0. The following section, therefore, provides an overview of relevant research areas before the first findings of the resulting systematic literature will be presented. Based on these findings, further questions that need to be addressed in future research will be identified and discussed.

1.2 Related Works

The status quo of the implementation of industry 4.0 can be derived from a number of different studies. This section will, therefore, present the most relevant categories of Industry 4.0 implementation research in order to illustrate the variety of potential sources and to facilitate future research undertakings. This section will illustrate that Industry 4.0 can be observed from various angles. Identifying these angles as well as bringing them together is crucial for the understanding of the big picture behind Industry 4.0 and its implementation.

1.2.1 Implementation Studies

Large-scale Industry 4.0 implementation studies offer a clear viewing angle on the topic and show the number of corporations that already have started with the transition towards Industry 4.0. In this context, several investigations suggest that the majority of corporations start to implement Industry 4.0 by initiating isolated projects [14, 27]. Corporations, therefore, first want to understand the underlying dynamics of an Industry 4.0 implementation before they start to choose a more comprehensive approach that encompasses the whole infrastructure. A plausible decision, as several studies came to the conclusion that corporations that have begun to implement Industry 4.0 struggle to achieve higher degrees. Other studies, in contrast, have been mainly focused on the challenges and opportunities of an Industry 4.0 implementation. Those studies offer possible explanations for what makes reaching higher degrees of Industry 4.0 difficult as well as why do companies hesitate to implement Industry 4.0 in the first place. For instance, the results of the empirical investigation of Lin et al. [12] challenged the view that the size of the company matters when it comes to the transition towards Industry 4.0. Nevertheless, previous investigations have shown the link between the size of a company and Industry 4.0 adaptation, illustrating the need for further investigation about the relevance of certain factors that already have been identified [18, 26]. The third category of studies that help to understand the dynamics of adapting Industry 4.0 is the category Industry 4.0 readiness indices. Investigations belonging to this stream of research typically identify areas companies need to improve in before they start to implement Industry 4.0. For example, Schumacher et al. [7] developed a maturity model that helps corporations to assess their own infrastructures to identify potential issues that need to be resolved before engaging with the transition towards Industry 4.0.

1.2.2 Industry 4.0 Technologies

While the previously mentioned categories of studies are directly tied to the implementation of Industry 4.0 and, therefore, provide a good overview of potential implementation factors, they are not representing the dominant part of research in that field. Instead, the majority of Industry 4.0 studies are rather focused on providing solutions for specific technical issues that might, or might not, be relevant for companies engaging in the transition towards Industry 4.0. In this sense, other factors such as the sector corporations are operating in or the compatibility with their infrastructure play a more dominant role. However, this does not mean that these studies can also be considered irrelevant for the research revolving around the implementation of Industry 4.0. They still present findings that allow drawing conclusions about what companies need to consider once they embark on implementing Industry 4.0 into their systems and processes. In this context, the study of Frank et al. [8] shows how findings on Industry 4.0 related technologies can be translated into concrete recommendations of actions on a more general basis that provides orientation for companies regardless of the technologies they intend to integrate into their own infrastructure. Consequently, this in its nature inductive approach can lead to further findings for a larger group of companies. What is more, it also allows taking studies into consideration that are mainly focused on technologies that regarded as Industry 4.0 technologies such as Big-Data and machine learning [10, 23, 31].

1.3 The Ancestors of Industry 4.0

The last categories of studies that can be considered relevant for the transition towards Industry 4.0 are studies that examine past industrial revolutions and studies that focus on the implementation of lean manufacturing. While both categories are not directly addressing Industry 4.0 by itself, they both allow making predictions about the overall development of Industry 4.0. For example, Maghazei and Netland [13] have shown parallels between the third and fourth industrial revolution by comparing the general approach taken by scientists. In both cases, the majority of published papers first examined the usefulness of potential technologies before the attention started to shift in favour of more implementation focused examinations.

On the other hand, building on the fact that Industry 4.0 is not mainly about technologies but on adapting and developing a new philosophy that helps to organize work more efficiently, scientist started to examine the connection between Lean Manufacturing and Industry 4.0 [2, 19, 20, 24]. Both approaches have far-reaching consequences for those who are trying to implement them into their companies [21]. Therefore, it is no surprise that scientists already have started to examine the transitional process of Lean Manufacturing in order to derive lessons that can help to improve the adaptation of Industry 4.0 technologies and, more importantly, principles. However, several investigations suggest that this relationship is not onedirectional as Lean Manufacturing also benefits from the advancements made in the field of Industry 4.0 [28].

1.4 Research Methods

As pointed out in the introduction to this paper, no single study exists that combined the recent findings which have been presented in the previous section. However, the combination of those findings is necessary in order to identify potential gaps that result from contradictory findings. Furthermore, an extensive list of factors that are important in the context of the implementation of Industry 4.0 has not been compiled so far. This list of factors could not only be used as a foundation for future research, but also serve as a map which gives orientation to all parties involved in the transition towards Industry 4.0 including corporations, governmental institutions, and universities. The tools that will be used to stake out that map will be presented in the following sections.

1.4.1 Systematic Literature Review

Systematic literature reviews help to identify and transparently select resources for a given topic. In order to maintain a predefined level of transparency, they follow a specific procedure that will be briefly described along with its four main phases [15, 29]. Firstly, appropriate search terms and research databases, as well as database settings, need to be selected based on a preliminary review of the literature. Secondly, filters must be defined to select papers that are relevant to the context of the investigation. Thirdly, the selected search terms and databases now will return scientific publications based on the predefined selection criteria. The filters, on the other hand, will then be used to remove duplicates and papers that are classified as not relevant after screening the titles and abstracts. Finally, the remaining articles will be thoroughly analysed in order to identify potential Industry 4.0 implementation factors. Papers that do not mention implementation factors or did not explain why those factors may be relevant will not be considered for the final analysis.

1.4.2 Qualitative Approach

Building on the results of the systematic literature review, qualitative and quantitative investigations will be conducted to validate the findings from the systematic literature review. In this context, interviewing participants who have been, or still are, involved in the transition towards Industry 4.0 provides insights into their motivation to get engaged with the topic. However, further selection criteria such as the current job position of the participant and the sector his/her organization is operating in will be applied in order to make sure that the research reflects the variety of companies, universities and governmental institutions involved in the implementation process. The interviews will then be used to identify the perceived benefits and the obstacles the participating individuals together with their organizations have faced as well as how their perception has changed over time. The resulting information will be translated into factors and compared with the results from the systematic literature review and the survey.

1.4.3 Quantitative Approach

The goal of the survey, on the other hand, is to find out how important the factors are that have been identified within the existing literature. However, since the implementation of Industry 4.0 is a long process, different implementation stages along the overall timeline will be introduced to participants. This allows them not just to state how important they perceive a given factor, but also when they think this factor becomes the most relevant. In other words, participants will also be asked to state when certain factors become particularly important during the transitional process. This is important as certain factors might be more critical at the beginning of the implementation phase, while other factors might become relevant towards the end of the transition.

1.4.4 Triangulation

By triangulating the results of the systematic literature review, the interviews, and the survey, a framework can be designed which is tailored around the question which factors are important in the context of implementing Industry 4.0. As previously mentioned, a multidimensional approach will be applied to make sure that the dynamic nature of the implementation process is sufficiently considered. In this respect, several studies have suggested that companies are at different stages of implementing Industry 4.0, which is why it is crucial to design a framework that takes these conditions into account [6]. However, while the needs of corporations build the core of the framework, it will also be addressed to other key players in the field. For instance, the framework can help scientists to get a better understanding of the research areas and factors that deserve more attention. Governmental institutions, on the other hand, can address the problems of their local business environment more accurately and as a result, contribute to more efficient funding measures.

1.5 Discussion

The systematic literature review identified fourteen factors (Table 1.1) that may be important in the context of the implementation of Industry 4.0. To illustrate the nature of those factors, three main categories have been designed from the perspective of corporations: External factors, internal factors, and company characteristics. However, the proposed categories are only a starting point as other categories might emerge throughout the course of the investigation.

1.5.1 External Factors

External factors are factors that are out of the reach of corporations' control. In other words, external factors cannot be influenced by the actions of single corporations. For instance, even though studies suggest that funding options matter in the context of implementing Industry 4.0, companies are not able to directly increase the number of available options. Hence, external factors particularly deserve the attention of governmental institutions and initiatives that want to support companies with the transitional process.

1.5.2 Internal Factors

In contrast, internal factors are factors that can be directly influenced by the actions of corporations. For example, as the review of the literature shows, the promotion of Industry 4.0 knowledge and skills might be relevant regarding an Industry 4.0 adaptation. However, companies themselves have to decide to which degree they promote these skills. Even though internal factors mainly fall under the responsibility of the organizations themselves, Industry 4.0 initiatives and governmental institutions can still have either a positive or negative impact on organizations' ability to address

Table 1.1 Industry 4.0—implementation factors

External factors	Internal factors	Company characteristics
Political support	Perceived benefits	Industry sector
IT-standardization	Strategic consideration	Company size
Institutional cooperation	IT-maturity	
Available funding options	Skills development	
Available knowledge	Lean manufacturing experience	
Pressure to adapt	Occupational health and safety	

these factors. For example, while the factor IT-Maturity mainly refers to the current state of the IT-Infrastructure in terms of flexibility and skill level, governments can initiate programs that facilitate and encourage the migration of foreign IT-experts. As a result, companies would be given more options to find specialized IT-workers [25].

1.5.3 Company Characteristics

Company characteristics, on the other hand, is a category that lists all the factors that are considered as neutral such as the size of a company or the sector it is operating in. While these factors cannot be influenced by external nor internal actions as they have a descriptive function, they still hold valuable information when it comes to the implementation of Industry 4.0. This became particularly clear after reviewing the relevant literature, which has shown that different industry sectors are more likely to implement Industry 4.0 than others. A fact that can help governmental institutions to develop Industry 4.0 measures that fit the needs of their local businesses, as mentioned previously.

1.5.4 The Dynamic Relationship Between Factors

As stated at the beginning of this article, the goal of the present research is to build a robust foundation for future Industry 4.0 implementation investigations. The results introduced above represent the first step of this endeavour. In this regard, the systematic review of the literature has shown that several factors have been the subjects of discussion throughout a wide range of publications, while none of the identified studies has synthesised or discussed all of the factors presented in this article. This increases the difficulty for corporations, governments, and scientist to get a holistic understanding of it. Furthermore, since most of the Industry 4.0 publications are referring to technological challenges and potentials, it may seem that these challenges, consequently, deserve more attention than others. However, as several studies have shown, not all of the challenges companies are currently experiencing are related to Industry 4.0 technologies [27]. Hence, the presented findings strengthen the idea that the factors, as well as the relationship between them, need to be discussed in greater detail. In the same vein, the findings suggest that the information on the factors themselves are sometimes contradicting, further demonstrating the need for a broader scientific discussion that helps to put the implementation of Industry 4.0 into perspective.

The three categories have been created to support that sense-making advancement by illustrating that different parties have an impact on the transitional process. For instance, the factor "Available Knowledge" has been classified as an external factor as it is mainly outside of the control of corporations. It refers to the knowledge that is available for corporations in various forms such as qualified employees on the job market and Industry 4.0 implementation guidelines. While companies can and do work together with universities and governments, it is still difficult for them to steer education policy or curriculum decisions in a particular direction. Hence, universities and governments have a more substantial impact on this factor. On the other hand, the factor "Skills Development" has been classified as an internal factor, while also mainly revolving around education as a necessary resource. Qualifying employees through programs, offering Industry 4.0 specific training, and initiating internal Industry 4.0 awareness campaigns are measures that can be taken by the corporations themselves to address the potential shortcomings of the job market. This example highlights the dynamic relationship between various factors and the created categories. In this context, the relationship between two or more chosen factors as well as between categories also depends on other factors. Going back to the education example, the ability of a company to compensate for a potential lack of qualified workers on the job market by intensifying the internal promotion of skills also depends on other factors such as whether a company has enough time and resources to increase its activities beyond the day-to-day operations. On the other hand, for governments and universities to effectively support this process, they first need to identify the needs and the specific characteristics of their local corporate infrastructure.

While it is unclear whether the presented categorisation of the factors serves its purpose or if a different and a more efficient form results from future investigations, it can be noted that relationship between the factors plays an important role and that this relationship deserves more attention. Similarly, it is too early to state that the presented list of factors is complete. The factor "Occupational Health and Safety" is a good example of this as compared to other factors; only two publications have discussed it so far in the context of the implementation of Industry 4.0. Therefore, it is likely that more factors will be added to the list over time [1].

1.6 Conclusion and Future Work

Implementing Industry 4.0 is an undertaking that depends on a number of factors that need to be considered. Furthermore, the results of the systematic review suggest that interrelations between various factors exist. These interactions offer another perspective on the implementation dynamics. Consequently, this perspective further argues in favour of a holistic approach when it comes to transitioning towards Industry 4.0. In addition, it can help to develop a broader understanding of Industry 4.0 which, for example, makes corporations and governments more aware of potential pitfalls.

1.6.1 Conclusion

Overall, the systematic literature review revealed that a number of potential factors that are important in the context of implementing Industry 4.0. However, the relevance of the identified factors cannot be derived from the findings of the review. While some factors have been mentioned more frequently than others, the question of the importance of each factor cannot be answered based on the number of references they appeared in. Furthermore, the analysis of the literature indicates that some findings contradict each other. For example, as previously mentioned, some findings suggest that the size of a company matters when it comes to the implementation of Industry 4.0 whereas other findings were not able to confirm this assumption [3, 5, 16]. Therefore, future investigations should be focused on validating the findings of the systematic literature review. As previously proposed, interviewing experts, as well as designing a survey that tests the findings of the systematic literature review, can help to create a solid foundation on which further investigations can be built. Once the most important factors are known and validated, it is essential to conduct further investigations that try to explain how companies, governmental institutions, and universities have to deal with certain factors. While knowing that the promotion of Industry 4.0 skills is important when it comes to implementing Industry 4.0, it still does not answer the question of which skills are particularly important or how certain skills should be taught.

1.6.2 Future Work

Without drifting off into trivia and without looking into the future through a crystal ball, it already can be stated that technologies referred to Industry 4.0, such as Cyber-Physical Systems and Artificial Intelligence, will have a significant impact on corporations organize work [4, 10, 22]. The answers to questions like to which degree workers will use smart glasses or how many jobs will fall victim to autonomous systems, still, cannot be answered yet [9]. Depending on which of the various interpretations and visions of Industry 4.0 paves its way to the core of how companies organize their work, the process of answering the previous questions can gradually become more than empirical curve-fitting and guesswork. What, in contrast, seems sufficiently inevitable, is that companies will have a significant share of the forces that shape the fourth industrial revolution as they, for instance, decide which machine communication protocols will be used or how the data of their employees will be processed. Against this backdrop, examining relevant factors can contribute to making the implementation of Industry 4.0 more accessible and therefore more diverse, helping those corporations that would otherwise stand on the sideline.

References

1. Badri, A., Boudreau-Trudel, B., Souissi, A.S.: Occupational health and safety in the industry 4.0 era: a cause for major concern? Saf. Sci. **109**, 403–411 (2018)
2. Bhamu, J., Sangwan, K.S.: Lean manufacturing: literature review and research issues. Int. J. Oper. Prod. Manag. (2014)
3. Braun, A., et al.: Der Weg zur Industrie 4.0-Roadmap. ZWF Z. Wirtsch. Fabr. **113**(4), 254–257 (2018)
4. Cohen, Y., Naseraldin, H., Chaudhuri, A. et al.: Assembly systems in industry 4.0 era: a road map to understand assembly 4.0. Int. J. Adv. Manuf. Technol. **105**, 4037–4054 (2019)
5. Deloitte Insights: The Fourth Industrial Revolution Is Here - Are You Ready. Deloitte Development LLC (2018)
6. Erol, S., Schumacher, A., Sihn, W.: Strategic guidance towards industry 4.0–a three-stage process model. In: International Conference on Competitive Manufacturing, vol. 9, pp. 495–501 (2016)
7. German Frank, A., Santos Dalenogare, L., Fabian Ayala, N.: Industry 4.0 technologies: implementation patterns in manufacturing companies. Int. J. Prod. Econ. **210**, 15–26 (2019)
8. Hamzeh, R., Zhong, R., Xu, X.: A survey study on industry 4.0 for New Zealand manufacturing. Procedia Manuf. **26**, 49–57 (2018)
9. Kong, X., Luo, H., Huang, G., Yang, X.: Industrial wearable system: the human-centric empowering technology in industry 4.0. J. Intell. Manuf. **30**(8), 2853–2869 (2018)
10. Li, B., Hou, B., Yu, W., Lu, X., Yang, C.: Applications of artificial intelligence in intelligent manufacturing: a review. Front. Inf. Technol. Electron. Eng. **18**(1), 86–96 (2017)
11. Liao, Y., Deschamps, F., Loures, E., Ramos, L.: Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. Int. J. Prod. Res. **55**(12), 3609–3629 (2017)
12. Lin, D., Lee, C., Lau, H., Yang, Y.: Strategic response to industry 4.0: an empirical investigation on the Chinese automotive industry. Ind. Manag. Data Syst. **118**(3), 589–605 (2018)
13. Maghazei, O., Netland, T.: Implementation of industry 4.0 technologies: what can we learn from the past? In: IFIP International Conference on Advances in Production Management Systems, pp. 135–142 (2017)
14. McKinsey, D.: "Industry 4.0 after the initial hype", Where manufacturers are finding value and how they can best capture it (2016)
15. Moher, D. et al.: Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst. Rev. **4**(1) (2015)
16. Moica, S., Ganzarain, J., Ibarra, D., Ferencz, P.: Change made in shop floor management to transform a conventional production system into an "industry 4.0": case studies in SME automotive production manufacturing. In: 2018 7th International Conference on Industrial Technology and Management (ICITM), pp. 51–56 (2018)
17. Mueller, E., Chen, X., Riedel, R.: Challenges and requirements for the application of industry 4.0: a special insight with the usage of cyber-physical system. Chin. J. Mech. Eng. **30**(5), 1050–1057 (2017)
18. Müller, J., Buliga, O., Voigt, K.: Fortune favors the prepared: how SMEs approach business model innovations in industry 4.0. Technol. Forecast. Soc. Chang. **132**, 2–17 (2018)
19. Martínez Sánchez, A., Pérez Pérez, M.: Lean indicators and manufacturing strategies. Int. J. Oper. Prod. Manag. **21**(11), 1433–1452 (2001)
20. Roblek, V., Meško, M., Krapež, A.: A complex view of industry 4.0. SAGE Open **6**(2), 215824401665398 (2016)
21. Rossini, M., Costa, F., Tortorella, G., Portioli-Staudacher, A.: The interrelation between industry 4.0 and lean production: an empirical study on European manufacturers. Int. J. Adv. Manuf. Technol. **102**(9–12), 3963–3976 (2019)
22. Saniuk, S., Saniuk, A., Cagáňová, D.: Cyber industry networks as an environment of the industry 4.0 implementation. Wirel. Netw. (2019)

23. Serdyukov, V., Serdyukova, N., Shishkina, S.: Improving operational reliability by means of artificial intelligence. Russ. Eng. Res. **38**(1), 15–18 (2018)
24. Shah, R., Ward, P.: Lean manufacturing: context, practice bundles, and performance. J. Oper. Manag. **21**(2), 129–149 (2003)
25. Sivathanu, B., Pillai, R.: Smart HR 4.0 - how industry 4.0 is disrupting HR. Hum. Resour. Manag. Int. Dig. **26**(4), 7–11 (2018)
26. Sommer, L.: Industrial revolution - industry 4.0: are German manufacturing SMEs the first victims of this revolution? J. Ind. Eng. Manag. **8**(5) (2015)
27. Stauffen, A.: Deutscher Industrie 4.0 Index. Industrie (2018)
28. Tortorella, G., Fettermann, D.: Implementation of industry 4.0 and lean production in Brazilian manufacturing companies. Int. J. Prod. Res. **56**(8), 2975–2987 (2017)
29. Tranfield, D., Denyer, D., Smart, P.: Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br. J. Manag. **14**(3), 207–222 (2003)
30. Wang, S., Wan, J., Li, D., Zhang, C.: Implementing smart factory of Industrie 4.0: an outlook. Int. J. Distrib. Sens. Netw. **12**(1), 3159805 (2016)
31. Xu, L.D., Duan, L.: Big data for cyber physical systems in industry 4.0: a survey. Enterp. Inf. Syst. 13(2), 148–169 (2019)

C. Conference Paper presented at the International Conference on Industry 4.0 and Artificial Intelligence Technologies 2019

Statement of Authorship

Title of Paper	Exploring the Factors that are Important in the Context of Industry 4.0
Publication Status	☒ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Presented at International Conference on Industry 4.0 and Artificial Intelligence Technologies 2019

Principal Author

Name of Principal Author (Candidate)	Christian Hoyer		
Contribution to the Paper	Conducted the systematic literature review and presentation of the findings		
Overall percentage (%)	70%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	15.10.2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Assoc. Prof Indra Gunawan		
Contribution to the Paper	15% - Evaluation of research articles and contribution to theory as well as methodology		
Signature		Date	15.10.2021

Name of Co-Author	Dr Carmen Haule Reaiche		
Contribution to the Paper	15% - Evaluation of research articles and contribution to theory as well as methodology		
Signature		Date	15.10.2021

Please cut and paste additional co-author panels here as required.

Exploring the Factors that are Important in the Context of Industry 4.0

Christian Hoyer[1], **Indra Gunawan**[1] **and Carmen Haule Reaiche**[1]

[1]*Entreprenuership, Commercialisation and Innovation Centre (ECIC), University of Adelaide, Australia*

Email: christian.hoyer@adelaide.edu.au[1], indra.gunawan@adelaide.edu.au [1], carmen.reaiche@adelaide.edu.au[1]

Abstract: Recent studies have shown that corporations around the world are aware of the topic industry 4.0 and the possible implications associated with it such as more flexible, resilient, and productive manufacturing sites. However, the findings of several studies have also documented that most of the companies that are aware of industry 4.0 technologies and concepts still have not started to implement them. In order to shed more light on this shortfall, this study set out to examine the factors that have an impact on the implementation of industry 4.0 and to build a solid foundation for future research.

Keywords: Industry 4.0; industrial revolution; implementation; systematic literature review

1 Introduction

Industry 4.0, also referred to the Fourth Industrial Revolution, gained international attention after its introduction in the year 2011. This attention is not only coming from the scientific world, which is mostly engaged with technological aspects of Industry 4.0, but also from corporations and governments. While corporations are interested in how Industry 4.0 can make them more efficient and responsive, governmental institutions, on the other hand, are mainly focused on supporting their local business infrastructures in order to save and create jobs [2, 10, 15]. In this regard, some findings suggest that the technical focus of scientists results from the need of corporation to understand the potential and usability of new technological innovations before they consider integrating them [5]. However, studies also have shown that identifying the potential of certain technologies is not the only factor corporations consider when it comes to the implementation of Industry 4.0 [8, 9, 13]. In this context, a wide variety of potential factors that have an impact on the implementation of Industry 4.0 have been identified within the Industry 4.0 literature. These factors not only make the implementation of Industry 4.0 more or less likely but also more or less successful. A compressive list of the factors as well as the knowledge why these factors are relevant in the context of implementing Industry 4.0, therefore, can help corporations, scientists, and governments to deal with the transition towards Industry 4.0 more efficiently. Yet, an investigation which compiles and validates the factors that have already been identified has not been carried out. Therefore, this paper will discuss how future investigations can close the resulting gap and shift the focus of Industry 4.0 more towards its implementation by creating a foundation for future research. Answering the questions which factors are important, when they are important, and how important they are, will be an essential part of the proposed foundation.

International Conference on Industry 4.0 and Artificial Intelligence Technologies (INAIT 2019)
Venue: Hughes Hall, University of Cambridge, United Kingdom
August 19-20, 2019
https://www.inait-conf.org

2 Related works

The status quo of the implementation of industry 4.0 can be derived from a number of different studies. For example, large-scale Industry 4.0 implementation studies show the number of corporations that already have started with the transition towards Industry 4.0. In this context, the findings of the Staufen AG suggest that the majority of corporations start to implement Industry 4.0 by initiating isolated projects [12]. Corporations, therefore, first want to understand the underlying dynamics of an Industry 4.0 implementation before they start to choose a more comprehensive approach that encompasses the whole infrastructure. A plausible decision as several studies came to the conclusion that corporations that have started to implement Industry 4.0 struggle to achieve higher degrees [6, 12]. Other studies, in contrast, have been mainly focused on the challenges and opportunities of an Industry 4.0 implementation. Those studies offer possible explanations for what makes reaching higher degrees of Industry 4.0 difficult as well as why do companies hesitate to implement Industry 4.0 in the first place. For instance, the results of the empirical investigation of Lin et al. [4] challenged the view that the size of the company matters when it comes to the transition towards Industry 4.0. Nevertheless, previous investigations have shown the link between the size of a company and Industry 4.0 adaptation, illustrating the need of further investigation about the relevance of certain factors that already have been identified [3, 9, 11]. The third category of studies that help to understand the dynamics of adapting Industry 4.0 is the category Industry 4.0 readiness indices. Investigations belonging to this stream of research typically identify areas companies need to improve in before they start to implement Industry 4.0. For example, Schumacher et al. [1] developed a maturity model which helps corporations to assess their own infrastructures to identify potential issues that need to be resolved before engaging with the transition towards Industry 4.0.

3 Research Methods

As pointed out in the introduction to this paper, no single study exists that combined the recent findings which have been presented in the previous section. However, the combination of those findings is necessary in order to identify potential gaps which result from contradictory findings. Furthermore, an extensive list of factors that are important in the context of the implementation of Industry 4.0 has not been compiled so far. This list of factors could not only be used as a foundation for future research, but also serve as a map which gives orientation to all parties involved in the transition towards Industry 4.0 including corporations, governmental institutions, and universities. Therefore, a systematic literature review that identifies all the factors that have been addressed in the current Industry 4.0 literature has been conducted [7, 14]. The reviewing process had four main phases. Firstly, appropriate search terms and research databases, as well as database settings, had been selected based on a preliminary review of the literature. Secondly, filters have been defined to select papers that are relevant to the context of the investigation. Thirdly, the selected search terms and databases have been used to return scientific publications based on the predefined selection criteria. The filters have been used to remove duplicates and papers that are classified as not relevant after screening the titles and abstracts. Finally, the remaining papers have been fully analyzed in order to identify potential Industry 4.0 implementation factors. Papers that did not mention implementation factors or did not explain why those factors may be important have not been considered for the final analysis.

Building on the results of the systematic literature review, qualitative and quantitative investigations will be conducted to validate the findings from the systematic literature review. In this context, interviewing participants who have been, or still are, involved in the transition towards Industry 4.0 provides insights into their motivation to get engaged with the topic. Additionally, the interviews will be used to identify the perceived benefits and the obstacles the participating corporation have faced as well as how their perception has changed over time. The resulting information will then be translated into factors and compared with the results from the systematic literature review. The goal of the survey, on the other hand, is to find out how important the factors are that have been identified within the existing literature. Consequently, the list of factors, together with a short explanation, will be presented to participants who then have the choice to state when certain factors become particularly important during the transitional process as certain factors might be more important at the beginning of the implementation phase while other factors might become relevant towards the end of the transition.

By triangulating the results of the systematic literature review, the interviews, and the survey, a framework can be designed which is tailored around the questions which factors are important, when are they important, and how important are they. Answering these questions can help scientist to get a better understanding of the research areas that deserve more attention. Governmental institutions, on the other hand, can address the problems of their local business environment more accurately, while corporations get a better understanding of the factors that need to be taken into consideration when it comes to implementing Industry 4.0.

4 Discussion

Table 1

Industry 4.0 Implementation Factors

External Factors	Internal Factors	Company Characteristics
Political Support	Perceived Benefits	Industry Sector
IT-Standardization and Security	Strategic Consideration	Company Size
Corporate and Institutional Cooperation	IT-Maturity	
Available Funding Options	Internal Knowledge and Skills Development	
Existing Knowledge and Education	Lean Manufacturing Experience	
Pressure to Adapt	Occupational Health and Safety	

The systematic literature review identified fourteen factors (Table 1) that may be important in the context of the implementation of Industry 4.0. To illustrate the nature of those factors, three main categories have been designed from the perspective of corporations: External factors, internal factors, and company characteristics. External factors are factors that are out of the reach of corporations' control. In other words, external factors cannot be influenced by the actions of single corporations. For instance, even though studies suggest that funding options matter in the context of implementing Industry 4.0, companies are not able to directly increase the number of available options. In contrast, internal factors are factors that can be directly influenced by the actions of corporations. For example, as the review of the literature shows, the promotion of Industry 4.0 knowledge and skills might be relevant regarding an Industry 4.0 adaptation. However, companies themselves have to decide to which degree they promote these skills. Company characteristics, on the other hand, is a category that lists all the factors that are considered as neutral such as the size of a company or the sector it is operating in. While these factors cannot be influenced by external nor internal actions as they have a descriptive function, they still hold valuable information when it comes to the implementation of Industry 4.0. This became particularly clear after reviewing the relevant literature which has shown that different industry sectors are more likely to implement Industry 4.0 than others. A fact that can help governmental institutions to develop Industry 4.0 measures that fit the needs of their local businesses.

5 Conclusion and future work

Overall, the systematic literature review revealed that a number of potential factors that are important in the context of implementing Industry 4.0 exist. However, the relevance of the identified factors cannot be derived from the findings of the review. While some factors have been mentioned more frequently than others, the question of the importance of each factor cannot be answered based on the number of references they appeared in. Furthermore, the analysis of the literature indicates that some findings contradict each other. For example, as previously mentioned, some findings suggest that the size of a company matters when it comes to the implementation of Industry 4.0 whereas other findings were not able to confirm this assumption. Therefore, future investigation should be focused on validating the findings of the systematic literature. As previously proposed, interviewing experts as well as designing a survey that tests the findings of the systematic literature review, can help to create a solid foundation on which further investigations can be built. Once the most important factors are known and validated, it is crucial to conduct further investigations that try to explain how companies, governmental institutions, and universities have to deal with certain factors. While knowing that the promotion of Industry 4.0 skills is important when it comes to implementing Industry 4.0 is helpful, it still does not answer the question of which skills are particularly important or how certain skills should be taught.

References

[1] Selim Erol, Andreas Schumacher, and Wilfried Sihn, Eds. 2016. *Strategic guidance towards* Industry *4.0 – a three-stage process model*.

[2] Yongxin Liao, Fernando Deschamps, Eduardo d. F. R. Loures, and Luiz F. P. Ramos. 2017. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *International Journal of Production Research* 55, 12, 3609–3629. DOI: https://doi.org/10.1080/00207543.2017.1308576.

[3] Karl Lichtblau, Volker Stich, Roman Bertenrath, Mathias Blum, Martin Bleider, Agnes Millack, Katharina Schmitt, Edgar Schmitz, and Moritz Schröter. 2015. Industrie 4.0 READINESS.

[4] Danping Lin, C.K.M. Lee, Henry Lau, and Yang Yang. 2018. Strategic response to Industry 4.0: an empirical investigation on The Chinese automotive industry. *Industr Mngmnt & Data Systems* 34, 5, 0. DOI: https://doi.org/10.1108/IMDS-09-2017-0403.

[5] Omid Maghazei and Torbjörn Netland. 2017. Implementation of Industry 4.0 Technologies: What Can We Learn from the Past? In *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing*, Hermann Lödding, Ralph Riedel, Klaus-Dieter Thoben, Gregor v. Cieminski and Dimitris Kiritsis, Eds. IFIP advances in information and communication

technology. Springer International Publishing, Cham, 135–142. DOI: https://doi.org/10.1007/978-3-319-66923-6_16.

[6] McKinsey Digital. 2016. *Industry 4.0 after the initial hype. Where manufacturers are finding value and how they can best capture it* (2016). Retrieved from.

[7] David Moher, Larissa Shamseer, Mike Clarke, Davina Ghersi, Alessandro Liberati, Mark Petticrew, Paul Shekelle, and Lesley A. Stewart. 2015. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic reviews* 4, 1. DOI: https://doi.org/10.1186/2046-4053-4-1.

[8] Egon Mueller, Xiao-Li Chen, and Ralph Riedel. 2017. Challenges and Requirements for the Application of Industry 4.0: A Special Insight with the Usage of Cyber-Physical System. *Chin. J. Mech. Eng.* 30, 5, 1050–1057. DOI: https://doi.org/10.1007/s10033-017-0164-7.

[9] Julian M. Müller, Oana Buliga, and Kai-Ingo Voigt. 2018. Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. *Technological Forecasting and Social Change. DOI: https://doi.org/*10.1016/j.techfore.2017.12.019.

[10] Vasja Roblek, Maja Meško, and Alojz Krapež. 2016. A Complex View of Industry 4.0. *SAGE Open* 6, 2, 215824401665398. DOI: https://doi.org/10.1177/2158244016653987.

[11] Lutz Sommer. 2015. Industrial revolution - industry 4.0: Are German manufacturing SMEs the first victims of this revolution? *JIEM* 8, 5. DOI: https://doi.org/10.3926/jiem.1470.

[12] Staufen AG. 2018. *Deutscher Industrie 4.0 Index 2018. Eine Studie der Staufen AG und der Staufen Digital Neonex GmbH* (2018). Retrieved from.

[13] Guilherme L. Tortorella and Diego Fettermann. 2017. Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. *International Journal of Production Research* 22, 2, 1–13. DOI: https://doi.org/10.1080/00207543.2017.1391420.

[14] David Tranfield, David Denyer, and Palminder Smart. 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *Br J Management* 14, 3, 207–222. DOI: https://doi.org/10.1111/1467-8551.00375.

[15] Shiyong Wang, Jiafu Wan, Di Li, and Chunhua Zhang. 2016. Implementing Smart Factory of Industrie 4.0: An Outlook. *International Journal of Distributed Sensor Networks* 12, 1, 3159805. DOI: https://doi.org/10.1155/2016/3159805.