Designing the transformation towards a digital supply chain

How to match the Industry 4.0 agenda to contextual needs and translate it into value

Colli, Michele

DESIGNING THE TRANSFORMATION TOWARDS A DIGITAL SUPPLY CHAIN

HOW TO MATCH THE INDUSTRY 4.0 AGENDA TO CONTEXTUAL NEEDS AND TRANSLATE IT INTO VALUE

BY
MICHELE COLLI

DISSERTATION SUBMITTED 2020

AALBORG UNIVERSITY
DENMARK

DESIGNING THE TRANSFORMATION TOWARDS A DIGITAL SUPPLY CHAIN

HOW TO MATCH THE INDUSTRY 4.0 AGENDA TO CONTEXTUAL NEEDS AND TRANSLATE IT INTO VALUE

by

Michele Colli

AALBORG UNIVERSITY
DENMARK

Dissertation submitted 2020

.

Dissertation submitted: 31st of August, 2020

PhD supervisor: Prof. Brian Vejrum Wæhrens,
Aalborg University

Assistant PhD supervisor: Prof. Ole Madsen,
Aalborg University

PhD committee: Associate Professor Atanu Chaudhuri (chairman)
Aalborg University

Associate Professor Sergio Terzi
Economics and Industrial Engineeringbil Politecnico
di Milano

Associate Professor Arne Bilberg
Southern University of Denmark

PhD Series: Faculty of Engineering and Science, Aalborg University

Department: Department of Materials and Production

ISSN (online): 2446-1636
ISBN (online): 978-87-7210-801-8

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2020

To my grandmother, Maria

CV

Michele Colli was born in Pavia, Italy, in 1990. After moving to Bergamo (Italy), he obtained his scientific high school diploma in 2009 and started a Bachelor degree in Mechanical Engineering at the Universita' degli Studi di Bergamo.

Parallel to his studies, he founded Royal Garden, a rock band with whom he published a record and played as lead guitarist more than a hundred shows. In the following years, he also published a solo EP and played as a session man for Diaphana's first EP.

In 2015, Michele decided to enrol in a Master of Science in Manufacturing Technology at Aalborg University and moved to Aalborg, Denmark. In 2017, his interest in the industrial digital transformation – the topic of his Master thesis – landed him on a Ph.D. position at Aalborg University, in collaboration with the Manufacturing Academy of Denmark.

As a Ph.D. candidate, he investigated, in collaboration with several industrial partners, how to approach the Industry 4.0 agenda and the transformation towards a "digital supply chain", linking it to contextual needs and translating the enabling of transparency (and the integration of IoT) into operational performance improvement. His investigations led to several publications written in collaboration with researchers from Aalborg University, TU Brandenburg and Universita' degli Studi di Bergamo, where he spent three months as a visiting researcher.

ENGLISH SUMMARY

The weakening of Western economies caused by the offshoring phenomenon generated, in the early 2010s, the need for a new competitiveness lever that could bring back manufacturing as one of their core contributors. This led to what has been labelled as the “fourth industrial revolution” or, more synthetically, Industry 4.0. This technology-driven agenda is founded on transparency, or the availability of data, shared across entire supply chains and used to take advantage of new (and old) digital technologies for generating value, either with the purpose of improving existing processes or enabling new ones. In its early phases plenty of literature discussed the newly available technologies, their potential application cases and the related benefits. However, solid guidance for their integration in manufacturing companies and across their supply chains is missing. Large manufacturers in the forefront of such industrial digital transformation – such as the ones we have been collaborating with - are in fact still struggling with the problem of structuring their transformation effectively and in translating it into actual value for their businesses.

The aim of this research is to address these issues providing knowledge and frameworks for guiding the formulation of digital transformation strategies and for enabling transparency across supply chains through the integration of Internet of Things, IoT, and translating it into actual business value. To do so and to contribute to extant literature, this research builds on two pillars:

- The constant attention on linking the transformation to the context, adopting a contingency theory perspective, and focusing on the learning activities necessary for understanding its characteristics

- The continuous search for a match between exploration efforts, such as the adoption of new technologies and concepts, and their exploitation from a business point of view

This thesis, in its form of collection of papers, presents the performed research as a progression of research activities. The majority of them have been performed in collaboration with industrial partners aiming to match the need for generating a rigorous academic contribution to the need for providing relevant support to practitioners. This represented one of the main challenges of this journey. Nevertheless, it also gave us the opportunity to empirically test and validate the outcome of most of the research activities.

This dissertation contributes to the operations management literature – mainly to its innovation management and technology implementation knowledge bases - in two main ways. Firstly, proposing new knowledge, in the form of conceptual artefacts or frameworks, building on top of – and with the intention to augment the existing knowledge base concerning the digital transformation towards digital supply chains.

Secondly, highlighting relevant insights concerning this transformation, such as drivers and barriers, emerged from the empirical testing of the conceptual artefacts.

The outcome of this work provides, on one hand, a support for researchers that intend to study the industrial digital transformation focusing their attention on the role of different contextual factors in affecting its success and the generated value. On the other hand, this work provides practitioners with a set of tools for managing the digital transformation of their supply chains according to the related contextual characteristics, needs and opportunities.

DANSK RESUME

Den vestlige økonomi er siden 2010 blevet svækket som konsekvens af kraftig offshoring og har derfor behov for en ny løftestang der kan bringe produktion tilbage som kernekompetence for økonomien. Dette behov har initieret det, som vi i dag kender som den fjerde industrielle revolution også kaldet Industri 4.0. Industri 4.0 er en teknologi-drevet agenda, som bygger på gennemsigtighed eller tilgængelighed af data på tværs af forsyningskæden med det formål at generere værdi gennem nye og eksisterende teknologier ved at optimere eksisterende processer eller etablere nye. I sine tidlige faser var litteraturen omkring Industri 4.0 domineret af diskussioner omkring disse nye teknologier, deres potentielle anvendelser samt fordele. Dog manglede der fokus og vejledning på, hvordan teknologierne kan integreres både internt i produktionsvirksomhederne samt på tværs af deres forsyningskæder. Store produktionsvirksomheder, der er førende i den industrielle digitale transformation – så som de virksomheder vi har samarbejdet med – står stadig over for udfordringer med at strukturere deres transformation effektivt samt skabe værdi for deres forretning gennem digitalisering.

Formålet med dette forskningsprojekt er at adressere disse udfordringer ved at bidrage med viden og teoretiske rammer, der guider formuleringen af digitale transformationsstrategier og muliggør gennemsigtighed på tværs af forsyningskæder ved anvendelse af Internet of Things, IoT, samt at omsætte dette til værdi for forretningen.

For at opnå det, samt at bidrage til eksisterende litteratur, er dette forskningsprojekt opbygget af to hjørnesten:

- Konstant fokus på at koble den digitale transformation til den specifikke kontekst ved at adoptere et contingency-theory perspektiv samt ved at fokusere på læringsaktiviteter, som er nødvendige for forståelse af konteksten

- Kontinuerlig stræben for at matche udforskende aktiviteter, såsom anvendes at ny teknologi med udnyttende aktivitet fra et værdiskabende standpunkt

Denne afhandling, der er opbygget som en samling af artikler, præsenterer den udførte forskning som en progression af forskningsaktiviteter. Størstedelen af aktiviteterne er udført i samarbejde med industrielle partnere med det formål at koble det rigoristiske akademiske bidrag med relevant støtte til praktikere i industrien. Denne kobling repræsenterer en primær udfordring i denne rejse. Ikke desto mindre gav dette os mulighed for at teste vores arbejde empirisk, og derved validere resultaterne af størstedelen af forskningsaktiviteterne.

Denne afhandling bidrager til litteraturen omhandlende operations management særligt de to vidensfelter forandringsledelse og teknologiimplementering på to måder.

Først ved at fremstille ny viden i form af konceptuelle rammeværktøjer, der bygger ovenpå og drager viden fra den eksisterende vidensbase omhandlende digital transformation rettet mod digitale forsyningskæder. Derefter ved at tydeliggøre relevant indsigt, såsom katalysatorer og barrierer, der opstod igennem empirisk test af disse konceptuelle rammeværktøjer.

Resultatet af dette arbejde bidrager til forskning indenfor industriel digitale transformation med særligt fokus på hvordan kontekstuelle faktorer påvirker den digitale transformations succes samt hvordan der skabes værdi heraf Herudover bidrager dette arbejde til praktikeren med et sæt rammeværktøjer til at lede den digitale transformation i deres forsyningskæde med hensyn til dens specifikke kontekstuelle karakteristika, behov og muligheder.

ACKNOWLEDGEMENTS

This thesis – and the whole Ph.D. journey – would not have been possible without the direct and indirect support of several people. I would like to thank them sincerely.

First of all, a special mention goes to my family, which has continuously supported me along the way, always believing in me. None of it would have been possible without them.

Secondly, I would like to thank my supervisor Brian and my co-supervisor Ole, for guiding me and trusting me during this three-year adventure, continuously engaging me in exciting projects and collaborations. Most importantly, for being friends and a great company during the many trips in Denmark, Italy, Germany, U.K…up to Hawaii. Many thanks also go to Ulrich, Charles, Harry, Hans-Henrik and Kenn for the inspiring discussions.

A mention also goes to the whole CELS team at the University of Bergamo for hosting me and making me part of the group during my visiting period. In particular, to Sergio and Roberto for their guidance.

Among the industrial partners I have had the chance to collaborate with during the past three years, some people have been particularly helpful: Thomas, Jens-Christian, Oscar, Martin and Mikkel, thank you.

Finally, I would like to thank all the friends that, either from Bergamo, Aalborg and everywhere in between, supported and shared with me this journey. Fortunately for me, they are too many to mention them. Nevertheless, I would feel guilty not to mention at least (some of) the ones that had a direct impact on the writing of this thesis, in a very challenging time for me and for many: Ralf and Romina for cheering me up with the (almost daily) late-night calls during the lockdown, Anders, Camilla, Veronika and Christian for showing up below my window on the day of my 30th birthday and Alva for the birthday song, Dorian for knocking at my door with a fantastic startup idea when I was in desperate need for a creative distraction, Lin for mobilizing half of the world to get me some face masks, Alex, Luca, Lidia, Giorgio, Mattia, Filippo and Jacopo for those three-hour-long Sunday calls, Yvonne for reminding me what is research, Emre for the discussions about the use of theory, Mohammad for the technical help, Jesper for the revisions and precious suggestions, Jonas and Maria for the Danish translations, Christoffer for the fights about the sustainability of electric vehicles and Melli for helping me finding a (diesel) rental car to reach my family after a four-month isolation. I should also mention Farhang, Kelvin, Souleyman, Gaetano and probably many more for all the long discussions about technology, data, connectivity and how they are changing the way we do things. A special mention goes to Markus for the help and his great company during this whole adventure, from day one to the very last day, and for the thousands of kilometers together.

Thank you!

TABLE OF CONTENTS

TABLE OF FIGURES

PREFACE

I would like to spend a few words to introduce this thesis, partly to contextualize it and partly to clarify its (my) perspective on the topic. Mostly to justify this work.

This three-year journey was originated by my interest in new technologies and by a – more or less – casual opportunity: a master thesis concerning the study and the development of an internet of things-based solution to improve the operational performance of a Danish manufacturing company. This introduced me, in unsuspicious times, to the Industry 4.0 agenda and, due to the practical nature of the thesis, gave me the chance to do more than scratch its surface. More importantly, it gave me the feeling of how such an agenda, although in its early days (2016), could have shaken the manufacturing field in the following years. It was the ambition to be at the forefront of this transformation – and to contribute to it - that made me decide to do a Ph.D..

The research performed afterwards as a Ph.D. candidate saw me shifting from a technology-oriented perspective to a more managerial one. Nevertheless, my technical background (a bachelor in mechanical engineering and a master of science in manufacturing technology) kept emerging during the journey, often conditioning my activities and their outcome. If this may have limited the depth of some managerial considerations, it indeed gave me the chance to link a managerial perspective to a technological one, fundamental in a technology-driven agenda such as Industry 4.0. This was, in my opinion, "my" opportunity to contribute to the knowledge base in this domain.

From a content perspective, the thesis will speak for itself. Nevertheless, I would like to prepare the reader unfolding the title "Designing the transformation towards a digital supply chain". We have three core aspects framing this work: the design aspect, suggesting the abductive approach characterizing this research, the transformation aspect, clarifying the typology of activities our research is addressing, and the digital supply chain aspect, definition of its target. The subtitle, "How to match the Industry 4.0 agenda to contextual needs and translate it into value", suggests the two pillars the thesis contribution is built on top of: the ability to take the context into account and to translate explorative activities characterizing an innovation agenda into actual business value.

The scoping of the thesis was gradual. It was helped by the continuous learnings obtained during this Ph.D., either from industrial collaborations or from academic feedback from colleagues during conferences or workshops. Because of that, some of the research activities performed during these three years were not completely aligned with what became the intention of this dissertation. As this was built as a collection of papers, I found myself selecting – to be included in this thesis - only some of the papers that have been (or are being) published during the last three years. The intention was not to devalue the excluded papers ("other works") but to provide a coherent product built around a linear story.

I wish you to enjoy the reading and hope that this will either provide you with interesting insights concerning the industrial digital transformation or leave you with plenty of interesting questions. Hopefully both.

LIST OF PAPERS

THESIS CONTRIBUTIONS (to be found online)

Paper I – Colli, M., Cavalieri, S., Cimini, C., Madsen, O., & Vejrum Wæhrens, B. (2020a). Digital Transformation Strategies for Achieving Operational Excellence: a Cross-Country Evaluation. In Proceedings of the 53rd Hawaii International Conference on System Sciences. http://hdl.handle.net/10125/64303 DOI: 10.24251/HICSS.2020.561

Paper II – Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., & Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. Ifac-papersonline, 51(11), 1347-1352. https://doi.org/10.1016/j.ifacol.2018.08.343

Paper III – Colli, M., Berger, U., Bockholt, M., Madsen, O., Møller, C., & Wæhrens, B. V. (2019a). A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era. Annual Reviews in Control, 48, 165-177. https://doi.org/10.1016/j.arcontrol.2019.06.001

Paper IV – Colli, M., Madsen, O., & Wæhrens, B. V. (2020b). Designing IoT solutions for improving operational performance: a systematic approach. In review for the Journal of Manufacturing Technology Management

Paper V – Nygaard, J., Colli, M., & Wæhrens, B. V. (2020). A self-assessment framework for supporting continuous improvement through IoT integration. Procedia Manufacturing, 42, 344-350. https://doi.org/10.1016/j.promfg.2020.02.079

Paper VI – Colli, M., Stingl, V., & Wæhrens, B. V. (2020c). Making or breaking the business case of digital transformation initiatives: the key role of learnings. In review for the Journal of Manufacturing Technology Management

OTHER WORKS

Published (or accepted):

Colli, M., Kristensen, J. H., Bockholt, M. T., & Wæhrens, B. V. (2019b). Circular economy in the Industry 4.0 era: Transparency's effect on the feasibility of a take-back program. 6th International EUROMA Sustainable Operations and Supply Chains Forum

Bockholt, M. T., Kristensen, J. H., Colli, M., & Wæhrens, B. V. (2019). Exploring the variables affecting the financial potential of Circular Economy initiatives: A case study approach. 6th International EUROMA Sustainable Operations and Supply Chains Forum

Colli, M., Sala, R., Pirola, F., Pinto, R., Cavalieri, S., & Wæhrens, B. V. (2019c). Implementing a dynamic FMECA in the digital transformation era. IFAC-PapersOnLine, 52(13), 755-760.

Bockholt, M. T., Kristensen, J. H., Colli, M., Jensen, P. M., & Wæhrens, B. V. (2020a). Exploring factors affecting the financial performance of end-of-life take-back program in a discrete manufacturing context. Journal of Cleaner Production, 120916. Accepted

Colli, M., Asmussen, C. B., & Wæhrens, B. V. (2020d). Translating digital maturity increase into quality performance: evidences from the dairy industry. Proceedings of the XXV Summer School Francesco Turco. Accepted

Bockholt, M. T., Andersen, A-L., Brunø, T. D., Kristensen, J. H., Colli, M., Jensen, P. M., & Wæhrens, B. V. (2020b). Changeable Closed-Loop Manufacturing Systems: A Case Study of Challenges in Product Take-Back (Ifip Advances in Information and Communication Technology)

CHAPTER 1. INTRODUCTION

1.1. INDUSTRY 4.0: MOTIVATIONS AND HISTORICAL BACKGROUND

1.1.1. ABOUT OPERATIONS MANAGEMENT, TECHNOLOGY AND THE CONSTANT NEED FOR COMPETITIVENESS

To improve the way we do things has always been a natural tendency of humankind, and technology played, throughout history, a key role in doing so.

If we think about game-changing inventions such as the wheel for facilitating land movements or the plough for scaling farming activities we immediately have a feeling of how technological evolution – no matter how old – had an impact on the way we do things. As a matter of fact, our interest in the level of "productivity" and its increase is documented since 1766, when Quesnay (1766) discussed it in the Journal de l'Agriculture (Tangen, 2005).

It was, however, the late 18th century when technology impacted the way we used to do things in such a remarkable way and on such a large scale to change not only the way we did things but also the way we lived. The invention of the steam machine and the flying quill led to the mechanization of manufacturing (which, from its Latin root manu facĕre, literally means "done by hand"). Mechanization led to the creation of factories, where the newly developed "machines" were located, and caused a vast migration of the population from the countryside to the cities, where industrial neighbourhoods and villages were providing housing to factory workers. Together with the mechanization of manufacturing, a new type of society was born. This had been labelled as the "industrial revolution".

About a hundred years later, industry – and the whole society, now deeply bounded to it – experienced another fundamental change. The introduction of electricity as a form of energy to power machines, factories and entire cities caused the "second industrial revolution". This had also been characterized by significant changes concerning how the work was organized. The advent of Taylorism first and Fordism afterwards enabled the adoption of concepts such as production line and mass production.

In the 1970s, the explosion of automation and information technologies, primarily developed during and after the second world war, provided industry with a new lever for revolutionizing itself. The advent of computers and CNC machines and, a few years later, the adoption of Lean Manufacturing principles to organize manufacturing processes profoundly changed, once again, the industrial panorama through what was considered to be the “third industrial revolution”.

Each industrial revolution gave us the chance to use technological advancements to manufacture goods differently and, ultimately, better, faster and cheaper (the mantra of operations management?), both generating and answering the needs of the new society they were actively shaping. Single companies, for their part, always tried to exploit technological innovation to put themselves into a position of advantage over their competitors, leveraging their efficiency – making sure they were “doing things right” – and effectiveness – making sure they were “doing the right things” (Sink & Tuttle, 1989). If they were to obtain as much as they could from the resources they were deploying, they also needed to make sure they were obtaining something valuable (Tangen, 2005).

The operations management research community has, in fact, always been devoted to studying (and proposing) the use of new technologies and concepts to improve the way companies operate and, ultimately, their competitiveness.

1.1.2. THE NEED FOR A NEW COMPETITIVENESS LEVER

In the first decade of the 21st century, Western countries saw a profound decrease in the share manufacturing industry had in their gross domestic product (GDP). In the European Union, this had fallen off about 30%, reaching a share of 15.3% in 2014 (Davies, 2015).

This had been caused by the offshoring phenomenon that characterized the 1990s and the 2000s. Manufacturing companies from high-labor cost countries saw the possibility of moving their production facilities, especially if characterized by a high degree of manual processes, to low-labor cost countries (i.e. especially in the Far East) as an opportunity to become more cost-competitive (Mykhaylenko et al., 2015; Wæhrens et al., 2015).

The offshoring advantages, however, started soon to present the bill to Western companies. The physical distance between product development teams – often kept in high-labor cost countries – and production facilities significantly reduced the possibility to operate design changes in an agile way (Mykhaylenko et al., 2017). Moreover, as some Far Eastern countries gradually became heavily industrialized (a transformation that was partly triggered by Western companies’ offshoring), they experienced very rapid economic growth. This led to a rise of the local labor cost, reducing the differential with high-labor cost countries and, consequently, the economic advantage that catalyzed offshoring in the first place (Haleem et al., 2018). In addition to that, local economies in Western countries experienced an increasing instability due to the progressive decrease of their manufacturing share, as the industrial sector both drives economic growth and catalyzes occupation in the other sectors (Colli et al., 2020a; Davies, 2015).

These issues raised an alert flag and called for a stop of the offshoring phenomenon and a (partial) "re-shoring" of the exported manufacturing activities (and jobs) in their original countries. It goes without saying that a necessary condition for making that happen was to be able to make manufacturing activities in high-labor cost countries as competitive (if not more) as manufacturing activities in low-labor cost countries. This implied, at first, a general transition from labor- to capital-intensive industry through significant investments in automation. However, this highlighted the importance of effectively using such equipment to maximize the capitalization of its value potential. The need for identifying a new lever that manufacturing companies could have used for closing this competitiveness gap taking advantage of the new equipment and from the high degree of automation emerged.

1.1.3. DATA (AND CONNECTIVITY): THE PATH TO THE FOURTH INDUSTRIAL REVOLUTION

In 2008, the European Union commissioned a research to identify this new competitiveness lever. This highlighted the use of information and communication technologies (ICT) – which have been exponentially developed over the past years – and the gigantic amount of data these are making available as that competitiveness lever (Davies, 2015). Systems based on the extensive use of ICT and on the exchange and use of data have been labelled "cyber-physical systems" (Wee et al., 2015).

In 2011, the German government-funded a national research scheme for formulating a vision concerning the use of cyber-physical systems to support the German manufacturing industry (Grube et al., 2017). This led to a report that became the foundation for the German "Industrie 4.0" agenda, outlining its core principles, enabling "digital" technologies and exemplary use cases (see Kagermann et al., 2013).

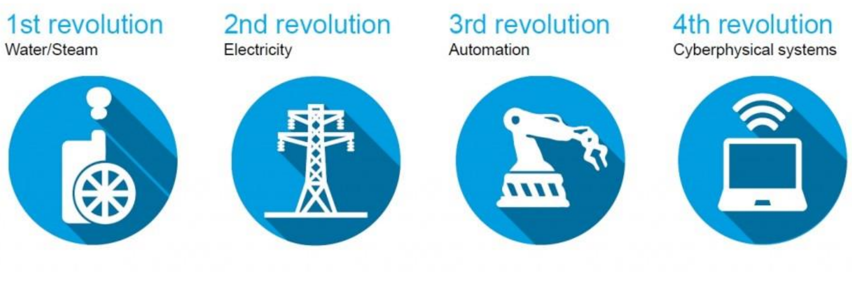

Figure 1: The four industrial revolutions and their core technological catalysts (Figure from Wee et al., 2015)

Due to its immediate diffusion on an international scale, and to the significant interest of national governments and private companies, this triggered what has now been considered to be "the fourth industrial revolution", or Industry 4.0 (Figure 1).

1.1.4. INDUSTRY 4.0: AN INTERNATIONAL AGENDA

The European Commission drafted its first guidelines concerning this digital transformation of the manufacturing industry in 2012 (Liao et al., 2018). The aim was to increase the value-added share of the manufacturing industry in the European economy to 20% (Davies, 2015). In 2014, these were translated in more tangible support by instituting a dedicated 80 billion Euro research program: Horizon 2020 (Liao et al., 2018). Most European countries adopted this as a starting point for the formulation of their own national industrial digital transformation agenda (Figure 2). Along with them, several countries across the world, such as the U.S.A. with its "Industrial Internet Consortium" and China with its "Internet Plus Initiative" within the "Made in China 2025" program (Liao et al., 2018).

Figure 2: Examples of industrial digital transformation agendas in Europe (Figure from European Commission, 2017)

1.1.5. THE ENABLING TECHNOLOGIES

The central aspect addressed in these agendas concerns the “digital” technologies enabling them. The Boston Consulting Group proposed a widely used representation of such enabling technologies (Rüßmann et al., 2015), which have been grouped into nine clusters (Figure 3). These consist of:

- Augmented and virtual reality, deployed, for instance, as assistance tools for supporting workers in off-site training activities, in daily assembly or quality control operations and “used for virtual modelling the manufacturing and assembly processes” (Cohen et al., 2019, page 4038)
- Autonomous robots, such as collaborative robots or autonomous guided vehicles (AGVs), deployed, for instance, for physically supporting workers in assembly operations as well as for automating logistics processes;
- Additive manufacturing, such as 3D printing or 3D knitting, deployed as a new manufacturing technology to increase production flexibility allowing small batches of customized products (Cohen et al., 2019) or, for instance, to decentralize low-volume and high-variety productions (such as spare parts and prototypes);
- Internet of Things (IoT), deployed for interconnecting systems and generating transparency across them, making relevant data available to the users and used, for instance, to enhance efficiency through process monitoring (Cohen et al., 2019);
- Cloud computing, deployed to store and process data coming from interconnected systems online;
- Big data and analytics, including new analytics tools such as machine learning services, deployed to analyzed massive amounts of data and to obtain further insights;
- Simulation, including tools such as digital twins, deployed, for instance, to create continuously up-to-date digital models of physical environments and forecast their behavior
- System integration, including tools deployed for facilitating the interoperability between different systems interconnected with each other;
- Cybersecurity, deployed to make data sharing and processing within and across interconnected systems secure.

Once the enabling technologies had been made clear, it became evident that the critical question was how to adopt them to fill that competitiveness gap the fourth industrial revolution was expected to address.

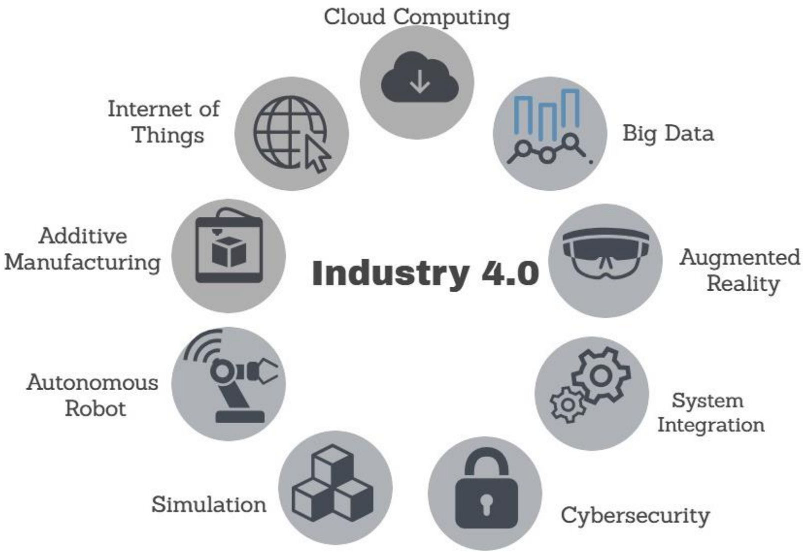

Figure 3: The Industry 4.0 nine enabling technologies (Figure from linkedip.com and inspired by Rüßmann et al., 2015)

1.2. TOWARDS A DIGITAL SUPPLY CHAIN

1.2.1. THE EVOLUTION OF SUPPLY CHAIN MANAGEMENT IN THE ERA OF INFORMATION

To manage supply chains has become increasingly complex due to varying customer demand, fast-paced technological innovation and increasing competition. At the same time, the rapid growth of information and communication technologies caused the exponential increase of digital data describing this complexity, providing support to manage it (Daft & Lengel, 1986).

The availability and use of data across supply chains have been a core topic of the operations management literature way before the advent of Industry 4.0. From the early 2000s, the operations management community started discussing the positive role of the internet in supporting the performance of business activities across supply chains (Rosenzweig, 2009). It emerged that the use of the internet for integrating companies in a network (what was called, at the time, “e-collaboration”) would have facilitated the exchange of information between them. This would have supported decision-making processes (Flynn & Flynn, 1999; Roth, 1996; Rosenzweig et al., 2003), enhancing competitiveness (Frolich & Westbrook, 2002) thanks to the improved coordination of activities (Johnson & Wang, 2002).

The increase of integration across the supply chain has been extensively studied (Kakhki & Gargeya, 2019; Liao et al., 2017) as a performance improvement catalyst (Haddud et al., 2017), both at a strategic level – facilitating the coordination between partners (Kakhki et al., 2018) – and at a tactical and operational level – facilitating process visibility (Sahin and Topal, 2019). Frohlich & Westbrook (2002) verified the positive impact of supply chain integration on performance investigating 322 manufacturing firms. An increased level of integration, in fact, reduces cost and improves service level and responsiveness (Haddud et al., 2017).

The Industry 4.0 agenda insists on these opportunities: the new connectivity and data processing capabilities are promising extensive collaboration and communication across the whole value chain, unlocking an unprecedented potential (Zelbst et al., 2019; Zhu et al., 2018; Leyh et al., 2016).

1.2.2. THE DIGITAL SUPPLY CHAIN: A "SYSTEM OF SYSTEMS"

All the new possibilities enabled by the Industry 4.0 agenda led the research community to the formulation of a new idea of supply chain. While researchers have not agreed on a common adjective to describe it – some address it as the "digital" or "e-" supply chain, others as the "smart" or "intelligent" supply chain, and so on (Wu et al., 2016) -, its underlying concept is the same. The digital supply chain (DSC) is seen as an integrated system, network of digitally interconnected partners, which, by exchanging information with each other, aim to improve the performance of their business processes synchronizing their interactions (Büyüközkan & Göçer, 2018). The operations management research community, in fact, extensively discussed how both external (between companies) and internal (within the company) integration is strongly linked to operational performance (Cheng et al., 2016; Williams et al., 2013).

Porter & Heppelmann (2014 and 2015) conceptualized this transparent and integrated system as a "system of systems" (Figure 4). In this "system of systems", even apparently disconnected supply chains could be connected with each other if the exchange of information between them could be beneficial for their performance. They discuss, as an example, the advantages that farming operations could have from the availability of data concerning both the farming machinery operating conditions and the parameters of the soil that has to be worked but also the weather forecasts. Farming equipment companies like John Deere and AGCO are, in fact, moving in this direction, extending their industrial boundaries to external systems that can help them generate additional value. The achievement of a functioning "system of systems" is considered a means for dramatically raising operational effectiveness, supporting companies in gaining competitive advantage (Porter & Heppelmann, 2014).

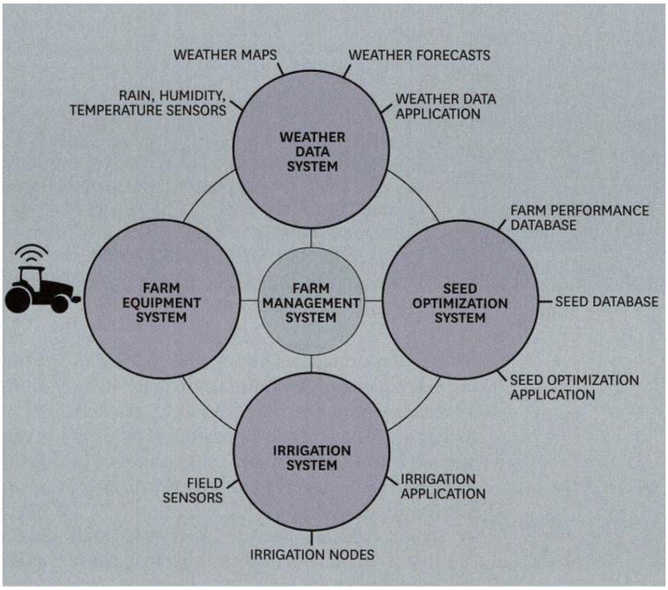

Figure 4: The concept of "system of systems" applied in the farming industry (Figure from Porter & Heppelmann, 2014)

1.3. "IT'S ALL ABOUT DATA, STUPID": THE CENTRAL ROLE OF IOT

1.3.1. TRANSPARENCY: THE DIGITAL TRANSFORMATION CATALYST

The underlying principle of the digital supply chain or, if we will, the "system of systems" concept, is the availability of data that is generated, shared and, mainly, used across the supply chain(s) (Schrauf et al., 2016). To be precise, we could argue that no, it is not all about data: it is more about information. The mere availability of data, in fact, is often not enough: it needs to be contextualized for us to understand it and to be able to take advantage from it (Wu et al., 2016). In the information management field this "information visibility" is named "transparency", and from a business perspective, it is generally considered as the availability of information for supporting decision-making processes (Winkler, 2000, Vaccaro & Madsen, 2006; Turilli & Floridi, 2009).

Transparency supports managers in effectively and efficiently managing supply chain processes (Holcomb et al., 2011; Tu, 2018). It provides the foundation for both operational control and organizational learning (Bernstein, 2012), key aspects to ensure productivity (Deming, 1986). Bernstein (2012) argues that operational control is supported by the transparency-enabled availability of timely, more prosperous and more accurate data, which improve both hierarchical control (Adler & Borys, 1996; Sewell, 1998) and peer control (Barker, 1993). At the same time, he considers transparency as a facilitator for organizational learning (Adler & Clark, 1991) due to the enabled access to expertise and experience (Hansen, 1999) and increased knowledge transfer capabilities (Argote et al., 2000).

Tangible examples of the business opportunities enabled by transparency include, from an operational control perspective, better demand forecasting (particularly relevant when adopting a make-to-order strategy or when dealing with perishable goods), better alignment with suppliers and increased responsiveness to customers' (changing) needs (Büyüközkan & Göçer, 2018). From an organizational learning perspective, instead, transparency acts as a support for accelerating innovation and automating business processes improving their efficiency (Büyüközkan & Göçer, 2018). Furthermore, the availability of data from the whole value chain enables new "service-oriented" business models (Veile et al., 2019) such as circular ones (Rosa et al., 2020).

1.3.2. IOT AS A TRANSPARENCY ENABLER

If the Industry 4.0 agenda includes several technologies, such as additive manufacturing, collaborative robots, augmented and virtual reality (AR and VR) or digital twins, their functioning principles – and the nature of their business potential - all rely on the availability of data from the environment they interact with (Cohen et al., 2019). 3D printers need to remotely access design data to succeed in decentralizing manufacturing processes, collaborative robots need to sense (and be aware of) the environment around them in order to be able to safely interact with it, AR and VR need to be able to match what is being observed or performed with existing models stored in a database and digital twins are based on the continuous communication between a physical device and its digital representation.

The common denominator is the presence of an infrastructure that generates transparency across all these different systems, providing them with the necessary information to operate. This consists of a network of sensors used for generating and transmitting data through internet-based networks, also known as the Internet of Things (IoT) (Cohen et al., 2019).

While the name has been originated from the work of Ashton (1999), the concept of IoT and its definitions are multiple and have been evolving over time (Lu et al., 2018; Haddud et al., 2017). To summarize them, we can define IoT as a "technological paradigm" which makes possible for a network of devices to interact together exchanging information in order to react to the environment and reach a common goal (Lu et al., 2018; Lee & Lee, 2015; Chen et al., 2014). Being a "technological paradigm" (Lu et al., 2018), IoT is characterized by the deployment of several technologies that make possible to, eventually, obtain an infrastructure that satisfies its definition. This infrastructure involves sensors for generating data from the environment, communication networks for providing the foundation for its transmission and gateway applications for transmitting generated data through them, platforms for collecting, storing and analyzing it and, eventually, interfaces for translating it in support for the user (UNIDO and Policy Links, 2017; Klingenberg et al., 2019; Vishwakarma et al., 2019). As these technologies are decreasing in price, the adoption of IoT is exponentially growing (Wee et al., 2015) (most likely, further supporting the price drop of such technologies), paving the way for the transition towards a digital supply chain. Due to its role in enabling transparency IoT acts, in fact, as the technology backbone of the industrial digital transformation (Wu et al., 2016).

However, if IoT-enabled transparency is vital, we have to remember that is crucial to understand which systems to interconnect, which data to make available and how to process it to translate the mere availability of data into the availability of information that benefits us and makes possible to capture the benefits the Industry 4.0 agenda is promising us.

1.4. MANAGING THE TRANSFORMATION: STILL A CHALLENGE

Due to the expected potential (and the related hype) Industry, 4.0 became, in the past few years, an integrating part of most (if not all) manufacturing companies' innovation agenda. While governments are providing guidelines as well as financial support for facilitating them in their digital transformation, companies are often struggling.

As a matter of fact, industrial transformations, in general, are challenging processes. The McKinsey Global Survey investigating the topic highlighted, over the years, how less than 30% of the interviewed companies had witnessed very or entirely successful transformations that led sustained performance improvement (i.e. 20% in 2012, 26% in 2014, 20% in 2016). The same survey, now focused on digital transformations, highlighted in 2018 how these were even more challenging, as the success rate dropped to 16% (De la Boutetière et al., 2018).

In 2016, Wu et al. (2016) did a comprehensive literature review about smart (i.e. digital) supply chains. This highlighted the need for further investigations concerning:

- The need for information across digital supply chains and how to collect, share, analyze and use them;
- The economic benefits related to the transformation towards digital supply chains;
- How to translate transparency across supply chains into business value;

- How to facilitate collaborations and increase integration in digital supply chain contexts;
- The technological and management challenges for the transformation towards digital supply chains.

While potential applications of the technologies included in the Industry 4.0 agenda have been extensively discussed, it was still hard for companies to grasp the value of this agenda relating it to their specific context, and hence to formulate a strategy to transform (Colli et al., 2018, Matt et al., 2015, Hess et al., 2016). The "elephant in the room" was the need for understanding how to translate this agenda into a competitive advantage for them (Hess et al., 2016). Even then, the challenge of translating a vision into a successful transformation remained: many companies, in fact, have not been able to successfully embrace this agenda as "integrating and exploiting new digital technologies is one of the biggest challenges that companies currently face" (Hess et al., 2016, page 123).

Two years later, in 2018, in their literature review about digital supply chains, Büyüközkan & Göçer (2018) highlighted, as the three main gaps for supporting the industrial digital transformation:

- The lack of frameworks (e.g. guidelines or roadmaps) to guide the transformation, in a context, towards a digital supply chain;
- The lack of tools and technologies to address issues in a digital supply chain environment;
- The lack of knowledge concerning how to address technological and managerial barriers preventing the transformation towards a digital supply chain.

We can observe that, if in 2016 the attention was more focused towards the identification of the business value behind digital supply chains, in 2018 this had shifted more towards the transformation process towards digital supply chains. Büyüközkan & Göçer (2018) further discussed that, as a large share of the studies investigating these topics are industrial reports, there is the need for academic research focusing on the development of frameworks to guide the industrial digital transformation and the adoption of digital technologies in the context of supply chains (Büyüközkan & Göçer, 2018).

1.5. THESIS OBJECTIVE

In accordance to the gaps emerged from the operations management literature concerning the DSC, this dissertation, culmination of a three-year work and collection of some of its crucial research activities (and publications), intends to provide the reader with:

1. *An understanding of how the transition towards a digital supply chain can be structured to be translated into competitive advantage for the individual company*

2. *A set of tools (such as frameworks and methodologies) and guidelines that can support him/her in successfully translating the enabling of transparency into performance improvement*

More specifically, this work will focus (1) on the formulation of company-specific digital transformation strategies and on the identification of the transformation initiatives they consist of and (2) on the integration of IoT in supply chains for enabling transparency and improving operational performance addressing context-specific application needs. This will be, however, further discussed in chapter 4, where the research questions will be presented.

1.6. THESIS STRUCTURE

This thesis is divided into seven chapters, which, together, aim at providing a frame for the collection of papers attached to it. While the individual papers are the synthesis of several research projects performed during this journey, with this thesis, we have the chance to contextualize the research projects, discussing them from a broader perspective.

In order to do so, we started by introducing the Industry 4.0 agenda, its historical background and motivations, the novel digital supply chain concept, the critical role of transparency – and IoT as an enabler of it –in catalyzing this industrial digital transformation and the current challenges for making it happen (chapter 1).

As this research has been funded by the Manufacturing Academy of Denmark, in its MADE Digital program, and performed in collaboration with several industrial partners, we will present the ones that helped us defining the research directions and the nature of the individual projects (chapter 2).

According to them, we will present a state-of-the-art overview focused on the research topics addressed through industrial projects. This will give us the chance to match industrial needs with actual knowledge-base gaps (or needs for further investigations) (chapter 3).

At this point we will be able to discuss the research design, clarifying to the reader our philosophical point of view in regards to this investigation and presenting (and motivating) the overall methodological approach we adopted to approach this work (chapter 4).

The core contribution of this work will follow, as we will be presenting the findings from the different research projects (and related academic papers attached in the appendix of this thesis) included in this dissertation. These will include additional reflections partly facilitated by the broader perspective this thesis is giving us the chance to take, partly by our supposedly higher “maturity level”. We will also be discussing each project in regards to its academic and managerial implications (chapter 5).

A discussion of the overall academic and managerial contribution of this thesis as a whole will follow (chapter 6).

We will be concluding this dissertation highlighting the value of this research at this point in time, its limitations and the opportunities for future research this work is unfolding (chapter 7).

CHAPTER 2. RESEARCH CONTEXT

Due to the applied nature of this research topic, the research activities included in this dissertation have been performed in close collaboration with industry.

More specifically, they have been sponsored by the Manufacturing Academy of Denmark (MADE), within its MADE Digital program. The Manufacturing Academy of Denmark is a national platform collecting Danish manufacturing companies interested in improving their competitiveness through collaborative innovation projects, that bring together research institutions, technology providers and the manufacturing companies themselves. Its MADE Digital program is mainly focused on the Industry 4.0 agenda, and on supporting manufacturing companies in their digital transformation. This program is divided into several different work packages, each one addressing a specific topic of this agenda. This mechanism aims to facilitate a "correct" matching between companies, which join specific work packages depending on their interests, and researchers and technology providers, both assigned to specific work packages depending on the demand and on their competences (for further information about the MADE platform see paper I, Colli et al., 2020a). The work presented in this dissertation is part of the work package dedicated to "intelligent supply chains", more specifically to the digital transformation of manufacturing companies which, increasingly interconnected together, are moving towards the digitalization of their supply chains.

The five industrial partners engaged in these research activities have been selected in order to cover the main industrial domains characterizing the Danish manufacturing industry, i.e. machinery (two companies), food, medical and textile. Their selection criteria concerned their interest in the Industry 4.0 agenda and maturity in its regards, as well as their (large) dimension – directly affecting the availability of resources, either human or financial, to be dedicated to explorative innovation activities. To contribute to novel issues concerning the industrial digital transformation, it has been decided to take into account companies which are not novices but in its forefront. Furthermore, it has been decided to consider leading companies in their industrial domains (in Denmark), as they will most likely act as a lighthouse for the others. According to these selection criteria, a preliminary screening of the potentially available industrial partners has been made to be able to select the most fitting ones.

Before initiating any research activity, the five selected industrial partners (A, B, C, D and E) have been interviewed to gain an understanding of the research context and to have a general overview of their specific needs in regards to the research topic (Ahlstrom et al., 2007). This gave us the chance to scope and contextualize our research.

The five cases are presented in the following and, eventually, compared to facilitate the identification of general affinities and differences between them. This will support the discussion concerning the representativeness of the research findings at the end of this thesis, as the use of multiple cases further supports the generalizability of the obtained conclusions (Voss et al., 2002).

2.1. CASE A: MULTINATIONAL MANUFACTURER IN THE FOOD SECTOR

The company is a Danish-based large multinational firm in the food sector, operating globally. It is controlling almost its entire supply chain, from the production of the raw material to the manufacturing plants, the logistic activities and the distribution centres, which, eventually, refurbish external retailers that are selling the product to the consumer. The company aims to improve the operational efficiency across its supply chain under a cost perspective, to increase the profit.

The company started several digital transformation initiatives in different facilities and business units, addressing diverse topic (e.g. using transparency for supporting waste reduction, see Colli et al., 2020d, not included in the dissertation). In order to support such initiatives, the company joined the MADE platform and established a number of collaborations with universities and external industrial partners.

In January 2019, the company established a collaboration with Aalborg University and a technology provider. The research project consisted of exploring the potential use of IoT to support the company in addressing the loss of structures used for moving finished products within the company and across its supply chain. The company stakeholders stressed the importance to translate this explorative activity into a solution with a positive business case. The project led to the design and prototyping of two IoT solutions that successfully addressed the initial issue, although with an unclear business case (for further information about this project, see paper VI, Colli et al., 2020c).

This project involved, on a continuous basis, the plant manager and a digital transformation strategist from the company side, a design thinking specialist (project manager) and an IT specialist from the technology provider side and two researchers (including the author) from the university side. On a sporadic basis, several employees from the case company have been involved for the provision of data or for supporting the testing phases, along with two additional experts from the technology provider.

After 13 months, in February 2020, once the IoT solutions had been developed, tested and evaluated, the project has been considered concluded.

2.2. CASE B: LOCAL MANUFACTURER OF AUTOMATION SOLUTIONS

The company is a large Danish manufacturer of automation solutions. It takes care of solution design, components (such as robots and conveyor belts, supplied by original equipment manufacturers) assembly and programming and of service activities. There are currently more than 2000 automation solutions installed globally, and service responsiveness became a key competitive advantage in the company's business. Because of that, the company started its digital transformation journey joining MADE and focusing the innovation efforts towards the improvement of its service operations.

In September 2016, the company established a collaboration with Aalborg University in order to investigate the use of IoT for increasing the responsiveness of its service operations. The underlying idea was to use IoT to interconnect installed automation solutions – operating on customers' premises – to the service team located at the case company, and to provide immediate notifications – as well as all the relevant information **-** in case of need. The collaboration aimed to design and prototype such IoT solution (for further information about this project, see paper IV, Colli et al., 2020b).

The project involved, on a continuous basis, the company product manager in charge of the digital transformation agenda, and two researchers (including the author). In addition to that, two representatives from the service department have been engaged, on a sporadic basis, for data collection and solution evaluation purposes.

In August 2017, after 12 months, the project had been concluded. In December 2017, the company implemented the obtained IoT solution in a pilot with a close customer. In January 2018, due to the success of the pilot, the company bought an equivalent solution from a technology provider and scaled it.

2.3. CASE C: MULTINATIONAL TEXTILE MANUFACTURER

The company is a Danish-based large textile manufacturer, operating globally. While design, sales, logistics and supply chain management are located in the Danish headquarters, production processes and material stocks have been decentralized in Eastern Europe and Asia. The company is controlling the majority of its supply chain, from the intermediate material stocks to most of the production processes. The company aims to improve the performance of its supply chain.

In August 2017, the company started a collaboration with Aalborg University to look at how the use of new technologies or methods, part of the digital transformation agenda, could have been translated into "supply chain performance" improvement. The company stakeholders stressed the importance of obtaining an implementable solution with a positive business case.

The wide breadth of the research project and of the very generic goal made necessary to scope the collaboration further. The first research activity concerned, therefore, the development and use of a digital maturity assessment model (i.e. the 360 DMA, Colli et al., 2019a) that could “read” the specific contextual needs - the increase of supply chain responsiveness and the reduction of stock - and facilitate the identification of a fitting research project according to the current company capabilities (for further information about this project, see paper II and paper III, Colli et al., 2018; Colli et al., 2019a). Out of three potential projects, the company opted for the most ambitious one. This concerned the development of an “autonomous integrated scheduling system”, aiming at exploiting the available connectivity across the company supply chain to automate the customer order processing, and to optimize the production schedule according to the available capacity and the incoming orders.

The collaboration involved, on a continuous basis, the innovation manager and the logistics and supply chain manager from the company side and a university professor, expert within the operations management domain, a group of five students from the same domain and the author. In addition to that, company representatives from the IT, planning, production and sales department have been engaged during part of the data collection and solution testing processes.

The research project was concluded in June 2018, after 11 months, when the autonomous integrated scheduling system’s algorithm was tested and delivered. In November 2018, after 16 months from the beginning of the collaboration, the company decided not to proceed with the implementation of the developed solution, due to the weak and perceived complexity, shifting the collaboration focus towards the investigation of a manufacturing strategy change, from make-to-stock to make-to-order. This had been caused by the need for financial liquidity – to be obtained, reducing the finished products’ stock - required for a company acquisition.

2.4. CASE D: MULTINATIONAL MANUFACTURER IN THE MEDICAL SECTOR

The company is a Danish-based large multinational firm in the medical sector, operating globally. It controls a large part of its supply chain, from the medical studies to the design of its devices, from the manufacturing of their components to the assembly of consumer-ready products in several plants located all over the world. The aim of the company – or, more specifically, of the company plant engaged in these research activities - is to improve its operational efficiency under a cost perspective, in order to increase its profit margin. This happens to be particularly relevant for the addressed plant which, although used as a “lighthouse” plant – and hence performing explorative innovation activities which are lowering its overall productivity – is measured against the other plants of the company in regards to its production output and the related profit.

The company manifested its interest in the Industry 4.0 agenda and joined the MADE platform. In October 2017, it established a collaboration with Aalborg University with the aim to formulate a digital transformation strategy and, more specifically, to identify specific initiatives to translate its digital transformation into an increase of competitiveness. The research project involved the development and use of a digital maturity assessment model (i.e. the 360 DMA, Colli et al., 2019a) that was capable of assessing the company's digital capabilities and, taking into account its contextual needs. This supported the formulation of company-specific transformation initiatives that would have helped the company in addressing its strategic goal (for further information about this project, see paper III, Colli et al., 2019a).

From the company side, the project involved, during all its phases, the company vice president, the head of quality, the project manager for the digitalization agenda, two plant directors and two middle managers. On a sporadic basis, depending on the need for specific data, additional employees – such as the IT manager and its deputy - have been involved. From the university side, a team of seven researchers (including the author) has been involved in all the performed activities.

After six months, in April 2018, the project has been concluded. However, the collaboration between the company and the university continued through the execution of some of the proposed transformation initiatives, mostly in the automation domain.

2.5. CASE E: MULTINATIONAL MANUFACTURER IN THE MACHINERY SECTOR

The company is a Danish-based large multinational firm in the machinery sector, operating globally. It is taking care of the manufacturing and the assembly of its products, which are eventually integrated – by its direct customers – in consumer goods. The company aims to take advantage of the Industry 4.0 agenda to improve its operational efficiency under a cost perspective, in order to make its Danish plant more cost-competitive despite the high labor cost, especially compared to the company plants located in Far Eastern Asia.

In order to address this strategic goal, the company experienced the need for unfolding – and understanding – the Industry 4.0 agenda and for identifying transformation initiatives that would have both been feasible and beneficial. To do so, the company joined the MADE platform. In August 2017, the company established a collaboration with Aalborg University with the aim to perform a digital maturity assessment and, as an outcome, to outline a digital transformation strategy composed by a spectrum of potential transformation initiatives.

The research project consisted in the development and use of a digital maturity assessment model (i.e. the 360 DMA, Colli et al., 2019a) that would have been capable of identifying company-specific initiatives taking into account both company's digital capabilities as well as its contextual needs and strategic goals. The project led to the identification of a set of transformation initiatives which have been used for defining a "roadmap" that the company could have followed to gradually address its strategic goal progressively developing its digital capabilities (for further information about this project, see paper III, Colli et al., 2019a).

From the company side, the project involved, in all its phases, the COO/executive vice president, the project manager for the digitalization agenda, a senior manager, an operations controller, the IT senior director and the supply chain director. From the university side, a team of four researchers (including the author) has been involved in all the performed activities.

After one month, in September 2017, the outcome of the digital maturity assessment has been delivered to the company, and the project has been concluded.

2.6. CASE MAPPING AND THESIS SCOPING

Some contextual information emerge from the description of the five industrial cases engaged in this research project (Table 1). The companies addressed in this research are all large (spanning from 400 to 40,000 employees and with annual revenues between 65 and 16,000 million Euro) and global manufacturers interested in leveraging their competitiveness. More specifically, they are interested in improving their operational performance from a speed or (mainly) cost perspective taking advantage of new digital capabilities. Nevertheless, the addressed business areas are all different, spanning from the service domain to production, production planning and logistics activities.

The needs of the engaged industrial partners in regards to the thesis objectives (see chapter 1) helped us scoping our research activities. The intention was to increase, in this way, the relevance of this research for both the industrial partners and for manufacturing companies that share the same needs (Hevner et al., 2004).

At a more general level, the thesis objectives concerned the provision of an understanding concerning (1) how to structure the transition towards a digital supply chain and (2) the development of tools and guidelines for operationalizing it, translating the enabling of transparency into performance improvement. The case companies highlighted how, under this umbrella, they were particularly interested (a) in the formulation of company-specific digital transformation strategies, (b) in the enabling (and use) of transparency through the integration of IoT in specific contexts and (c) in its translation into a positive business case (Table 2).

Table 1: Analysis of the industrial cases

	Case A	**Case B**	**Case C**	**Case D**	**Case E**
Industry	Food	Machinery	Textile	Medical	Machinery
Operating area	Global	Global	Global	Global	Global
Digital transformation initiative	IoT integration	IoT integration	Project scoping, IoT Integration	Project scoping	Project scoping
Competitive capability focus	Cost	Speed	Speed, cost	Cost	Cost
Business area	Logistics	Service	Production planning	Production	Production

Table 2: Needs from the industrial cases

Need	**Case A**	**Case B**	**Case C**	**Case D**	**Case E**
a. Formulate a company-specific digital transformation strategy identifying the related transformation initiatives			X	X	X
b. Enable transparency across the supply chain through the integration of IoT and translate it into operational performance improvement	X	X	X		
c. Translate the integration of IoT solutions into a positive business case	X		X		

CHAPTER 3. THEORETICAL FOUNDATION

Transformations have been a constant in industry (e.g. lean, offshoring, outsourcing). If manufacturing companies were initially solely focusing on achieving cost-efficiency (let us think about the economic boom in the 1960s), the ability to ensure a high-quality level gained increasing importance from the 1970s onwards. The customization trend emerged in the late 1980s, introduced the additional need for being flexible and capable of adapting to quick demand changes. Eventually, the rapid increase of the innovation clock-speed characterizing technological innovations since the late 1990s made clear that the ability to innovate continuously - and successfully - became crucial (Boer, 2004). From then on, the operations management research community directed significant efforts towards the innovation management field, aiming at understanding how to deal with innovation processes and transformations effectively (e.g. Rogers, 2010), whether these concern product innovation, process innovation or organizational innovation and whether these happen radically or incrementally (Boer & During, 2001).

Nevertheless, the failure ratio when it comes to innovation projects remains very high: successful transformations count for less than 30% (De la Boutetière et al., 2018).

The Industry 4.0 agenda, with its broad spectrum of new technologies, concepts and methods to leverage manufacturing competitiveness affecting product, processes and organizational structures (Matt et al., 2015) are seriously putting companies' ability to innovate at test. In fact, when it comes to innovation initiatives in pursuit of the industrial digital transformation, the success ratio goes down to 16% (De la Boutetière et al., 2018).

What are we missing?

To answer it – and to find more specific questions to be answered to address this issue - we will be looking at the problem framing it around our thesis objectives' (chapter 1) and focusing on the industrial needs emerged from our case companies (chapter 2). According to that, we will question, at first, extant knowledge concerning how to structure the transformation process formulating a digital transformation strategy and, eventually, the enabling of transparency through the introduction of IoT, to improve operational performance and obtain a positive business case.

3.1. MAKING THE DIGITAL TRANSFORMATION HAPPEN: A MATTER OF STRATEGY

To manage the complexity as well as the uncertainty characterizing the Industry 4.0 agenda, the research community identified the formulation of a "digital transformation strategy" as a key building block (Matt et al., 2015; Ivanov et al., 2016; Lee et al., 2013). It is worth remembering the original meaning of strategy as "a detailed plan for achieving success in situations such as war, politics, business, industry, or sport, or the skill of planning for such situations" (Cambridge Dictionary, 2020). From an industrial digital transformation perspective, this is meant as a strategy to support a company in addressing the transformation process identifying, prioritizing and coordinating digital transformation initiatives (Matt et al., 2015; Ivanov et al., 2016; Lee et al., 2013).

An aspect that needs to be (preliminarily) taken into account when formulating a digital transformation strategy is the context a company is operating in. As a matter of fact, countries – often even regions - may differ not only in terms of cultural aspects but also in terms of industrial policies, such as the ones supporting the industrial digital transformation (Liao et al., 2018). As highlighted by King et al. (1994), institutions have a fundamental role in shaping, according to their contingencies, the way companies address innovation processes in the information technology domain, and governments generally represent one of the most potent institutional forces affecting any type of innovation. Nevertheless, although exogenous factors such as national industrial policies steer innovation, they do not provide managerial procedures to translate a given directly into a specific transformation initiative a company should embark (Matheson, 2009). This needs to be individually established at the company level.

When formulating a company's digital transformation strategy, it is fundamental to align it to its endogenous factors, taking into account the company's business strategy as well as with its IT application systems and infrastructures (Matt et al., 2015). As Grover & Kohli (2013) discussed, greater use of digital technologies does not always mean greater value. It is worth remembering that the whole purpose of the industrial digital transformation is to translate these new technologies into an actual business value that leads towards competitive advantages, such as productivity improvements or cost reductions (Hess et al., 2016). Key aspect of a digital transformation strategy is, therefore, its business-centric orientation: instead of focusing on single – promising – technologies, it focuses on the business potential that can be realized in the specific company (Hess et al., 2016). Such strategies need to be individual, to provide companies with specific guidelines concerning the progression of steps to go through during their own digital transformation, helping them managing the complexity of the Industry 4.0 agenda and translating it into business value (Hess et al., 2016).

The presence of a digital transformation strategy clarifying the goals to be achieved and how to achieve them is fundamental to sustain the digital transformation of a company and critical for its success (Büyüközkan & Göçer, 2018; Hess et al., 2016). However, it is still a challenge for manufacturing companies to clearly understand the concepts and technologies characterizing the Industry 4.0 agenda and to identify the capabilities that need to be built to capitalize on them (Schumacher et al., 2016). This makes it hard for them to formulate a roadmap outlining the "right" initiatives to engage for transforming the organization (De Carolis et al., 2017) and, consequently, to formulate and implement company-wide digital transformation strategies (Hess et al., 2016; Matt et al., 2015).

3.1.1. FORMULATING A STRATEGY: THE ADOPTION OF THE MATURITY CONCEPT

Several research institutions, consultancy firms and even manufacturing companies addressed this issue by taking advantage of the maturity concept (Table 3). This draws on a psychological definition of "maturity", which concerns a learned ability to appropriately respond to the environment (Hyatt et al., 2007). This had been previously used to support transformations whenever characterized by a high degree of complexity and evolutionary nature.

Firstly adopted in the industrial domain to support the introduction of total quality management in the 1930s (Shewhart, 1931), the maturity concept has been extensively used in the 1970s to guide the implementation of information technology (Nolan, 1973; Crosby & Free, 1979) and in the 2000s for guiding software development (i.e. capability maturity model integration) (Torrecilla-Salinas et al., 2016).

Its effectiveness in supporting these complex transformative processes lies in its ability to simplify them. Adopting a maturity perspective means, in fact, to describe a complex evolutionary path (Becker et al., 2009) in a simplified way (Klimko, 2001), structuring it as a progression of "stages" (Nolan, 1973; Crosby & Free, 1979) characterized by well-defined capabilities that are built cumulatively (Miller et al., 1994) across different company "dimensions" (Nolan, 1973; Crosby & Free, 1979). This "maturity model" leads to the formulation of a series of "archetypes" that are describing an exemplary organization along its evolutionary path. These archetypes, matched with the assessment of the maturity of an organization, are used to identify its current evolutionary stage and to outline a vision for supporting its growth (Kohlegger, 2009), identifying weaknesses and recommending development initiatives accordingly (Solli-Saether & Gottschalk, 2010).

The industrial digital transformation has been considered as a complex transformation involving several different organizational dimensions (Hess et al., 2016) and characterized by cumulative capabilities (i.e. mostly concerning the processing and use of data, e.g. Schuh et al., 2017) (Table 3). Because of that, the research community adopted the maturity concept as a first step to address the Industry 4.0 agenda and support the industrial digital transformation (De Carolis et al., 2017), facilitating the adoption of new technologies and methods (Canetta et al., 2018). This led to the formulation of several "digital" maturity models and assessment approaches aiming at the identification of initiatives, consistently aligned with the available company capabilities, which could populate a digital transformation strategy (see Mittal et al., 2018; Kane et al., 2017; and Table 3). To do so, the assessment of digital maturity takes into account several organizational dimensions, aiming at formulating a transformation strategy that aligns technology implementation to the companies' strategy and culture, its integration across the supply chain, the competences and expectations of its workforce, partners and customers (Kane et al., 2017; Kane et al., 2015).

3.1.2. ASSESSING DIGITAL MATURITY TO IDENTIFY TRANSFORMATION INITIATIVES

Existing digital maturity assessment models generally structure the collection of company data, necessary for assessing its maturity level, through the use of a standardized questionnaire, composed by close-ended questions answered by company representatives (Table 3). It is the analysis of its answers – often based on a one-to-five Likert scale - that leads towards the assessment of the company maturity level – often operationalized applying a formula (Schumacher et al., 2016) - and, in some cases, to the identification of the maturity gaps that are preventing the company from a higher maturity stage. Depending on the maturity level (e.g. 2.7) and to the maturity gaps (e.g. low degree of automation of manufacturing processes) a set of initiatives can be recommended.

Table 3: Digital maturity assessments review (from the literature review performed for Colli et al., 2018 and Colli et al., 2019a).

Name	Maturity model: stages	Maturity model: dimensions	Assessment approach	Assessment outcome
SIMMI 4.0 Leyh et al., 2016	Five stages based on the extension of the digital ecosystem: 1. Basic 2. Cross-departmental 3. Horizontal and vertical 4. Full 5. Optimized full	Four dimensions: 1. Vertical integration 2. Horizontal integration: 3. Digital product development 4. Cross-sectional technology criteria	No assessment approach	Indication of general activities enabling maturity stage transitions

Schumacher et al., 2016	Likert-scale reaching from 1- “not implemented” - to 5 - “fully implemented” – based on the implementation level of key digital maturity items	Nine dimensions: 1. Strategy 2. Leadership 3. Customers 4. Products 5. Operations 6. Culture 7. People 8. Governance 9. Technology	Questionnaire for the assessment of digital maturity of the organization	No indications of activities for improving the maturity level
ACATECH Schuh et al., 2017	Six stages based on the capabilities concerning the use of digital data in support of business processes: 1. Computerization 2. Connectivity 3. Visibility 4. Transparency 5. Predictive capability 6. Adaptability	Four dimensions: 1. Resources 2. Information systems 3. Organizational structure 4. Culture	Questionnaire combined with visits for the assessment process	No indications of activities for improving the maturity level
IMPULS Lichtblau et al., 2015	Six stages: 0. Outsider 1. Beginner 2. Intermediate 3. Experienced 4. Expert 5. Top performer	Six dimensions: 1. Strategy and organization 2. Smart factory 3. Smart operations 4. Smart products 5. Data-driven services 6. Employees	Online self-assessment of the digital maturity of the organization based on a questionnaire	Indication of general activities for maturity stage transition
DREAMY De Carolis et al., 2017	Five stages based on management practices used in support of the digital transformation: 1. Initial 2. Managed 3. Defined 4. Integrated and interoperable 5. Digital-oriented	Four dimensions: 1. Process 2. Monitoring and control 3. Technology 4. Organization	A questionnaire with answers based on the maturity stages for the assessment process	No indications for maturity improvement

Qin et al., 2016	Five stages: 1. Digitalization 2. Communication 3. Standardization 4. Flexibility 5. Customization 6. Real-time responsibility 7. Predictive maintenance 8. Decision making 9. Early-aware 10. Self-optimization 11. Self-configuration	Four dimensions: 1. Factory 2. Business 3. Process 4. Customers	No assessment approach	Indication of general activities for maturity stage transition consisting of technology implementation and automation capabilities
Ganzarain & Errasti, 2016	Three stages focused on an organization's strategy: 1. Initial 2. Managed 3. Defined 4. Transform 5. Detailed business model	No dimensions	No assessment approach	No indications for maturity improvement

PWC Geissbauer et al., 2016	Four stages focused on strategy: 1. Digital novice 2. Vertical integrator 3. Horizontal collaborator 4. Digital champion	Seven dimensions: 1. Digital business models and customer access 2. Digitization of product and service offerings 3. Digitization and integration of vertical and horizontal value chains 4. Data and analytics as a core capability 5. Agile IT architecture 6. Compliance security, legal and tax 7. Organization, employees and digital culture	No assessment approach	Indication of general activities for maturity stage transition consisting of mapping of Industry 4.0 strategy, starting pilot projects, defining needed capabilities, data analytics activities, digitalizing the enterprise, planning with an ecosystem approach
Lee et al., 2017	Five stages focused on the factory level: 1. Checking 2. Monitoring 3. Control 4. Optimization 5. Autonomy	No dimensions	No assessment approach	No indications for maturity improvement
SPICE Gökalp et al., 2017	Six stages: 1. Incomplete 2. Performed 3. Managed 4. Established 5. Predictable 6. Optimizing	Five dimensions: 1. Asset management 2. Data governance 3. Application management 4. Process transformation 5. Organizational alignment		

Akdil et al., 2018	Four stages focused on data processing: 1. Absence 2. Existence 3. Survived 4. Maturity	Three dimensions: 1. Smart products and services 2. Smart business process 3. Strategy and organization	Survey-based instrument and index to translate answers in a specific maturity level	Proposal of a set of standard principles and technologies to improve digital maturity
AMM Scremin et al., 2018	Eight stages (maturity indicators)	Three dimensions: 1. Strategy 2. Maturity 3. Performance	Structured questionnaire linked to the maturity indicators and to understand the company context	

However, the recommended initiatives are usually selected from a pre-defined set, based on the digital maturity "number" obtained from the questionnaire's answers applying a formula. These detach them from any contextual need characterizing the assessed company. Schumacher et al. (2016) highlighted, in fact, the need for further research aiming at developing an assessment approach that could identify company-specific transformation initiatives. Büyüközkan and Göçer (2018), following the same line of thoughts, discussed the need for facilitating stakeholder engagement to do so. After all, the effectiveness of a digital transformation strategy lies not in a blind increase of digital maturity (Kane et al., 2017), but in addressing opportunities for greater business impact (Westerman, 2018), which may differ from company to company. This calls for an approach that leads to the identification of transformation initiatives taking account the specificity of the context, considering both the available capabilities – ensuring their feasibility - and the strategic goals – ensuring their value potential.

3.2. TRANSLATING TRANSPARENCY ENABLING INTO VALUE

As Industry 4.0 is a technology-driven agenda, the majority of the initiatives embarked by companies concerns the application of new digital technologies. However, the 2019 McKinsey Global Manufacturing Survey shows that two of the five main reasons for these projects to fail concern the business value that they can generate (Schmitz et al., 2019). 44% of interviewed managers pinpointed as one of the reasons the lack of short-term business value and 41% of them the presence of an unclear business case. This highlights how it is still difficult for companies to capitalize on their exploration concerning the Industry 4.0 agenda, and suggests the need for matching the focus on innovating with the generation of tangible business value. As Cohen et al. (2019) put it, “the path from the new technological abilities to improved productivity and profitability has not been well understood and has some missing parts” (Cohen et al., 2019, page 4037).

Vidgen & Wang (2009) stressed how it is paramount to consider the introduction of new technologies not as a goal per se, but as a means for improving the performance of the organization. To do so, it is essential to adopt a value-driven approach, scoping the introduction of new digital technologies starting from relevant business opportunities to make sure these will be translated into actual value for the company (Kane et al., 2017; Westerman, 2018). This is, however, nothing particularly new. Academic literature studying the integration of information technologies already made clear how this should be value-driven (Kohli & Grover 2008). Yet, there is an additional good reason for considering this approach nowadays: the exponentially higher amount of digital data generated and shared across supply chains - the backbone for the industrial digital transformation. Although transparency is considered support for the management of the operations across supply chains, the availability of data could easily exceed the analytical capability of a company (Daneshvar Kakhki & Gargeya, 2019), preventing it from translating it into actual value or, worse, becoming a liability. Companies need to be able to scope the generation of transparency according to relevant needs and strategic value (Davenport et al., 2010; Daneshvar Kakhki & Gargeya, 2019). Therefore, to have a proper approach to identify them is critical (Overby et al., 2006; Daneshvar Kakhki & Gargeya, 2019).

3.2.1. IOT INTEGRATION APPROACHES: PROCESS EXCELLENCE-DRIVEN AND LEARNING-ORIENTED

The enabling of transparency across supply chains is operationalized through the integration of IoT, which, by definition, is providing the necessary technological infrastructure to interconnect different systems and make data available.

When it comes explicitly to the integration of IoT in supply chains, there is plenty of research regarding the technological aspects to take into account (e.g. Vishwakarma et al., 2019; Lee & Lee, 2015; Ehret & Wirtz, 2017; Liu & Lu, 2012, Chen et al., 2014; Gubbi et al., 2013; Wang et al., 2016; UNIDO and Policy Links, 2017; Klingenberg et al., 2019) and what they could enable (e.g. Williams et al., 2013; Porter & Heppelmann, 2014 and 2015). Nevertheless, there is less concerning its integration process and the development of IoT solutions from a management perspective (Moeuf et al., 2018; Lee & Lee, 2015; Mishra et al., 2016). Haddud et al. (2017) identified, in their literature review on IoT integration in supply chains, several barriers that still need to be addressed when integrating IoT in supply chains. These spans from the lack of awareness concerning its business potential to the tailoring of IoT solutions to existing business processes, matching the maturity level of the environment where these are being integrated.

As IoT is still, in its nature, an information technology (IT), researchers questioned the technology implementation literature concerning the integration of IT to improve operational performance (e.g. Martinez, 2019; Ammirato et al., 2019). This body of knowledge offers two main approaches, either supporting radical change or continuous improvement (i.e. incremental change) (Martinez, 2019).

Martinez (2019) studied how four companies addressed the integration of digital technologies for improving their operational performance, aiming at identifying a common “digitalization path”. All companies started from mapping and analyzing the operations to identify any improvement potentials. After considering a digital technology to address the most relevant issues (or improvement opportunities), they proceeded with an evaluation of obtained improvement and the search for new improvement potentials. Martinez (2019) observed that all the analyzed companies adopted a continuous improvement approach: they maintained the processes as they were and introduced digital technologies to gradually improve their efficiency. Ammirato et al. (2019), on the other hand, albeit following a very similar digitalization path, studied the integration of IoT adopting a radical approach, more specifically business process reengineering (BPR) (Hammer & Champy, 1993). After mapping and analyzing the operations for identifying relevant improvement potentials, they redesigned the targeted business processes to maximize the improvement enabled by the integration of IoT. Both approaches have been considered acceptable (Martinez, 2019) and proven to be successful. If continuous improvement is less demanding financial wise, it also implies a longer progression of small improvements; BPR, on the other hand, is bringing – if successful – more prominent improvements in a shorter-term (Martinez, 2019).

Independently from the radical or incremental approach, Martinez (2019) observed the fundamental adoption of a process excellence perspective (which he described as “mandatory”): companies need to be able to identify where to introduce technological innovation to translate technology implementation into process improvement and, ultimately, actual business value. In addition to that, he discussed the presence of a learning scenario - rather than a unique path to be followed – for guiding the integration of digital technology in a company due to its idiosyncratic nature. Nevertheless, he points out the need for further investigations concerning the integration of IoT in industrial environments.

Although the integration of digital technologies in production systems is currently researched (Tortorella & Fettermann, 2018) the research community highlighted the lack of models that provide clear guidelines for managing the adoption of IoT (Jayaram, 2016; Ben-Daya et al., 2017; Ammirato et al., 2019) and for designing solutions that can fit into a specific context (Moeuf et al., 2018). The matching between digital technologies and organizational-specific needs still has to be investigated (Martinez et al., 2017; Whitmore et al., 2015) as it remains a fundamental issue when it comes to integrating such technologies in production operations (Veile et al., 2019).

3.3. OVERVIEW OF THE LITERATURE GAPS AND THEIR LINK TO THE OPERATIONS MANAGEMENT BODY OF KNOWLEDGE

If we look at the key literature gaps related to the formulation of digital transformation strategies or the integration of IoT in supply chains, we can clearly distinguish two aspects that have to be addressed:

- *The need for "contextualizing" both the formulation of a digital transformation strategy, identifying company-specific transformation initiatives, and the integration of digital technologies in supply chains, linking solution design to the context-specific application needs.*
- *The need for matching explorative digital transformation initiatives, such as the integration of IoT in companies' operations, to their exploitation potential, translating them into actual business value.*

These two research gaps emerged from the industrial digital transformation literature are, however, not new if we look at them from a more general operations management perspective. The operations management body of knowledge already highlighted them as key challenges and provided some indications for addressing them. After shortly presenting them below, we are going to take advantage of them to guide our research activities and support our theoretical contribution to the operations management knowledge-base.

3.3.1. THE IMPORTANCE OF CONTEXT IN OPERATIONS MANAGEMENT AND THE LESSONS FROM CONTINGENCY THEORY

The operations management literature extensively discussed the importance of considering the context when introducing new practices aiming at improving the competitiveness of a manufacturing company. While from a "best practices" perspective challenges in implementing them are considered as a natural part of process improvement, from a "contingency theory" perspective these are caused by a mismatch between the proposed practices and the context where these are implemented (Sousa & Voss, 2008).

Contingency theory is, in fact, a theoretical lens used to view organizations – and organizational change – as linked to the contextual factors characterizing them (Donaldson, 2001). The underlying principle of this theory is the "need for fit" between the structure and the processes in an organization and its context, in order for it to survive or for them to be effective (Drazin & Van der Ven, 1985; Dubin, 1976). There has been an increasing interest in – and need for - the adoption of a contingency theory lens in operations management (Ketokivi, 2006; Bozarth & McDermott, 1998).

In fact, the past two decades saw the development of a broad body of knowledge concerning contingency theory in operations management and investigating how different management practices can be effectively adopted in different contexts characterized by different contingency factors (Sousa & Voss, 2008). For instance, Flynn & Flynn (2004) highlighted the fundamental role of contingency factors when building competitive capabilities (Skinner, 1969), challenging the idea of a unique approach or progression (Ferdows & De Meyer, 1990; Rosenzweig & Roth, 2004). The very same contingency factors emerged as well as a crucial aspect related to the choice of management practices, such as total quality management or just-in-time, for improving operational performance (Sousa & Voss, 2008).

This proved contingency theory to be a useful theoretical lens for studying operations management issues, specifically in domains where operations management theory is less developed (Sousa & Voss, 2008), such as the industrial digital transformation. To adopt a contingency theory lens is particularly helpful when the aim is to generate prescriptive knowledge in operations management, especially when there is the need for addressing the technical fit of operations management practices in specific contexts (Sousa & Voss, 2008).

The adoption of a contingency theory lens – which we will be taking advantage of - implies the need for considering the aspects that characterize the context that is being considered. More specifically, exogenous factors (e.g. national context, size of an organization, manufacturing strategy, plant size, industrial domain, etc.), the performance objectives (operational performance, financial performance, market performance, customer satisfaction, etc.) and the management practices adopted to achieve them, either responding to or anticipating the contextual needs (Sousa & Voss, 2008).

3.3.2. TO EXPLORE OR TO EXPLOIT? THE INNOVATION DILEMMA

The capability to match explorative activities, such as the investigation of new technologies and capabilities, with exploitative ones, such as the translation of existing capabilities into business value – and a positive business case – is one of the fundamental challenges related to innovation processes in general (Sutcliffe et al., 2000; Boer & Bessant, 2004). As companies are currently getting increasingly involved in the introduction of new digital technologies in their plants, the dilemma between exploration and exploitation powerfully re-emerges (Papachroni et al., 2015). These two perspectives are considered to be diametrically opposite (O'Reilly & Tushman, 2008), yet researchers argued about the importance of pursuing both for innovation projects to succeed (March, 1991). Research has proven that this is not only possible but also has a positive effect on the performance of a company (O'Reilley & Tushman, 2004; He & Wong, 2004).

The research community proposed a spectrum of possible strategies for matching exploration and exploitation, achieving what has been defined as organizational ambidexterity. Alternating exploration and exploitation activities (i.e. temporal ambidexterity), having two separate business units focused either on exploration or exploitation (i.e. structural ambidexterity) or moving the focus depending on the contextual needs (i.e. contextual ambidexterity) are three examples (see Papachroni et al., 2015). Latter research stressed the importance of addressing the two perspectives at the same time (i.e. paradoxical ambidexterity) (Papachroni et al., 2015). For there is still very few empirical evidence concerning how innovators can operationally achieve ambidexterity (Papachroni et al., 2015), we will be taking this strategy – and the need for continuously addressing both perspectives – into account.

Based on that, we pose that to be able to match exploration and exploitation while managing the industrial digital transformation could (and, in this work, will) be paraphrased as the capability to continuously focus, while introducing new digital technologies, on how to translate them into tangible business value – hence supporting their business case and successful adoption.

CHAPTER 4. RESEARCH DESIGN

To be able to address the objective of this dissertation rigorously, the way the author approached this research project has to be disclosed. The clarification of the research design supports the solidity of the research outcomes and, hence, the strength of its contribution to the addressed domain knowledge.

After declaring the philosophical position adopted by the author during this study, the methodological approach adopted in this thesis is presented, along with the motivations justifying its choice. Its key phases and characteristics – such as its generalizability criteria – are presented. Eventually, the use of this methodological approach to frame the whole dissertation is discussed, along with the methodological approaches, data collection and triangulation methods adopted for each research activity.

4.1. RESEARCH PHILOSOPHY

Before discussing the philosophical position we will be adopting while addressing this research project, we have to take a step back and discuss the characteristics of the research field we are navigating in. Operations Management, while tied in a double thread with the engineering domain, is deeply impregnated with implications from social sciences, as it can – and often does - extensively deal with people (Van Aken et al., 2016). Organizational issues are considered as the "soft" aspects characterizing the Operations Management domain. Human perception and behavior considerably increase the complexity of a study, not only because they increase the number of variables to be considered, but also because those who perform the investigation is often not aware of some of these variables and, consequently, cannot control them. This challenges the adoption of a realistic or positivistic approach: it would be naïve to think about considering and controlling all the potential variables affecting a problem in this domain. Therefore, it would be hard to justify the proposal of "universal" considerations, knowing that the mediating effect of some contextual variables has, most likely, not been taken into account. On the other hand, the adoption of an interpretative approach would be challenged in the generalizability of its findings, as these would entirely depend on ones' means and perception, and in their longitudinal validity, if we consider contexts to change over time. What to do then?

The Operations Management research field, due to its "applied nature", has always been dealing with practical problems (Holmström et al., 2009; Boer et al., 2014). Its research community aims at providing practical solutions and, at the same time, creating knowledge interacting with the real world (McCutcheon & Meredith, 1993; Lewis, 1998). In line with these fundamental characteristics of the addressed research field, we decided to opt for the adoption of an instrumentalist (or, if we will, pragmatist) philosophical stance (see Laudan, 1977). This implies attention towards the practical effect of a research outcome. We argue that, due to the remarkable changes in industrial contexts and needs over time, theories in the Operations Management field are not necessarily continually progressing towards a "universal truth" and, most of all, that there is no "universal truth" in this field (e.g. Cartwright, 1983). However, theories are strongly bonded to their times and are developed to use them to solve practical problems. According to that, the theoretical contribution of a research project in the Operations Management field is aligned with an instrumentalist (and pragmatist) philosophical stance and consists "of a better predictive framework, model, or theoretical tool that helps solve an empirical problem even if the framework incorporates wildly inaccurate representations of reality" (Boer et al., 2014, page 1242).

4.2. RESEARCH APPROACH

The philosophical beliefs of the author inevitably affected (and, if we like, guided) the choice of the methodological approach adopted for this research project. The adoption of an instrumentalist and pragmatist philosophical stance, aiming at providing models or frameworks for supporting companies in addressing novel issues, guided the author towards the need for a rigorous research approach – ensuring a valid scientific contribution - capable of ensuring a relevant outcome for researchers and practitioners. This led the author to the adoption of the design science research (DSR) framework as an overall methodological approach for this thesis.

4.2.1. DESIGN SCIENCE RESEARCH

The use of DSR, inspired by Herbert Simon (1996), specifically aims at the generation of instrumental knowledge (Van Aken et al., 2016). This is in contrast to explanatory research, aiming at describing "the present (or past) from the perspective of a detached observer" (Van Aken et al., 2016, page 2), and concerns the application of knowledge for supporting design or action (Pelz, 1978). In our context (i.e. Operations Management field), this has been better translated by Van Aken et al. (2016) as the development and use of knowledge "to design and implement actions, processes or systems to achieve desired outcomes in practice" (Van Aken et al., 2016, page 1). In the past years, the Operations Management research community repeatedly called for knowledge that could support managers in solving actual problems (e.g. Boyer & Swink, 2008; Tang, 2015) and for a general increase of relevance concerning the research efforts in the Operations Management field (Van Mieghem, 2013). The adoption of DSR, already deployed mainly in fields such as engineering and medicine (Hevner et al., 2004), tackles this issue.

The application of DSR starts with a descriptive and explanatory stage, meant to provide the researcher with a solid foundation for the successive design/testing stage (Van Aken et al., 2016). This concerns the identification of the needs from the "environment" (Figure 6 and Table 6) or, to put it simply, from practitioners such as company managers. The context they operate in is analyzed in order to understand its complexity and the issues to address in the research project, supporting its relevance (Hevner et al., 2004). Once these are identified, the existing literature, or "knowledge base" (Figure 6 and Table 6), concerning them is analyzed to support the development of a solution and to identify the eventual knowledge gaps that its development and implementation could address. This would support the rigor of the research project, ensuring, as an outcome of the DSR process, not only a practical but also an academic contribution (Hevner et al., 2004).

The second stage, the core of the "research" project (Figure 6 and Table 6), concerns design and testing activities. The primary outcome of this stage is the "abduction phase" (Figure 5), or proposal of the solid solution, also called "artefact" (Van Aken et al., 2016; Vaishnavi & Kuechler, 2008; Holmström et al., 2009). This is realized to address the identified issues (i.e. "environment") and built on top of existing knowledge (i.e. "knowledge base") (Hevner et al., 2004). The fundamental attributes of the obtained artefact are its validity and relevance. Its validity concerns its capability to produce the desired outcome and results, as a drug curing a disease. Its relevance concerns the significance of the problem that the artefact addresses (Van Aken et al., 2016). In order to ensure such attributes, the proposed solution is built by the researcher and tested against the issue it is meant to address, observing its impact and generating – in this "deductive phase" (Figure 5) - an understanding of the addressed phenomenon (Vaishnavi & Kuechler, 2008; Holmström et al., 2009; Hevner et al., 2004). The effectiveness of the developed solution has to be verified based on a substantial body of evidence. This is collected through field testing within the intended application domain adopting, in most cases, a case study approach (Van Aken et al., 2016). In fact, while in explanatory research validity is proven through sound logical deductions, the justification of a design obtained through DSR "concerns not truth but effectiveness" (Van Aken et al., 2016, page 2). "The validity of a generic design is, unlike an explanation, not justified on the basis of how it has been made but by proving that it "works"" (Van Aken et al., 2016, page 2).

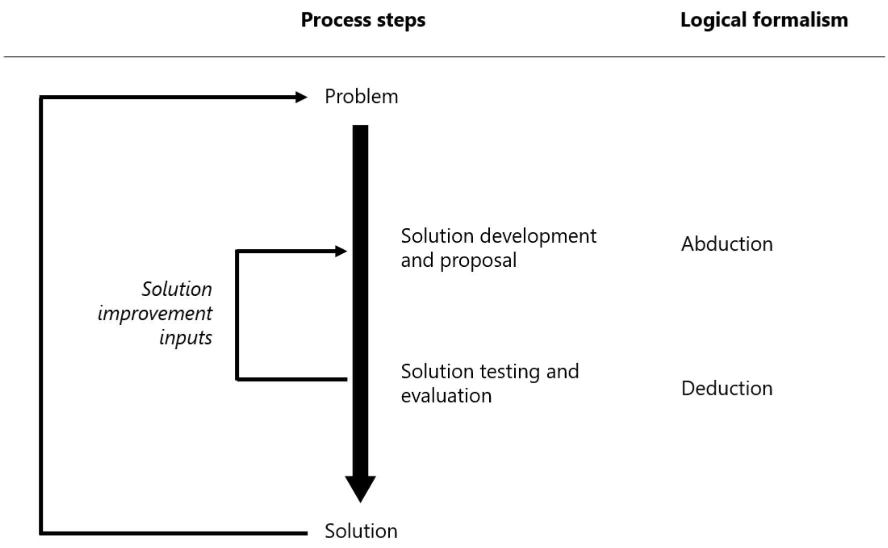

Figure 5: Logical formalism of the DSR process (figure inspired by Vaishnavi & Kuechler, 2008)

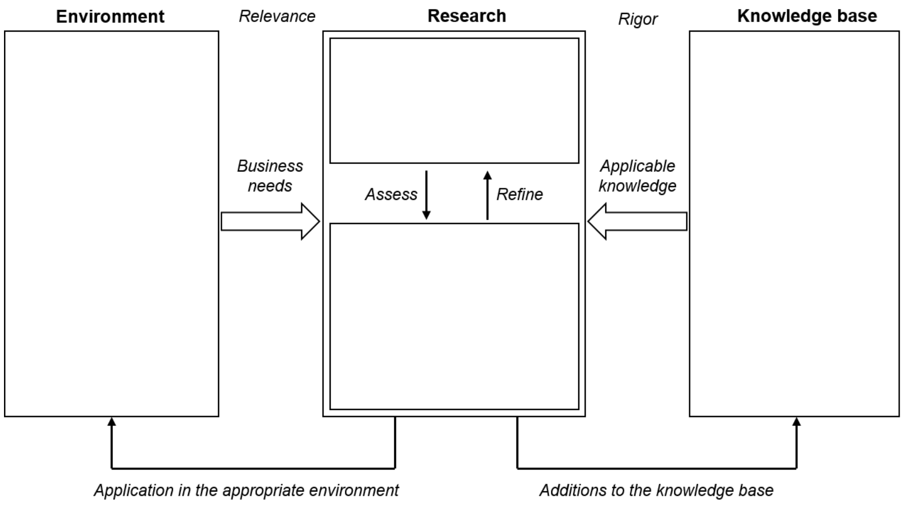

Figure 6: DSR framework (figure inspired by Hevner et al., 2004)

One could argue that, given these robust premises, DSR does not differ from consultancy. However, Van Aken et al. (2016) argue that, although both DSR and consultancy aim to improve, the second one addresses local contexts and case-specific designs, lacking the intention of generalizability that characterizes DSR, whose final aim is to be able to transfer generated knowledge across different contexts.

Generalizability is, therefore, a crucial aspect of DSR, and it directly affects the impact of its outcome. It is worth to consider that the generalizability criteria for DSR are substantially different compared to what is generally used for explanatory research approaches. While for the latter generalizability is derived, following a deductive logic, from the characteristic of the sample where the research activities have been performed, for DSR it can be proposed, following an inductive logic, based on the characteristics of the developed artefact, which potentially extend it in other contexts (Van Aken et al., 2016).

Table 4: DSR framework phases

DSR framework area		**Task**	**Outcome**
Environment		Identification of the industrial cases' issues to be investigated	Scoping of the different research activities
Knowledge base		Identification of the existing and missing knowledge (i.e. literature) to address the issues	Definition of the research questions to be answered in the different research activities
Research	Building	Development and proposal of solutions – based on extant literature - for the identified issues	Generic designs for addressing the identified issues
	Testing	Testing of the generic designs	Validated generic designs and inputs for designs improvement

4.2.2. THE USE OF DESIGN SCIENCE RESEARCH IN THIS RESEARCH PROJECT

According to the DSR framework, we started this research project by studying the environment to identify relevant research topics within our research domain and, ultimately, define our research objectives (Table 7 and see chapter 2). At first, a number of case companies have been selected following a set of pre-defined selection criteria after an initial screening (see chapter 2). These case companies, industrial partners for this research, have been questioned in regards to their interests and needs concerning the Industry 4.0 agenda and their digital transformation (see chapter Research Context). First-hand data concerning these interests and needs have been collected through semi-structured interviews. We engaged, from each case company (i.e. A, B, C, D and E), company representatives responsible for the digital transformation agenda and the business units interested by the transformation. In all cases, more than one data source has been questioned, and company documentation has been viewed and integrated by company visits in order to support data triangulation and ensure its validity (Yin, 2009). The research objectives this preliminary study highlighted led us to the definition of two work packages (WP) to cluster our research activities depending on their area of contribution and objective (Table 7). The first one (WP1) concern the formulation of digital transformation strategies and the second one (WP2) the design of effective (and economically feasible) IoT solutions.

Once the research topics and objectives have been identified, we started analyzing the related literature (i.e. knowledge base) both to identify the existing literature gaps – formulating our research questions – and to support us in our research activities, addressing our research objectives while contributing to the academic knowledge-base (Table 7 and see chapter 3). The scout for relevant literature started by a search on Scopus and Google Scholar using keywords related to the addressed issues (for instance, “digital transformation strategy” and “IoT integration”). The author observed that, as it often happens for topics in their early phases, there were a plethora of keywords indicating the same concepts (e.g. attributes such as intelligent, digital, 4.0, smart, etc.) (Wu et al., 2016). Because of that, for each of the issues to be addressed, we decided to proceed the search for relevant literature starting from known keywords and proceeding following a snowball approach (Wohlin, 2014). According to that, the search continued by following up on the relevant references noted in the analyzed articles, until the author (1) observed a consensus – in the analyzed literature - concerning the knowledge gaps in the addressed field and (2) had enough support for performing the research activities. This approach was preferred to a systematic literature review, which, as it heavily relies on the choice of keywords, could have missed entire branches of the relevant literature concerning the topic. This study led us to the formulation of a set of research questions and, to answer them, to the definition of several research activities to be performed in collaboration with our industrial partners and of the methodologies to adopt to perform each one of them

(Table 7) (further information concerning the adopted methodology can be found in each paper).

The research activities concerning the formulation of a company-specific digital transformation strategy (**WP1**) aimed, at first, at studying the link between the external context (i.e. framework conditions) and the digital transformation strategies adopted by companies – mostly their scope. This was performed analyzing the framework conditions characterizing two different countries and studying the digital transformation strategies adopted by four large manufacturers – two from each country. On the one hand, the study was supported by official documentation (e.g. national industrial policies), on the other by interviews and direct observations (paper I). The second part of the work package addressed, instead, the adaptation of a digital transformation strategy to the internal context. Starting from a review of state of the art, we proposed a digital maturity assessment approach built on the PBL model and capable of identifying context-specific transformation initiatives to build a digital transformation strategy on top of. Adopting a DSR framework, we iteratively improved the approach testing it in three industrial cases (paper II and paper III).

The research activities concerning the enabling of transparency through the integration of IoT (**WP2**) aimed, at first, at the formulation of a framework to guide the design of IoT solutions. To answer the need for tailoring them to the context and for translating them into actual business value, this had been based on lean practices and principles and extended in regards to the solution infrastructure design. To do so, we built upon existing knowledge regarding IoT technological aspects and, eventually, tested the full framework in an industrial case. We applied the framework to build a solution, based on the industrial requirements that we tested in a laboratory environment first and then scaled in the company (paper IV). To answer the need for continuous improvement through the use of transparency, we then formulated, supported by literature, a potential approach to study the digital maturity of the information flow and to identify where to potentially improve it (paper V). Eventually, we addressed the issue of translating innovation initiatives – such as the integration of IoT – into positive business cases. At first, we reviewed extant literature to identify where business opportunities can be recognized in innovation projects. This led to the formulation and testing of a framework to support innovators in recognizing them, starting from the learnings generated from these projects (paper VI).

Table 7: Research activities

WP	Research question	Research activity (paper)	Methodology	Data sources
WP1	**RQ1**: *"How is the digital transformation of a company affected by different framework conditions?"*	Identification of digital transformation strategies and their national context dependencies (**paper I**)	Multiple case study	Documentation, literature, observations, interviews
	RQ2: *"How can Problem-Based Learning be used to operationalize a digital maturity assessment, leading to context-specific improvement recommendations?"*	Proposal and testing of a digital maturity assessment approach for identifying company-specific transformation initiatives (**paper II and paper III**)	Design science research	Observations, documentation, literature, questionnaires, interviews
WP2	**RQ3**: *"How can the process of designing an IoT solution be addressed to tailor it to context-specific application needs?"*	Proposal and testing of an IoT solution design framework to link technology implementation to context-specific application needs (**paper IV**)	Design science research	Observations, interviews, literature
	RQ4: *"How can companies identify continuous improvement potential related to the integration of IoT?"*	Proposal of a self-assessment approach to identify IoT integration possibilities (**paper V)**	Design science research	Literature
	RQ5: *"Can learnings obtained through explorative innovation initiatives in manufacturing be exploited to support their business cases, and if so, how?"*	Translation of learnings into support for innovation projects' business cases (**paper VI**)	Design science research	Observations, interviews, literature

CHAPTER 5. RESEARCH FINDINGS

The chapter summarizes the findings from the research activities performed in the two work packages; this thesis consists of and supplements them through additional reflections.

The first work package (section 5.1) addressed the formulation of a company-specific digital transformation strategy and the identification of the related transformation initiatives, based on the characteristics of the environment a company operates in and on the company's characteristics, needs and strategic goals. The related section includes two research activities and three papers (paper I, paper II and paper III).

The second work package (section 5.2) addressed the enabling of transparency across the supply chain through the integration of IoT, aligning it to its context-specific application needs for improving the operational performance and for translating new technology implementation into a positive business case. The related section includes three research activities and papers (paper IV, paper V and paper VI).

For each work package, after an initial introduction concerning its relevance, the different research activities are presented singularly. At first, the research background is clarified, setting the scene for the presentation of the findings from the related research papers (either published or in the process of being published). These are followed by additional reflections catalyzed by the more comprehensive perspective the collection of papers we did while writing this thesis provided us. Each work package is concluded, eventually, with a discussion concerning both the theoretical and managerial implications of its findings.

5.1. FORMULATING COMPANY-SPECIFIC DIGITAL TRANSFORMATION STRATEGIES (WP1)

In order for companies to succeed in their digital transformation and the integration of new digital technologies, extant literature highlighted the fundamental importance of formulating transformation strategies capable of linking this technology agenda to their needs and internal strategies (Matt et al., 2015, Westerman, 2018; Kane et al., 2017; Kane et al., 2015). In their 2017 Digital Business Global Executive Study, Kane et al. (2017) identify the presence of a well-defined strategic approach to this agenda as "the strongest differentiator of digitally maturing companies" (Kane et al., 2017, page 7). A digital transformation strategy represents, for a company, a management practice adopted to coordinate and prioritize its transformation activities and translate them into business value (Matt et al., 2015; Kane et al., 2017). Yet, "creating an effective strategy and linking it to overall business objectives remains one of the biggest challenges standing in the way of increasing a company's digital maturity" (Kane et al., 2017, page 7).

This attention towards linking a digital transformation strategy to the context collocates the task of formulating it in complete opposition to a best practice perspective, where we adopt practices based on good examples, without considering contextual elements. Most famously, Michael Porter addressed this issue by adopting the structure-conduct-performance paradigm in the industrial organizations' domain for prescribing context-dependent practices to become more competitive (Porter, 1981). Lipczynski et al. (2013) later summarized, as one of the critical hypotheses of this paradigm, the categorization of industries depending on a set of contextual aspects (e.g. product differentiation, pricing strategy). Different categories imply different practices. However, we argue that for increasing our contextualization capabilities, we need to look at specific contingencies characterizing companies at a micro-level (e.g. individual efficiency needs, strategic goals, etc.). Because of that, although opposite to the best practice perspective, our perspective slightly differs from the structure-conduct-performance paradigm. In fact, it is more aligned to a resource-based view (Barney et al., 2001) that takes into account not only the available resources that can support a company in gaining competitive advantage (as the resource-based view usually do) but also the "available" issues to be addressed. According to that and aligned to the extant literature, we argue that a digital transformation strategy needs to be aligned, on the one hand, to endogenous contextual factors such as organizational and functional strategies internal to a company as well as internal needs and capabilities (Matt et al., 2015; Bharadwaj et al. 2013).

On the other hand, it is of crucial importance to consider the characteristics of the external environment, as different framework conditions affect industry differently (Porter, 1990, e.g. the "diamond model") and generate the need for different innovation practices (Lundvall et al., 2002). We have to remember that innovation, being a learning process, is inevitably interactive, and cannot be understood without taking into account exogenous contextual factors such as government support and culture (Lundvall, 2010). The way people work or the benefits companies receive from different kind of activities inevitably shape transformative processes. Moreover, innovation is a result of (and strongly linked to) a complex set of relationships such as the ones between companies, universities and governmental institutions (Lundvall, 2010).

The two following sub-sections address the formulation of digital transformation strategies and their alignment both in regards to the framework conditions a company operates in and to its internal context. They are based on the findings of two research activities presented, respectively, in the paper I (section 5.1.1.) and in paper II and paper III (section 5.1.2.).

5.1.1. ALIGNING STRATEGIC CHOICES TO FRAMEWORK CONDITIONS

This sub-section presents and discusses the findings concerning the research questions "*how is the digital transformation of a company affected by different framework conditions?*", summarizing the research described in paper I (Colli et al., 2020a).

Research background

Although the industrial digital transformation is affecting the manufacturing industry at a global level, different nations are formulating their own agenda according to their environmental characteristics and needs, and adopting different policies to support their manufacturers in this journey (Liao et al., 2018). Because of that, individual companies, in order to tackle the transformation effectively, need to shape their transformation strategy aligning it with the aspects that are characterizing the context they are operating in, for instance, its industrial policies.

The following research findings are the result of an investigation performed during 2019 in collaboration with the Universita' degli Studi di Bergamo (Italy). During a visiting period, we observed how different the national industrial agenda and the industrial perspectives were across our two countries (i.e. Denmark and Italy), although both within the European Union.

Research findings (summary of paper I)

In our study, we observed several differences concerning, mainly, the industrial policies adopted at a national level to support companies in their industrial digital transformation.

The Italian policies (i.e. Piano Nazionale Industria 4.0) are based on individual subsidy and are translated in the provision of financial support concerning specific aspects of the Industry 4.0 agenda. This consists of tax benefits related, at first, to the acquisition of new "digital" technological assets (preliminarily defined by policymakers) and, lately, to the engagement of external experts for supporting the company in managing the innovation process, addressing the emerged competence gap. At the moment, the Italian government, in collaboration with academic institutions, is establishing a three-level national infrastructure to provide Italian companies with more structured support for their digital transformation. At a higher level, "digital innovation hubs" will be responsible for supporting companies in identifying their needs and addressing them to the more adequate "competence center", whose aim will be to supply them with the competences for addressing the identified needs. At a more operational level there will be innovation centers ("Punti Impresa Digitale") that support companies (mostly small and medium enterprises) in the actual implementation of new technologies for addressing these needs. This infrastructure targets individual companies. Each one can benefit from it differently, depending on its innovation initiatives (e.g. choice to invest in new technologies, type of technology and size of the investment) and needs (e.g. consultancy time from the external expert or support through digital innovation hubs or competence centers).

The Danish policies concerning the Industry 4.0 agenda are, on the other hand, characterized by a collaborative nature. Danish institutions established a national platform (i.e. Manufacturing Academy of Denmark, MADE) to catalyze the industrial digital transformation, bringing together manufacturing companies, technology providers (e.g. research and technology organizations) and research institutions. From a financial standpoint, the support is directed towards the funding of time to engage these parties in explorative collaborations. These mainly concern the investigation of new digital technologies and their potential application and benefits in industrial environments. While each collaboration project involves a limited number of partners, according to their interests, the ultimate intention is to generate shareable knowledge that all companies engaged in the platform can potentially apply in their context afterwards.

The analysis of four large manufacturing companies, two located in Denmark and two located in Italy, highlighted how the way they approached the Industry 4.0 agenda was aligned to the framework conditions (i.e. mainly the national industrial policies) characterizing the context they operate in. Several similarities in the digital transformation strategies from companies located in the same country have been identified. On the Italian side, the investigated companies had the tendency to focus on the acquisition and implementation of new-generation physical assets (i.e. supported by taxation benefits), such as connected machines, and, more specifically, on their deployment for the automation of production processes (e.g. painting, quality control, internal logistics). On the Danish side, on the other hand, the investigated companies were more engaged in explorative collaboration projects together with research institutions and technology providers. These aimed at a broad spectrum of activities, going from the understanding of the potential behind the use of data (e.g. waste reduction) to the development of new technology solutions (e.g. asset tracking) and the adoption of agile project management approaches. These activities, primarily focused on the generation of awareness concerning the digital transformation agenda, were being performed through the development of demonstrators: small-scale projects deploying a simplified version of the investigated solution, aiming at providing companies with tangible indications concerning its integration needs as well as its potential in an industrial setting.

This investigation suggests us to take into account framework conditions when formulating company-specific digital transformation strategies, as they (especially the industrial policies that intend to catalyze the transformation) can provide significantly different opportunities worth to be captured, shaping the way we address the transformation agenda.

Additional reflections

The outcome of this research shows how, in a context characterized by a subsidy philosophy targeting individual companies (i.e. individual subsidy, see Table 8), these may adopt an opportunistic behavior, aiming for implementable initiatives in line with available financial opportunities – such as taxation benefits – and moving the initiatives' focus accordingly. However, it also emerged how this behavior can generate blind spots in a company transformation journey, as it tends to narrow the topics of interest. As institutions are responsible for steering companies' opportunistic behavior, they need to ensure such opportunities will cover all the necessary aspects companies will need to address in their digital transformation. The dependency that companies have on industrial policies augments the responsibility of the institutions about the success or failure of their industrial digital transformation agenda.

On the contrary, the presence of funding for more generic collaborative and explorative activities (i.e. explorative collaboration, see Table 8), may enlarge the companies' focus in a broader spectrum of initiatives. This could give them more freedom of choice when defining the topics to be addressed, and may facilitate a more comprehensive coverage of their actual transformation needs. However, to do so, a necessary condition is their ability to identify such needs, to define how to address them and to engage the right collaboration partners accordingly. In this regards, Radizwon et al. (2017) identified five key aspects to be taken into account in explorative collaborations: (1) the presence of a monetary incentive or support for financing the collaboration time (not sufficient, but often necessary condition), (2) the sharing of common (i.e. learning) goals among the collaborating partners, (3) inter-organizational facilitation of the collaboration initiatives (i.e. such as the MADE platform), (4) the possibility for the partners to capture actual value for their businesses and (5) the alignment between each partner's business model and the collaboration initiative's.

A metaphoric comparison between the two different framework conditions identified in this investigation (i.e. individual subsidy and explorative collaboration) could be the one between an autobahn and network of country roads. While the first (i.e. a metaphor of individual subsidy) aims at guiding all cars in the same direction – although often longer - ensuring high speed, the second (i.e. metaphor of explorative collaboration) aims at letting each car choose its path to its destination – often covering a shorter distance, although at a slower speed. A fundamental aspect to take into account before choosing which one to adopt is the way the company and its employees are used to work. Moreover, the availability of strategic partners for can be another discriminant, as well as the presence of the five enablers – proposed by Radizwon et al., 2017, and discussed above - for succeeding in explorative collaborations.

Table 8: Different framework conditions affecting digital transformation strategies

	Individual subsidy (e.g. Italy)	**Explorative collaboration (e.g. Denmark)**
National support target	Single companies	Clusters of companies
Support form	Taxation benefits for the purchase of specific assets or services	Financed time for collaborative innovation projects
Support focus	Moving (i.e. assets purchase first, competence support services purchase afterwards)	Fixed
Company strategy	Opportunistic: it follows the continuously changing (e.g. financial) opportunities	Explorative: it unfolds all the aspects concerning the innovation agenda
Initiative outcome	Implementable solution	Solution demonstrator and shareable knowledge

It is worth considering that, for global companies operating in different countries, it may be valuable to consider different digital transformation strategies depending on the location of the different business units. The way innovation concerning this agenda is approached at a local level should be strategically aligned to the local framework conditions (e.g. the national industrial policies regulating the specific context). This suggests a decentralization of the choices concerning the typology of a transformation strategy to adopt: while the strategic goals can be common for the whole corporation, the most effective way these goals can be achieved may be different.

Once companies defined how to approach the industrial digital transformation agenda and scope their digital transformation strategy – defining its goals – according to framework conditions and the related opportunities, they need to identify which initiatives to embark to operationalize the transformation pursuing these goals. To do so, they also need to take into account the contextual factors (e.g. needs and goals) that are characterizing them internally.

5.1.2. IDENTIFYING COMPANY-SPECIFIC DIGITAL TRANSFORMATION INITIATIVES

This sub-section presents and discusses the findings concerning the research questions "*how can Problem-Based Learning be used to operationalize a digital maturity assessment, leading to context-specific improvement recommendations?*", summarizing the research described in paper II (Colli et al., 2018) and paper III (Colli et al., 2019a). Paper III represents the extension of paper II: they have both been included in this dissertation as they give the reader the chance to see how the contribution developed over time due to the presence of additional empirical evidence.

Research background

The adoption of a maturity perspective and the assessment of the digital maturity of an organization are well-established approaches to support companies in identifying the transformation initiatives their digital transformation strategy may consist of. The available approaches for doing so are, however, failing in taking context-specific needs and goals into account, providing companies with generic indications, based on available capabilities, but lacking more individual ones (Schumacher et al., 2016).

Accordingly, case companies C, D and E highlighted the need for more individualized treatment for supporting their transformation process. To answer it we need to have the ability to pinpoint specific activities for a company that both aim at improving its digital capabilities but also at translating them, at the same time, into value for the individual company.

To support the required context-specific analysis, diagnosis and identification of initiatives, Barreto et al. (2017) and Büyüközkan and Göçer (2018) highlighted the need for a novel approach focused on facilitating stakeholder engagement. Aalborg University is historically addressing stakeholder engagement - catalyzing more individual learning processes - through the adoption of the Problem-Based Learning (PBL) model. PBL helps its users in structuring dialectic processes that facilitate the understanding of a problem in its specific context. This is being used extensively at Aalborg University for supporting students in addressing semester projects in collaboration with industrial partners. Having an in-depth knowledge of the PBL model, we decided to take advantage of it for guiding us in the development of a novel and more individual way to approach the assessment of digital maturity.

Research findings (summary of paper II and paper III)

In accordance with the PBL founding principles, we proposed the novel 360 Digital Maturity Assessment (360DMA). The 360DMA is composed by a maturity model, outlining the Industry 4.0 evolutionary path, and by an assessment approach, core research contribution, guiding the process of evaluating the digital maturity of a company and translating it into the formulation of company-specific transformation initiatives.

The maturity model is based on extant literature and outlines the Industry 4.0 evolutionary path, the related dimensions and capabilities. Our literature study led us to the identification of five key dimensions to be addressed in the digital maturity progression. These concern the technology domain and, more specifically, the available assets and their data processing capabilities, connectivity aspects such as the vertical and horizontal integration, the ways data availability is translated into value creation, the governance structure used to support and manage transformation activities and the available competences. In addition to that, extant literature guided us in the definition of six maturity stages, archetypes of the digitally maturing organization. They are named after the key capabilities characterizing them – none, basic, transparent, aware, autonomous and integrated (Figure 7, where they are summarized) (for further insights, see paper II and paper III).

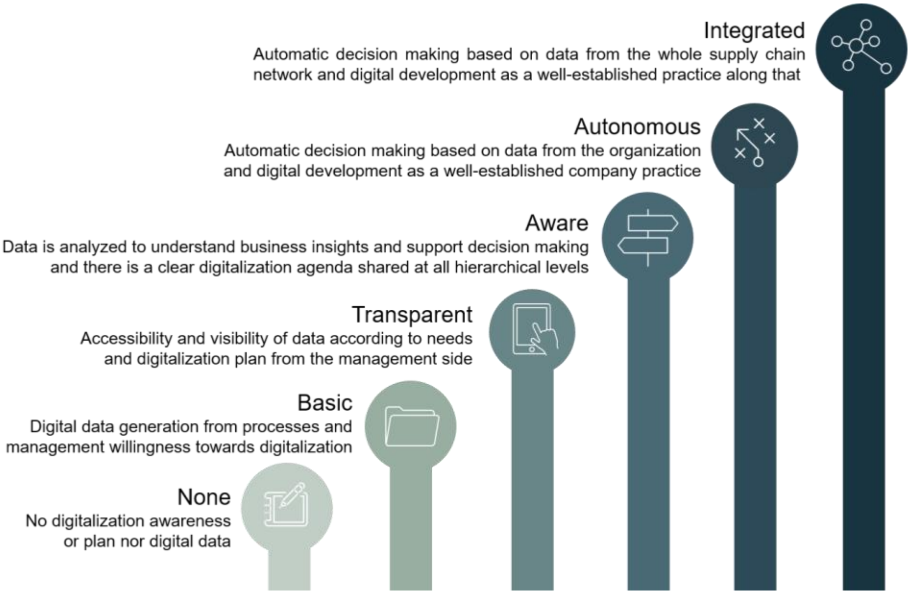

Figure 7: Digital maturity stages (figure inspired by Colli et al., 2019a)

The assessment approach, core contribution of the research, is novel and based on the PBL model and its progression. Its underlying principle is the structured dialectic process between the assessment team and company representatives. This enables a progressive funneling of the investigation performed to assess the digital maturity of a company (Figure 9) and is intended to support the assessment team in focusing the attention where more required – and where the business potential is higher. To do so, the assessment approach – proposed and refined during three testing iterations -

consists of five steps, presented in Table 9 (for further information, see paper II and paper III). The adoption of the PBL model to structure the dialogue aims at ensuring the effectiveness of these steps, facilitating the assessment team in uncovering development opportunities fitting to the specific context.

The assessment is operationalized by an external team composed by domain experts, a rapporteur formally collecting data and a facilitator coordinating the activities. This "external helper model" (Schein, 1995, 2008, 2009) bases the assessment process, according to the PBL model (Barge, 2010), on continuous interaction between the assessment team and the assessed party. This fosters the learning process and increases the validity of the collected data (Lewin, 1997). Furthermore, the primarily engaged stakeholders from the company side are part of its top management. This helps to generate a sense of urgency that leads to the legitimization of the needed management actions for pursuing the innovation agenda, acting as a catalyst for change (Schmidt et al., 1983).

Table 9: 360DMA: assessment approach steps, activities and involved stakeholders (Colli et al., 2019a)

Step	**Activity**	**Involved stakeholders**
Creation of awareness	Half-day company presentation (activities, key performance indicators, strategic goals)	Company representatives engaged in the assessment, assessment team
	Half-day industrial digital transformation awareness seminar (technological and organizational aspects)	Assessment team, company representatives engaged in the assessment
Definition of scope	Definition of the unit of analysis to be considered in the assessment (e.g. production line, department, factory)	Company representatives engaged in the assessment
Data collection	Self-assessment questionnaire: preliminary maturity investigation to identify critical areas	Company representatives engaged in the assessment
	Data collection workshop design: focus on areas (and they are responsible) related to low-grade or mismatching answers to the self-assessment questionnaire	Assessment team

	Full-day data collection workshop: an in-depth dialogic investigation of the critical areas, investigation of the maturity gaps, their causes and consequences on the company strategic goals	Assessment team, company representatives engaged in the assessment and company responsible for the focus areas
Evaluation and solution selection	Mapping of collected data according to the digital maturity model (dimensions and stages), identification of the key maturity gaps and formulation of transformation initiatives to address them	Assessment team
Debriefing	Presentation and discussion of the assessment results, the key maturity gaps and the transformation initiatives	Assessment team, company representatives engaged in the assessment

The outcome of the assessment consists of a spider web diagram indicating the digital maturity stage of the company in regards to each dimension (Figure 8), an indication of the maturity gaps, limiting the company in its digital transformation, and the presentation of a set of short-, medium- and long-term digital transformation initiatives addressing these gaps. This way the company will have the chance to pursue both low-hanging fruits, generating traction for the whole transformation agenda, and operational and strategic goals, bringing more significant benefits but also requiring a longer time horizon. It is worth considering that the focus is not on finding the most important gap or the optimal initiative to address it but to provide the company with an indication of a spectrum of relevant and feasible activities to ignite its transformation.

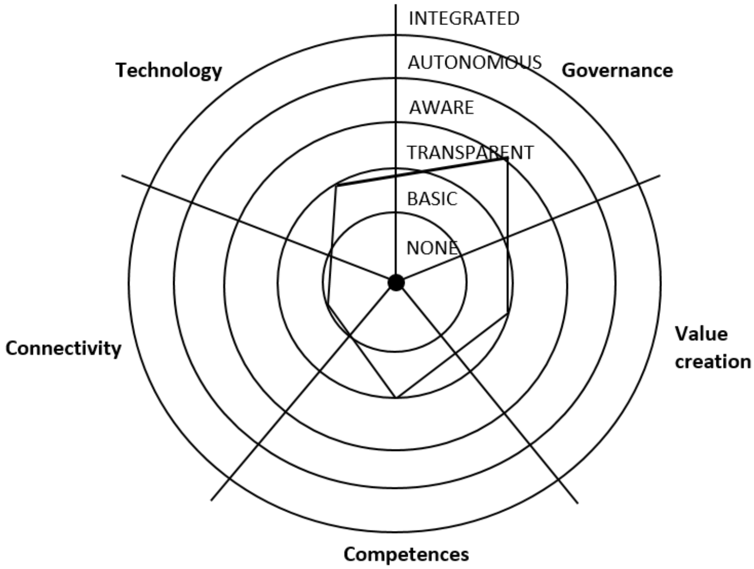

Figure 8: Spider web showing the assessment stages concerning the different dimensions

Additional reflections

The adoption of the 360DMA during its testing phases made some aspects emerge. The initial creation of awareness (step 1) provides the assessment team with an overview of the company, its needs, key performance indicators and strategic goals, and company representatives (at a top management level) with information concerning the industrial digital transformation agenda such as enabling technologies and their potential, exemplary cases and best practices. The use of a laboratory environment to actually demonstrate these technologies, their use, and the related advantages were observed as particularly effective in doing so. It catalyzed further interest in company representatives and led to additional discussions concerning the demonstrated technologies and their potential applications in the company context. This facilitated company representatives in defining the scope of the assessment (step 2) according to their vision and objectives, a key aspect for formulating an effective digital transformation strategy (Kane et al., 2015). The self-assessment questionnaire (the first activity of step 3), preliminarily adjusted according to the company characteristics (learned in step 1), led in all cases to the identification of critical points to be further investigated. The questionnaire was answered by company representative at a management level and, for all three case companies (C, D and E), some questions have been answered in a completely different way, depending on the respondent. Others have been answered negatively (with "low grades") by all the respondent. These two types of answers have been used – by the assessment team - as a starting point for the preparation of the data collection workshop.

Nevertheless, although possible, the outcome of the self-assessment questionnaire has not been used to provide the company with an indication of its digital maturity, but more as a guide for further focusing the investigation. The following data collection workshop consists, in fact, of several in-depth interviews, each one directed explicitly to company representative responsible for the critical areas concerning the gaps that emerged from the self-assessment questionnaire. This was the stage of the assessment process, where the usefulness of a dialogic process emerged the most. To progressively focus towards the fundamental issues made possible to unfold them and obtain in-depth information – something impossible if adopting only a standard questionnaire. To involve company representative from many different parts of the organization helped in tackling the cross-functional nature of the Industry 4.0 agenda, looking at issues to be addressed with new technologies and concepts from multiple angles (e.g. support to quality control processes and challenges of the IT department managing the related data).

Furthermore, engaging (and empowering) middle management - instead of top management - at this stage of the investigation helped to collect more practical information concerning the emerged issues while tackling the potential biases related to the company hierarchy. This way, this workshop provided the assessment team with the necessary information concerning not only the current capabilities of the assessed company but also the reasons behind the emerged gaps. By qualitatively analyzing their dependencies and their role in limiting the achievement of the company strategic objectives, it was possible for the assessment team to identify some key gaps and to formulate a number of digital transformation initiatives for addressing them (step 4). It is worth considering that this analysis,, as well as the formulation of digital transformation initiatives, is strongly dependent on the expertise of the assessment team. The more technological and organizational domains the team covers, the more comprehensive the analysis and the recommended initiatives will be; the more profound the expertise will be, and the more specific the recommended initiatives will be. The progressive funneling characterizing the sequence of steps of the 360DMA assessment approach made possible for the assessment team to debrief the assessed company with an indication of its maturity level and key gaps and with a precise set of initiatives to bring forward its digital transformation (step 5) (Figure 9).

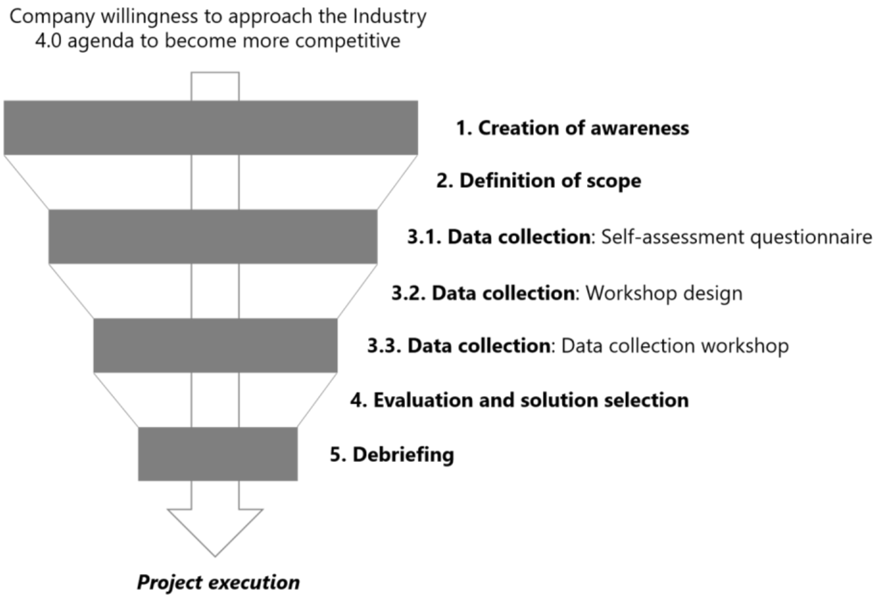

Figure 9: 360DMA funneling process throughout its steps

As Kane et al. (2017) observed in their Digital Business Global Executive Study, "digital maturity is a continuous and ongoing process of adaptation to a changing digital landscape" (Kane et al., 2017, page 6). We may argue that, because of this mutating nature, it is of fundamental importance to perform such exercise iteratively. This would make it possible to both provide a company with continuous support for its digital maturity growth as well as to consider the new technological and organizational opportunities the market has to offer. Because of that, even though it leads to the execution of the recommended digital transformation initiatives, the 360DMA is considered to be performed periodically (Figure 10). This also reminds us how the dialogical form can fit the need for adapting to such changes, in opposition to over complex questionnaires that would need to be periodically updated.

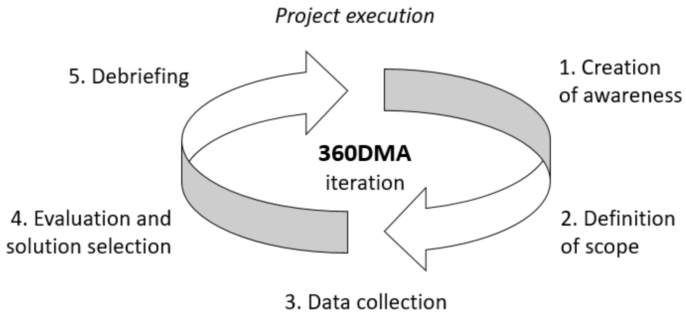

Figure 10: 360DMA iterative assessment approach (figure from Colli et al., 2019a)

5.1.3. RESEARCH IMPLICATIONS

This work package answers the need, emerged from case companies C, D and E, to identify transformation initiatives for formulating a digital transformation strategy. This implies the capability to formulate a strategy that is addressing company-specific needs and goals and to capture unique opportunities. The work package consists of two research activities concerning, respectively, the study of dependencies between companies' digital transformation strategies and the framework conditions they operate in (paper I), and the proposal - and testing - of a methodological approach for guiding the identification of company-specific digital transformation initiatives (paper II and paper III). These investigations have been performed involving several industrial partners, including case companies C, D and E.

Theoretical implications

From a theoretical perspective, the research performed in this work package addresses the lack of academic research that provides guidance – in the form of frameworks, guidelines or roadmaps - for digitally transforming supply chains, formulating and implementing strategies tailored to specific contexts (Matt et al., 2015; Hess et al., 2016; Büyüközkan & Göçer, 2018). These research activities specifically contribute to the digital transformation strategy and digital maturity bodies of literature, taking into account, in the formulation of a digital transformation strategy, both exogenous and endogenous contextual factors.

On the one hand, the study of the potential dependencies between exogenous factors, characterizing the context a company operates it, and endogenous factors, characterizing its own digital transformation strategy, aims at answering to "how is the digital transformation of a company affected by different framework conditions?" (paper I). Starting from the notion that the presence of different framework conditions generates the need for different innovation practices (Lundvall et al., 2002; Sousa & Voss, 2008), this research contributes to the need for providing guidelines for identifying such practices in diverse contexts and, more specifically, formulating the different goals that lead to the adoption of such practices. The formulation of these goals is, in fact, a key aspect for outlining a digital transformation strategy (Büyüközkan & Göçer, 2018).

On the other hand, the actual formulation of a digital transformation strategy at a company level is addressed through the proposal of the 360DMA (paper II and paper III), a digital maturity assessment approach focused on the need for tailoring the assessment process and outcome to the endogenous contextual factors characterizing the company (Schumacher et al., 2016). The use of the PBL model as a foundation for the proposed assessment approach answered the demand for increasing stakeholder engagement, highlighted by Barreto et al. (2017) and Büyüközkan & Göçer (2018). In fact, this is considered to support a context-specific analysis, diagnosis and identification of company-specific transformation initiatives (Barreto et al., 2017; Büyüközkan & Göçer, 2018; Schumacher et al., 2016). The research answered, accordingly, to "how can Problem-Based Learning be used to operationalize a digital maturity assessment, leading to context-specific improvement recommendations?". Ultimately, this investigation provides researchers with an example of DSR in both its abductive (i.e. proposal of an artefact – the 360DMA) and deductive (i.e. testing of the artefact in the three industrial cases) phases.

Further research needs to be performed to validate the effectiveness of the digital transformation strategies obtained (1) by following the guidelines proposed for aligning them to framework conditions (paper I) and (2) by applying the 360DMA model for identifying the transformation initiatives (paper II and paper III).

Managerial implications

From a managerial perspective, the research performed in this work package provides practitioners with new guidelines and tools to assist them in consistently structuring the digital transformation of a company. More specifically, they facilitate the formulation a digital transformation strategy that fits the specific context, supporting the coordination and prioritization of transformation activities for translating them into business value (Matt et al., 2015; Kane et al., 2017).

The understanding of some of the framework conditions (by all means not all of them) characterizing the environment a company operates in and the reflections concerning their role in affecting a company digital transformation strategy (paper I) provide practitioners with support for outlining their strategic objectives according to the external context. Through the performed cross-country evaluation, we discussed different strategic choices adopted in different environments and provided suggestions to practitioners concerning which ones to consider, e.g. wide-scope collaboration projects or narrow-scope individual ones. In addition to that, this research may support policymakers in their future strategic choices, by supplying them with information concerning different national industrial policies used to support the Industry 4.0 agenda and reflections regarding their implications on companies' digital transformation strategies.

The proposal of a methodology for assessing digital maturity of a company, facilitating the identification of company-specific transformation initiatives (paper II and paper III), instead, provides innovators with support for operationalizing their digital transformation. This methodological approach acts as a tool for formulating transformation strategies capable of linking the industrial digital transformation agenda to companies' individual needs, goals and business opportunities. This is, in fact, a fundamental aspect for sustaining the digital transformation of a company (Matt et al., 2015, Westerman, 2018; Kane et al., 2017; Kane et al., 2015). The proposal of a structured approach for identifying maturity gaps facilitates the adoption of new technologies and methods (Canetta et al., 2018) and the aligning between transformation initiatives and business objectives support the translation of existing capabilities into a higher level of performance (Raab & Griffin-Cryan, 2011). Ultimately, the description of the empirical testing (in three industrial cases) of the proposed approach supplies practitioners with tangible indications concerning how the assessment can be performed in an industrial environment, who needs to be involved, which types of information and key gaps can emerge and which types of transformation initiatives can be suggested to address them. In addition to that, the in-depth description of the maturity model used to frame the information collected during the assessment can be used as an assessment tool as well as a source of inspiration for formulating a transformative vision (Kane et al., 2017; Westerman, 2018).

5.2. ENABLING TRANSPARENCY THROUGH IOT INTEGRATION ADDRESSING CONTEXT-SPECIFIC APPLICATION NEEDS (WP2)

Once a transformation initiative involves (or requires) the enabling of transparency across the supply chain, the integration of IoT becomes an obliged passage. However, how to operationalize it remains an open question for academia as well as practitioners.

Studying the extant literature regarding this topic, we identified two main aspects we need to take care of when integrating IoT: the tailoring of the technology solutions to context-specific characteristics (Veile et al., 2019; Chen et al., 2014; Moeuf et al., 2018) and the translation of the enabled transparency into actual business value, addressing relevant needs (Martinez, 2019; Ammirato et al., 2019).

Martinez (2019) observed how the introduction of digital technologies consists more of a structured learning process rather than a standard sequence of instructions. Companies need to be able to analyze their own context and to understand where to adopt technologies, which ones and how to translate them into value generation for their own business. However, a comprehensive approach capable of supporting innovators in this learning process, linking technology development to context-specific application needs is still missing. This should lead to the successful integration of IoT in supply chains and the consequent enabling of transparency. While facilitating the design of IoT solutions under a technology perspective, this would have to address the need for matching explorative efforts – such as the integration of novel technology - to exploitative needs – or its translation into business value. This is still a key challenge while managing innovation processes (Papachroni et al., 2015); in fact, the absence of solid business cases related to the Industry 4.0 agenda represents one of the main barriers for the integration of digital technologies in supply chains (Schmitz et al., 2019).

The following sub-sections address, at first, the need for tailoring technology implementation to these context-specific application needs. Focusing on learning from the context, we aimed to systematically address the design of IoT solutions to be tailored to a specific context for improving its operational performance. Secondly, they investigate how to further support critical business cases – often characterizing these solutions - taking into account the applicability of the learnings obtained during their development. The sub-sections are based on the findings of two research projects presented, respectively, in paper IV and paper V (section 5.2.1.) and in paper VI (section 5.2.2.).

5.2.1. LINKING IOT SOLUTION DESIGN TO CONTEXT-SPECIFIC NEEDS: A SYSTEMATIC APPROACH

This sub-section presents and discusses the findings concerning the research questions “*how can the process of designing an IoT solution be addressed to tailor it to context-specific application needs?*” and “*how can companies identify continuous improvement potential related to the integration of IoT?*”, summarizing the research described, respectively, in paper IV (Colli et al., 2020b) and paper V (Nygaard et al., 2020).

Research background

The adoption of IoT and the development of solutions based on this technology are meant to generate transparency across supply chains - an information flow that provides companies with support for performing (or automating) their decision-making processes (Tu, 2018; Haddud et al., 2017; Holcomb et al., 2011; Zelbst et al., 2019). However, there is still a lack of systematic approaches for guiding the integration of IoT in a supply chain and the translation of the enabled transparency into business value (Moeuf et al., 2018; Martinez et al., 2017; Whitmore et al., 2015; Veile et al., 2019).

Case companies A, B and C highlighted the generic importance of this knowledge-base gap by asking for tangible guidelines for successfully integrating IoT in their supply chains, aiming for operational performance improvement.

To address this need, we engaged in a research activity studying how to systematically design an IoT solution with the intention to improve the performance of a company's operations. This activity was performed together with case company B, with the aim to obtain generalizable knowledge to answer the more general need emerged from case companies A, B and C. For us to be able to link the IoT solution design process to a specific company, it was fundamental to focus on learning: to understand the needs and characteristics of an environment provided the necessary indications for designing an effective solution. In line with the extant knowledge concerning this topic, we based our learning process – translated into the proposed IoT solution design framework - on the adoption of a (value-driven) process-excellence perspective (Martinez, 2019; Ammirato et al., 2019; Westermann, 2018) and on the link between technology and contextual characteristics (Chen et al., 2014; Moeuf et al., 2018; Veile et al., 2019). While the first is about translating the integration of new technology into business value, addressing actual problems or business opportunities, the second is about adapting the deployed technologies and infrastructures to the characteristics of the production system where they are to be integrated.

This research intended to contribute to extant literature both providing a framework that was capable of guiding the contextualization of IoT solution design, as well as to identify – while testing it – key drivers for supporting its effective use.

Research findings (summary of papers IV and V)

The performed research led to the proposal (and testing) of a novel framework (paper IV) for systematically designing IoT solutions, ensuring both their value contribution and contextual fit. This acts as a structured learning process that leads to an understanding of the addressed context. It had been developed with a normative purpose (i.e. to guide the design of IoT solutions) but also to facilitate the understanding of contextual drivers to be considered for ensuring the balancing between an explorative activity and the capitalization of exploitative needs. According to that, the framework consists of six phases, which are acting as a structured learning process (Table 10). The contribution does not lie in the operationalization of the phases, but in their identification and – most importantly – in understanding why and how these are important for the contextualization of the design of an IoT solution – and of the consequent enabling of transparency.

The first four phases are focused on the identification of contextual needs and business opportunities,to be able to translate technology implementation into actual value and to quantify it. The last two are focused on the definition of the technological infrastructure required to address such needs and business opportunities in the addressed context.

To translate the introduction of new technology into value, the identification of relevant technology implementation possibilities can be guided through the adoption of a process excellence perspective (Martinez, 2019). Whether this is matched to a continuous improvement philosophy or Business Process Reengineering (BPR), the learning process required to identify relevant technology implementation possibilities can be initiated through the use of value stream mapping (VSM). It has already been discussed how lean tools and management practices provide a valuable backbone for the industrial digital transformation (Tortorella & Fettermann, 2018; Lugert et al., 2018) by supporting the search for process improvement (Adler et al., 2009). Both continuous improvement (Martinez, 2019) and BPR (Ammirato et al., 2019) are relying on the systematic mapping and analysis of the operations to identify critical improvement needs in a specific context. This supports innovators not only in identifying where it is particularly relevant to integrate IoT, but also in quantifying the improvement potential, often a challenging task. This facilitates the match between the explorative efforts - concerning the introduction of new technology in a company - and its exploitative needs - concerning its translation into actual business value. The difference in adopting BPR rather than a continuous improvement philosophy emerges during the proposal of a solution concept. The adoption of BPR, contrarily to a continuous improvement philosophy, does not limit the proposal of a future scenario to a more efficient version of the existing one but takes into consideration the possibility of re-shaping business processes to maximize the value creation possibilities enabled by new technology.

The actual design – from an infrastructural point of view - of the conceptualized IoT solution can be obtained through the definition of the information flow that has to be processed to address the identified improvement needs, and of the technologies that need to be deployed to establish such flow. The definition of the information flow can be performed adopting a hierarchical approach, following the Goal-Question-Metric (GQM) method, a systematic way to structure data collection processes aiming at translating a task into the specific metrics needed to support it (Caldiera et al., 1994). Starting from the critical process that needs to be improved, the first task is to identify the related decision-making processes, highlighting the need for information to support them – the "goal" of the IoT solution is to provide it - and, eventually, the raw data – or "metrics" - and the data processing needs to be required to generate and make such information available. The type, location and destination of the raw data to be collected as well as its processing needs indicate the functionalities that the IoT solution infrastructure will need to satisfy. This acts as a reference for the selection of the technologies to be deployed in the solution infrastructure. In fact, following the Task-Technology-Fit (TTF) critical construct (Goodhue & Thompson, 2015), these are selected concerning their capability to satisfy the identified functional needs.

Table 10: IoT solution design framework and related learnings (Table from Colli et al., 2020b)

Phase	Activity	Approach	Data needs	Learnings
Operations mapping	Mapping of the business processes	VSM (value stream mapping)	Business processes and information to support decision-making regulating the business processes	A qualitative and quantitative description of the targeted business processes
Operations analysis	Identification of the issues and criticalities concerning the mapped processes in regards to the company competitive needs	VSM	Value-adding and non-value-adding activities concerning the mapped business processes. Entity and implications of the non-value adding ones	Key issues and criticalities to be addressed through the enabling of transparency
Target situation definition	Proposal and mapping of the ideal ("reengineered") business processes, supported by the enabling of transparency	VSM	(Proposed) improved activities and information to support decision-making processes regulating the activities	Solution concept and industrial requirements for guiding its development and of solution features to achieve them

Performance improvement potential	Discussion concerning the potential improvement related to the transition from the current to the target situation	Gap analysis	Operations mapping, target situation mapping, entity and implications of the addressed issues and criticalities	A qualitative and quantitative description of the impact of the proposed solution
Information flow definition	Definition of the information flow for sustaining the target situation activities	GQM (goal-question-metric)	Decision-making processes to be supported, the solution features to support them, a description of what data supports the decision-making processes	Information flow to be processed by the solution (identification of the gaps with the existing one)
Solution components definition	Definition of the technical components needed for processing the information flow	TTF (task-technology fit)	Functional needs concerning the information flow processing	Solution infrastructure and technical components to be deployed

The testing of the proposed framework, performed in collaboration with case company B, indirectly validated its effectiveness, as it led to the development of an implementable (and implemented) IoT solution that successfully addressed the case company's operational performance improvement needs. This consisted of a digital platform for remotely monitor the operating conditions of supplied automation solutions. Its objectives concerned the improvement of the responsiveness of service operations - obtained through the enabling of error alerts and the provision of the related information – and the quantification of their impact – obtained through the collection of longitudinal data concerning the performance of the supplied automation solutions (for further information about the developed IoT solution and its use and effectiveness, see paper IV, Colli et al., 2020b).

Other than validating the effectiveness of the framework, its testing in an industrial setting highlighted several drivers for tailoring the design of an IoT solution and the enabling of transparency to a specific context (Table 11). This contributes to guiding our behavior and supporting our activities during the solution design phases. First of all, it was of key importance to identify the company's strategic goal (e.g. to have a fast-response service department). This was fundamental for giving the solution development a wider perspective compared to the solely "technological" one. This helps the "reengineering" of the processes instead of the mere digitalization of the existing activities. Secondly, the adoption of an agile approach during the solution design facilitated the development of an effective solution. The several small changes required while developing the solution suggested that the close collaboration with the industrial partner and the periodical and frequent (i.e. one-hour sessions every second or third week) interactions ensured a continuous alignment between the ongoing solution development and the company requirements. As these changes often emerged after the discovery of either new technology capabilities or additional contextual needs, we could deduce that the frequency of the needed interactions is directly dependent on the degree of uncertainty concerning the solution space. These interactions also supported the triangulation of the data collected by the solution developer from other company responsible, company documentation or through observations during the multiple company visits.

Furthermore, the availability of a controlled environment (a laboratory) were to test the IoT solution facilitated its agile development: testing activities did not cause any downtime to the case company and have been allowed until the effectiveness of the solution was verifiable, avoiding the related risks in industrial settings. Another key driver concerned the in-depth awareness of the company representative in regards to the addressed business processes and their criticalities. Together with the presence of an underlying idea for improving them, this made it possible to quickly formulate a detailed target situation and to conceptualize a solution. This suggests the importance of such awareness in influencing the potential of the latter. On the solution developer side, relevant competences concerned operations mapping and analysis as well as of state-of-the-art application cases concerning the addressed technology. Information technology (IT) knowledge was also relevant for matching of functional solution needs to available technologies capabilities. These aspects may condition, on the one hand, the proposed solution concept and its impact and, on the other, the optimal choice of the technologies to be deployed, affecting its business case. Although the proposed framework tries to structure the IoT solution design process making it as systematic as possible, it also highlights how its outcome is still inevitably dependent on the humans adopting it. A necessary aspect (and not only a driver) to allow the enabling of transparency across the company's supply chain was the acceptance – from the customer side – of the technologies to be deployed for processing its production data as well as of sharing such data with a supplier. This shows how we cannot talk about a context-specific solution without also socially embedding it. If data sharing was a matter of mindset and strategic choices, the deployment of specific technologies depended more on the technological capabilities and financial resources of the company. A mismatch could lead to a complete change of the target situation and, according to that, of the designed solution.

This aspect may be addressed through the preliminary assessment of the company's digital maturity concerning the technologies used to process the information flow (paper V). This would require an assessment of the digital maturity concerning the information flow and the deployed technologies for processing it. In addition to that, this could also act as a support for further integrating IoT adopting a continuous improvement philosophy: low-maturity data processing nodes can be highlighted as potential IoT integration candidates. In contrast, high-maturity yet low-performing nodes can be highlighted as in need for better exploiting the already deployed technology. Such an approach would progressively increase the digitalization of the existing information flow. As this would not generate the sharing of further information, this process could implicitly ensure user acceptance from a data-sharing point of view. On the one hand, information processing performance would gradually increase due to the increase of its digitalization; on the other, new opportunities would be limited by the limited use of further information.

Table 11: Drivers for contextualizing the IoT solution design, clustered by digital maturity dimension (according to Colli et al., 2019a)

Dimension	**Drivers**	**Effects**
Value creation	Identification of the user's strategic goal and objectives	Effective scoping of the solution space
Governance	Agile project management and frequent iterations and feedback from the solution user	Alignment between developed solution and user needs
	Controlled environment for testing	Reduction of downtime and of the risk of failure

Competences	Awareness of the operations' criticalities	Speed up the solution concept formulation
	Operations management (lean production and Industry 4.0 agenda)	Effective mapping and analysis of the operations and proposal of an up-to-date solution concept
	Information technologies	Identification of optimal technologies for satisfying the solution requirements
Connectivity	Willingness (of the user) of sharing the data (i.e. information flow) and of adopting the selected technologies	Implementation of the designed solution with no need to re-define the target situation or selecting alternative technologies
Technology	Availability of the resources and capabilities for implementing the required technologies (or availability of the required technologies)	Implementation of the designed solution with no need to re-define the target situation or selecting alternative technologies

Additional reflections

As both technologies,, as well as companies, are becoming more digitally mature over time, we may expect a shift of focus regarding their implementation in a company. If at an early stage the main objectives may be more oriented towards the exploration of their capabilities and requirements as well as the identification of their potential application cases, as soon as these aspects become clearer and "off-the-shelf" solutions start being available, the industrial focus can be expected to progressively shift towards the exploitation of the new capabilities. This would imply an increasing relevance of the proposed framework over time. In fact, the integration of IoT in a systematic way, adopting a process excellence perspective, matches the explorative nature of introducing new technology with the exploitative need for capitalizing on it (Figure 11).

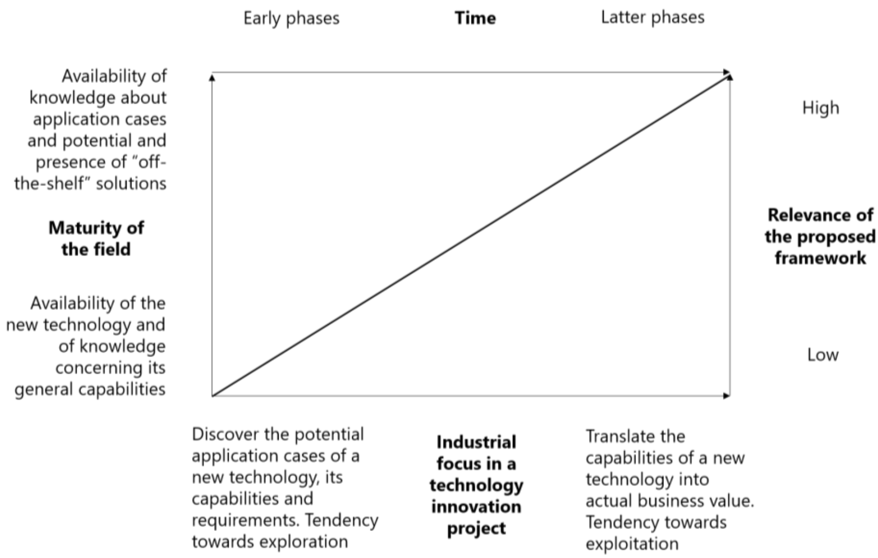

Figure 11: Relevance of the proposed framework (or of the adoption of a process-excellence perspective) in relation to the maturity of the field

While the adoption of a process excellence perspective (Martinez, 2019) is facilitating the introduction of IoT and the enabling of transparency in a consistent way, we can argue that this does not address the identification of more "disruptive" innovation possibilities. If the enabling of transparency supports the improvement of business processes, we have also seen how it may enhance completely new ways to do business. One example is its role in facilitating servitized as well as circular business models (Chen et al., 2019; Colli et al., 2019b). As a matter of fact, while discussing this framework with a large Danish technology provider, it emerged that, within their projects, the exploration of new technologies and their capabilities often inspired new business ideas. We can argue that to make sure our process improvements lead to a global optimum and not to a local one, it is therefore paramount to have an overview of the potential application cases related to new technology and to link its integration to the company strategy.

As mentioned above, a necessary condition for translating an IoT solution design in an implementable IoT solution design is user acceptance. There have been a plethora of discussions concerning this issue, especially in relation to data security. This research highlighted, indeed, the importance of this aspect. However, there is a more nuanced yet fundamental aspect to be included in the discussion: the increased dependency users will experience in regards to their product or service providers. From the providers' perspective, the enabling of transparency across their supply chains would act as a new tool to enforce a "lock-in strategy" with their customers. Siggelkow & Terweisch (2019) discussed how the ability to look into companies' business processes and identifying their needs supports product or service providers in addressing them (or in suggesting customers how to address them) even before they arise. We can argue that this would provide a performance advantage on both sides, although resulting in an increased dependency to whom is in control of the information. This may result in reduced freedom when considering any supplier change (i.e. "lock-in strategy") and in a strong dependency on the ability of the supplier in processing such information. Other than proving a positive business case, IoT solution developers will need to be able to address these discussions and make sure that either the business advantages provided by the enabled transparency will compensate for the risks, either there will be specific agreements to tackle them.

5.2.2. THE ROLE OF LEARNINGS IN SUPPORTING THE BUSINESS CASE OF AN INNOVATION INITIATIVE

This sub-section presents and discusses the findings concerning the research question "*can learnings obtained through explorative innovation initiatives in manufacturing be exploited to support their business cases, and if so, how?*", summarizing the research described in paper VI (Colli et al., 2020c).

Research background

As we already know from the nature of the exploration and exploration dilemma (e.g. March, 1991), it is often challenging to match the integration of new technology to the generation of actual business value. Schmitz et al. (2019) identified the presence of an unclear business case and the lack of short-term benefits as two of the main barriers for the success of digital transformation initiatives. In fact, case companies A and C stressed, from their side, the need for a solid business case as a necessary condition to succeed in their IoT integration initiatives.

We also know, however, that when it comes to the value that innovation brings on the table "there is more than meets the eye". To engage in innovation activities is fundamental for a sustainable business and necessary for ensuring its long-term success (Tushman & Nadler, 1986). As the industrial digital transformation is considered to be a learning process (Martinez, 2019), if the uncertainty related to its innovation initiatives is certainly a risk for a business, the learnings obtained from them may also enable potentially unseen business opportunities. We argue that the identification of such opportunities could be a way to support its business case. However, as Rice et al. (1997) observed, technologists mainly lead explorative innovation initiatives, and it is often unlikely for them to envision business opportunities associated with innovation.

The following research, performed in collaboration with case company A, consists of the proposal and testing of a theoretical model for facilitating the recognition of business opportunities starting from the learnings obtained through an explorative innovation initiative - the design and integration of an IoT solution for improving the company's operational performance.

Research findings (summary of paper VI)

Following the Design Science Research framework (Hevner et al., 2004), we proposed the "digital transformation focus shift" theoretical model to structure the different ways learnings obtained from innovation initiatives can be used to uncover new business opportunities and, hence, be translated in (additional) business value.

Starting from extant literature (Rice et al., 2001, Clark, 1987; McGrath, 1997; Myers & Rosenbloom, 1993; Bowman & Hurry, 1993) we identified three different "value categories" to build the model on top of. These represent the different ways innovation can generate value, and provide us with a foundation for identifying business opportunities starting from the innovation's outcome and its related learnings. These "value categories" concern:

- Problem-solving or the performance of an innovation initiative addressing a specific issue with the intention is to improve the key competitive capabilities of a firm;
- Extended potential, or the use of the innovation outcome to address additional issues, to further capitalize on the innovation initiative;
- Innovation, or the use of the innovation outcome to catalyze and sustain further innovation, characterized by a higher level of maturity and aligned with the firm's strategy, aiming at unlocking new business opportunities.

As these three different "value categories" are a source of business opportunities, they all contribute to the potential increase of the business value related to an innovation initiative.

However, it is worth considering that these "value categories" are characterized by different temporal foci (Figure 12): innovation initiatives will be triggered by – and start from - well-defined problems linked to specific performance objectives, and new solutions will be developed to address them. Additional application possibilities concerning the innovation initiatives' outcome may be identified afterwards, and developed solutions adapted to tackle further issues. At a later time, when the learnings obtained from the innovation initiatives will be consolidated, it will be possible to use them as a foundation for supporting further innovation.

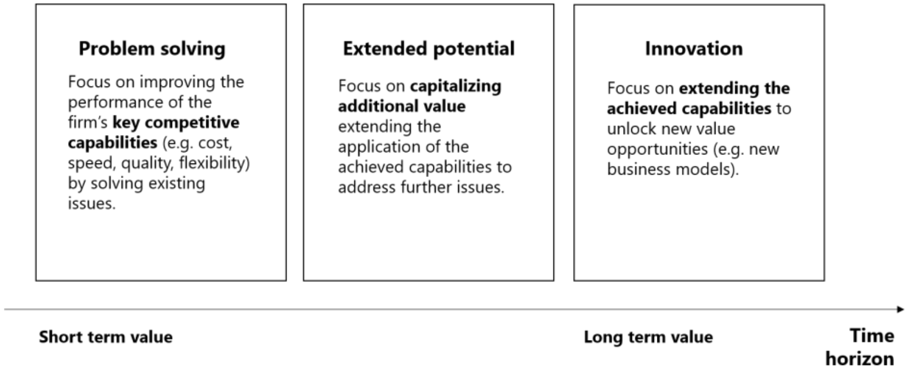

Figure 12: Different value categories seen from a temporal perspective (from Colli et al., 2020c)

Innovation initiatives and their outcome (e.g. solutions based on new technologies) are usually evaluated in regards to their direct impact on a specific performance objective. This concerns the effect of the innovation initiative on the issues that initially triggered it (i.e. problem solving) as well as on other impacted issues (i.e. extended potential) affecting the same performance objective. However, additional business opportunities may lie into the use of the innovation outcome and of the related learnings for addressing other issues (i.e. extended potential) and support further innovation (i.e. innovation) which do not directly affect the initial performance objective. Nevertheless, the indirect applicability of such learnings still represents a source of value, although characterized by a different "localization". This calls for the adoption of a different – and wider – perspective while assessing the business case of an innovation project.

To take into account this "value localization" aspect, we thus proposed the "business case ecosystem" concept. Instead of assessing innovation initiatives and the required investment only against their direct impact on the initial performance objective, we included the indirect value linked to the application of the innovation's learnings to additional company issues, either tackling other performance objectives or sustaining further innovation and the related maturity growth. This is providing support to innovation initiatives' business cases, widening their assessment horizon (Figure 13). This way, the model implies an increase in business value if a longer time perspective and a wider application spectrum of the innovation outcome are considered.

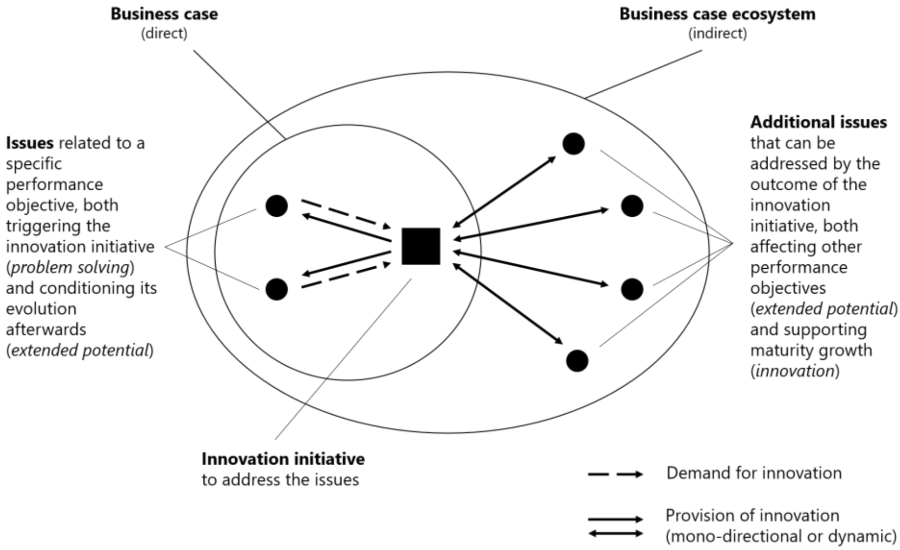

Figure 13: About value localization: the "business case ecosystem" concept (from Colli et al., 2020c)

These three value categories, their different temporal foci and value localization compose what we defined as the "digital transformation focus shift" theoretical model, which intends to support innovators in recognizing additional business opportunities enabled by innovation initiatives, ultimately supporting their business case.

The model has been tested in case of company A, right after the development of two effective, yet financially weak, IoT solutions. If these proved to be capable of addressing the issues that triggered their development, the company stakeholders perceived the estimated business case as unfavourable, jeopardizing the future of the innovation initiative. After a preliminary mapping of the learnings obtained through the development and testing of the two IoT solutions, the "digital transformation focus shift" model has been introduced to all the stakeholders, which reflected on the short- and long-term value lying behind the direct or indirect applicability of the learnings obtained from the innovation initiative. This led to the formulation of the "digital transformation focus shift" matrix (Figure 14), which summarizes the developed theoretical model.

More specifically, the testing of the model highlighted how the innovation initiative, which directly targeted an immediate need for efficiency increase addressing a well-defined operational issue, led to the enabling of a set of additional business opportunities. On the one hand, the new knowledge concerning the domain addressed by the innovation initiative appeared to be applicable for solving other operational issues the company was suffering from (short-term, indirect value). On the other, while performing the innovation project, further efficiency improvement opportunities to be addressed, evolving the outcome of the project also emerged (long-term, direct value). Ultimately, the realization of the obtained learnings and their potential applicability and evolution direction supported the formulation of further innovation opportunities, aligned with the company strategy (long-term, indirect value) (for case-specific information concerning the model testing, see paper VI, Colli et al., 2020c).

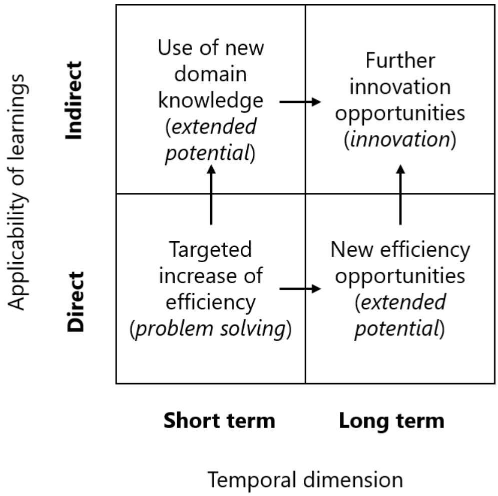

Figure 14: The "digital transformation focus shift" matrix (from Colli et al., 2020c)

Once the emerged business opportunities had been discussed together with the company stakeholders, they led to a change in perception in regards to the innovation initiative's business case. It has been decided, in fact, to follow-up on it, further investigating the pursue of such business opportunities, and to partially implement the developed solutions.

It is worth considering that these business opportunities have been translated in the form of project proposals, arguing which of the obtained learnings would have supported them and how, and discussing their impact on the current operations and on the company's strategy. We can argue that this helped in making them more tangible for the company stakeholders that had to reconsider the innovation initiative's business case. To be able to do so, it was fundamental for the innovators to have a clear understanding of the company's operations as well as of its strategic goals and long-term perspective. The performance of a systematic mapping of the operations (e.g. VSM) and of a digital maturity assessment could have provided further support for identifying additional business opportunities – either related to the extended potential or innovation value categories - and for quantifying their value.

Additional reflections

If the model could indeed facilitate the identification the potential additional applicability of the innovation projects' learnings (and of the related business opportunities), it is also true that their actual capitalization requires additional time and financial resources. This could be a challenge for small and medium enterprises, as they often suffer from a lack of resources (Mittal et al., 2018) and they could have the need to ensure the capitalization on innovation projects sooner than large companies (like case company A), characterized by higher financial availability. If large companies have the freedom to perform several explorative projects, smaller ones often need to make sure that every activity they are going to move forward with can be translated into actual value. This suggests that the relevance of the proposed "digital transformation focus shift" model could be limited by the availability of the resources of the company. Companies with fewer resources available may only consider innovation initiatives directly addressing their core performance objective, and that can ensure a positive business case based on the related short-term benefits (problem-solving). To pursue the business opportunities related to extended potential and innovation value categories implies, in fact, further exploration, additional investments and a higher uncertainty in terms of value capturing.

According to that, we propose that "the perceived value of the additional business opportunities enabled by the learnings obtained from an innovation project is directly proportional to the resource availability of the company". Based on that, we speculate that the proposed theoretical model would, most likely, be effectively applied in large companies.

5.2.3. RESEARCH IMPLICATIONS

This work package addresses the general need, emerged from case companies A, B and C, for supporting the successful integration of IoT and the related enabling of transparency in their supply chains, leading to operational performance improvement. It consists of two main research projects concerning the ability to link the design of IoT solutions and the related enabling of transparency to a specific context (paper IV and paper V) and the use of the learnings obtained during the solution development process for supporting their business case (paper VI).

Theoretical implications

From a theoretical perspective, the research performed in this work package tackles the general problem of translating technology innovation into value. This remains one of the fundamental challenges in the operations management field and, more specifically, in the innovation management body of literature. The matching between the performance of explorative activities, aiming at building new capabilities, and the exploitation of these capabilities, leading towards the capitalization of innovation, is still an issue when introducing new technologies (Papachroni et al., 2015).

Addressing this general issue, we focused our investigations on the digital transformation of supply chains and on one of its key building blocks: the enabling of transparency through the integration of IoT. The proposal of a framework for systematically designing IoT solutions (paper IV), capable of addressing context-specific application needs, answers the demand for academic literature dealing with the integration of new digital technologies in idiosyncratic business processes (Moeuf et al., 2018; Veile et al., 2019; Martinez et al., 2017; Whitmore et al., 2015). This research activity contributes to the operations management body of literature answering to “how can the process of designing an IoT solution be addressed to tailor it to context-specific application needs?”. The progression of the framework is built on top of – and extending the - extant literature highlighting the importance of adopting a process-excellence perspective (Martinez, 2019) and, more in general, value-driven approaches when introducing digital technologies (Westerman, 2018). The testing of the framework in an industrial setting provides empirical evidence about how the adoption of this perspective makes it possible to start the technology implementation process from actual business requirements (Vidgen & Wang, 2009), ensuring a “business-technology alignment” (Chen et al., 2014) and facilitating the exploitation of activity – such as the introduction of a new technology – which is explorative by nature. This represents a practical way to structure the introduction of IoT and the enabling of transparency while addressing the renewed need for matching explorative activities to exploitative needs (Papachroni et al., 2015). Furthermore, it answers the need for understanding how to develop solutions based on IoT (Lu et al., 2018) and how to translate the enabled supply chain transparency into value (Wu et al., 2016; Davenport et al., 2010; Daneshvar Kakhki & Gargeya, 2019). The follow-up conceptual research proposed a self-assessment tool for progressively improving the enabled transparency, adopting the “continuous improvement” approach companies are used to adopt when addressing the digital transformation (Martinez, 2019) and answering “how can companies identify continuous improvement potential related to the integration of IoT?” (paper V).

The successive formulation of the “digital transformation focus shift” theoretical model (paper VI) answers the need for supporting the business case of such innovation initiatives (e.g. the development of IoT solutions for enabling transparency across supply chains), as this is often a critical barrier for companies to succeed in their digital transformation (Schmitz et al., 2019). The performed research investigated the framing of the learnings obtained from an innovation initiative (i.e. the development of an IoT solution) to identify potential business opportunities related to their additional application possibilities and to translate them into business value. This answered the need for “opportunity recognition” Rice et al. (2001) identified and discussed in regards to the application of innovations’ outcome to address additional issues (Rice et al., 2001; McGrath, 1997; Myers & Rosenbloom, 1993; Bowman &

Hurry, 1993; Clark, 1987) or to support further innovation (Rice et al., 2001). This research, while answering "can learnings obtained through explorative innovation initiatives in manufacturing be exploited to support their business cases, and if so, how?", contributes to the need for facilitating the establishment of a management mindset with a broader perception of the "innovation's categorical boundaries" (Anderson & Tushman, 2004), a key driver for succeeding in radical innovation processes.

Managerial implications

From a managerial perspective, the research performed in this work package provides practitioners, on the one hand, with operational guidance for integrating IoT and enabling transparency addressing their specific needs and, on the other, with conceptual indications for identifying and valuing the learnings obtained during the development of such solutions, supporting their business cases.

The IoT solution design framework is meant to provide innovators with a progression of steps - and a set of tools to be adopted to operationalize them - these can adopt to systematically approach the integration of IoT in production operations, linking the development of the solution itself to the specific industrial context and both its needs and business opportunities. This aims at facilitating the development of solutions that are both implementable and effective in addressing relevant issues. The proposal of a self-assessment tool for identifying continuous improvement potential is meant as an approach for following up on it, systematically improving operational performance through the gradual increase of transparency.

The proposed "digital transformation focus shift" theoretical model aims to support innovators in identifying additional business opportunities "hidden" behind the learnings generated from a digital transformation initiative, and the company management in taking them into account when evaluating its business case.

CHAPTER 6. DISCUSSION

This dissertation aimed to both generate an understanding of how the transition towards a digital supply chain could be structured and translated into a competitive advantage and to provide a set of tools and guidelines for supporting this transition (see chapter 1). This was motivated by the need emerged from the operations management literature for frameworks, guidelines and tools for addressing the Industry 4.0 agenda, taking advantage of the new portfolio of technologies and concepts (Büyüközkan & Göçer, 2018). In line with the interests and needs of the case companies engaged in this research project (see chapter 2), the focus of the different research activities was divided between the formulation of digital transformation strategies and the enabling of transparency across the supply chain – a fundamental building block of the digital supply chain – through the integration of IoT. According to what emerged from extant literature in regards to the addressed topics, the study was focused around the capability to link such activities to specific contextual needs and characteristics and to translate them into actual business value (chapter 3).

The novelty of this thesis and its contribution to the operations management body of knowledge, concerns, in promise, the adoption of a contingency theory perspective to study the digital transformation. The operations management research community extensively discussed the importance of taking the context into account when dealing with new practices for improving operational performance (Sousa & Voss, 2008). Our work, mainly addressing the lack of frameworks for structuring and guiding the transformation towards a digital supply chain (Büyüközkan & Göçer, 2018) led to the generation of knowledge keeping a constant eye on the context, its characteristics and needs. At first, concerning the formulation of company-specific digital transformation strategies (Hess et al. 2016; Matt et al., 2015), supporting the identification of the related goals and transformation initiatives. Then the enabling of transparency through the integration of IoT, tailoring technology implementation to contextual characteristics (Moeuf et al., 2018; Martinez et al., 2017; Whitmore et al., 2015; Veile et al., 2019). Here also lied the second main contribution to the operations management literature. To be able to translate the enabling of transparency into actual business value (Daneshvar Kakhki & Gargeya, 2019), our work concerning the integration of IoT to improve operational performance has been building on top of a process excellence perspective. While this contributed, on a more detailed level, to the latest technology implementation research regarding the use of a continuous improvement philosophy or BPR for integrating new digital technologies in supply chains (Martinez, 2019; Ammirato et al., 2019), on a more general level, it contributed to the innovation management body of knowledge addressing the still relevant exploration and exploitation matching issue (Papachroni et al., 2015).

In summary, the contextualization of the transformation – from the formulation of a digital transformation strategy to the enabling of transparency integrating IoT – and the attention towards the matching of explorative activities - inevitable in such a young innovation agenda - and exploitative needs - paramount for its success - represent the two pillars of this dissertation and of the contribution of its research activities.

Table 12 shows the specific contribution of each research activity included in this dissertation (which is further discussed in the related publications and at the end of each work package in the research findings chapter), discussing its usability and robustness. Nevertheless, this dissertation is also meant to stand by itself. As a whole, it aims to provide a knowledge base which supports academics in studying how different contextual factors may affect the digital transformation of a supply chain and practitioners in structuring and operationalizing it accordingly.

Table 12: Overview of the contribution of the different research initiatives in regards to the two addressed topics, of its usability and robustness

Topic	Contribution	Usability	Robustness
Formulation of a digital transformati on strategy	Guidelines to scope the transformation depending on the external context (e.g. national industrial policies) (exogenous factors) (**paper I**)	It provides a real example of how the external context is influencing digital transformation strategies and highlights the importance of considering external contextual factors.	Based on four cases from two different environments
	Methodology to identify transformation initiatives according to the internal context (e.g. maturity, goals, needs) (endogenous factors) (**paper II** and **paper III**)	It provides operational and comprehensive guidelines that lead to a tangible outcome (i.e. the formulation of digital transformation initiatives). Time and resource-consuming, highly dependent on the knowledge of the stakeholders, subjective outcome	Empirically tested in three cases

Integration of IoT for enabling transparency across the supply chain	A framework to design of an IoT solution tailored to the context and leading to operational performance improvement (**paper IV**)	It provides operational and comprehensive guidelines that lead to a tangible outcome (i.e. the design of an IoT solution). Time-consuming, highly dependent on the knowledge of the stakeholders	Empirically tested on a single case and currently adopted by an IoT solution development company
	A framework to identify how to continuously increase supply chain transparency through the integration of IoT (**paper V**)	It provides operational guidelines leading to the identification of transparency improvement potential (i.e. where to integrate IoT depending on the digital maturity of the information flow nodes). It requires an understanding of the technologies adopted to process the information used to support processes	Not tested empirically
	A theoretical model to support the business case of innovation projects through the identification of further business opportunities enabled by their learnings (**paper VI**)	It provides a model for framing innovation initiatives (i.e. the integration of IoT). It requires a comprehensive understanding of the innovation initiative, the addressed processes and of the overall company strategy	Empirically tested on a single case

The adoption of a DSR framework to orchestrate the whole research project (and most of its activities) proved to be an interesting choice for matching academic contributions to industrial relevance. As it often happens with compromises, the risk of not achieving any of the intended results is mixed with the opportunity of capturing both well. We think that the research activities included in this dissertation are closer to the latter, as the related academic articles have been (or are in the process of being) published and the case companies engaged in the activities have generally been satisfied with the research outcome which, in most cases, actively influenced their digital transformation agenda. In retrospective, we may argue that the adoption of a case study methodology would probably have been less challenged (especially by journal reviewers); however, due to its nature, it would have provided lower support and impact for (hopefully, not only) the engaged industrial partners.

The performed research has, however, its limitations. Some are related to its usability, others to its robustness (Table 12). From a usability point of view, the collection of research outcomes, this dissertation builds its discussions on top of are strongly dependent on the knowledge-base and on the skill-set of the user. Whether it is a researcher or a practitioner, the provided guidelines and frameworks, as well as the reflections that emerge from their development and testing, can be read an operationalized assuming an awareness of the Industry 4.0 agenda (introduced in chapter 1) and, more in general, of operations management (e.g. process excellence and lean manufacturing concepts and tools). For this research has the ambition to provide "operational" support for both researchers and practitioners, it is important to consider the audience limitation. In addition to that, the practical use of the proposed methodologies, frameworks and models requires an in-depth understanding of the environment (i.e. the company) where these are to be applied and, for most of them, a significant amount of resources in terms of engaged stakeholders and time. This is mostly due to the lack of prescriptive capabilities related to the proposed artefact and to the need for "understanding the context", a central aspect of the whole dissertation. From a robustness point of view, it is worth considering that most of the outcomes coming from the different research activities collected in this dissertation either are empirically based or have been empirically tested (except paper V). Although this supports the robustness of the research contributions, we need to remember that the industrial cases involved in such research activities were limited and that we performed all the research activities – the testing of the proposed frameworks for instance. This dissertation,, in general, limited its industrial horizon to five prominent industrial cases (A, B, C, D and E, see chapter 2). To discuss the generalizability of the emerged findings and reflections, we will inevitably go back to their characteristics (chapter 2), as these conditioned the outcome of the research activities. We can observe how all companies that originated (and took advantage of) the research outcomes, are large manufacturers operating globally and based in a high-labor cost country (i.e. Denmark), aiming for improving their operational performance from either a cost or a speed perspective. Their shared need consisted of operational support for identifying company-specific digital transformation initiatives and for successfully (economically and operationally) enabling transparency in their supply chains integrating IoT.

Nevertheless, as already discussed when presenting the research design (chapter 4), the generalizability of DSR artefacts lies not in the characteristics of the sample (although this may help us in scoping its application) but in the characteristics of the artefact (Van Aken et al., 2016). It is then worth considering that the outcome of the different research activities has generally been characterized by a strong focus on production operations, focusing on the manufacturing domain, and by a high need for contextual information and engaged stakeholders, implying a certain resource availability to be dedicated to (process) innovation. This may further scope the generalizability of the proposed artefacts around large manufacturing companies, in need for designing their industrial digital transformation and for gradually translating the related explorative activities and maturity growth into operational performance improvement.

CHAPTER 7. CONCLUSIONS

With this research project, we had the chance to empirically investigate topics such as the formulation of company-specific digital transformation strategies and the identification of their initiatives (WP1) as well as at the enabling of transparency across the supply chain through the integration of IoT as well as its translation into business value (WP2). The several research activities we have been performing through this three-year journey provided us with a greater understanding of these topics and with the support for contributing to the extant knowledge-base. At the same time, we had the opportunity to support the engaged industrial partner in their digital transformation journey.

Due to the significant interest in the topics addressed in this dissertation, both from the academic and the industrial sides, we took part of several knowledge dissemination activities, where the findings outlined in this thesis have been presented and discussed. From the academic side, these concerned, in addition to sporadic lecturing at two universities, the publication of several scientific articles on operations management journals and, after conference presentations, on conference proceedings (see chapter 4). From the industrial side, these activities concerned several seminars and workshops as well as MADE events, where both companies and other researchers had the chance to question them, adopt them and to provide their feedback.

These activities also highlighted the additional research efforts that may support the robustness of the research outcomes presented in this dissertation (chapter 6). First of all, their adoption and testing from third parties would tackle the inevitable bias implied by having us testing our own research. Secondly, their testing in a higher number of cases – possibly from diverse industrial sectors – would support and increase their generalizability. Moreover, this would give researchers the chance to identify particularly relevant contextual factors and to observe their effect on the formulation of company-specific digital transformation strategies as well as in the integration of IoT in supply chains. This would enable the development of more prescriptive knowledge and guidelines to further support companies in their digital transformation journey. Finally, as the industrial digital transformation is seen as a maturity progression and since we investigated it at a certain point in time (and generally low maturity stage), we may expect that the increase of digital maturity in manufacturing companies will imply the insurgence of different drivers and barriers concerning their transformation. At a later point, both the formulation of digital transformation strategies or the enabling of transparency through the integration of IoT could require different approaches to be addressed not only effectively but also more efficiently. This will require further research.

Concluding this dissertation, it is worth considering that, as we have discussed throughout this work, the industrial digital transformation is a complex agenda, including a plethora of technologies and concepts on multiple complexity levels. If this research provides a foundation for the transition towards a digital supply chain, future research will need to investigate how to maximize the value potential enabled by such transition. While we looked at how to obtain the “system of systems” described by Porter & Heppelmann (2014) (chapter 1), new Ph.D. candidates will be studying approaches to identify how to translate the novel digital solutions supported by the enabled transparency into new forms of value.

.

LITERATURE LIST

Adler, P. S., & Borys, B. (1996). Two types of bureaucracy: Enabling and coercive. Administrative science quarterly, 61-89.

Adler, P. S., & Clark, K. B. (1991). Behind the learning curve: A sketch of the learning process. Management Science, 37(3), 267-281.

Ahlström, P., Nilsson, F., & Olve, N. G. (2007). Mobilising and nurturing collaboration in research–the value of a focused imagination. International Journal of Action Research, 3(3), 297-323.

Akdil, K. Y., Ustundag, A., & Cevikcan, E. (2018). Maturity and Readiness Model for Industry 4.0 Strategy. In Industry 4.0: Managing The Digital Transformation (pp. 61-94). Springer, Cham.

Ammirato, S., Sofo, F., Felicetti, A. M., & Raso, C. (2019). A methodology to support the adoption of IoT innovation and its application to the Italian bank branch security context. European Journal of Innovation Management, 22(1), 146-174.

Anderson, P., & Tushman, M. L. (Eds.). (2004). Managing strategic innovation and change: A collection of readings. Oxford University Press.

Argote, L., Ingram, P., Levine, J. M., & Moreland, R. L. (2000). Knowledge transfer in organizations: Learning from the experience of others. Organizational behavior and human decision processes, 82(1), 1-8.

Ashton, K. (1999). An Introduction to the Internet of Things (IoT). RFID Journal.

Barge, S. (2010). Principles of Problem and Project Based Learning. The Aalborg PBL Model. Aalborg: Aalborg University

Barker, J. R. (1993). Tightening the iron cage: Concertive control in self-managing teams. Administrative science quarterly, 408-437.

Barney, J., Wright, M., & Ketchen Jr, D. J. (2001). The resource-based view of the firm: Ten years after 1991. Journal of management, 27(6), 625-641.

Barreto, L., Amaral, A., & Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. Procedia Manufacturing, 13, 1245-1252.

Becker, J., Knackstedt, R., & Pöppelbuß, J. (2009). Developing maturity models for IT management. Business & Information Systems Engineering, 1(3), 213-222.

Ben-Daya, M., Hassini, E., & Bahroun, Z. (2019). Internet of things and supply chain management: a literature review. International Journal of Production Research, 57(15-16), 4719-4742.

Bernstein, E. S. (2012). The transparency paradox: A role for privacy in organizational learning and operational control. Administrative Science Quarterly, 57(2), 181-216.

Bharadwaj, A., El Sawy, O. A., Pavlou, P. A., & Venkatraman, N. (2013). Digital business strategy: toward a next generation of insights. MIS quarterly, 471-482.

Boer, H. (2004). Continuous innovation: a challenge and a dilemma. Published as Boer, H.(2004), Continuous innovation: en udfordring og et dilemma. Johansen, J. and Riis, JO, Fremtidens Produktion i Danmark, Copenhagen: Dansk Industri, 65-76.

Boer, H., & Bessant, J. (2004). Organising for Continuous Innovation. In J. Johansen, & J. O. Riis (Eds.), Fremtidens produktion i Danmark

Boer, H., Holweg, M., Kilduff, M., Pagell, M., Shmenner, R., & Voss, C. (2014). Making a meaningful contribution to theory. International Journal of Operations & Production Management.

Bowman, E. H., & Hurry, D. (1993). Strategy through the option lens: An integrated view of resource investments and the incremental-choice process. Academy of management review, 18(4), 760-782.

Boyer, K. K., & Swink, M. L. (2008). Empirical elephants—why multiple methods are essential to quality research in operations and supply chain management. Journal of Operations Management, 26(3), 338-344.

Bozarth, C., McDermott, C. (1998). Configurations in manufacturing strategy: a review and directions for future research. Journal of Operations Management 16 (4), 427–439.

Büyüközkan, G., & Göçer, F. (2018). Digital Supply Chain: Literature review and a proposed framework for future research. Computers in Industry, 97, 157-177.

Caldiera, V. R. B. G., & Rombach, H. D. (1994). The goal question metric approach. Encyclopedia of software engineering, 528-532.

Cambridge Dictionary. (2020). Strategy. Retrieved July 28, 2020, from https://dictionary.cambridge.org/dictionary/english/strategy

Canetta, L., Barni, A., & Montini, E. (2018, June). Development of a Digitalization Maturity Model for the manufacturing sector. In 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-7). IEEE.

Cartwright, N. (1983), How the Laws of Physics Lie, Clarendon Press, Oxford.

Chen, K. L., Li, C., & Møller, C. (2019). Bootstrapping Product-Service Business: An Experimental Data-Driven Approach. In ISPIM Conference Proceedings (pp. 1-18). The International Society for Professional Innovation Management (ISPIM).

Chen, S., Xu, H., Liu, D., Hu, B., & Wang, H. (2014). A vision of IoT: Applications, challenges, and opportunities with china perspective. IEEE Internet of Things journal, 1(4), 349-359.

Cheng, Y., Chaudhuri, A., & Farooq, S. (2016). Interplant coordination, supply chain integration, and operational performance of a plant in a manufacturing network: a mediation analysis. Supply Chain Management: An International Journal.

Clark, K. (1987). Investment in new technology and competitive advantage. The competitive challenge, 59(82), 543-565.

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.

Colli, M., Cavalieri, S., Cimini, C., Madsen, O., & Vejrum Wæhrens, B. (2020a). Digital Transformation Strategies for Achieving Operational Excellence: a Cross-Country Evaluation. In Proceedings of the 53rd Hawaii International Conference on System Sciences.

Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., & Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. Ifac-papersonline, 51(11), 1347-1352.

Colli, M., Berger, U., Bockholt, M., Madsen, O., Møller, C., & Wæhrens, B. V. (2019a). A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era. Annual Reviews in Control, 48, 165-177.

Colli, M., Madsen, O., & Wæhrens, B. V. (2020b). Designing IoT solutions for improving operational performance: a systematic approach. In review for the Journal of Manufacturing Technology Management

Colli, M., Stingl, V., & Wæhrens, B. V. (2020c). Making or breaking the business case of digital transformation initiatives: the key role of learnings. In review for the Journal of Manufacturing Technology Management

Colli, M., Kristensen, J. H., Bockholt, M. T., & Wæhrens, B. V. (2019b). Circular economy in the Industry 4.0 era: Transparency's effect on the feasibility of a take-back program. 6th International EUROMA Sustainable Operations and Supply Chains Forum

Colli, M., Asmussen, C. B., & Wæhrens, B. V. (2020d). Translating digital maturity increase into quality performance: evidences from the dairy industry. Proceedings of the XXV Summer School Francesco Turco. Accepted

Crosby, P. B., & Free, Q. I. (1979). The art of making quality certain. New York: New American Library, 17.

Daft, R. L., & Lengel, R. H. (1986). Organizational information requirements, media richness and structural design. Management science, 32(5), 554-571.

Daneshvar Kakhki, M., & Gargeya, V. B. (2019). Information systems for supply chain management: a systematic literature analysis. International Journal of Production Research, 57(15-16), 5318-5339.

Davenport, T. H., Harris, J. G., & Morison, R. (2010). Analytics at work: Smarter decisions, better results. Harvard Business Press.

Davies, R. (2015). Industry 4.0 Digitalisation for productivity and growth. European Parliamentary Research Service, 10

De Carolis, A., Macchi, M. , Negri, E., & Terzi, S. (2017). A Maturity Model for Assessing the Digital Readiness of Manufacturing Companies. IFIP International Federation for Information Processing 2017. Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing. APMS 2017, Part I, IFIP AICT 513, pp. 13-20, 2017

De la Boutetière, H., Montagner, A., & Reich, A. (2018). Unlocking success in digital transformations. McKinsey & Company, October, Available Online: https://mck.co/2AzwomG [Accessed 10 May 2019]

Deming, W. E. (1986). Out of the Crisis. Cambridge, MA: Center for Advanced Engineering Study. Massachusetts Institute of Technology.

Donaldson, L. (2001). The contingency theory of organizations. Sage.

Drazin, R., & Van de Ven, A. H. (1985). Alternative forms of fit in contingency theory. Administrative science quarterly, 514-539.

Dubin, R. (1976). Theory building in applied area. Handbook of industrial and organizational psychology.

Ehret, M., & Wirtz, J. (2017). Unlocking value from machines: business models and the industrial internet of things. Journal of Marketing Management, 33(1-2), 111-130.

European Commission. (2017). European countries join forces to digitise industry. Shaping Europe’s Digital Future - European Commission. https://ec.europa.eu/digital-single-market/en/news/european-countries-join-forces-digitise-industry

Ferdows, K., A. De Meyer. (1990). Lasting improvements in manufacturing performance: In search of a new theory. Journal of Operations Management 9(2) 168–184.

Flynn, B., J. Flynn. (2004). An exploratory study of the nature of cumulative capabilities. Journal of Operations Management 22(5) 439–457.

Flynn, B. B., & Flynn, E. J. (1999). Information‐processing alternatives for coping with manufacturing environment complexity. Decision Sciences, 30(4), 1021-1052.

Frohlich, M. T., & Westbrook, R. (2002). Demand chain management in manufacturing and services: web-based integration, drivers and performance. Journal of operations Management, 20(6), 729-745.

Ganzarain, J., & Errasti, N. (2016). Three stage maturity model in SME's toward industry 4.0. Journal of Industrial Engineering and Management (JIEM), 9(5), 1119-1128.

Geissbauer, R., Vedso, J., & Schrauf, S. (2016). Industry 4.0: Building the digital enterprise. Retrieved from PwC Website: https://www. pwc. com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016. pdf.

Gökalp, E., Şener, U., & Eren, P. E. (2017). Development of an assessment model for industry 4.0: industry 4.0-MM. In International Conference on Software Process Improvement and Capability Determination (pp. 128-142). Springer, Cham.

Goodhue, D. L., & Thompson, R. L. (1995). Task-technology fit and individual performance. MIS quarterly, 213-236.

Grover, V., & Kohli, R. (2013). Revealing your hand: caveats in implementing digital business strategy. Mis Quarterly, 655-662.

Grube, D., Malik, A. A., & Bilberg, A. (2017). GENERIC CHALLENGES AND AUTOMATION SOLUTIONS IN MANUFACTURING SMES. Annals of DAAAM & Proceedings, 28.

Gubbi, J., Buyya, R., Marusic, S., and Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. Future generation computer systems, 29(7), 1645-1660.

Haddud, A., DeSouza, A., Khare, A., & Lee, H. (2017). Examining potential benefits and challenges associated with the Internet of Things integration in supply chains. Journal of Manufacturing Technology Management.

Haleem, F., Farooq, S., Wæhrens, B. V., & Boer, H. (2018). Offshoring experience and performance: the role of realized drivers and risk management. Supply Chain Management: An International Journal.

Hammer, M., & Champy, J. (1993). Business process reengineering. London: Nicholas Brealey, 444(10), 730-755.

Hansen, M. T. (1999). The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits. Administrative science quarterly, 44(1), 82-111.

He, Z-L., & Wong, P-K. (2004). Exploration vs. exploitation: An empirical test of the ambidexterity hypothesis. Organization Science, 15, 481-494.

Hess, T., Matt, C., Benlian, A., & Wiesböck, F. (2016). Options for formulating a digital transformation strategy. MIS Quarterly Executive, 15(2).

Hevner, A. R., March, S. T., Park, J., and Ram, S. (2004). Design science in information systems research. Management Information Systems, vol. 28, No. 1, pp. 75-105

Holcomb, M. C., Ponomarov, S. Y., & Manrodt, K. B. (2011, January). The relationship of supply chain visibility to firm performance. In Supply Chain Forum: An International Journal (Vol. 12, No. 2, pp. 32-45). Taylor & Francis.

Holmström, J., Ketokivi, M., & Hameri, A. P. (2009). Bridging practice and theory: A design science approach. Decision Sciences, 40(1), 65-87.

Hyatt, L., Hyatt, B., & Hyatt, J. (2007). Effective leadership through emotional maturity. Academic Leadership: The Online Journal, 5(2), 4.

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

Jayaram, A. (2016, December). Lean six sigma approach for global supply chain management using industry 4.0 and IIoT. In 2016 2nd international conference on contemporary computing and informatics (IC3I) (pp. 89-94). IEEE.

Johnson, M. E., & Whang, S. (2002). E-business and supply chain management: an overview and framework. Production and Operations management, 11(4), 413-423.

Kagermann, H., Wahlster, W., & Helbig, J. (2013). Recommendations for implementing the strategic initiative Industrie 4.0. Acatech, April 2013

Kakhki, M. D., Nemati, H., & Hassanzadeh, F. (2018). A Virtual Supply Chain System for Improved Information Sharing and Decision Making. International Journal of Business Analytics (IJBAN), 5(1), 16-32.

Kane, G. C., Palmer, D., Phillips, A. N., Kiron, D., & Buckley, N. (2015). Strategy, not technology, drives digital transformation. MIT Sloan Management Review and Deloitte University Press, 14(1-25).

Kane, G. C., Palmer, D., Phillips, A. N., Kiron, D., &Buckley, N. (2017). Achieving Digital Maturity. MIT Sloan Management Review and Deloitte University Press, July 2017.

Ketokivi, M. (2006). Elaborating the contingency theory of organizations: the case of manufacturing flexibility strategies. Production and Operations Management 15 (2), 215–228.

King, J. L., Gurbaxani, V., Kraemer, K. L., McFarlan, F. W., Raman, K. S., & Yap, C. S. (1994). Institutional factors in information technology innovation. Information systems research, 5(2), 139-169.

Klimko, G. (2001, November). Knowledge management and maturity models: Building common understanding. In Proceedings of the 2nd European Conference on Knowledge Management (pp. 269-278). Bled, Slovenia.

Klingenberg, C. O., Borges, M. A. V., & Antunes Jr, J. A. V. (2019). Industry 4.0 as a data-driven paradigm: a systematic literature review on technologies. Journal of Manufacturing Technology Management.

Kohlegger, M., Maier, R., & Thalmann, S. (2009). Understanding maturity models. Results of a structured content analysis (pp. 51-61).

Kohli, R., & Grover, V. (2008). Business value of IT: An essay on expanding research directions to keep up with the times. Journal of the association for information systems, 9(1), 1.

Laudan, L. (1977). Progress and its problems. Berkeley.

Lee, I., & Lee, K. (2015). The Internet of Things (IoT): Applications, investments, and challenges for enterprises. Business Horizons, 58(4), 431-440.

Lee, J., Jun, S., Chang, T. W., & Park, J. (2017). A smartness assessment framework for smart factories using analytic network process. Sustainability, 9(5), 794.

Lee, J. H., Phaal, R., & Lee, S. H. (2013). An integrated service-device-technology roadmap for smart city development. Technological Forecasting and Social Change, 80(2), 286-306.

Lewin, K. (1997). Action research and minority problems. In: Lewin K. Resolving Social Conflicts, 143-154. Washington D.C.: American Psychological Association (Original publication, 1946)

Lewis, M. W. (1998). Iterative triangulation: a theory development process using existing case studies. Journal of operations Management, 16(4), 455-469.

Leyh, C., Schäffer, T., & Forstenhäusler, S. (2016). SIMMI 4.0–Vorschlag eines Reifegradmodells zur Klassifikation der unternehmensweiten Anwendungssystemlandschaft mit Fokus Industrie 4.0. Proceedings zur Multikonferenz Wirtschaftsinformatik (MKWI), 1651-1662.

Lewin, K. (1997). Action research and minority problems. In: Resolving Social Conflicts, 143-154. Washington D.C.: American Psychological Association (Original publication, 1946)

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.

Liao, Y., Loures, E. R., Deschamps, F., Brezinski, G., & Venâncio, A. (2018). The impact of the fourth industrial revolution: a cross-country/region comparison. Production, 28.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., Schmitt, K., Schmitz, E., & Schröter, M. (2015). "IMPULS - Industrie 4.0- Readiness". Impuls-Stiftung des VDMA, Aachen-Köln

Lipczynski, J., Wilson, J. O., & Goddard, J. A. (2005). Industrial organization: competition, strategy, policy. Pearson Education.

Liu, T., & Lu, D. (2012). The application and development of IoT. In 2012 International Symposium on Information Technologies in Medicine and Education, Vol. 2, pp. 991-994.

Lu, Y., Papagiannidis, S., and Alamanos, E. (2018). Internet of Things: A systematic review of the business literature from the user and organisational perspectives. Technological Forecasting and Social Change, 136, 285-297.

Lugert, A., Batz, A., & Winkler, H. (2018). Empirical assessment of the future adequacy of value stream mapping in manufacturing industries. Journal of Manufacturing Technology Management.

Lundvall, B. Å., Johnson, B., Andersen, E. S., & Dalum, B. (2002). National systems of production, innovation and competence building. Research policy, 31(2), 213-231.

Lundvall, B. Å. (Ed.). (2010). National systems of innovation: Toward a theory of innovation and interactive learning (Vol. 2). Anthem press.

Madsen, O., & Møller, C. (2017). The AAU Smart Production Laboratory for teaching and research in emerging digital manufacturing technologies. Procedia Manufacturing, Vol. 9, pp. 106-112

Martinez, F., Jirsak, P., & Lorenc, M. (2017). Implications, Applications, Trends, and Topics of Industry 4.0. In International Business and Management Conference (pp. 213-216).

Martinez, F. (2019). Process excellence the key for digitalisation. Business Process Management Journal.

Matt, C., Hess, T., & Benlian, A. (2015). Digital transformation strategies. Business & Information Systems Engineering, 57(5), 339-343.

Matheson, C. (2009). Understanding the policy process: The work of Henry Mintzberg. Public Administration Review, 69(6), 1148-1161.

McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. Journal of operations management, 11(3), 239-256.

McGrath, R. G. (1997). A real options logic for initiating technology positioning investments. Academy of management review, 22(4), 974-996.

Miller, J. G., & Roth, A. V. (1994). A Taxonomy of Manufacturing Strategies. Management Science, vol. 40 (3), pp. 285–304

Mishra, D., Gunasekaran, A., Childe, S. J., Papadopoulos, T., Dubey, R., & Wamba, S. (2016). Vision, applications and future challenges of Internet of Things. Industrial Management & Data Systems, 116(7), 1331-1355.

Mittal, S., Khan, M. A., Romero, D., & Wuest, T. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of manufacturing systems, 49, 194-214.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., & Barbaray, R. (2018). The industrial management of SMEs in the era of Industry 4.0. International Journal of Production Research, 56(3), 1118-1136.

Myers, M. B., & Rosenbloom, R. S. (1993, February). Research management and corporate renewal. In Conference on the Future of Industrial Research.

Mykhaylenko, A., Motika, Á., Waehrens, B. V., & Slepniov, D. (2015). Accessing offshoring advantages: what and how to offshore. Strategic Outsourcing: An International Journal, 8(2/3), 262-283.

Mykhaylenko, A., Waehrens, B. V., & Slepniov, D. (2017). The impact of distance on headquarters' network management capabilities. Journal of Manufacturing Technology Management.

Nolan, R. L. (1979). Managing Crises of Data Processing. Harvard business review, 3(4).

Nygaard, J., Colli, M., & Wæhrens, B. V. (2020). A self-assessment framework for supporting continuous improvement through IoT integration. Procedia Manufacturing, 42, 344-350.

O'Reilly, C. A., & Tushman, M. L. (2004). The ambidextrous organization. Harvard Business Review, 82, 74-81.

O'Reilly, C. A., & Tushman, M. L. (2008). Ambidexterity as a dynamic capability: Resolving the innovator's dilemma. Research in Organizational Behavior, 28, 185-206.

Overby, E., Bharadwaj, A., & Sambamurthy, V. (2006). Enterprise agility and the enabling role of information technology. European Journal of Information Systems, 15(2), 120-131.

Papachroni, A., Heracleous, L., & Paroutis, S. (2015). Organizational ambidexterity through the lens of paradox theory: Building a novel research agenda. The Journal of Applied Behavioral Science, 51(1), 71-93.

Pelz, D. C. (1978). Some expanded perspectives on use of social science in public policy. Major social issues: A multidisciplinary view.

Pöppelbuß, J. and Röglinger, M. (2011), What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management. 19th European Conference on Information Systems (ECIS 2011). Helsinki, Finland

Porter, M. E. (1981). The contributions of industrial organization to strategic management. Academy of management review, 6(4), 609-620.

Porter, M. E. (1990). The competitive advantage of nations: with a new introduction. Free Pr.

Porter, M. E., & Heppelmann, J. E. (2014). How smart, connected products are transforming competition. Harvard business review, 92(11), 64-88.

Porter, M. E., and Heppelmann, J. E. (2015). How smart, connected products are transforming companies. Harvard Business Review, 93(10), 96-114.

Quesnay, F. (1766). Analyse de la formule arithmétique du tableau économique de la distribution des dépenses annuelles d'une nation agricole (juin 1766).

Qin, J., Liu, Y., & Grosvenor, R. (2016). A categorical framework of manufacturing for industry 4.0 and beyond. Procedia Cirp, 52, 173-178.

Raab, M., & Griffin-Cryan, B. (2011). Digital transformation of supply chains. Creating Value–When Digital Meets Physical, Capgemini Consulting.

Radziwon, A., Bogers, M., & Bilberg, A. (2017). Creating and capturing value in a regional innovation ecosystem: a study of how manufacturing SMEs develop collaborative solutions. International Journal of Technology Management, 75(1-4), 73-96.

Rice, M. P., & Kelley, D. J. (1997). Opportunity recognition in the domain of discontinuous innovation: An exploratory study. In Proceedings of the Babson College–Kauffman Foundation Entrepreneurship Conference (pp. 679-680). University of Washington, Seattle.

Rice, M., Kelley, D., Peters, L. and Colarelli O'Connor, G. (2001), Radical innovation: triggering initiation of opportunity recognition and evaluation. R&D Management, 31: 409-420. doi:10.1111/1467-9310.00228

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., & Terzi, S. (2020). Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. International Journal of Production Research, 58(6), 1662-1687.

Rosenzweig, E. D., Roth, A. V., & Dean Jr, J. W. (2003). The influence of an integration strategy on competitive capabilities and business performance: an exploratory study of consumer products manufacturers. Journal of operations management, 21(4), 437-456.

Rosenzweig, E. D., Roth, A. V. (2004). Towards a Theory of Competitive Progression: Evidence from High-Tech Manufacturing. Production and Operations Management 13(4), pp. 354–368

Rosenzweig, E. D. (2009). A contingent view of e-collaboration and performance in manufacturing. Journal of Operations Management, 27(6), 462-478.

Roth, A.V. (1996). Neo-operations strategy: linking capabilities-based competition to technology. In: Gaynor, G. (Ed.), Handbook of Technology Management. McGraw-Hill, New York, NY, pp. 38.1–38.44.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. Boston Consulting Group, 9(1), 54-89.

Şahin, H., & Topal, B. (2019). Examination of effect of information sharing on businesses performance in the supply chain process. International Journal of Production Research, 57(3), 815-828.

Savery, J. R., & Duffy, T. M. (1996). Problem Based Learning: An Instructional Model And Its Constructivist Framework. In Constructivist Learning Environments: Case Studies in Instructional Design (Wilson, B. G.), pp. 135-148

Schein, E. H. (1995). Process consultation, action research and clinical inquiry, are they the same? Journal of Managerial Psychology, 10(6): 14-19

Schein, E. H. (2008). Clinical inquiry/research. In: Reason, P. and Bradbury, H. (eds) The SAGE Handbook of Action Research, 2nd edn, 266-279. London: SAGE Publications

Schein, E. H. (2009). Helping. San Francisco, CA: Berrett-Kohler

Schmidt, H. G. (1983), Problem-based learning: rationale and description. Medical Education, vol. 17, pp. 11–16

Schmitz, C., Tschiesner, A., Jansen, C., Hallerstede, S., Garms, F. (2019). Industry 4.0. Capturing value at scale in discrete manufacturing, McKinsey and Company. Retrieved from https://www.mckinsey.com/~/media/mckinsey/industries/advanced%20electronics/our%20insights/capturing%20value%20at%20scale%20in%20discrete%20manufacturing%20with%20industry%204%200/industry-4-0-capturing-value-at-scale-in-discrete-manufacturing-vf.ashx

Schrauf, S., & Berttram P. (2016). How digitization makes the supply chain more efficient, agile and customer-focused. PWC, published September 7, 2016

Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M., & Wahlster, W. (2017). Industrie 4.0 Maturity Index Managing the Digital Transformation of Companies. Acatech Study, April 2017

Schumacher, A., Erol, S., & Sihn, W. (2016). A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. In proceedings of Sixth International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2016), Bath, UK, 4-6 Sep. 2016

Scremin, L., Armellini, F., Brun, A., Solar-Pelletier, L., & Beaudry, C. (2018). Towards a Framework for Assessing the Maturity of Manufacturing Companies in Industry 4.0 Adoption. In Analyzing the Impacts of Industry 4.0 in Modern Business Environments(pp. 224-254). IGI Global.

Sewell, G. (1998). The discipline of teams: The control of team-based industrial work through electronic and peer surveillance. Administrative science quarterly, 397-428.

Shewhart, W. A. (1931). Economic control of quality of manufactured product. ASQ Quality Press.

Siggelkow, N., & Terwiesch, C. (2019). The Age of Continuous Connection New technologies have made 24/7 customer relationships possible. It's time to change your business model accordingly. Harvard Business Review, 97(3), 63-73.

Simon, H. A. (1996). Designing organizations for an information-rich world. International Library of Critical Writings in Economics, 70, 187-202.

Sink, D. S., Tuttle, T. C., & Shin, S. I. (1989). Planning and measurement in your organization of the future (pp. 170-84). Norcross, GA: Industrial Engineering and Management Press.

Skinner, W. (1969). Manufacturing—the missing link in corporate strategy. Harvard Business Review 47 (May/June), 136–144.

Solli-Sæther, H., & Gottschalk, P. (2010). The modeling process for stage models. Journal of Organizational Computing and Electronic Commerce, 20(3), 279-293.

Sousa, R., & Voss, C. A. (2008). Contingency research in operations management practices. Journal of Operations Management, 26(6), 697-713.Tangen, S. (2005). Demystifying productivity and performance. International Journal of Productivity and performance management.

Sutcliffe, K.M., S.B. Sitkin and L.D. Browning (2000), "Tailoring process management to situational requirements", in: R.E. Cole and W.R. Scott (eds.), The quality movement & organization theory, Sage Publications, Thousand Oaks (Cal.).

Tang, C. S. (2016). OM forum—making OM research more relevant:"why?" and "how?". Manufacturing & Service Operations Management, 18(2), 178-183.

Torrecilla-Salinas, C. J., Sedeño, J., Escalona, M. J., & Mejías, M. (2016). Agile, Web Engineering and Capability Maturity Model Integration: A systematic literature review. Information and Software Technology, 71, 92-107.

Tortorella, G. L., & Fettermann, D. (2018). Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. International Journal of Production Research, 56(8), 2975-2987.

Tu, M. (2018). An exploratory study of Internet of Things (IoT) adoption intention in logistics and supply chain management. The International Journal of Logistics Management.

Turilli, M., & Floridi, L. (2009). The ethics of information transparency. Ethics and Information Technology, 11(2), 105-112.

Tushman, M., & Nadler, D. (1986). Organizing for innovation. California management review, 28(3), 74-92.

UNIDO and Policy Links (2017). Emerging Trends In Global Advanced Manufacturing: Challenges, Opportunities and Policy Responses. Institute for Manufacturing, University of Cambridge, Cambridge

Vaccaro, A., & Madsen, P. (2006, September). Firm information transparency: Ethical questions in the information age. In IFIP International Conference on Human Choice and Computers (pp. 145-156). Springer, Boston, MA.

Vaishnavi, V., Kuechler, W. (2008). Design Science Research Methods and Patterns, Innovating Information and Communication Technology. CRC Press, Taylor & Francis Group. Pag. 31

Van Aken, J., Chandrasekaran, A., and Halman, J. (2016). Conducting and publishing design science research: Inaugural essay of the design science department of the Journal of Operations Management. Journal of Operations Management, 47, 1-8.

Van de Vrande, V., De Jong, J. P., Vanhaverbeke, W., & De Rochemont, M. (2009). Open innovation in SMEs: Trends, motives and management challenges. Technovation, 29(6-7), 423-437.

Van Mieghem, J. A. (2013). OM forum—Three Rs of operations management: Research, relevance, and rewards. Manufacturing & Service Operations Management, 15(1), 2-5.

Veile, J. W., Kiel, D., Müller, J. M., & Voigt, K. I. (2019). Lessons learned from Industry 4.0 implementation in the German manufacturing industry. Journal of Manufacturing Technology Management.

Vidgen, R., & Wang, X. (2009). Coevolving systems and the organization of agile software development. Information Systems Research, 20(3), 355-376.

Vishwakarma, N. K., Singh, R. K., & Sharma, R. R. K. (2019). Internet of things architectures: do organizational strategies matters?. Business Process Management Journal.

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. International journal of operations & production management.

Wæhrens, B. V., Slepniov, D., & Johansen, J. (2015). Offshoring practices of Danish and Swedish SMEs: effects on operations configuration. Production Planning & Control, 26(9), 693-705.

Wang, S., Wan, J., Zhang, D., Li, D., and 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.

Wee, D., Kelly, R., Cattel, J., & Breunig, M. (2015). Industry 4.0-how to navigate digitization of the manufacturing sector. McKinsey & Company, 58.

Westerman, G. (2018). Your Company Doesn't Need a Digital Strategy. MIT Sloan Management Review, 59(3), 1-5.

Whitmore, A., Agarwal, A., and Da Xu, L. (2015). The Internet of Things—A survey of topics and trends. Information Systems Frontiers, 17(2), 261-274.

Williams, B. D., Roh, J., Tokar, T., & Swink, M. (2013). Leveraging supply chain visibility for responsiveness: The moderating role of internal integration. Journal of Operations Management, 31(7-8), 543-554.

Winkler, B. (2000). Which kind of transparency? On the need for clarity in monetary policy-making. Frankfurt: European Central Bank.

Wu, L., Yue, X., Jin, A., & Yen, D. C. (2016). Smart supply chain management: a review and implications for future research. The International Journal of Logistics Management.

Yin, R. K. (2014). Case study research, design and methods, SAGE Publications Inc.

Zelbst, P. J., Green, K. W., Sower, V. E., & Bond, P. L. (2019). The impact of RFID, IIoT, and Blockchain technologies on supply chain transparency. Journal of Manufacturing Technology Management.

Zhu, S., Song, J., Hazen, B. T., Lee, K., & Cegielski, C. (2018). How supply chain analytics enables operational supply chain transparency. International Journal of Physical Distribution & Logistics Management

ISSN (online): 2446-1636
ISBN (online): 978-87-7210-801-8

AALBORG UNIVERSITY PRESS